Gaps Assessment and Impacts Document

(Version 5.0)

GAIA-CLIM
Gap Analysis for Integrated
Atmospheric ECV Climate Monitoring
Mar 2015 - Feb 2018

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Work Package 6; Edited by Michiel van Weele (KNMI)

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Executive Summary

In the GAIA-CLIM project (2015 - 2018) an assessment was made of the global capabilities to use ground-based, balloon-borne and aircraft measurements (termed non-satellite measurements henceforth) to better characterise space-borne satellite measurement systems.

To achieve this the following specific project tasks were undertaken:

1. Defining and mapping of existing non-satellite measurement capabilities;
2. Improving the metrological characterisation of a subset of non-satellite (reference) observational techniques;
3. Better accounting for co-location mismatches between satellite observations and non-satellite (reference) observations;
4. Exploring the role of data assimilation as an integrator of information;
5. Creation of a ***Virtual Observatory*** bringing together all comparison data, including their uncertainties, and providing public access to the information they contain;
6. Identifying and prioritizing gaps in knowledge and capabilities.

Under Task 6, an in-depth gaps assessment was made. Within the definition used in GAIA-CLIM gaps constitute ***unfulfilled user needs*** with respect to capabilities and/or knowledge relevant to the use of non-satellite data to better characterise satellite measurements of a set of Essential Climate Variables (ECVs). Any such gaps assessment is by definition limited through its neglect of currently fulfilled user needs which (a) may not necessarily be sustainable in the long-term and (b) may experience funding competition arising from enacting some of the remedies to identified unfulfilled user needs, potentially creating new gaps. For the GAIA-CLIM gap assessment within each of the Tasks 1 to 6 as outlined above, presently unfulfilled user needs (gaps) have been identified, discussed and reviewed internally and externally, and iteratively improved during the 3-year GAIA-CLIM project.

We note that this assessment was deliberately limited to gaps identified as being within the project scope of GAIA-CLIM, i.e., to assess and improve capabilities to use non-satellite measurements to characterise satellite measurement systems. A much wider gap assessment on ECVs and other observables has been performed in, *e.g.*, the H2020 project ConnectinGEO or as part of GCOS adequacy reports. The gaps identified for ECVs in GAIA-CLIM have been added to the collected set of gaps that has been identified in ConnectinGEO.

Within GAIA-CLIM, a set of key user communities were identified for whom the impact of the identified gaps would be most relevant. These user communities include:

- Service providers (ECMWF Copernicus services CAMS/C3S, as well as national providers)
- Users and providers of Essential Climate Variable (ECV) data records (GCOS, Space agencies and satellite data user communities)
- Users of reference observations
- Users of baseline network observations
- Users that would like to match different types of observations, e.g., through the GAIA-CLIM ***Virtual Observatory*** tool

For each gap and remedy specific potential actors related to these user communities were identified. This Gaps Assessment and Impacts Document (GAID) summarises the project outcome of the collection of gaps and includes a detailed overview of proposed remedies. This document is the fifth and final version of the living document used during the project.

The purpose of the GAID is threefold:

- to provide an overview of the information content on the final set of gaps and remedies assembled in the on-line Catalogue of Gaps[1],
- to provide an analysis of these final gaps and remedies by taking some cross-sections through the catalogue: along type of gap and type of remedy, instrument technique, costs and time scale of the remedies, and potential actors addressed
- to document and justify the process that has led to the final set of gaps and remedies

The gap remedies were drafted such that they would constitute a plausible description of specific work in a funding call: time bound, assigned to potential actors and with an indicative coast estimate. Each of the gaps and remedies in the on-line catalogue could finally be assigned as a traceable cornerstone for one of the overall project recommendations provided in Deliverable 6.10 “Recommendations document to address gaps in observing capabilities”. In the end, the GAID provided the detailed justifications and the traceability for the unfulfilled user needs underlying these final project recommendations.

The evolutionary process to fill the GAID and catalogue, from scratch to full maturity throughout the 3-year project, very much helped to structure and provide actionable, traceable project recommendations. The process included intensive internal inputs and external consultation.

Internally, the project structure with repeating deliverables (three times over the 3-years project duration) for each of the Tasks 1 to 6 has worked well to provide improved and complete sets of gaps and remedies.

External reviews further shaped the contents of the on-line catalogue. Comments on earlier versions of this GAID were invited from external parties. From the outset of the project a designated e-mail address and a specific template for gap reporting was provided at the project website. Extensive user engagement was achieved further via a user survey, two user workshops and a series of visits to key stakeholders throughout the second half of the final year of the project. This extensive and actively sought user feedback was considered very important in both refining the GAID and in ensuring its usefulness to different user communities as well as space agencies, international organisations and funding bodies, and also in creating broad user awareness of the specific recommendations and their underlying gaps and remedies arising from GAIA-CLIM.

The ‘*Catalogue of Gaps’* included in Annex C provides the full content of the final collected set of 41 gaps and associated remedies. After the end of the project the catalogue will remain online available from: http://www.gaia-clim.eu/page/gap-reference-list.

[1] The contents of the online Catalogue of Gaps - per end of project - is provided in Annex C of this document

GAID version history

Version	Principal updates	Owner	Date
0	Framework document	KNMI	9 April 2015
1.0	First version including the inputs received per work package by end of June 2015 through D1.1, D1.2, D1.3, D1.4, D1.5, and D6.1 and reviewed by work package leads in September 2015.	KNMI	10 September 2015
1.1	Interim version including author suggestions in preparation of v2.0	KNMI	4 November 2015
2.0	Version 2 is based on all inputs received by December 2015, including the results of the first user workshop, and reviewed by work package leads in January 2016; The public version does not indicate the personal e-mail addresses of the gap owners	KNMI	24 February 2016
3.0	Version 3 is rather drastically restructured and simplified compared to GAID versions 1 and 2. The Catalogue of Gaps which has been defined is kept up-to-date online at the project website. The most recent copy of the catalogue is included here. The new content in GAID Version 3 is based on the input materials received until early August 2016 and this includes the set of deliverables D1.4, D2.2, D3.3, D4.3 and D5.2. An updated list of governance gaps has been included by work package 6.	KNMI	31 August 2016
4.0	Version 4 is updated from version 3 to include in Section 2 the template used to identify the gaps and their remedies. The cross-sections through the list of gaps and remedies in Section 3 have been updated and extended. An updated and consolidated list of gaps is included in the Annex. Texts in the different sections have been updated and modified.	KNMI	16 May 2017

5.0	Version 5 is updated from version 4 using the gap changes proposed in the final deliverables providing input to the GAID from the individual workpackages (D1.12; D2.9, D3.8; D5.6; D6.12), D6.9 “Report on external stakeholder consultation exercise”. Annex A contains the Catalogue of Gaps per end of project.	KNMI	2 March 2018

1 Introduction

In the GAIA-CLIM project (2016 - 2018) an assessment was made of the global capabilities to use ground-based, balloon-borne and aircraft measurements (termed non-satellite measurements henceforth) to characterise space-borne satellite measurement systems. To achieve this the following activities were undertaken:

1. Defining and mapping of existing non-satellite measurement capabilities;
2. Improving the metrological characterisation of a subset of non-satellite (reference) observational techniques;
3. Better accounting for co-location mismatches between satellite observations and non-satellite (reference) observations;
4. Exploring the role of data assimilation as an integrator of information;
5. Creation of a ***Virtual Observatory*** bringing together all comparison data, including their uncertainties, and providing public access to the information they contain;
6. Identifying and prioritizing gaps in knowledge and capabilities.

In each of these tasks, the currently most important gaps have been identified and assessed. Within the definition used in GAIA-CLIM gaps constitute ***unfulfilled user needs*** with respect to capabilities and/or knowledge relevant to the use of non-satellite data to better characterise satellite measurements of a set of target Essential Climate Variables (ECVs).

Background: The need for a non-satellite ECV monitoring capacity

Europe has taken a leading role in the global Earth Observation constellation with the development of its own operational space infrastructure. This implies an increased need for assessment of and planning for observations from space. The growing European space infrastructure for climate monitoring builds upon the existing European geostationary (*Meteosat*, since 1977) and low-earth orbit (*MetOp*, since 2006) operational monitoring capacity in space, supporting the operational meteorological and climate services. It is currently being extended with *Sentinels*, forming the Copernicus Space Segment (CSS). A first set of Sentinels is now in orbit and several subsequent Sentinels are to be launched within the next few years. The long-term evolution of the CSS into its second generation during the next decade is under active development. In addition, ESA research satellites form an important component of Europe’s space segment.

To maximise the return on investment in the expanding European space infrastructure, a sustained and high quality characterisation capability, using both satellite and non-satellite data, is required. A multi-faceted approach is required for the production of sustained homogenized time series of Essential Climate Variables (ECVs) at both global and regional scales. The activities should include non-satellite based ECV monitoring, intensive field campaigns, regular satellite-to-satellite comparisons as well as dedicated calibration payload missions.

So far, the ESA Climate Change Initiative (CCI) has helped to strengthen the climate monitoring contribution of the past and present-day space segment for atmospheric composition. Its contributing projects cover several primary ECVs targeted by GAIA-CLIM, specifically ozone (O_3), Greenhouse Gases (GHGs) and aerosol, amongst many others.

Secondly, the EUMETSAT Satellite Application Facility (SAF) Networks contributes substantially to ECV monitoring. In particular, the Climate Monitoring SAF (CM SAF), provides climate data records of temperature and humidity, and the Atmospheric Composition SAF (AC SAF) provides climate data records of ozone, aerosols, and their precursors.

Thirdly, the Copernicus Data Store (CDS) is currently being filled with a large set of long-term regional and global data records through dedicated Copernicus service contracts. These projects will provide a wealth of satellite-based climate data records for users.

For climate monitoring, science, and applications, the need for long-term sustained (> 30 years) homogenized time series of guaranteed high quality constitutes a huge challenge, both on the observational sensors and the Copernicus Space Segment. All satellite observations need to be calibrated and validated to standards that enable them to be used for climate services. This requires long-term sustained datasets from non-satellite platforms that need to be of high quality and sufficient quantity to robustly characterise satellite-sensor performance and radiative-transfer modelling, to provide confidence in the satellite observations.

Currently, few, if any, of the non-satellite-to-satellite comparisons regularly undertaken provide fully traceable robust uncertainty estimates, taking into account uncertainty in both measurements and the inevitable additional variations owing to non-coincidence. Without such full traceability, ambiguity remains in any data comparison, and this ultimately limits the scientific value and utility for climate monitoring of both the satellite and non-satellite data records. Basically, this realisation underlies the user need for a sustainable non-satellite ECV monitoring capacity. A basic reference for the assessment of the broader identified unfulfilled user needs is provided through the *Climate Monitoring Principles* as defined by the Global Climate Observing System (GCOS)[2].

Essential Climate Variables and their user communities

Given the finite resources and time available, the GAIA-CLIM project focussed upon a selected subset of atmospheric ECVs: temperature, water vapour (H_2O), ozone (O_3), carbon dioxide (CO_2), methane (CH_4), and aerosols. (Cf. Section 2.1 for an overview on the non-satellite observations utilised within GAIA-CLIM per ECV). For this set of ECVs, the GAID brings together the gaps in the availability of, and ability to utilize, truly reference quality traceable measurements in support of climate monitoring from satellites.

For the selected set of atmospheric ECVs, the following target user communities were distinguished:

- Service providers (ECMWF Copernicus Atmospheric Monitoring Service (CAMS), Copernicus Climate Change Service (C3S), as well as national providers)
- Users and providers of ECV climate data records (GCOS, Space agencies and satellite data user communities)
- Users of reference observations
- Users of baseline network observations
- Users that would like to match different types of observation, e.g., through the GAIA-CLIM ***Virtual Observatory*** tool

In practice, there might be some overlap between these user communities. Because within GAIA-CLIM it was the aim to be application driven, the impact(s) of each of the gaps was – as much as possible – assessed from both a (end-)user perspective and a service and data provider

[2] GCOS Climate Monitoring Principles:
https://www.wmo.int/pages/prog/gcos/Documents/GCOS_Climate_Monitoring_Principles.pdf

perspective.

The gap assessment process

The three key challenges regarding the GAIA-CLIM gap assessment were:

1) To ***identify*** the most important limitations of the non-satellite monitoring segment for characterising space-based measurements for climate monitoring focusing on unfulfilled user needs;
2) To ***assess*** these gaps and to evaluate their user impact for climate services and research; and
3) To ***create*** a set of specific potential ***remedies*** to address the identified gaps

The identification of gaps was strengthened with periodic deliverables (three times over the 3 years project duration) for each of the Tasks 1 to 6. This structure worked well to provide iteratively improved sets of gaps and remedies. Further, the set up as a living document open for review has benefitted from broad stakeholder engagement. External input was solicited actively at user workshops, various meetings and conferences, and through a dedicated webpage[3]. The gap assessment and external review in the last year further shaped the contents of the identified gaps and their (sets of) remedies.

Importantly, it is noted that any gaps assessment is by definition limited through its neglect of currently fulfilled user needs which (a) may not necessarily be sustainable in the longer-term and (b) may experience funding competition in addressing some of the remedies to unfulfilled user needs, potentially creating new gaps. Finally, the gap remedies have been continuously (re-)drafted during the project such that they finally all constitute a plausible and *SMART* description of potential specific work in a funding call: time bound, assigned to potential actors and with an indicative coast estimate.

The remainder of this document is structured as follows.

In Section 2, the process for the identification, documentation and management of the gaps and remedies is briefly described. In Section 3, we present a set of cross-sections through the list of gaps and remedies. In Section 4, we summarize the achievements reached within the GAIA-CLIM gap assessment. Annex A provides a List of Acronyms. Proposed remedies linked to potential actors are summarized in Annex B. Finally, the final full version of the GAIA-CLIM Catalogue of Gaps is archived in Annex C.

[3] GAID website: http://www.gaia-clim.eu/page/gaid

2 The Identification, Documentation and Management of Gaps

2.1 Primary ECVs and Contributing Instrumental Techniques

The primary ECVs addressed in GAIA-CLIM are temperature, water vapour, ozone, aerosols, and the well-mixed greenhouse gases CO_2 and CH_4. The gap analysis for precursor ECVs – CO, CH_2O, SO_2, NH_3, and NO_2, was covered by the sister EU FP7 project *Quality Assurance for ECVs'* (QA4ECV)[4]. Remaining ECVs have not been assessed, but insights can be reached from a consideration of, e.g. the latest GCOS Implementation Plan[5].

Principal observations utilised within various aspects of GAIA-CLIM are summarised in Table 2.1, although it should be noted that only a subset of these were pulled through to the final version of the virtual observatory. A number of the gaps pertain directly to the entries in this table. The information content of Table 2.1 has been built partly on the mapping of non-satellite measurement capabilities and the assessment of geographical gaps that was performed within GAIA-CLIM under work package 1 (deliverables D1.6[6] and D1.7[7]).

Table 2.1 provides an overview of contributing surface networks and airborne observations per primary ECV addressed in GAIA-CLIM, split by altitude domain and network. The networks considered in GAIA-CLIM include:

- The Network for the Detection of Atmospheric Composition Change (NDACC),
- The GCOS Reference Upper-Air Network (GRUAN),
- The Total Carbon Column Observing Network (TCCON),
- The EUMETNET Aircraft Meteorological Data Relay Operational Service (E-AMDAR),
- The In-Service Aircraft for a Global Observing System (IAGOS),
- The Aerosol Robotic Network (AERONET),
- Aerosols, Clouds, and Trace gases Research InfraStructure / European Aerosol Research Lidar Network (ACTRIS/EARLINET),
- The NOAA Global Greenhouse Gas Reference Network (GGGRN),
- National Air Quality (AQ) networks.

Per network, the instrument platform or specific instrument techniques used are indicated in the table. The categories of observation include: surface in-situ, lidar, sunphotometers, Fourier Transform InfraRed spectroscopy (FTIR), microwave radiometers (MWR), UV-visible (MAX)DOAS spectrometers, sondes, aircraft in-situ, balloon, and cryogenic frost point hygrometers (CFH).

[4] More information on the QA4ECV project website: http://www.qa4ecv.eu/

[5] GCOS Implementation Plan: https://library.wmo.int/opac/doc_num.php?explnum_id=3389

[6] D1.6 Report on data capabilities by ECV and by system of systems layer for ECVs measurable from space

[7] D1.7 Report on the collection of metadata from existing network and on the proposed protocol for a common metadata format

Table 2.1 *Overview, per ECV, of the contributions of surface networks and airborne observation programmes (incl. the applied instrumental techniques) to climate monitoring per atmospheric domain (PBL = planetary boundary layer; LT = lower troposphere < 6km; UT = upper troposphere > 6km; LS = lower stratosphere < 25 km; US+M = upper stratosphere + mesosphere > 25 km).*

ECV per altitude domain	**Surface/PBL (< 1-2 km)**	**Total column**	**LT (< 6km)**	**UT (> 6km)**	**LS (< 25 km)**	**US+M (> 25 km)**
T	GRUAN Surface in-situ, sondes, MWR	Not applicable	GRUAN Lidar, sondes E-AMDAR, IAGOS Aircraft in-situ	GRUAN Lidar, sondes, CFH E-AMDAR, IAGOS Aircraft in-situ	GRUAN Lidar, sondes, CFH	Lidar (NDACC, non-NDACC), sondes (up to 30-35 km)
H_2O	GRUAN Surface in-situ, sondes	GRUAN GNSS, sondes NDACC sondes, FTIR, MWR	GRUAN Lidar, sondes NDACC Lidar, sondes, FTIR, MWR E-AMDAR, IAGOS Aircraft in-situ	GRUAN Lidar, sondes NDACC Lidar, sondes, FTIR, MWR E-AMDAR, IAGOS Aircraft in-situ	GRUAN Lidar, sondes NDACC Lidar, sondes, FTIR, MWR E-AMDAR, IAGOS Aircraft in-situ	Not available
O_3	NDACC Surface in-situ, sondes, UV-visible, MAX-DOAS	NDACC Brewer-Dobson, UV-visible, MAX-DOAS, FTIR	NDACC Sondes, UV-visible, FTIR IAGOS Aircraft in-situ	NDACC Sondes, UV-visible, FTIR IAGOS Aircraft in-situ	NDACC Lidar, sondes, UV-visible, FTIR, MWR IAGOS Aircraft in-situ	NDACC Lidar, sondes (up to 30-35 km), UV-visible, FTIR, MWR
Aerosols	AQ networks Surface in-situ	ACTRIS / Earlinet Lidar Aeronet sunphotometer, MAX-DOAS	ACTRIS / Earlinet Lidar NDACC Lidar, MAX-DOAS	ACTRIS / Earlinet Lidar NDACC Lidar, sondes	ACTRIS / Earlinet Lidar NDACC Lidar, sondes	Not available
CO_2	NOAA-GGGRN Surface in-situ / flask	TCCON FTIR	NDACC FTIR	NDACC FTIR	NDACC FTIR	Not available
CH_4	NOAA-GGGRN Surface in-situ / flask	TCCON FTIR	NDACC FTIR	NDACC FTIR	NDACC FTIR	Not available

2.2 The Structure of Each Gap in the Online Catalogue (Gap template)

A common template was provided to collect the input from the underlying GAIA-CLIM work packages. During the project this template was updated, benefitting from external stakeholder review at the second user workshop[8]. This process has helped to populate the on-line catalogue with *e.g.*, dropdown menus. Moreover, it has helped to harmonise the style in which especially the remedies to the gaps were formulated. For example, specific actions could be assigned to potential actors, and measurable outcomes of success could be formulated.

The gap collection template is provided below, together with the input as received for Gap G6.03, *in italics*, providing an example for the full content in the Catalogue of Gaps.

Gap collection template used to populate the Catalogue of Gaps with worked example *(in italics)*

Gap ID and Gap Title

G6.03 Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects

Gap Abstract

There are many non-satellite measurement systems that, in principle, could be used for the purposes of satellite characterisation on a sustained basis. Such measurements are metrologically well characterised and understood. They often measure variables, which are measured or measurable from space. However, many of the measurement systems are discontinuous (discrete) in time and their measurement scheduling is typically made with no regard to satellite-overpass times. This considerably diminishes their value for satellite Cal/Val activities. Better scheduling would increase their intrinsic value for satellite programs.

Part I Gap Description

(1) Primary Gap Type

Governance

(2) Secondary Gap Type(s)

Spatiotemporal coverage
Uncertainty in relation to comparator measures

(3) ECVs Impacted (GAIA-CLIM targeted ECVs only)

Temperature, Water vapor, Ozone, Aerosols, Carbon Dioxide, Methane

(4) User Categories / Application Areas Impacted

- *Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)*
- *International (collaborative) frameworks and bodies (space agencies, EU institutions, WMO programmes / frameworks etc.)*
- *Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)*

[8] D6.6 Report from the 2nd User Workshop

(5) Non-satellite Instrument Techniques Involved

Radiosondes
Ozone sondes
Lidar
FPH/CFH

(6) Related gaps

- *G6.01 - Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions*
- *G6.06 - Provision of reference-quality measurements on a sustained and continuous basis to maximise opportunities for the validation of satellite and derived products*

G6.01 - To be addressed with G6.03
Argument: The resolution to the current gap will be simpler if a more unified governance of non-satellite measurement networks is achieved and the data is provided from these networks in a more unified manner.
G6.06 To be addressed with G6.03
Argument: Operationalising instruments that can be operated 24/7 removes the current gap for the instruments affected.

(7) Gap detailed description

For some non-satellite instruments, there are geophysical limitations as to when measurements can be undertaken, e.g. an FTIR requires direct line of sight to the sun or a MAX-DOAS can only measure at sunrise/sunset.

Other instruments can and do operate 24/7 and therefore could always capture a co-location, if the satellite passes overhead. For example, both GNSS-PW and microwave radiometers, in principle, operate on a 24/7 basis. G6.06 discusses issues around their continuous operation where this is not yet assured.

But for many non-satellite measurement techniques, it is for financial or logistical reasons that measurements are solely episodic. For example, operational radiosonde launches tend to be twice-daily or at best four times daily at fixed local times. Similarly, for many instrument configurations, lidar operations may be made only when staff are available. These types of considerations effect very many non-satellite measurements, which could, in principle, be better targeted to support EO-sensor characterization by taking measurements much closer to satellite-overpass time. This would reduce the co-location mismatch and thus the attendant mismatch uncertainties. Because funding for these observations typically is not concerned with satellite characterisation, the current sampling strategy ends up being sub-optimal for satellite characterisation. Better aligning sampling strategies with times of satellite overpass, which are predictable a substantial time in advance, would increase their utility to satellite Cal/Val activities.

(8) Operational space missions or instruments impacted

Independent of specific space mission or space instruments

(9) Validation aspects addressed

Radiance (Level 1 product)
Geophysical product (Level 2 and higher level products)
Time series and trends
Representativity (spatial, temporal)
Calibration (relative, absolute)
Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

(10) Expected Gap Status after GAIA-CLIM

After GAIA-CLIM this gap remains unaddressed

Part II Benefits to Resolution and Risks to Non-resolution

Table 2.2 *Summary of the benefits to gap resolution*

Identified benefit	User category / application area benefitted	Probability of benefit being realised	Impacts
Better intra-satellite and inter-satellite data characterization using the ground segment through increased pool of co-locations to common non-satellite tie-points	Operational services and service development Climate research	High	Better characterized satellite data will yield improved utilization in derived products including reanalyses products and resulting services
More robust funding support for ground-based observations continuity. Recognizing that ground-based products may have unique value in e.g. providing vertically resolved profiles	International (collaboration) frameworks Operational services and service development	Medium	Increased diversity and quality of tools and data available to support service providers to develop bespoke products

Table 2.3 *Summary of the risks to non-resolution of the gap*

Identified risk	User category / application area at risk	Probability of occurrence if gap not remedied	Impacts
Insufficient number of high quality co-locations in the future that meet co-location match-up criteria to meaningfully constrain (at least some) satellite missions	Operational services and service development Climate research	High	Reduced confidence in satellite measurements and products and services derived therefrom
Inability to use non-satellite segment to effectively bridge across any unplanned gap in spaceborne EO capabilities	Operational services and service development Climate research	Low	Reduced colocations reduces the opportunity to use the non-satellite series to bridge the effects of any gap and yield a homogeneous series. This reduces the value of the satellite record for monitoring long-term environmental changes
Reduction in perceived utility and value of measurements leading to reduction in funding	International (collaboration) frameworks	Low	Diversifying the usage base of the high-quality measurements increases their intrinsic value and helps support widespread adoption

Part III Gap Remedy/Remedies

- Remedy 1: Optimization of scheduling to enhance capability for satellite Cal/Val activities
- Remedy 2: Operationalize use of double-differencing techniques in co-location matchups to minimize the effects of scheduling mismatch

Remedy 1: Optimization of scheduling to enhance capability for satellite Cal/Val activities

(1) Primary gap remedy type

Deployment

(2) Secondary Gap Remedy Type(s)

Governance

(3) Proposed Remedy Description

Sustained funding and governance mechanisms need to be instigated and assured that optimise the observational scheduling of relevant high-quality non-satellite periodic (non-continuous) measurements and their provision in NRT for satellite characterisation, if the full potential value of these measures is to be realised.

To be effective, space agencies and non-satellite high-quality observing networks need to work together to design, instigate, and fund a sustained program of targeted measurements that optimise collection and dissemination of non-satellite data in support of the space-based observational segment. The scientific benefits will be maximised if a strategy can be devised, which optimizes the ability of the non-satellite data segment to characterize satellite instrument performance across time, across platforms and across instrument types.

This, in turn, points to individual non-satellite observational segments being tasked with helping to characterise across multiple missions from multiple agencies from multiple countries to maximise the scientific value of the Cal/Val exercise rather than this support being extended and decided on a per mission basis. The strategy should include recourse to other measurements. For example, EUMETSAT have recently introduced a forecasting tool, which can, with high probability, forecast colocations of radio-occultation measurements with a ground-based instrument and any given polar orbiter mission. Finding such occurrences potentially enhances the value of co-locations substantially by making them multi-point comparisons.

Care must be taken for any changes in scheduling not to impact deleteriously upon existing functions and purposes of the non-satellite segment. This implies that, in at least some cases, the remedy will need to involve funding support commensurate with taking new or additional measurements at sites. The most obvious solution would be to instigate an international measurements support program, which would administer and disperse funding support for sustained satellite Cal/Val with reference-quality data from operators who optimise spending decisions and have as active stakeholders space agencies, non-satellite data providers, and end-users.

(4) Relevance

Better scheduling would increase the number of co-locations available for measurement systems that are discontinuous in time and increase the intrinsic value of the non-satellite observations for satellite Cal/Val.

(5) Expected Viability for the Outcome of Success

High

(6) Scale of Work

Programmatic multi-year multi-institution activity

(7) Time Bound to Remedy

Less than 5 years

(8) Indicative Cost Estimate (investment)

Medium cost (<5 million)

(9) Indicative Cost Estimate (exploitation)

Yes

(10) Potential Actors

- *Copernicus funding*
- *National funding agencies*
- *WMO*
- *ESA, Eumetsat, or other satellite agencies*
- *Academia, individual research institutes*
- *SMEs/industry*
- *National Measurement Institutes*

Remedy 2: Operationalize use of double-differencing techniques in co-location matchups to minimize the effects of scheduling mismatch

(1) Primary gap remedy type

Deployment

(2) Secondary Gap Remedy Type(s)

Research

(3) Proposed Remedy Description

In some circumstances, competing demands make it impossible to better align scheduling of non-satellite measurements to satellite measurements. In other cases, the measurement itself is constrained by the measurement technique. Thus, efforts are required to quantify and reduce the impacts of scheduling mismatches if these cannot be avoided. Within GAIA-CLIM, much effort has been made on quantifying mismatch effects, but there are also potentially tools and techniques to effectively remove the effects, at least to first order.

One potential way to do so, which has shown promise for ECVs amenable to data assimilation in NWP models, is double differencing (Tradowsky et al., 2017). This involves the calculation and comparison of the pair of differences to a model estimate between observations that are relatively proximal in space and time under the assumption that the model biases are either negligible or constant. In theory, the technique could be applied to a broad range of ECVs and problems although work would be required to develop such approaches using chemistry models or similar models.

Work is additionally required to operationally produce such estimates and tag the co-locations with these estimates, if they are to prove useful in reducing the impact of unavoidable mismatch effects arising from conflicting scheduling requirements.

(4) Relevance

Reduces the potential impact if a scheduling mismatch is unavoidable by removing a first order dynamical estimate of the effects of the differences in the sensed air mass.

(5) Expected Viability for the Outcome of Success

High

(6) Scale of Work

Single institution
Consortium

(7) Time Bound to Remedy

Less than 5 years

(8) Indicative Cost Estimate (investment)

Medium cost (<5 million)

(9) Indicative Cost Estimate (exploitation)

Yes

(10) Potential Actors

- *National meteorological services*
- *Academia, individual research institutes*
- *SMEs/industry*
- *National Measurement Institutes*

2.3 Version Control of Individual Gaps and the GAID as a living project document

As the GAID has been a living document during the project with several official versions being produced over the project lifetime, the following practices were adopted to ensure the traceability and provenance of gaps between versions:

- Once identified, a gap was given a unique identifier associated with the most logical GAIA-CLIM work package from which the gap derives;
- A gap may have changed principal work package responsibility, but its unique identifier remained;
- A gap could have been retired if felt by project participants either to be resolved or to be no longer relevant. If so, the gap identifier was also retired; and
- Gaps might have been merged. In this case, the most appropriate initial identifier was retained and all other versions that were merged were retired.

All earlier versions of gaps can be found in the preceding versions of the GAID.

A total of 101 gaps had been identified throughout the process. The reasons for earlier gap retirements are articulated in underlying deliverables such as D1.4[9], D2.2[10], D3.3[11], D4.3[12] and D5.2[13].

In some cases, a new more specific or more generic gap has been added in its place with a new identifier. For GAIDv3, a total number of 88 gaps was identified and documented. Users felt that this was too many gaps and many gaps identified contained substantive overlaps. Thus, for GAIDv4, these were rationalised radically to a total of 43 gaps, primarily through merging of sufficiently similar gaps to formulate more holistic gaps with one or more actionable remedies. The final Catalogue of Gaps contains 41 gaps with one or more proposed remedies. For GAIDv5 seven more specific remedies have been added: G2.08(R2), G3.04(R2), G4.01(R2) and G4.08(R3) and G4.08(R4), G6.03(R2), and G6.06(R2).

Table 2.4 provides a trace for the retired gaps. Because gaps are not being renumbered during the course of the project, several sequential identifier numbers do not appear in the catalogue of gaps included as Annex C to this GAID.

Table 2.4 *Overview of the retired gaps within GAIA-CLIM. Note that the issues raised within retired gaps were often maintained through a merge with other gaps and/or proposed remedies in the Catalogue of Gaps (Annex C).*

Gap	Title	Change	Rationale
G1.02	Unknown suitability of measurement maturity assessment	Merged with G1.03	Made more coherent sense as a merged gap
G1.07	Need for a scientific approach to the assessment of gaps in the existing networks measuring ECVs	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap

[9] D1.4 Review of and input to Gap Analysis and impacts document aspects relevant to WP1
[10] D2.2 Intermediate report on measurement uncertainty gap analysis
[11] D3.3 Review of and input to Gap Analysis and impacts document aspects relevant to WP3
[12] D4.3 Review of and input to Gap Analysis and impacts document aspects relevant to WP4
[13] D5.2 Review of and input to Gap Analysis and impacts document aspects relevant to WP5

G1.08	Evaluation of the effect of missing data or missing temporal coverage of fully traceable data provided by ground-based networks	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G1.09	Limited availability of quantitative CO profiles	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G1.11	Lack of understanding of traceable uncertainty estimates from baseline and comprehensive networks	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G1.12	Propagate uncertainty from well-characterized locations and parameters to other locations and parameters	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G1.13	Uncoordinated lidar and microwave radiometer water vapour measurements	Removed	Too specific, redundant with gaps elsewhere
G1.14	Currently limited aircraft measurements in Eastern Europe	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G1.15	Northern Hemisphere bias in NDACC and PANDORA network sites distribution	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G2.01	Common lack of continuous operation of aerosol lidar measurements systems	Merged with G6.03 / G6.06	Specific case in point of the more generic gaps identified in WP6
G2.02	Lidar measurements missing vertical coverage in lowermost altitude range	Merged with G2.06	Aerosol lidar gaps combined into a more coherent single gap
G2.03	Incomplete collocation of sun and lunar photometers with day and night time aerosol lidars	Merged with G2.06	Aerosol lidar gaps combined into a more coherent single gap
G2.04	Missing continued intercomparison of lidars with appropriate reference systems	Merged with G2.06	Aerosol lidar gaps combined into a more coherent single gap
G2.05	Lack of metrologically rigorous aerosol lidar error budget availability	Merged with G2.06	Aerosol lidar gaps combined into a more coherent single gap
G2.09	Continuous water vapour profiles from Raman lidars limited during daytime	Merged with G6.03/G6.06	Specific case in point of the more generic gaps identified in WP6
G2.14	Lack of a comprehensive review of the uncertainty associated with MW absorption models used in MWR retrievals	Merged to form G2.36	Combination of MWR gaps into a more comprehensive gap
G2.15	Lack of unified tools for automated MWR data quality control	Merged to form G2.36	Combination of MWR gaps into a more comprehensive gap
G2.16	Missing agreement on calibration best practices and MWR instrument error characterization	Merged to form G2.36	Combination of MWR gaps into a more comprehensive gap
G2.17	Lack of a common effort in homogenization of MWR retrieval methods	Merged to form G2.36	Combination of MWR gaps into a more comprehensive gap
G2.19	Line of sight and vertical averaging kernel are only approximations of the real 3D averaging kernel of a FTIR retrieval	Merged with G3.04	Combination of FTIR gaps into a more restricted set of more comprehensive gaps
G2.20	Lack of coordinated assessment of the spectroscopic uncertainties in infrared retrievals	Merged with G2.27	Combination of FTIR gaps into a more restricted set of more comprehensive gaps
G2.21	Current spectroscopic databases contain uncertainties specifically affecting TCCON retrievals of CH_4 and CO_2	Merged with G2.37	More generic spectroscopic gap required following user feedback
G2.23	Lack of calibrated in-situ vertical profiles of CH_4, CO_2 (and CO) for improving the accuracy of FTIR (partial) column measurements of CH_4, CO2 (and CO)	Merged with G2.24	Combination of FTIR gaps into a more restricted set of more comprehensive gaps
G2.25	NDACC FTIR: Currently, no calibration with respect to standards	Merged with G2.24	Combination of FTIR gaps into a more restricted set of more comprehensive gaps
G2.28	Lack of understanding of the a priori profile shape for AMF calculations for zenith sky ozone retrievals	Merged with G2.27	Combination of FTIR gaps into a more restricted set of more comprehensive gaps
G2.29	Lack of knowledge of the vertical averaging kernels used for DOAS total column ozone retrievals	Merged with G2.27	Combination of FTIR gaps into a more restricted set of more comprehensive gaps

G2.32	Better characterization of the different MAXDOAS tropospheric ozone retrieval methods needed	Merged with G2.31	Combination of MAXDOAS related gaps into one gap to make a more coherent case
G2.33	Lack of in-depth understanding of random and systematic uncertainties of MAX-DOAS tropospheric ozone measurements	Merged with G2.31	Combination of MAXDOAS related gaps into one gap to make a more coherent case
G2.34	Limit in traceability of GNSS-IPW ZTD estimates owing to dependency on 3rd party software	Removed	The main issue comes from different initial constraints for uncertainty analysis in the software as outlined in D2.8. This deliverable closed the identified gap insofar as closure was seen as possible at the present time
G2.35	TCCON sites with high/low albedo and hot spot monitoring	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G3.03	Missing generic and specific standards for co-location criteria in validation work	Merged with G3.02	Merged gaps felt to be more appropriate
G4.02	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to humidity	Merged with G4.01	Gaps were considered sufficiently similar to be better as a combined gap
G4.03	Traceable uncertainty estimates are often limited to a few locations and parameters where reference datasets are available. Comprehensiveness is lacking for extension to locations and parameters where reference datasets are not available	Removed	Merged within other WP4 gaps
G4.04	Datasets from baseline and comprehensive networks provide valuable spatiotemporal coverage, but often lack the characteristics needed to facilitate traceable uncertainty estimates	Removed	Merged within other WP4 gaps
G4.05	Limited knowledge about how to propagate uncertainty from well-characterized locations and parameters to other locations and parameters	Removed	Merged within other WP4 gaps
G4.06	Difficulty to assess the importance of natural variability in the model-observation error budget	Removed	Merged within other WP4 gaps
G4.07	Error correlations for reference sonde (GRUAN) measurements	Merged with G5.09	The set of level-1 comparator tools were amalgamated to make a stronger case
G4.11	Geographical sampling of reference in-situ data	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G5.02	Access to and use of reference and satellite data provided in different data formats and structures (e.g. granularity of data) prevents easy exploitation	Merged with G1.06	All gaps to do with data access modalities combined and rationalised
G5.03	No common source for co-located data exists which prevents use of reference data to validate reference measurements to each other and to evaluate satellite data	Merged with G5.01	Combined gap felt to be more user relevant
G5.04	Usability of reference data needs to be improved: high functionality in subset selection	Removed	Merged within other WP5 gaps
G5.05	Usability of reference data needs to be improved: format	Removed	Merged within other WP5 gaps
G5.08	Missing quantification of additional uncertainties introduced in the comparison results due to differences in (multi-dimensional) sampling and smoothing of atmospheric inhomogeneity	Removed	Merged within other WP5 gaps
G5.10	Characterisation of different types of uncertainty has not been systematically addressed per ECV preventing and potentially delaying inclusion of various instrument/ECV combinations into the Virtual Observatory	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G6.04	Mixed level of user experience with using uncertainty information	Removed	Insufficiently specific / actionable and overlapped with several other gaps

G6.05	Future support for GRUAN-processor	Merged with G5.09	The set of level-1 comparator tools were amalgamated to make a stronger case
G6.07	Different data policies in different networks harm the use of complementary data from different networks	Merged with G5.01	Topic now covered by G5.01
G6.08	a) INSPIRE : Application of INSPIRE Implementing Rules to atmospheric and any other 3D/4D-data is not straightforward w.r.t. dimensionality, quality, etc. b) INSPIRE: Where do data of one Member State end up which acquired in another Member State and/or is derived from satellite?	Removed	INSPIRE is intergovernmental and it was felt to be outside the scope of GAIA-CLIM
G6.09	Observations in developing countries (Africa - Asia - S America)	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap
G6.10	An unlimited growth of data portals, metadata standards and formats might make data discovery and access increasingly difficult	Merged into G1.06	All gaps to do with data access modalities combined and rationalised
G6.11	The possible gradual loss of island radiosonde stations	Merged with G1.10	Combination of gaps to do with spatial coverage made for a more powerful combined gap

2.4 Dissemination and Outreach Activities in Relation to the GAID

The GAID was set up as a living document that benefitted from broad stakeholder engagement and external input solicited at various meetings and conferences and through a dedicated webpage[14]. The on-line catalogue of gaps[15] has been set up and maintained at the GAIA-CLIM website[16].

Within GAIA-CLIM, a user survey was undertaken (deliverable D6.1 'Report on results of user survey'), and two user workshops were held (October 2015 in Rome and November 2016 in Brussels, with associated reports under deliverables D6.3[17] and D6.6[18]). These activities provided important information on user needs, the formulation of gaps, as well as the information needed to develop and describe potential remedies as concrete actions assigned to potential actors with e.g. cost estimates and measurable outcome of success.

The results of the user survey indicated a clear need for user education and capacity building on how satellite and non-satellite data can be used in conjunction for scientific and practical applications. Also, the user needs for functional match-up facilities were clear. Another important gap that was revealed in the survey was related to user familiarity with, and use of, uncertainties in non-satellite (reference) observations. These inputs have been taken on board in formulating the list of gaps.

The first user workshop in Rome provided specific operational user needs, e.g. for the CAMS operational validation. Also, a set of specific gaps related to GHG monitoring were identified and taken on board in the list of gaps. Inputs to the identified gaps were further derived informally through a bottom up approach, put forward by individual scientists within the project, and from external sources, such as GCOS Climate Monitoring Principles and (target) requirements, the ESA Climate Change Initiative (CCI), EUMETSAT Satellite Application Facilities (SAF), and the Copernicus services. Input from external parties continued to be invited through the GAID website. A designated e-mail address[19] was created and a specific template for gap reporting was provided at the website.

For the different prior versions of the GAID, a range of outreach activities was undertaken:

- GAID Version 1.0 was presented at the first GAIA-CLIM user workshop on 6 October 2015 in Rome, Italy.
- GAID Version 2.0 was presented at the GCOS conference *Global Climate Observation: the Road to the Future*, 2-4 March 2016, Amsterdam, The Netherlands, and at the European Space Solutions (ESS 2016) Conference, 30 May - 3 June 2016, The Hague, The Netherlands.
- GAID Version 3.0 was presented at the ConnectinGEO workshop on 'Gaps in EO and its prioritization', 10-11 October 2016 in Laxenburg, Austria and at the second GAIA-CLIM user workshop, 21-23 November 2015 in Brussels, Belgium.
- GAID Version 4.0 was used as input for the first version of the recommendation document D6.8 ('Recommendation for future work (user consultation version)') and for the intensive user engagement process (*roadshow*) during the second half of 2017 as summarized in D6.9 'Report on external stakeholder consultation exercise'

[14] GAID website: http://www.gaia-clim.eu/page/gaid
[15] online Catalogue of Gaps: http://www.gaia-clim.eu/page/gap-reference-list
[16] GAIA-CLIM website: http://www.gaia-clim.eu/

[17] D6.3 Summary of first workshop with external users
[18] D6.6 Report from the 2nd User Workshop
[19] Email address for GAID feedback: gaid@gaia-clim.eu

Specific technical feedback on GAIDv4 was found rather difficult to obtain during the roadshow events. Mostly, the audience was insufficiently prepared for it, despite advertisement and provision of the material beforehand. The feedback was diverse among communities. Most questions were raised about the addressees and the scope of the GAID. The details of the various comments received in relation to GAIDv4 are summarised in D6.9 ‘Report on external stakeholder consultation exercise’.

Inevitably, the technical materials that are brought together in the GAID have a bias towards those gaps and ECVs that are considered important by GAIA-CLIM project participants. The user feedback collected within the GAIA-CLIM project, however, has been found of crucial importance for refining the GAID and to ensure its long-term usefulness to the broader scientific and policymaker communities, as well as to space agencies, international organisations and other funding bodies.

3 Gaps Analysis

3.1 Cross-sections through the Catalogue

Gaps in the catalogue are enumerated such that the first number denotes the work package from which it arose. Cross-sections through other dimensions, such as gap type and the instrument technique used for validation of observations, provide support to further analysis of the identified gaps and to find e.g. any similarities, complementarities and/or inconsistencies. Note that some of the 41 gaps in total might appear multiple times by taking such cross-sections, e.g. a gap may pertain to technical, educational and governance issues, so when split by category, it would appear three times. The cross-sections are selected inclusively rather than exclusively to provide the most complete possible overview.

3.2 Gaps per Primary Gap Type

Seven generic gap types have been distinguished in the GAIA-CLIM gap identification process:

- ***Gaps in Spatiotemporal Coverage of Validation Observations of ECVs***: gaps in geographical and/or temporal coverage, i.e. a lack of measurements of the ECVs
- ***Gaps in the Coverage of the Vertical Domain and/or in Vertical Resolution***: either limitations in the altitude range covered or not resolving the vertical column sufficiently
- ***Gaps in the Measurement Uncertainty***: incomplete knowledge of the uncertainty budget, including calibration and e.g. spectroscopic uncertainties, i.e. all uncertainties intrinsic to one measurement
- ***Gaps in the Comparator Uncertainty***: uncertainties relating to comparator measures, i.e. uncertainties related to comparisons between (types of) measurements which have different attributes individually
- ***Technical gaps***: the more specific user needs related to data dissemination, specific missing tools, formats, etc.
- ***Parameter gaps***: missing parameter knowledge, missing metadata and auxiliary information related to the measurement of an ECV
- ***Governance gaps***: user needs related to network governance, data policies and data access, as well as gaps in QA/QC methodologies, traceability, documentation and education/training

Each of the identified gaps is being associated with one generic primary gap type, complemented by one or more secondary gap types in cases where the gap is cross-cutting. In the following tables only the primary gap type is used to sort the gaps. The secondary typs are included together with full gap descriptions in the catalogue of gaps.

3.2.1 Gaps in Spatiotemporal Coverage of Validation Observations of ECVs

Gaps in coverage typically correspond to user needs related to missing non-satellite (reference) observations. Gaps in coverage could be either temporal (i.e. insufficient time sampling) or geographical (i.e. missing network locations). Gaps in either the vertical coverage and/or vertical resolution are categorized separately. Gaps in spatiotemporal coverage, which have been identified within GAIA-CLIM, are:

Table 3.1 *Gaps in the spatiotemporal coverage of validation observations of ECVs*

G1.04	Lack of a comprehensive review of current non-satellite observing capabilities for the study of ECVs across domains
G2.06	Current poor spatial coverage of high-quality multi-wavelength lidar systems capable of characterising aerosols
G2.10	Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions
G6.02	Analysis and optimisation of geographical spread of observational assets to increase their utility for satellite Cal/Val, research, and services
G6.06	Requirement to make reference quality measurements on a sustained and continuous basis, to maximise opportunities for the validation of satellite L1 products and derived higher level products

3.2.2 Gaps in the Vertical Domain and/or in Vertical Resolution

The gaps in the vertical domain and resolution specifically refer to user needs on (better-resolved) vertical profile observations for the ECVs, mostly extending on existing observations at the surface or lower atmosphere, or total column observations, but also e.g. through aircraft observations. Gaps related to the vertical domain or vertical resolution that have been identified within GAIA-CLIM are:

Table 3.2 *Gaps in the Vertical Domain and/or in Vertical Resolution.*

G2.24	Lack of calibrated in-situ vertical profiles of CH4, CO2 (and CO) for improving the accuracy of FTIR (partial) column measurements of CH4, CO2 (and CO)
G4.12	Lack of reference quality data for temperature in the upper stratosphere and mesosphere

3.2.3 Gaps in Knowledge of the Uncertainty Budget and Calibration

The gaps in relation to the uncertainty budget and calibration refer to the missing knowledge on the (reference) quality of a single observation or a certain type of observation, relating to its traceability and comparability that limit its scientific utility and value. The gaps in knowledge of the uncertainty budget and calibration, which have been identified within GAIA-CLIM, are:

Table 3.3 *Gaps in Knowledge of the Uncertainty Budget and Calibration*

G1.10	Relative paucity and geographical concentration of reference-quality measurements, with limited understanding of uncertainty in remaining measurements, limits ability to formally close satellite to non-satellite comparisons
G2.07	Lack of uptake of lidar measurements in data assimilation
G2.08	Need for a metrologically rigorous approach to long - term water vapour measurements from Raman lidars in the troposphere and UT/LS
G2.11	Lack of rigorous tropospheric ozone lidar error budget availability
G2.12	Lack of rigorous pure rotational Raman temperature lidar error budget availability limits utility for applications, such as satellite characterisation
G2.13	Missing microwave standards maintained by national/international measurement institutes
G2.18	Better agreement needed on systematic and random components of the uncertainty in FTIR measurements and how to evaluate them
G2.22	FTIR cell measurements carried out to characterize Instrument Line Shape have their own uncertainties
G2.26	Poorly understood uncertainty in ozone cross-sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis
G2.27	Lack of understanding of random uncertainties, AMF calculations and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy
G2.30	Incomplete uncertainty quantification for Pandora ozone measurements

G2.31	Incomplete understanding of the different retrieval methods, information content, and random and systematic uncertainties of MAX-DOAS tropospheric ozone measurements
G2.36	Lack of traceable uncertainties in MWR measurements and retrievals
G2.37	Poorly quantified uncertainties in spectroscopic information
G3.04	Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties
G3.05	Representativeness uncertainty assessment missing for higher-level data based on averaging of individual measurements
G4.08	Estimates of uncertainties in ocean surface microwave radiative transfer
G4.09	Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer
G4.10	Incomplete estimates of uncertainties in land surface infrared emissivity atlases

3.2.4 Gaps in Knowledge of the Uncertainty in Relation to Comparator Measures

Uncertainty gaps in relation to comparator measures typically include validation uncertainties, such as uncertainties on representativeness, uncertainties due to co-location mismatches and due to differences in spatiotemporal sampling and smoothing, and in other specific observation attributes. These comparator uncertainties exclude the uncertainties related to a single observation. The uncertainty gaps in relation to comparator measures, which have been identified within GAIA-CLIM, are:

Table 3.4 *Gaps in Knowledge of the Uncertainty in Relation to Comparator Measures*

G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and their co-location
G3.02	Missing standards for, and evaluation of, co-location criteria
G3.06	Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences
G4.01	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity

3.2.5 Technical Gaps

Technical gaps might include e.g. specific missing tools, data portal technicalities, instrument technology limitations etc. The technical gaps, which have been identified within GAIA-CLIM, are:

Table 3.5 *Technical Gaps*

G1.05	Lack of integrated user tools showing all existing observing capabilities for measuring ECVs with respect to satellite spatial coverage
G1.06	Currently heterogeneous metadata standards hinder data discoverability and usability
G5.01	Vast number of data portals serving data under distinct data policies in multiple formats for fiducial reference-quality data inhibits their discovery, access and usage for applications, such as satellite Cal/Val
G5.06	Extraction, analysis and visualization tools to exploit the potential of reference measurements are currently only rudimentary
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G5.09	Need to propagate various reference quality geophysical measurements and uncertainties to TOA radiances and uncertainties to enable robust characterisation of satellite FCDRs

3.2.6 Parameter Gaps

Parameter gaps are a separate generic category. These gaps include user needs related to parameters (or reported observations) that are missing with respect to ECV monitoring and which would have value on their own and/or as auxiliary data to the ECV monitoring. For example, users typically wish to have a temperature vertical profile provided with the sonde ozone profile. As another example: modellers might need additional parameters with the observed ECVs to verify their models, e.g., parameters related to the Brewer-Dobson Circulation, convective mixing, etc. The parameter gaps that have been identified within GAIA-CLIM, are:

Table 3.6 *Parameter Gaps.*

G1.03	Lack of internationally recognised framework for assessment of fundamental observation capabilities

3.2.7 Governance Gaps

Governance gaps include user needs related to network and data policies, including data provision, open access, etc.

Table 3.7 *Governance Gaps*

G5.11	Non-operational provision of fiducial reference measurement data and some satellite-derived products reduces their utility for monitoring and applications
G6.01	Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions
G6.03	Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects
G6.12	Under-capacity of workforce to exploit satellite data and satellite characterisation

3.3 Gaps per Instrument Technique and the Primary Calibration and Validation Aspects involved

3.3.1 Gaps identified per Instrument Technique

In this section, we include the gaps which are specific for only one, or maybe two, instrument techniques. There are, of course, many gaps which do not relate just to one or two techniques specifically, and are of a more general nature. Such more generally applicable gaps are not repeated in these cross-sections of gaps separated per instrument technique. The GAIA-CLIM target instrument techniques considered include:

- Lidar
- FTIR
- UV-visible
- Radiosondes
- Ozone sondes
- MWR
- GNSS-IPW

UV-visible instrument techniques involve UV-visible zenith DOAS, UV-visible MAX-DOAS and Pandora observations.

Table 3.8 *Gaps related to Lidar*

G2.06	Current poor spatial coverage of high-quality multi-wavelength lidar systems capable of characterising aerosols
G2.07	Lack of uptake of lidar measurements in data assimilation
G2.08	Need for a metrologically rigorous approach to long - term water vapour measurements from Raman lidars in the troposphere and UT/LS
G2.10 (also UV-visible)	Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions
G2.11	Lack of rigorous tropospheric ozone lidar error budget availability
G2.12	Lack of rigorous pure rotational Raman temperature lidar error budget availability limits utility for applications, such as satellite characterisation

Table 3.9 *Gaps related to FTIR*

G2.18	Better agreement needed on systematic and random components of the uncertainty in FTIR measurements and how to evaluate them
G2.22	FTIR cell measurements carried out to characterize Instrument Line Shape have their own uncertainties
G2.24	Lack of calibrated in-situ vertical profiles of CH_4, CO_2 (and CO) for improving the accuracy of FTIR (partial) column measurements of CH_4, CO_2 (and CO)

__Table 3.10__ Gaps related to UV-visible

G2.10 (also lidar)	Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions
G2.26	Poorly understood uncertainty in ozone cross-sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis
G2.27	Lack of understanding of random uncertainties, AMF calculations and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy
G2.30	Incomplete uncertainty quantification for Pandora ozone measurements
G2.31	Incomplete understanding of the different retrieval methods, information content, and random and systematic uncertainties of MAX-DOAS tropospheric ozone measurements

__Table 3.11__ Gaps related to Radiosondes

G4.01	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity
G4.12	Lack of reference quality data for temperature in the upper stratosphere and mesosphere

__Table 3.12__ Gaps related to Ozone Sondes

G2.10	Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions

__Table 3.13__ Gaps related to MWR

G2.13	Missing microwave standards maintained by national/international measurement institutes
G2.36	Lack of traceable uncertainties in MWR measurements and retrievals
G4.08	Estimates of uncertainties in ocean surface microwave radiative transfer
G4.09	Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer

3.3.2 Gaps grouped along Primary Calibration and Validation Aspects addressed

The following, potentially partially overlapping, calibration and validation (Cal/Val) aspects have been identified:

- Representativity (spatial, temporal)
- Calibration (relative, absolute)
- Spectroscopy
- Time series and trends
- Radiance (level 1 products)
- Geophysical, gridded and/or assimilated products (product levels 2,3,4)
- Other aspects (auxiliary parameters, timeliness, education on validation aspects)

The Cal/Val aspects addressed by a gap could involve one or more aspects. Here, the primary Cal/Val aspect of the gap has been selected. The cross-sections addressed are as follows:

Table 3.14 *Gaps related to representativity (spatial/temporal)*

G1.03	Lack of internationally recognised framework for assessment of fundamental observation capabilities
G1.04	Lack of a comprehensive review of current non-satellite observing capabilities for the study of ECVs across domains
G1.05	Lack of integrated user tools showing all existing observing capabilities for measuring ECVs with respect to satellite spatial coverage
G1.06	Currently heterogeneous metadata standards hinder data discoverability and usability
G2.10	Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions
G2.11	Lack of rigorous tropospheric ozone lidar error budget availability
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and their co-location
G3.02	Missing standards for, and evaluation of, co-location criteria
G3.04	Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties
G3.05	Representativeness uncertainty assessment missing for higher-level data based on averaging of individual measurements
G3.06	Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences
G4.01	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity
G5.01	Vast number of data portals serving data under distinct data policies in multiple formats for fiducial reference-quality data inhibits their discovery, access and usage for applications, such as satellite Cal/Val
G5.06	Extraction, analysis and visualization tools to exploit the potential of reference measurements are currently only rudimentary
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G6.01	Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions
G6.02	Analysis and optimisation of geographical spread of observational assets to increase their utility for satellite Cal/Val, research, and services
G6.03	Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects

Table 3.15 *Gaps related to calibration*

G1.03	Lack of internationally recognised framework for assessment of fundamental observation capabilities
G1.10	Relative paucity and geographical concentration of reference-quality measurements, with limited understanding of uncertainty in remaining measurements, limits ability to formally close satellite to non-satellite comparisons
G2.10	Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions
G2.11	Lack of rigorous tropospheric ozone lidar error budget availability
G2.13	Missing microwave standards maintained by national/international measurement institutes
G2.26	Poorly understood uncertainty in ozone cross-sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis
G2.36	Lack of traceable uncertainties in MWR measurements and retrievals
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and their co-location
G3.02	Missing standards for, and evaluation of, co-location criteria
G3.04	Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties
G3.06	Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences
G4.01	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity
G5.01	Vast number of data portals serving data under distinct data policies in multiple formats for fiducial reference-quality data inhibits their discovery, access and usage for applications, such as satellite Cal/Val
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G6.01	Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions

G6.02	Analysis and optimisation of geographical spread of observational assets to increase their utility for satellite Cal/Val, research, and services
G6.03	Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects
G6.06	Requirement to make reference quality measurements on a sustained and continuous basis, to maximise opportunities for the validation of satellite L1 products and derived higher level products

***Table 3.16** Gaps related to spectroscopy*

G1.10	Relative paucity and geographical concentration of reference-quality measurements, with limited understanding of uncertainty in remaining measurements, limits ability to formally close satellite to non-satellite comparisons
G2.13	Missing microwave standards maintained by national/international measurement institutes
G2.26	Poorly understood uncertainty in ozone cross-sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis
G2.27	Lack of understanding of random uncertainties, AMF calculations and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy
G2.36	Lack of traceable uncertainties in MWR measurements and retrievals
G2.37	Poorly quantified uncertainties in spectroscopic information
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and their co-location
G3.02	Missing standards for, and evaluation of, co-location criteria
G3.04	Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties
G3.06	Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G5.09	Need to propagate various reference quality geophysical measurements and uncertainties to TOA radiances and uncertainties to enable robust characterisation of satellite FCDRs

***Table 3.17** Gaps related to time series and trends*

G1.06	Currently heterogeneous metadata standards hinder data discoverability and usability
G1.10	Relative paucity and geographical concentration of reference-quality measurements, with limited understanding of uncertainty in remaining measurements, limits ability to formally close satellite to non-satellite comparisons
G2.06	Current poor spatial coverage of high-quality multi-wavelength lidar systems capable of characterising aerosols
G2.10	Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions
G2.11	Lack of rigorous tropospheric ozone lidar error budget availability
G2.12	Lack of rigorous pure rotational Raman temperature lidar error budget availability limits utility for applications, such as satellite characterisation
G2.13	Missing microwave standards maintained by national/international measurement institutes
G2.26	Poorly understood uncertainty in ozone cross-sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis
G2.27	Lack of understanding of random uncertainties, AMF calculations and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy
G2.30	Incomplete uncertainty quantification for Pandora ozone measurements
G2.31	Incomplete understanding of the different retrieval methods, information content, and random and systematic uncertainties of MAX-DOAS tropospheric ozone measurements
G2.36	Lack of traceable uncertainties in MWR measurements and retrievals
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and their co-location
G3.02	Missing standards for, and evaluation of, co-location criteria
G3.04	Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties
G3.05	Representativeness uncertainty assessment missing for higher-level data based on averaging of individual measurements
G3.06	Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing

	differences
G5.01	Vast number of data portals serving data under distinct data policies in multiple formats for fiducial reference-quality data inhibits their discovery, access and usage for applications, such as satellite Cal/Val
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G6.01	Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions
G6.03	Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects
G6.06	Requirement to make reference quality measurements on a sustained and continuous basis, to maximise opportunities for the validation of satellite L1 products and derived higher level products

Table 3.18 *Gaps related to radiance (level 1 products)*

G1.06	Currently heterogeneous metadata standards hinder data discoverability and usability
G2.13	Missing microwave standards maintained by National/International Measurement Institutes
G2.36	Lack of traceable uncertainties in MWR measurements and retrievals
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and their co-location
G3.02	Missing standards for, and evaluation of, co-location criteria
G3.04	Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties
G3.06	Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences
G4.08	Estimates of uncertainties in ocean surface microwave radiative transfer
G4.09	Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer
G4.10	Incomplete estimates of uncertainties in land surface infrared emissivity atlases
G4.12	Lack of reference quality data for temperature in the upper stratosphere and mesosphere
G5.01	Vast number of data portals serving data under distinct data policies in multiple formats for fiducial reference-quality data inhibits their discovery, access and usage for applications, such as satellite Cal/Val
G5.06	Extraction, analysis and visualization tools to exploit the potential of reference measurements are currently only rudimentary
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G5.09	Need to propagate various reference quality geophysical measurements and uncertainties to TOA radiances and uncertainties to enable robust characterisation of satellite FCDRs
G6.01	Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions
G6.02	Analysis and optimisation of geographical spread of observational assets to increase their utility for satellite Cal/Val, research, and services
G6.03	Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects
G6.06	Requirement to make reference quality measurements on a sustained and continuous basis, to maximise opportunities for the validation of satellite L1 products and derived higher level products

Table 3.19 *Gaps related to geophysical, gridded and/or assimilated products (product levels 2,3,4)*

G1.06	Currently heterogeneous metadata standards hinder data discoverability and usability
G1.10	Relative paucity and geographical concentration of reference-quality measurements, with limited understanding of uncertainty in remaining measurements, limits ability to formally close satellite to non-satellite comparisons
G2.07	Lack of uptake of lidar measurements in data assimilation
G2.08	Need for a metrologically rigorous approach to long - term water vapour measurements from Raman lidars in the troposphere and UT/LS
G2.10	Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions
G2.11	Lack of rigorous tropospheric ozone lidar error budget availability
G2.13	Missing microwave standards maintained by national/international measurement institutes
G2.18	Better agreement needed on systematic and random components of the uncertainty in FTIR measurements and how to evaluate them
G2.22	FTIR cell measurements carried out to characterize Instrument Line Shape have their own uncertainties

G2.24	Lack of calibrated in-situ vertical profiles of CH_4, CO_2 (and CO) for improving the accuracy of FTIR (partial) column measurements of CH_4, CO_2 (and CO)
G2.27	Lack of understanding of random uncertainties, AMF calculations and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy
G2.30	Incomplete uncertainty quantification for Pandora ozone measurements
G2.31	Incomplete understanding of the different retrieval methods, information content, and random and systematic uncertainties of MAX-DOAS tropospheric ozone measurements
G2.36	Lack of traceable uncertainties in MWR measurements and retrievals
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and their co-location
G3.02	Missing standards for, and evaluation of, co-location criteria
G3.04	Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties
G3.05	Representativeness uncertainty assessment missing for higher-level data based on averaging of individual measurements
G3.06	Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences
G4.08	Estimates of uncertainties in ocean surface microwave radiative transfer
G4.09	Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer
G4.10	Incomplete estimates of uncertainties in land surface infrared emissivity atlases
G4.12	Lack of reference quality data for temperature in the upper stratosphere and mesosphere
G5.01	Vast number of data portals serving data under distinct data policies in multiple formats for fiducial reference-quality data inhibits their discovery, access and usage for applications, such as satellite Cal/Val
G5.06	Extraction, analysis and visualization tools to exploit the potential of reference measurements are currently only rudimentary
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G6.03	Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects
G6.06	Requirement to make reference quality measurements on a sustained and continuous basis, to maximise opportunities for the validation of satellite L1 products and derived higher level products

***Table 3.20** Gaps primarily related to other Cal/Val aspects: auxiliary parameters, timeliness and education on validation aspects*

Auxiliary parameters	
G2.12	Lack of rigorous pure rotational Raman temperature lidar error budget availability limits utility for applications, such as satellite characterisation
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and their co-location
G3.02	Missing standards for, and evaluation of, co-location criteria
G3.04	Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties
G3.06	Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences
G4.08	Estimates of uncertainties in ocean surface microwave radiative transfer
G4.09	Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer
G4.10	Incomplete estimates of uncertainties in land surface infrared emissivity atlases
G5.07	Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems
G6.02	Analysis and optimisation of geographical spread of observational assets to increase their utility for satellite Cal/Val, research, and services
Timeliness	
G5.11	Non-operational provision of fiducial reference measurement data and some satellite-derived products reduces their utility for monitoring and applications
Education on validation aspects	
G6.12	Under-capacity of workforce to exploit satellite data and satellite characterisation

3.4 Remedies: Types of Actions along with their Cost Estimates and Potential Actors

3.4.1 Remedies sorted by Primary Remedy Types

Six types of remedies are distinguished. A remedy type is the proposed type of action in response to the identified user need(s). In total, six different types of action have been distinguished. The remedy types along which the proposed remedies can be sorted are:

- Technical work,
- Laboratory work,
- Scientific research,
- (Instrument) Deployment,
- Governance, and
- Education/Training

Technical work, laboratory work and scientific research are more or less self-explanatory proposed types of activity. Deployment is mostly related to the implementation of new or improved instrumentation. Governance type of remedies would address user needs related to coordination, funding, data policies (dissemination, free access), clarification of methodologies, missing traceability, and missing documentation. Educational activities could involve a range of levels of specific user training.

A proposed remedy might involve different types of activities. The primary proposed activity has been used to categorize the remedies. Secondary types of the proposed remedies have been identified as well and these are provided, and can be further selected, through the on-line catalogue of gaps. However, in the following tables only the primary remedy type is used to sort the gaps.

For some of the gaps, multiple remedies have been proposed and therefore the remedies are numbered as Rx. Here, (R1) is used for the first remedy proposed, (R2) for a second remedy to the same gap, etc. Within the set of multiple remedies for one gap, there is no priority, i.e., the second (R2) and third remedy (R3), etc., are on equal footing with the first remedy listed (R1).

Table 3.21 *Remedies involving technical work*

G1.05(R1)	Provision of mapping tools to match satellite and non-satellite observations
G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.13(R1)	Development and testing of MWR standards and secondary standards
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.22(R1)	Regular cell measurements and ILS retrievals are to be performed in a consistent manner
G2.27(R1)	Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error
G2.27(R4)	An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables is needed
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G4.01(R1)	Development of tools to propagate geophysical profile data and attendant uncertainties to TOA radiances and uncertainties

G4.01(R2)	Evaluate quality of NWP and reanalysis fields through comparisons with reference data as a means of establishing direct traceability
G4.08(R1)	Intercomparison of existing surface emissivity models
G4.08(R3)	Establish an ocean emissivity reference model in the spectral region 1 – 200 GHz
G4.10(R1)	Provision of validated land surface infrared emissivity atlases
G4.12(R1)	Use of GNSS-RO temperature profiles as a reference dataset for satellite Cal/Val
G5.06(R1)	Operationalisation of a *satellite – non-satellite matchups* facility with appropriate discovery and user tools
G5.09(R1)	Implement means to provide the community with a forward radiative transfer capability or results of computations
G5.09(R2)	Improved characterisation of error covariances in GRUAN measurements
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis

Table 3.22 *Remedies involving laboratory work*

G2.08(R1)	Synergy between water vapour Raman lidar and other measurement techniques
G2.08(R2)	Verification and further deployment of the GAIA-CLIM approach to metrological characterisation to Raman Lidar measurements

Table 3.23 *Remedies involving scientific work*

G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques without necessitating new observational deployments
G1.10(R2)	Take steps to better realise the benefits of a system of systems approach to observing strategies
G2.07(R1)	Extension of the GAIA-CLIM data assimilation approach to aerosol lidars
G2.11(R1)	Create and disseminate a fully traceable reference quality DIAL lidar product
G2.12(R1)	Create a fully traceable reference-quality temperature lidar product
G2.26(R1)	Improved understanding of the effects of differences in ozone cross-sections
G2.27(R2)	Improve climatological databases of a priori ozone profiles
G2.27(R3)	Standardize AMF calculation methods and databases of a-priori information used in AMF calculations
G2.30(R1)	Steps towards reference quality measurement program for Pandora measurements
G2.31(R1)	Improved understanding of potential for MAX-DOAS high quality measurements of tropospheric ozone
G2.31(R2)	Improved understanding of retrieval techniques for tropospheric ozone from MAX-DOAS
G2.37(R1)	Establish traceability of spectroscopic properties of Essential Climate Variables
G3.01(R1)	Improved high-resolution modelling to quantify mismatch effects
G3.01(R2)	Use of statistical analysis techniques based upon available and targeted additional observations
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.04(R2)	Empirical determination of true resolution by comparison with high-resolution data
G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments (OSSEs)
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G4.08(R4)	Reference-quality dielectric constant measurements of pure and saline water for the frequency range 1 – 200 GHz
G4.09(R2)	Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables

Table 3.24 *Remedies involving (instrument) deployment*

G1.03(R2)	Adoption of measurement systems approach and assessment by international bodies
G2.06(R1)	Improve the coverage, metrological characterisation, and operational capabilities of Raman lidars
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G4.08(R2)	The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz
G4.09(R1)	The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based).

G5.01(R1)	Successful implementation of the Copernicus Climate Change Service activity on baseline and reference network data access via the Climate Data Store
G5.01(R2)	Operationalisation and extension of the GAIA-CLIM Virtual Observatory facility
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation of current non-satellite observational capabilities
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.03(R2)	Operationalise use of double-differencing techniques in co-location matchups to minimise the effects of scheduling mismatch

Table 3.25 *Remedies involving governance*

G1.04(R1)	Extension and continuous update of a comprehensive review of existing geographical gaps for non-satellite observations
G1.06(R1)	Design and implementation of unified metadata format under a common data model
G5.07(R1)	Propagation and adoption of metrological best practices in sustained validation activities
G5.11(R1)	Operationalise processing and delivery for non-satellite reference measurements and satellite CDR interim L2 products
G6.01(R1)	Undertake short-term cross-network governance improvements
G6.01(R2)	Longer-term rationalisation of observational network governance
G6.06(R2)	Ensuring sustained funding of the non-satellite observing system

Table 3.26 *Remedies involving education/training*

G1.03(R1)	Further deployments and refinements of the GAIA-CLIM approach
G6.12(R1)	Undergraduate, masters and doctoral training programs in Copernicus-relevant programs
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

3.4.2 Cost Estimates of the Proposed Remedies (Costs on Investment)

The provided cost estimates are rough estimates, based upon the scope of the work proposed and the likely timeline to completion. However, these provide a useful first indication of the scale of the proposed remedy. Costs are differentiated between investment, i.e. initial costs, and operational, i.e. (annual) recurring costs.

Table 3.27 *Proposed Remedies with Low (< 1 Meuro) Cost Estimates (Costs on Investment)*

G1.03 (R1)	Further deployments and refinements of the GAIA-CLIM approach
G1.05(R1)	Provision of mapping tools to match satellite and non-satellite observations
G1.06(R1)	Design and implementation of unified metadata format under a common data model
G2.08(R1)	Synergy between water vapour Raman lidar and other measurement techniques
G2.08(R2)	Verification and further deployment of the GAIA-CLIM approach to metrological characterisation to Raman Lidar measurements
G2.11(R1)	Create and disseminate a fully traceable reference quality DIAL lidar product
G2.12(R1)	Create a fully traceable reference-quality temperature lidar product
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.22(R1)	Regular cell measurements and ILS retrievals are to be performed in a consistent manner
G2.27(R1)	Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error
G2.27(R2)	Improve climatological databases of a priori ozone profiles
G2.27(R3)	Standardize AMF calculation methods and databases of a-priori information used in AMF calculations
G2.27(R4)	An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables is needed

G2.30(R1)	Steps towards reference quality measurement program for Pandora measurements
G2.31(R1)	Improved understanding of potential for MAX-DOAS high quality measurements of tropospheric ozone
G2.31(R2)	Improved understanding of retrieval techniques for tropospheric ozone from MAX-DOAS
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.04(R2)	Empirical determination of true resolution by comparison with high-resolution data
G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments (OSSEs)
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G4.01(R1)	Development of tools to propagate geophysical profile data and attendant uncertainties to TOA radiances and uncertainties
G4.01(R2)	Evaluate quality of NWP and reanalysis fields through comparisons with reference data as a means of establishing direct traceability
G4.08(R1)	Intercomparison of existing surface emissivity models
G4.12(R1)	Use of GNSS-RO temperature profiles as a reference dataset for satellite Cal/Val
G6.01(R1)	Undertake short-term cross-network governance improvements
G6.12(R1)	Undergraduate, masters and doctoral training programs in Copernicus-relevant programs

Table 3.28 *Proposed Remedies with Low-Medium (1-5 Meuro) Cost Estimates (Costs on Investment)*

G1.03(R2)	Adoption of measurement systems approach and assessment by international bodies
G1.04(R1)	Extension and continuous update of a comprehensive review of existing geographical gaps for non-satellite observations
G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques
G1.10(R2)	Take steps to better realise the benefits of a system of systems approach to observing strategies
G2.06(R1)	Improve the coverage, metrological characterisation, and operational capabilities of Raman lidars
G2.07(R1)	Extension of the GAIA-CLIM data assimilation approach to aerosol lidars
G2.13(R1)	Development and testing of MWR standards and secondary standards
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G2.26(R1)	Improved understanding of the effects of differences in ozone cross-sections
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G2.37(R1)	Establish traceability of spectroscopic properties of Essential Climate Variables
G3.01(R2)	Use of statistical analysis techniques based upon available and targeted additional observations
G4.08(R2)	The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz
G4.08(R3)	Establish an ocean emissivity reference model in the spectral region 1 – 200 GHz
G4.08(R4)	Reference-quality dielectric constant measurements of pure and saline water for the frequency range 1 – 200 GHz
G4.09(R1)	The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based).
G4.09(R2)	Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables
G4.10(R1)	Provision of validated land surface infrared emissivity atlases
G5.01(R1)	Successful implementation of the Copernicus Climate Change Service activity on baseline and reference network data access via the Climate Data Store
G5.01(R2)	Operationalisation and extension of the GAIA-CLIM Virtual Observatory facility
G5.06(R1)	Operationalisation of a *satellite – non-satellite matchups* facility with appropriate discovery and user tools
G5.07(R1)	Propagation and adoption of metrological best practices in sustained validation activities
G5.09(R1)	Implement means to provide the community with a forward radiative transfer capability or results of computations
G6.01(R2)	Longer-term rationalisation of observational network governance
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.03(R2)	Operationalise use of double-differencing techniques in co-location matchups to minimise the effects of scheduling mismatch
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

Table 3.29 *Proposed Remedies with Medium-High (5-10 Meuro) Cost Estimates (Costs on Investment)*

G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G3.01(R1)	Improved high-resolution modelling to quantify mismatch effects

Table 3.30 *Proposed Remedies with High (>10 Meuro) Cost Estimates (Costs on Investment)*

G5.11(R1)	Operationalise processing and delivery for non-satellite reference measurements and satellite CDR interim L2 products

3.4.3 Cost Estimates of the Proposed Remedies (Annual Recurring Costs)

For a subset of the gap remedies, there are ongoing repeating costs associated with operations and upkeep following instigation. In those cases, and based upon the scale of the remedy, an indicative estimate of the annual recurring costs has been provided.

Table 3.31 *Proposed Remedies with Low-Medium (<100 keuro/yr) Cost Estimates (Annual Recurring Costs)*

G1.03(R2)	Adoption of measurement systems approach and assessment by international bodies
G5.01(R1)	Successful implementation of the Copernicus Climate Change Service activity on baseline and reference network data access via the Climate Data Store

Table 3.32 *Proposed Remedies with Medium-High (100-500 keuro/yr) Cost Estimates (Annual Recurring Costs)*

G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G5.01(R2)	Operationalisation and extension of the GAIA-CLIM Virtual Observatory facility

Table 3.33 *Proposed Remedies with High (>500 keuro/yr) Cost Estimates (Annual Recurring Costs)*

G2.06(R1)	Further deployments and refinements of the GAIA-CLIM approach to metrological characterization of multi-wavelength Raman lidars
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation of current non-satellite observational capabilities
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities

Table 3.34 *Proposed Remedies with identified though unspecified annual Recurring Costs*

G2.07(R1)	Extension of the GAIA-CLIM data assimilation approach to aerosol lidars
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G5.09(R2)	Improved characterisation of error covariances in GRUAN measurements
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation of current non-satellite observational capabilities
G6.06(R2)	Ensuring sustained funding of the non-satellite observing system
G6.12(R1)	Undergraduate, masters and doctoral training programs in Copernicus-relevant programs
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

4 Summary

The GAID has constituted a living document throughout the three years of the GAIA-CLIM project. Each iteration has benefitted from internal and external stakeholder engagement, and over time, it has become progressively more complete and consistent. In total five versions of the GAID have been produced as individual deliverables. To facilitate the management of the evolving gaps, gap identification numbers have been created and this numbering has been maintained between versions for backward traceability.

The GAIA-CLIM catalogue focuses on gaps in the availability of, and ability to utilize, non-satellite observations in support of the long-term sustained space-borne monitoring of a set of ECVs. Inevitably, the materials that are brought together in the GAID have some bias towards those gaps and ECVs that were considered important for the community by the GAIA-CLIM project participants. The external review has helped to increase our confidence in the robustness and general applicability of the identified gaps and remedies.

Finally, a total number of 41 gaps was identified and maintained after an important consolidation process in which project partners were tasked to review the collected set of gaps and harmonize the suggested remedies. For some of the gaps, a set of several distinct remedies is proposed, reflecting different types of remedies that can be addressed by different potential actors.

The Annex C to this document provides the full content of the materials that have been brought together for the catalogue. The catalogue will remain online at http://www.gaia-clim.eu/page/gap-reference-list after the end of the project. The search facility helps to guide users and potential stakeholders through the catalogue of gaps and their suggested remedies. In Annex B the proposed remedies are all assigned to potential actors.

Cross-sections such as presented in Section 3 of this GAID also aided the gap definition and harmonisation process by finding potentially missing gap elements, by identifying relationships between gaps and remedies, and by flagging of complementarity or inconsistency between gaps originating from different user or data provider communities.

Finally, an often-ignored issue in a gap analysis as undertaken here is the inherent risks to continuity it presents. A gap analysis is designed to identify, assess and address deficiencies. It is not designed to highlight existing capabilities. In the real world, there is only a finite resource of expertise and finance available to fulfil user needs. In this context, there is a risk that addressing a gap is achieved via removal of resources from elsewhere, which in turn then raises a new gap. That is not to say that efficiencies cannot be realised, but rather, that the consequences of reallocating resources to address a perceived gap need to be carefully considered.

Annex A List of Acronyms

ACSO	Absorption Cross Section of Ozone (IGACO activity)
AQ	Air Quality
AMF	Air Mass Factor
C3S	Copernicus Climate Change Service
Cal/Val	Calibration and Validation
CAMS	Copernicus Atmospheric Monitoring Service
CCI	Climate Change Initiative (ESA)
CDR	Climate Data Record
CDS	Copernicus Data Store
CEOS	Committee on Earth Observation Satellites
CFH	Cryogenic Frost point Hygrometer
DIAL	Differential Absorption Lidar
DOAS	Differential Optical Absorption Spectroscopy
E-AMDAR	Eumetnet Aircraft Meteorological Data Relay
EARLINET	European Aerosol Research Lidar Network
EARTHCARE	Earth Clouds, Aerosols and Radiation Explorer
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
ESA	European Space Agency
EC	European Commission
EU	European Union
EUMETNET	European Meteorological Network
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FCDR	Fundamental Climate Data Record
FTIR	Fourier Transform InfraRed spectroscopy
GAIA-CLIM	Gap Analysis for Integrated Atmospheric ECV CLImate Monitoring
GAID	Gaps Assessment and Impacts Document
GCOS	Global Climate Observing System
GEOMS	Generic Earth Observation Metadata Standard
GEOSS	Global Earth Observation System of Systems
GHG	Green House Gas
GNSS-IPW	Global Navigation Satellite Systems Integrated Precipitable Water
GRUAN	GCOS Reference Upper-Air Network
IAGOS	In-service Aircraft for a Global Observing System
IGACO	Integrated Global Atmospheric Chemistry Observations

ILS	Instrument Line Shape
IR	Infrared radiation
LIDAR	LIght Detection And Ranging
LOS	Line Of Sight
LS	Lower Stratosphere
LSM	Land Surface Models
LT	Lower Troposphere
MAX-DOAS	Multi-Axis Differential Optical Absorption Spectroscopy
MWR	Microwave Radiometry
NDACC	Network for the Detection of Atmospheric Composition Change
NMI	National Metrological Institute
NMS	National Meteorological Service
NWP	Numerical Weather Prediction
PBL	Planetary Boundary Layer
QA/QC	Quality Assurance / Quality Control
QA4ECV	Quality Assurance for Essential Climate Variables
SMART	Specific, Measurable, Achievable, Realistic and Timely
SME	Small and Medium sized Enterprise
SZA	Solar Zenith Angle
TCCON	Total Carbon Column Observing Network
TCWV	Total Column Water Vapour
TCLW	Total Cloud Liquid Water
TOA	Top of Atmosphere
US+M	Upper Stratosphere and Mesosphere
UT	Upper Troposphere
UT/LS	Upper Troposphere / Lower Stratosphere
UV	Ultraviolet
VO	Virtual Observatory
WMO	World Meteorological Organization
WP	Work Package
ZTD	Zenith Total Delay

Annex B Proposed Remedies per Potential Actor(s)

In order to facilitate the use of the catalogue of gaps by stakeholders and potential actors, this Annex provides additional tables listing the proposed remedies per potential actor. Note that many of the proposed remedies have been assigned to (many) more than one potential actor and, therefore, each of the remedies might appear multiple times in the tables below.

The potential actors that have been distinguished include:

- Copernicus Programme
- EU Horizon 2020 Programme
- Space Agencies
- WMO
- National Funding Programmes
- Academia and Individual Research Institutes
- National Meteorological Services
- National Measurement Institutes
- SMEs and Industry

Table B.1 *Remedies proposed for the Copernicus Programme*

G1.03(R1)	Further deployments and refinements of the GAIA-CLIM approach
G1.04(R1)	Extension and continuous update of a comprehensive review of existing geographical gaps for non-satellite observations
G1.05(R1)	Provision of mapping tools to match satellite and non-satellite observations
G1.06(R1)	Design and implementation of unified metadata format under a common data model
G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques without necessitating new observational deployments
G1.10(R2)	Take steps to better realise the benefits of a system of systems approach to observing strategies
G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G2.11(R1)	Create and disseminate a fully traceable reference quality DIAL lidar product
G2.12(R1)	Create a fully traceable reference-quality temperature lidar product
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G2.26(R1)	Improved understanding of the effects of differences in ozone cross-sections
G2.27(R1)	Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error
G2.27(R2)	Improve climatological databases of a priori ozone profiles
G2.27(R3)	Standardize AMF calculation methods and databases of a-priori information used in AMF calculations
G2.27(R4)	An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables is needed
G2.30(R1)	Steps towards reference quality measurement program for Pandora measurements
G2.31(R1)	Improved understanding of potential for MAX-DOAS high quality measurements of tropospheric ozone
G2.31(R2)	Improved understanding of retrieval techniques for tropospheric ozone from MAX-DOAS
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G3.01(R1)	Improved high-resolution modelling to quantify mismatch effects
G3.01(R2)	Use of statistical analysis techniques based upon available and targeted additional observations
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria

G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.04(R2)	Empirical determination of true resolution by comparison with high-resolution data
G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments (OSSEs)
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G5.01(R1)	Successful implementation of the Copernicus Climate Change Service activity on baseline and reference network data access via the Climate Data Store
G5.01(R2)	Operationalisation and extension of the GAIA-CLIM Virtual Observatory facility
G5.06(R1)	Operationalisation of a *satellite – non-satellite matchups* facility with appropriate discovery and user tools
G5.07(R1)	Propagation and adoption of metrological best practices in sustained validation activities
G5.09(R1)	Implement means to provide the community with a forward radiative transfer capability or results of computations
G5.11(R1)	Operationalise processing and delivery for non-satellite reference measurements and satellite CDR interim L2 products
G6.01(R1)	Undertake short-term cross-network governance improvements
G6.01(R2)	Longer-term rationalisation of observational network governance
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation of current non-satellite observational capabilities
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.12(R1)	Undergraduate, masters and doctoral training programs in Copernicus-relevant programs
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

Table B.2 *Remedies proposed for the EU Horizon 2020 Programme and follow-on framework programs*

G1.03(R1)	Further deployments and refinements of the GAIA-CLIM approach
G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques without necessitating new observational deployments
G1.10(R2)	Take steps to better realise the benefits of a system of systems approach to observing strategies
G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G2.11(R1)	Create and disseminate a fully traceable reference quality DIAL lidar product
G2.12(R1)	Create a fully traceable reference-quality temperature lidar product
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G2.26(R1)	Improved understanding of the effects of differences in ozone cross-sections
G2.27(R1)	Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error
G2.27(R2)	Improve climatological databases of a priori ozone profiles
G2.27(R3)	Standardize AMF calculation methods and databases of a-priori information used in AMF calculations
G2.27(R4)	An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables is needed
G2.30(R1)	Steps towards reference quality measurement program for Pandora measurements
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G2.37(R1)	Establish traceability of spectroscopic properties of Essential Climate Variables
G3.01(R1)	Improved high-resolution modelling to quantify mismatch effects
G3.01(R2)	Use of statistical analysis techniques based upon available and targeted additional observations
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.04(R2)	Empirical determination of true resolution by comparison with high-resolution data
G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments (OSSEs)
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G4.01(R1)	Development of tools to propagate geophysical profile data and attendant uncertainties to TOA radiances and uncertainties

G4.01(R2)	Evaluate quality of NWP and reanalysis fields through comparisons with reference data as a means of establishing direct traceability
G4.12(R1)	Use of GNSS-RO temperature profiles as a reference dataset for satellite Cal/Val
G5.06(R1)	Operationalisation of a *satellite – non-satellite matchups* facility with appropriate discovery and user tools
G5.07(R1)	Propagation and adoption of metrological best practices in sustained validation activities
G5.09(R1)	Implement means to provide the community with a forward radiative transfer capability or results of computations
G5.09(R2)	Improved characterisation of error covariances in GRUAN measurements

Table B.3 *Remedies proposed for Space Agencies*

G1.03(R2)	Adoption of measurement systems approach and assessment by international bodies
G1.05(R1)	Provision of mapping tools to match satellite and non-satellite observations
G1.06(R1)	Design and implementation of unified metadata format under a common data model
G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques without necessitating new observational deployments
G1.10(R2)	Take steps to better realise the benefits of a system of systems approach to observing strategies
G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.06(R1)	Improve the coverage, metrological characterisation, and operational capabilities of Raman lidars
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G2.11(R1)	Create and disseminate a fully traceable reference quality DIAL lidar product
G2.12(R1)	Create a fully traceable reference quality temperature lidar product
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G2.26(R1)	Improved understanding of the effects of differences in ozone cross-sections
G2.27(R1)	Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error
G2.27(R2)	Improve climatological databases of a priori ozone profiles
G2.27(R3)	Standardize AMF calculation methods and databases of a-priori information used in AMF calculations
G2.27(R4)	An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables is needed
G2.30(R1)	Steps towards reference quality measurement program for Pandora measurements
G2.31(R1)	Improved understanding of potential for MAX-DOAS high quality measurements of tropospheric ozone
G2.31(R2)	Improved understanding of retrieval techniques for tropospheric ozone from MAX-DOAS
G3.01(R1)	Improved high-resolution modelling to quantify mismatch effects
G3.01(R2)	Use of statistical analysis techniques based upon available and targeted additional observations
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.04(R2)	Empirical determination of true resolution by comparison with high-resolution data
G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments (OSSEs)
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G4.08(R1)	Intercomparison of existing surface emissivity models
G4.08(R2)	The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz
G4.09(R1)	The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based).
G4.09(R2)	Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables
G4.10(R1)	Provision of validated land surface infrared emissivity atlases
G5.01(R2)	Operationalisation and extension of the GAIA-CLIM Virtual Observatory facility
G5.06(R1)	Operationalisation of a *satellite – non-satellite matchups* facility with appropriate discovery and user tools
G5.07(R1)	Propagation and adoption of metrological best practices in sustained validation activities
G5.09(R1)	Implement means to provide the community with a forward radiative transfer capability or results of computations
G5.11(R1)	Operationalise processing and delivery for non-satellite reference measurements and satellite CDR interim L2 products

G6.01(R1)	Undertake short-term cross-network governance improvements
G6.01(R2)	Longer-term rationalisation of observational network governance
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation of current non-satellite observational capabilities
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

Table B.4 *Remedies proposed for WMO*

G1.03(R1)	Further deployments and refinements of the GAIA-CLIM approach
G1.03(R2)	Adoption of measurement systems approach and assessment by international bodies
G1.04(R1)	Extension and continuous update of a comprehensive review of existing geographical gaps for non-satellite observations
G1.05(R1)	Provision of mapping tools to match satellite and non-satellite observations
G1.06(R1)	Design and implementation of unified metadata format under a common data model
G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques without necessitating new observational deployments
G1.10(R2)	Take steps to better realise the benefits of a system of systems approach to observing strategies
G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G2.11(R1)	Create and disseminate a fully traceable reference quality DIAL lidar product
G2.12(R1)	Create a fully traceable reference-quality temperature lidar product
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G5.07(R1)	Propagation and adoption of metrological best practices in sustained validation activities
G6.01(R1)	Undertake short-term cross-network governance improvements
G6.01(R2)	Longer-term rationalisation of observational network governance
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation of current non-satellite observational capabilities
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis

Table B.5 *Remedies proposed for National Funding Programmes*

G1.04(R1)	Extension and continuous update of a comprehensive review of existing geographical gaps for non-satellite observations
G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques without necessitating new observational deployments
G1.10(R2)	Take steps to better realise the benefits of a system of systems approach to observing strategies
G2.06(R1)	Further deployments and refinements of the GAIA-CLIM approach to metrological characterization of multi-wavelength Raman lidars
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G2.12(R1)	Create a fully traceable reference-quality temperature lidar product
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G2.27(R1)	Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error
G2.27(R2)	Improve climatological databases of a priori ozone profiles
G2.27(R3)	Standardize AMF calculation methods and databases of a-priori information used in AMF calculations
G2.27(R4)	An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables is needed
G2.30(R1)	Steps towards reference quality measurement program for Pandora measurements
G2.31(R1)	Improved understanding of potential for MAX-DOAS high quality measurements of tropospheric ozone

G2.31(R2)	Improved understanding of retrieval techniques for tropospheric ozone from MAX-DOAS
G3.01(R1)	Improved high-resolution modelling to quantify mismatch effects
G3.01(R2)	Use of statistical analysis techniques based upon available and targeted additional observations
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.04(R2)	Empirical determination of true resolution by comparison with high-resolution data
G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments (OSSEs)
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G4.08(R1)	Intercomparison of existing surface emissivity models
G4.08(R2)	The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz
G4.08(R3)	Establish an ocean emissivity reference model in the spectral region 1 – 200 GHz
G4.08(R4)	Reference-quality dielectric constant measurements of pure and saline water for the frequency range 1 – 200 GHz
G4.09(R1)	The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based).
G4.09(R2)	Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables
G4.10(R1)	Provision of validated land surface infrared emissivity atlases
G5.11(R1)	Operationalise processing and delivery for non-satellite reference measurements and satellite CDR interim L2 products
G6.01(R2)	Longer-term rationalisation of observational network governance
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation of current non-satellite observational capabilities
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis
G6.12(R1)	Undergraduate, masters and doctoral training programs in Copernicus-relevant programs
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

Table B.6 *Remedies proposed for Academia and Individual Research Institutes*

G1.10(R1)	Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques without necessitating new observational deployments
G1.10(R2)	Take steps to better realise the benefits of a system of systems approach to observing strategies
G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.06(R1)	Improve the coverage, metrological characterisation, and operational capabilities of Raman lidars
G2.07(R1)	Extension of the GAIA-CLIM data assimilation approach to aerosol lidars
G2.08(R1)	Synergy between water vapour Raman lidar and other measurement techniques
G2.08(R2)	Verification and further deployment of the GAIA-CLIM approach to metrological characterisation to Raman Lidar measurements
G2.13(R1)	Development and testing of MWR standards and secondary standards
G2.18(R1)	Improved traceability of uncertainties in FTIR measurements
G2.22(R1)	Regular cell measurements and ILS retrievals are to be performed in a consistent manner
G2.24(R1)	Use of AirCore data to contribute to the FTIR calibration
G2.26(R1)	Improved understanding of the effects of differences in ozone cross-sections
G2.27(R1)	Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error
G2.27(R2)	Improve climatological databases of a priori ozone profiles
G2.27(R3)	Standardize AMF calculation methods and databases of a-priori information used in AMF calculations
G2.27(R4)	An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on the look-up tables is needed
G2.31(R1)	Improved understanding of potential for MAX-DOAS high quality measurements of tropospheric ozone
G2.31(R2)	Improved understanding of retrieval techniques for tropospheric ozone from MAX-DOAS
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.04(R2)	Empirical determination of true resolution by comparison with high-resolution data

G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments (OSSEs)
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G4.08(R1)	Intercomparison of existing surface emissivity models
G4.08(R2)	The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz
G4.08(R3)	Establish an ocean emissivity reference model in the spectral region 1 – 200 GHz
G4.08(R4)	Reference-quality dielectric constant measurements of pure and saline water for the frequency range 1 – 200 GHz
G4.09(R1)	The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based).
G4.09(R2)	Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables
G4.10(R1)	Provision of validated land surface infrared emissivity atlases
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

Table B.7 *Remedies proposed for National Meteorological Services*

G1.04(R1)	Extension and continuous update of a comprehensive review of existing geographical gaps for non-satellite observations
G1.06(R1)	Design and implementation of unified metadata format under a common data model
G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.07(R1)	Extension of the GAIA-CLIM data assimilation approach to aerosol lidars
G2.10(R1)	Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone
G2.11(R1)	Create and disseminate a fully traceable reference quality DIAL lidar product
G2.12(R1)	Create a fully traceable reference-quality temperature lidar product
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G3.01(R1)	Improved high-resolution modelling to quantify mismatch effects
G3.01(R2)	Use of statistical analysis techniques based upon available and targeted additional observations
G3.02(R1)	Systematic quantification of the impacts of different co-location criteria
G3.04(R1)	Comprehensive modelling studies of measurement process.
G3.04(R2)	Empirical determination of true resolution by comparison with high-resolution data
G3.05(R1)	Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques
G3.06(R1)	Use of observing system simulation experiments (OSSEs)
G3.06(R2)	Statistical estimation of typical co-location mismatch effects
G4.01(R1)	Development of tools to propagate geophysical profile data and attendant uncertainties to TOA radiances and uncertainties
G4.01(R2)	Evaluate quality of NWP and reanalysis fields through comparisons with reference data as a means of establishing direct traceability
G4.08(R1)	Intercomparison of existing surface emissivity models
G4.08(R2)	The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz
G4.08(R3)	Establish an ocean emissivity reference model in the spectral region 1 – 200 GHz
G4.09(R1)	The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based).
G4.09(R2)	Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables
G4.10(R1)	Provision of validated land surface infrared emissivity atlases
G4.12(R1)	Use of GNSS-RO temperature profiles as a reference dataset for satellite Cal/Val
G5.09(R2)	Improved characterisation of error covariances in GRUAN measurements
G5.11(R1)	Operationalise processing and delivery for non-satellite reference measurements and satellite CDR interim L2 products
G6.01(R2)	Longer-term rationalisation of observational network governance
G6.02(R1)	Reviews of capabilities leading to action plans for rationalisation of current non-satellite observational capabilities
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities

G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

Table B.8 *Remedies proposed for National Measurement Institutes*

G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.08(R1)	Synergy between water vapour Raman lidar and other measurement techniques
G2.08(R2)	Verification and further deployment of the GAIA-CLIM approach to metrological characterisation to Raman Lidar measurements
G2.13(R1)	Development and testing of MWR standards and secondary standards
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis
G6.12(R2)	Instigate formal qualification of competency in provision of Copernicus services

Table B.9 *Remedies proposed for SMEs and Industry*

G1.10(R3)	Improved quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data
G2.08(R1)	Synergy between water vapour Raman lidar and other measurement techniques
G2.08(R2)	Verification and further deployment of the GAIA-CLIM approach to metrological characterisation to Raman Lidar measurements
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G2.36(R1)	Adoption of multidisciplinary review approach and further implementation by international bodies
G5.06(R1)	Operationalisation of a *satellite – non-satellite matchups* facility with appropriate discovery and user tools
G5.11(R1)	Operationalise processing and delivery for non-satellite reference measurements and satellite CDR interim L2 products
G6.03(R1)	Optimization of scheduling to enhance capability for satellite Cal/Val activities
G6.06(R1)	Operationalize measurements to be 24/7 on an instrument by instrument and site by site basis

Annex C GAIA-CLIM Catalogue of Gaps

This Annex contains the full content of the on-line GAIA CLIM Catalogue of Gaps per end of project. Each full gap description follows the template as provided in Section 2.2, including a gap title with short gap description, a proposed remedy or set of remedies, and the relevance (impact) of the remedy.

- For each gap there is a clear trace
- For each remedy there is a *SMART* description of the required activities

Note that some identified gaps have been retired in the process. The original set of gaps retained their identification number s Gx.xx throughout the consolidation process of the GAIA-CLIM project (Section 2.4). Therefore, a non-continuous gap numbering appears in the catalogue. The retired gaps numbers are listed separately in Table 2 (Section 2.3).

G1.03 Lack of internationally recognized and adopted framework for assessment of fundamental observing capabilities

Gap Abstract

There currently exists no universally recognized approach for assessing quantifiable aspects of the measurement system maturity of existing observing networks. Although absolute measurement quality cannot be assured, fundamental properties of the measurement system that build confidence in its appropriateness and metrological verity can be assessed. The lack of an agreed international framework for such an assessment leads to heterogeneity in the approaches used to select the most suitable measurement series for any given application. This frequently has deleterious effects for downstream applications in that often the measurements are used in a manner that is not optimal or even not appropriate.

Part I Gap Description

Primary gap type

Parameter (missing auxiliary data etc.)

Secondary gap type

Governance (missing documentation, cooperation etc.)

ECVs impacted (GAIA-CLIM targeted ECVs only)

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User Categories/Application Areas Impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite Instrument Techniques Involved

Independent of instrument technique

Related gaps

- G1.04 Lack of a comprehensive review of current non-satellite observing capabilities for the study of ECVs across domains

The resolution of the current gap will aid resolution of G1.04 by providing an assessable basis with broad buy-in to classify individual contributing measurement systems.

- G1.06 Currently heterogeneous metadata standards hinder data discoverability and usability.

G1.03, as well as G1.04, must be addressed after G1.06, which will provide all the required information to proceed towards an effective approach to resolving both G1.03 and G1.04.

Gap Detailed Description

No systematic effort has been made to define and broadly agree amongst global stakeholders on the measurement and network characteristics underlying a systemic approach to Earth Observation. Nor is there any recognized approach in place to ensure a consistent way of assessing where any given observation sits within such a framework. Different observational domain areas (atmospheric, composition, marine, terrestrial, cryospheric, etc.) use domain-specific, but overlapping naming conventions. These often use the same label such as 'reference' or 'baseline' to mean very different things. The unwary user is faced with an unenviable task as a result, and this yields sub-optimal and / or incorrect usage of available observational records in many cases and confusion for funders, users, and stakeholders.

This gap potentially inhibits realization of the full benefits of an explicitly system-of-systems architecture (trickle down calibration, characterization, etc.) across the global networks. It also places the burden of appropriate use of data squarely on the user, which is an unrealistic expectation in the majority of cases as the user is not, at least ordinarily, sufficiently expert in the nuances of observational programs (and nor should they be expected to be so). The gap has been recognized in the most recent (2016) GCOS Implementation Plan and an action (G13 Review of ECV observational networks) associated, which speaks to elements of this gap.

Action G13:	Review of ECV observation networks
Action	For all ECV products not covered by a review following actions G11 and G12: develop and implement a process to regularly review ECV observation networks, comparing their products with the ECV product requirements; identify gaps between the observations and the requirements; identify any deficiencies and develop remediation plans with relevant organizations; and ensure the data is discoverable and accessible. This action may also contribute to the definition of reference grade observing network and standards The GCOS science panels should identify stakeholders who will perform this review and regularly check all ECV products are being reviewed.
Benefit	Increase quality and availability of climate observations.
Who	Organizations listed in Annex A.GCOS Panels to maintain oversight.
Time-frame	Develop and demonstrate review process in 2017. Review each ECV's observing systems at least every 4 years.
Performance Indicator	Reports of results of ECV reviews produced by panels each year.
Annual Cost	100k-1M US$, Also part of work of panels

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

- Representativity (spatial, temporal)
- Calibration (relative, absolute)

Gap status after GAIA-CLIM

GAIA-CLIM has partly closed this gap:

The GAIA-CLIM-related activities are described in peer-reviewed literature (Thorne et al., 2017). This clearly articulates the method that GAIA-CLIM used, but does not close the gap as it is, at this stage, only an approach used by a single project. Therefore, while it shows a potential approach to solving the gap, it lacks the broad community and institutional buy-in aspects necessary to close the gap. Remaining aspects to be addressed include a broader assessment of applicability to other observational capabilities and discussion and agreement by appropriate international entities.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Homogeneous basis for choice of appropriate observations for particular applications	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium to High	Consistent use of observations across diverse applications on a verifiable basis. Increased confidence for users. Increased provenance behind data selection decisions
Identified pathways to improving quality of observational programs	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) International (collaborative) frameworks and bodies (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	High	Targeted basis for improving quality of assessable aspects of measurement programs. Enhanced informed funding support decisions programmatically and internationally
Realizing synergies between observational programs	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) International (collaborative) frameworks and bodies (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	Medium	Assessment process would highlight potential synergies achievable between national, regional, and global observational capabilities. See gaps related to governance (G06.XX) to which this may contribute as a result

Identified risk	**User category/Application area benefited**	**Probability of benefit being realised**	**Impacts**
Continued ad hoc decision-making process for selection of observations for given uses	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Incomparability of analyses owing to differences in choices of observations to use. Inappropriate observations being used and risk of making false inferences as a result (conflating observational error with real phenomena)
Support decisions targeting the wrong observation programs	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) International (collaborative) frameworks and bodies (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	High Medium	Good observational programs put under pressure / discontinued. Not realizing the full benefit of past financial investments for science and society. Reduction of cost-effectiveness in the use of resources. Synergies between observing capabilities not realized leading to degraded assessments of observational change
Full value of programs such as WIGOS not realized	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) International (collaborative) frameworks and bodies (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	Medium	Reduced utility of global observational capabilities and coordination of programs. Lack of buy-in at national and regional level to integrated observing system concepts
Continued within and across domain confusion in naming conventions and data-quality assessments	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) International (collaborative) frameworks and bodies (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	High	Confusion to end-users on what different data streams constitute

Part III Gap Remedies

Remedy 1 – Further deployments and refinements of the GAIA-CLIM approach

Primary gap remedy type

- Education/Training

Secondary gap remedy type

- Deployment
- Research
- Governance

Proposed remedy description

To develop, refine, and deploy a system-of-systems measurement maturity assessment as developed by GAIA-CLIM across a range of use cases to determine the degree to which it is potentially applicable across non-satellite observing platforms and problems. Already under way for the Arctic domain under the H2020 INTAROS project in the context of the Copernicus Climate Change Service Evaluation and Quality Control program, its use and further development could be undertaken across a broader range of cases and with a range of international programmatic cases. This would constitute further refinement and proof-of-concept testing of the applicability, utility, and value of a measurement system maturity assessment approach to enable subsequent adoption. This testing should include a consideration of applicability across a diverse range of observational networks and across the full range of observational domains (surface, atmospheric, oceanic, terrestrial, hydrological, cryospheric). This will permit an evaluation of the value of the measurement maturity assessment, as well as its fitness-for-purpose for applications such as the Copernicus Climate Change Service and the WMO Integrated Observing System (WIGOS).

Relevance

The application of GAIA-CLIM approach to other cases shall lead to improvements in the guidance and approach and enable greater buy-in from a more diverse range of stakeholders.

Measurable outcome of success

One or more reports or peer-reviewed papers describing the application and developments.

Expected viability for the outcome of success

High

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- EU H2020 funding
- Copernicus funding
- WMO

Remedy 2 – Adoption of measurement systems approach and assessment by international bodies

Primary gap remedy type

Deployment

Secondary gap remedy type

Education/Training
Governance

Proposed remedy description

Adoption of the GAIA-CLIM approach or of a similar approach to measurement maturity assessment established by globally responsible entities, such as the Global Climate Observing System (GCOS) or WIGOS and / or in subsequent relevant scientific projects. A single approach needs to be formulated, adopted, and rolled out across a broad range of non-satellite observing capabilities to assess their maturity and appropriately categorise their role in the global observing system. Periodic re-review of observing capabilities should then be instigated to ensure that assessments reflect up-to-date snapshots of measurement capabilities. A mechanism of feedback to the contributing measurement networks should be codified and enacted. The results of the assessments should be made available in a way that provides actionable information to end-users and to ensure they use the most appropriate data for their applications.

Relevance

The adoption of an international programmatic effort to assess measurement capabilities would directly address the gap and ensure broad buy-in.

Measurable outcome of success

Documentation of adopted mechanism, results of assessment available to users.

Expected viability for the outcome of success

High

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Low recurring costs for evaluations and process management

Potential actors

- Copernicus funding
- WMO
- ESA, EUMETSAT or other space agency

References

- Global Climate Observing System GCOS 2016 Implementation Plan. https://ane4bf-datap1.s3-eu-west-1.amazonaws.com/wmocms/s3fs-public/programme/brochure/GCOS-200_OnlineVersion.pdf?PlowENiCc1RGh9ReoeAoGBT0QhnJYm6_
- Thorne, P. W., Madonna, F., Schulz, J., Oakley, T., Ingleby, B., Rosoldi, M., Tramutola, E., Arola, A., Buschmann, M., Mikalsen, A. C., Davy, R., Voces, C., Kreher, K., De Maziere, M., and Pappalardo, G. (2017) : "Making better sense of the mosaic of environmental measurement networks: a system-of-systems approach and quantitative assessment", Geosci. Instrum. Method. Data Syst., 6, 453-472, https://doi.org/10.5194/gi-6-453-2017, 2017.

G1.04 Lack of a comprehensive review of current non-satellite observing capabilities for the study of ECVs across domains

Gap Abstract

While a comprehensive review of space-based missions and needs has been put together within official documents of the international community and coordinated by an agreed international framework in the Committee on Earth Observation Satellites (CEOS), in contrast, the mapping and coordination of current non-satellite observing capabilities is piecemeal and poorly documented. Extensive reviews have been provided by WMO (World Meteorological Organization), GEOSS (Group on Earth Observations), Global Climate Observing System (GCOS), amongst others, but they are invariably limited to those networks and ECVs relevant for their institutional mission, and often substantively disagree with one another in regard to both the perceived adequacy of the current capabilities and the required innovations.

Part I Gap Description

Primary gap type gaps

Spatiotemporal coverage

Secondary gap type

Governance (missing documentation, cooperation etc.)

ECVs impacted

Temperature, Water vapor, Ozone, Aerosols, Carbon Dioxide, Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)

Non-satellite instrument techniques involved

Independent of instrument technique

Related gaps

- G1.03 Lack of internationally recognized and adopted framework for assessment of fundamental observing capabilities
- G1.05 Lack of integrated user tools showing all existing observing capabilities for measuring ECVs with respect to satellite spatial coverage
- G1.06 Currently heterogeneous metadata standards hinder data discoverability and usability

G1.04, as well as G1.03, must be addressed after G1.06, which will provide all the required information to proceed towards an effective approach to G1.03 and G1.04.

G1.03 and G1.05 are both critically dependent gaps which should be addressed with G1.04.
There is an interdependency between G1.03 and G1.04, whereby the resolution of G1.03 will aid resolution of G1.04 by providing an assessable basis with broad buy-in to classify individual contributing measurement systems.
There is also an interdependency between G1.04 and G1.05. A comprehensive review of the current observing capabilities at the European and global scale for all the ECVs is a pre-requisite to implement any user-friendly mapping software supporting the broad use of non-satellite observation by EO data providers and data users.

Detailed description

Non-satellite observations support a wide range of applications in monitoring and forecasting of the atmosphere, of the oceans, and land surfaces, across a broad range of time scales (including near-real-time and delayed mode applications). These activities support an increasing range of services with high socio-economic benefits. User requirements have become more stringent and emergent requirements have increasingly appeared with respect to these applications (and undoubtedly will continue to do so). These observing systems provide their products in one or more of real-time, near-real-time and non-real-time (those that provide a mix may apply different processing to different timescale releases with, in general, greater quality assurance for delayed mode products). In order to allow EO providers and users to maximize the value of existing observations and implement a user-friendly mapping facility, a comprehensive review of the current observing capabilities at both the European and global scales is needed for all ECVs. This will also facilitate an identification of the existing geographical gaps in the global observing system. The mapping of current non-satellite observing capabilities is insufficient compared to the comprehensive review of space-based missions. For satellite missions, the review must be reported and routinely updated within official documents of the international community (e.g. for satellite observations, the CEOS Handbook and the "Satellite Supplement" to the GCOS Implementation Plan). For the in-situ segment in contrast, it is based on the information provided voluntarily by each network or station to some international data portals in an uncoordinated way, often on an ECV by ECV and network by network basis. WMO, GEOSS, GCOS have provided extensive metadataset and station inventories, but their sets of information are limited to their own specific mission and to those networks and ECVs upon which they have a coordination role. This inevitably increases the level of heterogeneity among the different assessments, which may often disagree with one another over both perceived adequacy of the current capabilities and posited remedies / innovations. This leads to reduced uptake of the outcomes of such assessments.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

Representativity (spatial, temporal)

Gap status after GAIA-CLIM

GAIA-CLIM has partly closed this gap:

GAIA-CLIM delivered in September 2016 a review of the current surface-based and sub-orbital observing capabilities at the global scale for a subset of ECVs and networks, also identifying geographical regions where specific observations are missing and should be established in the future.

Part II: Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
To facilitate an identification of the existing geographical gaps in the global observing system.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High Medium	To enable users to maximize the value of existing observations at the global scale for the validation of satellite CDRs and for any kind of climate study.
To stimulate international and regional capacity development in the data and metadata exchange also in support of the existing international initiatives on metadata collection carried out by WMO, GEOSS, EU research infrastructures (e.g. INSPIRE, C3S, CAMS)	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	To improve standardization and harmonization of the existing data archives in EU and outside. To facilitate users' access to in-situ observations. To increase the number of in-situ observations available for the satellite cal/val and the data assimilation in global or regional numerical models. To facilitate the work required to deliver downstream services in several sectors.
Support decisions to drive future investment to remedy to the current observation gaps.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) International (collaborative) frameworks and bodies (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	High	Identify the geographical areas and perform specific scientific studies to assess the most critical gaps in the current observing system to prioritize investments. An assessment of any potential redundancy will be facilitated.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Fragmentation of metadata among repositories maintained by international bodies and measurements programs. Leading to under-exploitation of the existing surface-based and sub-orbital observing capabilities	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High Medium	Underuse or under-exploitation of existing observations affecting climate studies and their capability to catch climate change signals; potential redundant investments for improving the observing networks at the global scale.
Reduced capability to classify the maturity of individual contributing measurement systems and to assess the gaps in current non-satellite observing system.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate	High	Reduced capability to support the users to identify the most suitable product for a given application and the equivalence across the various networks, measurements techniques, and data archives. Reduced capability to support

	Data Records)		funding agencies and decision makers in the assessment of the most critical gaps in the current observing system to prioritize investments.

Part III: Gap Remedies

Remedy 1 – Extension and continuous update of a comprehensive review of existing geographical gaps for non-satellite observations

Primary gap remedy type

Governance

Proposed remedy description

The extensive review of existing observing non-satellite capabilities for the measurement of a multitude of ECVs provided in GAIA-CLIM should be considered for viability over the long term as a service activity updated on a regular basis. The process towards the implementation of such a service comprises of the following steps:

- Establishing of broad synergies among the international bodies, research infrastructures, and meteorological services, maintaining the repositories where the observations provided by the existing networks operating at the global scale are stored;
- Establishing a functioning governance structure between the data suppliers (i.e. networks) and the international data providers (WMO, GCOS, GAW, Research Infrastructures, etc), which must count on the effort of each network in maintaining the highest quality level for its own metadata. This should also include a reward to the data suppliers for maintaining service activities.
- Facilitating the processes described above, by funding projects whose aim must be to demonstrate the feasibility of the proposed service activity for specific ECVs over the long term; these projects should involve experimental scientists, modellers, and ICT experts, along with representatives from international research bodies.

With respect to the last point above, the review offered within GAIA-CLIM will be improved and supported over the long term by Copernicus Climate Change Service (C3S) for the in-situ measurements component for a subset of the atmospheric, land and oceanic ECVs considered in GAIA-CLIM through the provision of extensive inventories of the investigated networks. C3S is dealing with the access to in-situ observation and shall provide valuable examples of structuring such governance between the data suppliers. The C3S outreach system ensures the coordination of its activities with other international activities for a sustained exchange of rich measurement metadata information ongoing at WMO's Commission for Basic Systems, GCOS, GEOSS, GAW (Global Atmospheric Watch). In particular, a synergy with the INSPIRE (Infrastructure for Spatial Information in Europe), at the EU level, and with WIGOS (WMO Integrated Global Observing System), at the international level, must be established.

Relevance

The Copernicus Climate Data Store (CDS) will facilitate the access to rich discovery metadata and support the reduction of the fragmentation already experienced in the metadata sets available worldwide for a large number of networks.

Measurable outcome of success

Use of the collected geographical metadata through the CDS, the GAIA-CLIM 'Virtual Observatory' or similar efforts, and hence downstream applications. The timeline for the assessment and quantification of these datasets can be quantified on the basis of user's level of satisfaction (via feedback collection) in the first two years after the release of metadata through each specific access platform.

Expected viability for the outcome of success

High

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- Copernicus funding
- National funding agencies
- National Meteorological Services
- WMO

G1.05 Lack of integrated user tools showing all existing observing capabilities for measuring ECVs with respect to satellite spatial coverage

Gap Abstract

The availability of user tools able to jointly visualize the current satellite and non-satellite observing capabilities for measuring ECVs at the global scale has never been provided in the past. Several tools have been implemented for specific instruments or networks of the global observing system, but all of them have been designed on the basis of very specific needs, using different criteria/functionalities, and typically including just one or a few ECVs and only one or a small subset of the available networks at the global scale. They have often been designed without user consultation. This lack of integrated user tools serves to inhibit the uptake of non-satellite measurements to characterize satellite observations.

Part I Gap Description

Primary gap type

Technical (missing tools, formats etc.)

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/Application area Impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)

Non-satellite instrument techniques involved

Independent of instrument technique

Related gaps

- G1.03 Lack of internationally recognised and adopted framework for assessment of fundamental observing capabilities
- G1.04 Lack of a comprehensive review of current non-satellite observing capabilities for the study of ECVs across domains

There is an interdependency between G1.03 and G1.04, and consequently with this gap, whereby the resolution of the former will aid resolution of G1.04 by providing an assessable basis with broad buy-in to classify individual contributing measurement systems
In order to allow EO providers and users to maximize the value of existing observations and implement a user-friendly mapping facility, a comprehensive review of the current observing capabilities, at both European and global scales, is needed for all the ECVs.

Detailed description

Several independent tools to enable discovery-metadata visualisation and exploitation have been implemented for specific networks of the global observing system. However, their design is often driven on the basis of very specific and particular needs, using different criteria / tools, and typically including just one ECV and only one or a small subset of the available networks. Users therefore have limited access to user-friendly tools, which can be used to explore the full and comprehensive view of all the sub-orbital observing capabilities. Users thus currently have a cumbersome and time-consuming search process to complete, if they wish to understand and exploit non-satellite data to its full potential. What is required is a unified tool that provides access to all relevant discovery metadata and appropriate search functionalities to enable users to discover and access the appropriate subset of data for their needs.

One of the most apposite examples of such a tool is represented by the OSCAR (Observing Systems Capability Analysis and Review Tool) system of CEOS and WMO and in particular for the surface based capabilities, which is still under development. At its present state, this tool is focused on national operational services and does not include all the ECVs and all the existing networks. For example, many of the high quality observational facilities are not run by National Meteorological or Hydrological Services and thus are not currently catalogued via OSCAR. Moreover, satellite-observing capabilities are collected separately from in-situ under WMO. This inhibits co-exploration of satellite and non-satellite capabilities. An integrated tool able to show simultaneously all the existing non-satellite capabilities, along with the field of view of the satellite-based instruments would greatly help end-users in the design of new validation strategies and in the full exploitation of both satellite and non-satellite data. This would in turn help inform users on the available ECV measurements within different domains (atmosphere, land, and ocean) through a facilitated analysis of the geographical distribution of the full suite of networks at the global scale.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

Representativity (spatial, temporal)

Gap status after GAIA-CLIM

GAIA-CLIM has partly closed this gap:

The GAIA-CLIM Virtual Observatory allows users to jointly explore data and metadata from available non-satellite and satellite observing capabilities, providing information on in-situ surface, in-situ sounding, columnar and profiling observations.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Users to be able to fully exploit the content of surface-based and sub-orbital data and metadata	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	To facilitate the use of non-satellite data and their selection for satellite cal/val To enhance the analysis of the degree of temporal sampling mismatch between satellite instruments and surface-based stations for a relevant subset of EO platforms at real or selected time
To provide user-friendly open-source tools in support of a powerful strategy to interact with users and communicate science	All users and application areas will benefit from it	High	Availability of an interactive graphical user interface to explore the existing observing capabilities strongly facilitates the dialogue with end users, the identification of their needs, and the interaction with any type of broader audience, including students, policy-makers, and citizens
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Lack of tools to drive support in future investments for the EO	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	Lack of services in the frame of the EO programs enabling users to quickly access and assess the suitability of a number of fully traceable reference measurements for a given application to satellite characterisation
Lack of open-source tools to develop a virtual community of scientist and ICT experts capable to improve data exploitation	All users and application areas will suffer from it.	High	Reduction in the number of experts involved in the development of tools for the data exploitation. Missing support to the implementation of robust downstream services

Part III: Gap Remedies

Remedy 1 – Provision of mapping tools to match satellite and non-satellite observations

Primary gap remedy type

Technical

Specific remedy proposed

The GAIA-CLIM 3D-mapping software is able to visualize a comprehensive list of in-situ metadata along with the main related satellite instruments. The software has the capability to continuously update the metadata also in an automatic fashion depending on the availability of updated metadata from in-situ networks.

Future potential work might include an extension of the current software capabilities to visualize also the observational data for a few instruments (e.g. the radiosonde flying from the launch station) and the capability to perform queries for a few existing data archives to check the data availability on-line. This work might be offered to the community also to encourage a joint effort amongst global stakeholders like GCOS, GEOSS, GAW to foster the design of further relevant tools.

In a broader context, the implementation of a unified tool that provides users with access to all metadata and data should be cognizant of a global community already sensitized to open-source software that can be easily accessed. Therefore, efforts should be made to implement an efficient, useful, platform-independent and open-source based service.

The work should consider:

- Use of open-source codes: examples include the Python ARM Radar Toolkit (Py-ART; https://github.com/ARM-DOE/pyart) and the GAIA-CLIM Virtual Observatory.
- Provide a detailed documentation of the codes, installation instructions, frequently asked questions, and other help facilities for users;
- Support enabling the users to program macros and small applications for a range of hardware platforms and compilers;
- Allocate resources to strengthen cooperation programmes between research institutes and global stakeholders to efficiently implement joint initiatives, which could offer a number of opportunities to the users and facilitate the implementation of downstream services.

For the last two items listed above, the forthcoming Copernicus Climate Change Service Data Store toolbox shall offer a first example of the direction to follow over the coming decade.

Relevance

The GAIA-CLIM 3D-mapping software is a flexible open-source solution to visualize and quickly identify geographical gaps and, therefore, the starting point for any scientific assessment within the GAIA-CLIM project, but also going forward to support stakeholder's data visualisation. It also offers some potential opportunities to work a use case of C3S and to support the development of downstream services.

Expected viability for the outcome of success

High

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- Copernicus funding
- WMO
- ESA, EUMETSAT or other space agency

G1.06 Currently heterogeneous metadata standards hinder data discoverability and usability

Gap Abstract

The need for extensive and accurate metadata is ever increasing in both research and operations, enabling large-scale, distributed management of resources. Recent years have seen a growth in interaction between previously relatively isolated communities, driven by a need for cross-domain collaboration and exchange of data and products. However, metadata standards have generally not been able to meet the needs of interoperability between independent standardization communities. Observations without useable metadata are of very limited use as the metadata provides key context such as the time, location, and modality of the measurements. Several efforts have been undertaken to improve the harmonization of metadata across the networks and international programs, but currently this is still insufficient.

Part I Gap Description

Primary gap type

Technical (missing tools, formats etc.)

Secondary gap type

Governance (missing documentation, cooperation etc.)

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Independent of instrument technique

Related gaps

- G1.03 Lack of internationally recognised and adopted framework for assessment of fundamental observing capabilities
- G1.04 Lack of a comprehensive review of current non-satellite observing capabilities for the study of ECVs across domains
- G5.01 Vast number of data portals serving data under distinct data policies in multiple formats for fiducial reference-quality data inhibits their discovery, access, and usage for applications, such as satellite Cal/Val

G1.03 and G1.04 should be addressed after G1.06
The resolution of G1.06 would bring invaluable benefits to support the resolution of G1.03 and G1.04 by facilitating the review of existing capabilities, starting from rich standardized information and enabling classification of measurement maturity in a more accurate way.
G5.01 should be addressed with this gap
Metadata harmonization across multiple data provides will also positively impact on the interoperability among different data repositories with clear benefits for addressing gap G5.01

Detailed description

Metadata is an increasingly essential tool enabling large-scale, distributed management of resources. Recent years have seen a growth in interaction between previously relatively isolated communities across observing domains and techniques, driven by a need for interdisciplinary research and understanding. However, metadata standards have not been able to meet the needs of interoperability between these to date largely independent communities and networks. Observations without metadata are of very limited use: it is only when accompanied by adequate metadata (data describing the data) that the full potential of the observations can be realized. Format conversions always bring with them the danger of destroying information in the process, in particular in the accompanying metadata, which usually receives less attention.

Several efforts have been undertaken to improve the harmonization of metadata across numerous networks and international programs, but this is still not sufficient. Harmonization effort in the atmospheric science community is starting to be addressed by the emerging WIGOS standards, currently under development and subsequent implementation at the WMO, and by the ESA Climate Change Initiative (CCI), amongst others. Copernicus Climate Change Service Data Store activities are also highly relevant to this gap. There are also challenges that arise due to interoperability across observational domains (surface, atmospheric, oceanic, terrestrial etc.).

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Assimilated product (Level 4)
- Time series and trends
- Representativity (spatial, temporal)

Gap status after GAIA-CLIM

GAIA-CLIM explored and demonstrated potential solutions to close this gap in the future:

GAIA-CLIM metadata standards and format harmonization have been carried out with aim to provide a model for facilitating the users' access and the usability in-situ data. This exercise included the establishment and documentation of common metadata and data formats for a selected subset of networks that will contribute to the Virtual Observatory. The Virtual Observatory facility shall also support the remedy of this gap by providing data format conversion for various input data and a data extraction function that makes the outputs available in user friendly formats.

GAIA-CLIM activities will be followed up by the Copernicus Climate Change Service, where, for a selected number of networks reviewed within GAIA-CLIM, the harmonization of the data and metadata format and structure is ongoing. According to the requirements provided by the Copernicus end-users through the C3S Sectoral Information System (SIS) projects, this effort involves the implementation of a common data model compliant with the ECWMF Observational DataBase (ODB) and a data-management facility, which shall become part of the operational C3S services at the end of the above-mentioned contract.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Full data interoperability and availability of full metadata records for reprocessing of CDRs	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Unlimited use of available datasets in a synergetic way for any kind of climate and weather study. Facilitate the interoperability among the existing international data repository.
Increase in the usage of multiple satellite and non-satellite products for research study, operational and downstream services.	All users and application areas will benefit from it	High	Improved accuracy of the weather and climate projections. Increased number of products delivered by any type of service for different sectors.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Missing interoperability between independent metadata standardization communities	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	Limited cross-domain collaboration and data exchange between different communities. Limits the ability to appropriately use and derive value from the data.
Limitations on the development of robust downstream services	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium to High	Challenges to the creation of downstream products and services by Copernicus able to satisfy the needs of European and global markets.
Continued need for data format conversion tools that are established by many different groups.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Preventing easy data exploitation due to continued need for data format conversion tools that are established by many different groups. General higher cost or longer times for data handling before achieving results.

Part III Gap Remedies

Remedy 1 – Design and implementation of unified metadata format under a common data model

Primary gap remedy type

Governance

Secondary gap remedy type

Technical ; TRL7

Proposed remedy description

To develop a sustained service, metadata, and data quality and data validation are of crucial importance. Their harmonization is a requirement which is intended to establish a common understanding of the data content, to ensure correct and proper use and interpretation of the data by its owners and users, thus maximizing the benefit for the users. To address the current heterogeneity in the metadata standards, a collaborative effort among different communities and stakeholders must be undertaken. The technical approach to adopt could be of two different types:

1. A common data model merging the metadata information provided in the various existent metadata formats (CFNetCDF, WIGOS, ISO-19115, and NASA-Ames mainly) must be adopted. This allows users to provide, as realised within GAIA-CLIM, a unified metadata format (UMDF) that retains all contributing metadata and that is extendable should new metadata elements be required. This leads to an improvement in the discoverability of data and enables an easy and comprehensive conversion into a multitude of formats desired by end users. Similar efforts include the smart extensions of existing international standards like "Climate Science Modelling Language" (CSML), developed by University of Reading on the basis of ISO19115 or the UNIDATA abstract model.

   The Copernicus Climate Change Service is already extending the scope of the GAIA-CLIM work for selected Baseline and Reference in-situ observations to make metadata and data compatible with Observation Data Base (ODB) developed at ECMWF. The use of a CDM (and consequently of a UMD) could make a significant attempt to improve the metadata harmonization at the international level can also facilitate the interoperability and, if possible, the integration of the existing data repositories improving the users' access to the data from multiple suppliers and collected with different measurement techniques.

2. A different approach is to adopt or customize one broadly used standard for both discovery and observation metadata and to provide users with a number of software converters to map the metadata onto the most commonly used international standards. To date, this has been the approach adopted by various international bodies (WMO, ESA, GCOS, GEOSS, GAW...). It must be noted that this solution, as well as being more computationally consuming, might arise substantial challenges in the metadata conversion from one format to another (often left to the users themselves), with the possibility to lose information in the conversion between standards as the element-wise mapping is often not 1-to-1.

Relevance

The proposed remedy will help to aid discoverability and interoperability of holdings and avoid the repetition of work for format conversions and conversions of data. The first suggested approach also allows us to preserve the richness of the original metadata. Its benefit may be expected to be large and affecting many type of (primarily expert) data users.

Expected viability for the outcome of success

Medium

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 1 year

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- Copernicus funding
- National Meteorological Services
- WMO
- ESA, EUMETSAT or other space agency

G1.10 Relative paucity and geographical concentration of reference-quality measurements, with limited understanding of uncertainty in remaining measurements, limits ability to formally close satellite to non-satellite comparisons

Gap Abstract

Limited availability of traceable uncertainty estimates limits the direct applicability of the majority of existing data to high-quality applications, such as satellite-data characterisation, model validation, and reanalysis. While a vast amount of data are available, the uncertainty of these data is - in a metrological sense - often only insufficiently specified, estimated, or even unknown. The reference-quality measurements that exist, tend to be geographically concentrated in the Northern Hemisphere mid-latitudes. In order to achieve progress, it is critical to have sufficient global coverage of reference quality data records that are stable over time, across the various methods of measurement, uniformly processed, and based on traceable references. This will allow to establish the robust scientific basis for using such data as a transfer standard in satellite-dataset characterization and other activities, such as trend analysis, and for assessing the cost-effectiveness of potential observing system enhancements. It is also essential to identify the scope for baseline and comprehensive networks to leverage expertise from reference networks, including adopting elements of best practice, and/or facilitating reprocessing that iteratively improves dataset quality.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques Involved

Independent of instrument technique

Related gaps

- G5.11 Non-operational provision of fiducial reference-measurement data and some (L2) satellite products may prevent use in Copernicus operational product monitoring
- G6.02 Analysis and optimisation of geographical spread of observational assets to increase their utility for satellite Cal/Val, research, and services.
- G6.03 Lack of sustained dedicated periodic observations to coincide with satellite overpasses to minimise co-location effects
- G6.06 – Provision of reference-quality measurements on continuous basis, accompanied with rapid delivery of data, to maximise opportunities for the validation of satellite and derived products.

This family of gaps collectively being addressed would substantively increase the pool of reference qualified techniques and instrument assets available globally to undertake measurements suitable for satellite Cal/Val.

Detailed description

Presently, limited availability of traceable uncertainty estimates for non-satellite measurement techniques propagates to other applications, such as satellite characterisation. Such applications would be significantly improved were traceable uncertainty estimates more broadly available on the comparator measurements. The development work of the GAIA-CLIM Virtual Observatory has been addressing the selection of reference data, provision of measurement and co-location uncertainty estimates, and the provision of match-ups with satellite data to be characterized. This work has highlighted the relative geographical paucity of reference quality qualified measurement systems and their concentration in certain regions, principally Northern Hemisphere mid-latitudes. It can be expected that for other ECVs in atmospheric, but also oceanic and terrestrial domains, similar issues exist.

The issue of uneven geographical distribution of high-quality observation sites pervades many observational networks. In earlier versions of the GAID, a number of gaps pertaining to weaknesses in individual networks were identified. On further reflection, these gaps are sufficiently similar that the underlying challenges, and therefore solutions, were better addressed collectively through a recognition that this uneven sampling is a generic cross-cutting issue requiring a holistic, rather than per network consideration from the perspective of end-users, such as satellite calibration and validation activities. Compounding that is a lack of work that extends that knowledge to enable utilisation of remaining observations with requisite confidence.

While a vast amount of data are potentially available, unfortunately, the uncertainty of these data is all too often - in a metrological sense - insufficiently specified, estimated or even unknown, which frequently limits the applicability of the measurements to uses such as satellite characterisation. In order to achieve progress, it is critical to have data records that are stable over time, metrologically traceable to the method of measurement, uniformly processed worldwide (and thus comparable), and based on traceable references. This will allow us to establish the robust scientific basis for using such data as a transfer standard in satellite-dataset characterization and other activities, and for assessing the cost-effectiveness of potential observing system enhancements.

Thorne et al. (2017) provide the rationale behind and defining characteristics of a system-of-systems approach of “reference”, “baseline” and “comprehensive” networks. In that work, it is recognised that datasets from baseline and comprehensive networks provide valuable spatiotemporal coverage, but lack the metrological characteristics needed to facilitate traceable uncertainty estimates. It is therefore essential to identify the scope for baseline and comprehensive networks to leverage expertise from reference networks, including adopting elements of best practice from reference networks, and/or facilitating reprocessing that iteratively improves dataset quality. Such work may increase their utility for a range of applications, including satellite characterisation.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

- Geophysical product (Level 2 product)
- Time series and trends
- Calibration (relative, absolute)
- Spectroscopy

Gap status after GAIA-CLIM

GAIA-CLIM explored and demonstrated potential solutions to close this gap in the future:

GAIA-CLIM participants have undertaken work on this issue on both a network and product level by working to improve mapping of current capabilities and addressing shortcomings of traceable uncertainty estimates. However, these activities have not completely addressed the issues arisen in this gap.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Improved metrological characterisation of measurements	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Clear improvement in the accuracy of climate data records Improved instrumentation arising from better understanding.
Increased pool of reference-quality measurements for satellite characterisation	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Clear improvement in the capability to reliably validate satellite-data products.
Better propagation of measurement technology and analysis innovations across complementary observing systems	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Improved quality and qualification of baseline- and comprehensive-network data suitable for satellite characterisation.
Maturity matrix assessment provided by GAIA-CLIM project allows classification of observations into appropriate tiers	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Better use of observations arising from better understanding of suitability for given applications.

Identified risk	User category/Application area benefitted	Probability of benefit being realised	Impacts
Limited impact of reference measurements on the observations provided by baseline and comprehensive networks for climate studies and satellite Cal/Val	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High Medium	Poor or lack of calibration procedures and data quality/traceability from baseline and comprehensive networks critically impacts on all those applications requiring high-quality measurements in time and space (i.e. satellite Cal/Val).
Limited or neutral improvement of assimilation-based measurements	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High Medium	Products lacking metrological traceability provide limited improvement in the characterization of model-based & assimilation-based uncertainties.
Restricted set of reference-quality observations persists	All users and application areas will suffer from it	Medium	Continued uncertainty about the quality of satellite products for many ECVs used in service relevant applications.

Part III Gap Remedies

Remedy 1 – Improved characterisation of high quality instrumentation to increase the pool of reference quality observing techniques without necessitating new observational deployments

Primary gap remedy type

Research

Proposed remedy description

Work to substantially improve the breadth of existing measurement techniques and programs that can be considered truly reference quality measurement systems. Building upon foundational work in existing EU H2020 projects such as QA4ECV, GAIA-CLIM, and FIDUCEO and by other international activities such as METEOMET, GRUAN, NDACC, GAW, the ESA Fiducial Reference Measurements program, etc. Undertake to improve the metrological characterisation of present and planned non-satellite measurement techniques for a broad range of atmospheric, oceanic, and terrestrial ECVs. Necessary steps include:

- Full characterisation of the processing chain for each individual measurement technique considered;
- Establishing traceability to SI or community standards;
- Quantifying the uncertainty in each processing step with metrological rigor;
- Ensuring comparability through necessary standardisation of techniques;
- Documentation of final product via the peer-reviewed literature and associated documentation.

This work shall require the involvement of instrument experts, metrologists, and potential end-users. The remedy should involve those measurement networks, which may deploy the developed measurement techniques as key partners to ensure uptake of the newly developed measurement streams in the field.

Relevance

Directly addresses the paucity of reference-quality instrumentation by developing improved metrological understanding for a broad range of instrumentation that is either currently in the field or could be deployed.

Measurable outcome of success

Improved number of reference qualified measurement techniques and increase in number of data streams available to end-users as a result.

Expected viability for the outcome of success

- Medium
- High

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- WMO
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

Remedy 2 – Take steps to better realise the benefits of a system-of-systems approach to observing strategies

Primary gap remedy type

Research

Proposed remedy description

Current observational networks are treated as distinct entities, all too frequently meaning that synergies resulting from a system-of-systems approach to observing are not realised. Without means to propagate innovations, practices, and know-how, the benefits of improved understanding from high-quality reference networks are limited. Work is required to develop tools and approaches that allow the effective flow of information from reference quality measurement networks to baseline and comprehensive observing networks, so that the benefits of that improved understanding can be realised. In the first instance, a case study based approach may be advisable that considers a well-defined problem set and allows testing of various approaches, following which are more substantial roll-out would be possible. An obvious candidate may be atmospheric temperature and humidity measurements for which several reference quality measurement techniques exist or are in the advanced stages of preparation and for which assimilation models and other techniques are similarly advanced. Work may include (but not be limited to) aspects such as:

- Use of reference sites to qualify uncertainties in techniques used in remaining networks via intercomparison campaigns. This may benefit from improved management of holdings if the new Copernicus Climate Change Service C3S 311a Lot 3 (access to observations from baseline and reference networks) activity is successfully executed.
- Enhancing observational practices in non-reference networks by taking realisable aspects of best practices from reference techniques. For example, the use of 100%-RH checks on radiosondes to characterise hysteresis effects more explicitly.
- Using data assimilation and statistical techniques to propagate information from reference sites to surrounding locales.

The work would need to involve operators of both reference and baseline / comprehensive networks to be effective and to recognise the realities involved in measurement programs. Cost-effective solutions that were technically and financially achievable should be developed that more effectively integrate information across networks and improve the quality of all observations.

Relevance

Better propagating information across observing networks increases the value of all measurement programs to a range of applications, including satellite characterisation.

Measurable outcome of success

Improved data quality leading to new and / or improved applications.

Expected viability for the outcome of success

- Medium
- High

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Non-Applicable

Potential Actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- WMO
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

Remedy 3 – Improving quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data

Primary gap remedy type

Research

Secondary gap remedy type

Technical

Proposed remedy description

Robust assessments of the impacts of geographical spatial and temporal gaps in the availability of reference quality measurement systems are required. GAIA-CLIM has developed studies based on global chemistry models, as well as on advanced statistical techniques, to evaluate these issues for a restricted subset of networks and ECVs (aerosol, ozone, trace gases, temperature and humidity). Similarly, other assessments have been undertaken elsewhere. But, historically, these have variously considered a subset of ECVs and / or networks and undertaken distinct methodological approaches which serve to inhibit their synthesis. Therefore, there is no clear and definitive set of analyses which unambiguously points to where additional observational assets would add most value. As evidenced by the interest in programs like Copernicus and the Fiducial Reference Measurements (FRM) program of European Space Agency (ESA), users are generally interested in the totality of capabilities and not a per network approach. Therefore, what is required is a holistic assessment approach that considers the issue across the full range of both reference-quality networks and ECVs.

In assessing against competing stakeholder needs, a robust means to quantify the cost-benefit trade-offs of different measurement capability expansion options (including both locations and scheduling of measurement strategies) that considered the problem more holistically (across ECVs and networks) would lead to more optimal configurations (or reconfigurations) of networks, recognising that there exists an ecosystem of synergistic and complementary networks. A substantive program that holistically assessed current capabilities and potential expansions / reconfigurations would require the participation of experts in modelling (climate, chemistry, weather), dynamics, statistics, and field measurement techniques. It would also require the engagement of the numerous stakeholders (end-users) of these data and the assessed networks.

Relevance

A more robust scientific basis to assessing the impacts of current gaps would greatly aid decision makers in deciding how and where to expand reference-network capabilities

Measurable outcome of success

Availability of a quantified basis to support decision-making.

Expected viability for the outcome of success

Medium

Scale of work

Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

High cost (> 5 million)

Indicative cost estimate (exploitation)

No

Potential actors

- EU H2020 funding
- Copernicus funding
- National Meteorological Services
- WMO
- ESA, EUMETSAT or other Space agency
- Academia, individual research institutes
- SMEs/industry
- National Measurement Institutes

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G2.06 Current poor spatial coverage of high-quality multi-wavelength lidar systems capable of characterizing aerosols

Gap Abstract

Raman lidars or multi-wavelength Raman lidars are undoubtedly an integral component of an aerosol global measurement infrastructure as they can provide quantitative range-resolved aerosol optical and microphysical properties. It is very important to carefully assess the value of the retrieval of advanced lidar systems and to study if the global coverage of the existing networks is sufficient to carry out adequate satellite-retrieval characterisation. The availability of a larger number of multi-wavelength Raman lidar measurements would strengthen the global observing system for the upcoming research satellite mission Cal/Val (Sentinels 4/5, ADM-Aeolus, Earth-CARE, ACE) and ensure a critical contribution to distinguish natural and anthropogenic aerosols from satellite data. Multi-wavelength Raman lidars could be considered to be the future backbone of a larger network incorporating simpler lidar instruments and/or ceilometers, and so be able to have a denser global spatial coverage.

Part I Gap Description

Primary gap type

Spatiotemporal coverage

ECVs impacted

Aerosols

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Lidar

Detailed description

Raman lidars or multi-wavelength Raman lidars are undoubtedly an integral component of an aerosol global measurement infrastructure as they can provide quantitative range-resolved aerosol optical and microphysical properties throughout much of the column. Whereas the detection of aerosol layers and their vertical extent requires only simple single wavelength backscatter lidars, the derivation of extinction coefficient profiles and of a series of derived aerosol properties requires advanced lidar setups and techniques such as high-spectral resolution lidars (HSRL, Shipley et al., 1983) or Raman lidars (Ansmann et al., 1992). The estimation of aerosol microphysical properties and mass concentration requires at minimum a one-wavelength Raman lidar, though the error affecting these estimations can be dramatically reduced if a multi-wavelength Raman lidar system is used. This highlights the relevance of having an enhanced number of multi-wavelength Raman lidars globally if they are to be used to characterise satellite measurements that aim to discern such properties.

Such lidars also have a potential role as anchor reference stations for the study of the impact of aerosols on weather and climate more generally. The availability of multi-wavelength Raman lidar measurements also ensures that ground-based instruments can deliver wavelength conversion information for different aerosol and cloud types to relate the current and future space-borne measurements performed by different satellite missions at different wavelengths (for example, CALIPSO at 532 nm and the future EarthCARE mission at 355 nm). In addition, space-based measurements have the advantage of obtaining global spatial coverage, but long-term ground-based observations can provide a critical contribution to distinguish natural and anthropogenic aerosols from satellite data.

Multi-wavelength Raman lidars could be considered to be the future backbone of a larger network incorporating simpler lidar instruments and/or ceilometers, and so be able to have a denser global spatial coverage. In this process, it is very important to carefully assess the value of the retrieval of advanced lidar systems and to study if the coverage of the existing networks globally is sufficient to carry out a sufficiently accurate aerosol study.

Steps towards automatic or semi-automatic usage of the most advanced lidars are needed to reduce the traditional intensive manpower typically required to operate these systems. In this sense, the effort spent over the last year by the biggest aerosol lidar networks (EARLINET, MPLnet) to develop automatic lidar data processing chain must be acknowledged.

The working groups of lidar network representatives involved in the Aerosol SAG (Scientific Advisory Group) of the WMO-GAW programme has recently started working to address (on voluntarily basis) specific harmonisation issues on the global scale.

Operational space missions or space instruments impacted

- Copernicus Sentinel 4/5
- Active sensors

Validation aspects addressed

Time series and trends

Gap status after GAIA-CLIM

After GAIA-CLIM this gap remains unaddressed

Some activities pertinent to this gap have been addressed but the gap could not be solved completely within the timeframe of GAIA-CLIM.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Improved coverage of aerosol lidar measurements at the global scale	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Increase the accuracy of estimation of aerosol effects on weather and climate; improved monitoring of aerosol related natural hazards e.g. volcanic plumes, dust storms
Stronger global observing system for the upcoming research satellite Cal/Val (e.g. for missions like ADM-Aeolus, EarthCARE, Sentinels).	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High Medium	Availability of Fiducial Reference Measurements (FRM) for ensuring the harmonization of satellite data products
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Lower spatial coverage for satellite validation using Raman lidar measurements	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	There is a continuously increasing demand for aerosol products for different applications (climate, weather, satellite, air quality, solar applications, agriculture, health), but quantitative measurements of aerosol microphysical properties in the column can only be provided by Raman lidar systems, the spatial coverage of which is also essential for the calibration of baseline observations (i.e. ceilometers).

Need for the harmonization of aerosol satellite measurements performed at different wavelengths	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Over coming decades, the number of aerosol satellite missions will increase and this requires the establishment of databases containing the conversion factors to allow a physically consistent use of measurements performed at different wavelengths, as described in Pappalardo et al., 2010 (JGR). The risk is to have non-harmonized CDRs that cannot effectively contribute to the interpretations of global climate change.

Part III Gap Remedies

Remedy 1 – Improve the coverage, metrological characterisation, and operational capabilities of Raman lidars

Primary gap remedy type

Deployment

Proposed remedy description

A first step would be to identify existing Raman lidar measuring aerosol properties globally and then subsequently study the representativeness of each station in the characterization of aerosol variability in a range of different vertical atmospheric regions. This would allow the identification of those priority climatic regions where additional multi-wavelength Raman lidars are required and taking advantage of existing lidar station which are not operating a Raman lidar yet.

To make such activities sustainable and operational at the a global scale, many further steps are needed including:

a. Establishment of mechanisms for regular communication between networks (under GAW coordination);
b. Developing an agreement on a shared/common metadata access portal and automatic product calculation;
c. Improving the metrological characterisation of many systems (e.g. existing assessments indicate some potential systematic errors in the aerosol characterisation)
d. developing common harmonised methodologies, data quality objectives, quality assurance/quality control procedures across measurement frameworks to the extent possible;
e. Performing frequent intercomparison activities.

Relevance

A complete remedy for this gap is strongly related to the strategies of the international research institutions which are at present the key players in the deployment and the operation of Raman lidar measurements. A well-defined strategy implementing integration of aerosol measurement capabilities on continental or larger scales will result in clear benefits such as improved data access and availability, improved comparability of data, more uniform data quality standards from different networks, increased synergy of measurements and prevention of unnecessary duplication.

Commercial lidars or ceilometers will benefit of an improved metrological characterization, with a consequent impact of the ingestion of massive higher quality data from low-cost monitoring systems in real-time within weather numerical models.

Measurable outcome of success

This is obviously related to the establishment of multi-wavelength Raman lidars in those regions where a lack of lidar instruments is identified by a study of representativeness of the existing measurements of aerosol properties. Such study also allows a rationalization of the required investments.

Expected viability for the outcome of success

Medium

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

- National funding agencies
- ESA, EUMETSAT or other Space agency
- Academia, individual research institutes

References

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G2.07 Lack of uptake of lidar measurements in data assimilation

Gap Abstract

Aerosol lidar data can potentially be used to constrain uncertain model processes in global aerosol-climate models. Satellite-borne lidar data can be effectively assimilated to improve model skill but, currently, aerosol lidar data assimilation experiments are mainly limited to the assimilation of attenuated backscatter, which is a non-quantitative optical property of aerosol. There is much additional valuable data that could be utilised to improve data assimilation. Such improved data assimilation may allow attenuation of data to allow broader inferences about satellite quality as being developed by GAIA-CLIM for temperature and humidity via the GRUAN processor.

Part I: Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

ECVs impacted

Aerosols

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)

Non-satellite instrument techniques involved

Lidar

Detailed description

Uncertainties associated with aerosol emissions in terms of their intensity and distribution pattern, atmospheric processes, and optical properties, represent a significant part of the uncertainty associated with the quantification of the impact of aerosols on climate and air quality in regional and global models. Lidar assimilation in global aerosol-climate models is an active area of research at many forecasting centres and research institutes. Assimilation systems used range from variational to ensemble methods, variables assimilated are aerosol extinction and backscatter coefficients or lidar raw signals (by using customized forward models). Applications range from aerosol global forecasts, to volcanic ash detection and regional air quality.

Data assimilation techniques are implemented to decrease these uncertainties, constraining models with available information from observations in order to make a best estimate of the state of the atmosphere. The short-range forecasts from such systems have the potential to be useful for the calibration/validation (Cal/Val) of new satellite data as they provide a stable reference for inter-comparison between products from different satellites. In particular, the use of a forecast model minimises errors due to temporal differences when comparing two different observational datasets.

This Cal/Val technique has been found to be useful for satellite observations sensitive to temperature and humidity, since the short-range forecasts are highly accurate for these variables, and this has been explored further within the GAIA-CLIM project. However, for aerosol products the short-range forecasts are not yet accurate enough to be able to identify more than gross errors in the satellite observations.

Further improvements to the aerosol data assimilation systems are needed, particularly in the area of bias correction, before aerosol forecasts can be used as a reference for satellite Cal/Val. This is a long-term goal, however, and in the short-term direct comparisons between aerosol observations should continue to be carried out for the Cal/Val of new satellite products.

Aerosol lidar data can also be used to constrain uncertain model processes in global aerosol-climate models. Satellite-borne lidar data can be effectively assimilated to improve model skill but, currently, aerosol lidar data assimilation experiments are mainly involving lidar attenuated backscatter, which is a non-quantitative optical property of aerosol. Ground based lidar networks can in addition provide quantitative measurements of aerosol backscatter and extinction coefficients. However, a limited number of aerosol lidar data assimilation experiments have been performed, preventing us from assessing the effective impact of assimilating continuous satellite lidar data and whether the current state of the lidar technology fulfils the modellers' needs.

Operational space missions or space instruments impacted

- Copernicus Sentinel 4/5
- Active sensors

Validation aspects addressed

- Assimilated product (Level 4)

Gap status after GAIA-CLIM

After GAIA-CLIM this gap remains unaddressed.
GAIA-CLIM has undertaken no specific activities to help addressing this gap.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Improved model performances to determine aerosol effect at the global scale on weather and climate	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Reduction of the IPCC identified uncertainties related to the aerosol direct and indirect effects, with a consequent improvement of climate and weather forecast.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Bias correction for satellite lidar data using a variational bias correction scheme not feasible	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	High	Assimilation of satellite lidar data will continue to bias the model output instead of improving the forecast skills.
Larger uncertainty if aerosol lidar data are not used to constrain uncertain model processes in global aerosol-climate models.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High	Uncertainties associated with aerosol emissions impacts on climate and air quality simulations in regional and global models.

Part III Gap Remedies

Remedy 1 – Extension of the GAIA-CLIM data assimilation approach to aerosol lidars

Primary gap remedy type

Research

Proposed remedy description

New solutions for assessing and enhancing the value of lidar data assimilation must be developed. This requires efforts in two complementary areas:

1. Firstly aerosol lidar networks must strongly work on their capability to provide NRT data, through the implementation of automatic processing calculus chains and to adopt shared/common metadata international standards in order to facilitate the data usage and manipulation.
2. Secondly, modellers must develop methodologies to use the available lidar Near-Real time (NRT) data for routine evaluation of operational models or data assimilation, through the development of improved forward operators, while quality-checked (QC) and added-value (higher level data) products must be used for the retrospective assessments of model simulations (reanalysis/reforecast).

Building on the growing interest from the global NWP community in using high accuracy data from ground-based networks to constrain satellite data biases, ground-based lidar data could be used by modellers also to anchor the bias correction for satellite lidar data, using a variational bias correction scheme.

However, further work must be implemented aimed at improving model skill, i.e models are better at predicting horizontal transport than vertical distributions. Formulation of a specified workplan should take into account that:

- Collaboration with data providers is paramount;
- NRT data delivery from all lidar satellite missions is important;
- With respect to other lidar measurements of atmospheric composition, the community is largely ready to use lidar data to improve aerosol predictions;
- Wind data will also improve atmospheric composition prediction by improving the model wind fields.

Relevance

Aerosol in one the key factors in the determination of the radiative balance with its direct and indirect effect. An appropriate and successful assimilation within numerical models may strongly improve our climate knowledge as well as the prediction of severe weather events.

This values is enhanced by the multitude of data which will be available at global scale–with the advent of next satellite missions with a lidar technique on-board including the ESA missions, ADM-Aeolus and EarthCARE.

Measurable outcome of success

A number of initiatives are currently ongoing and their outcome will give us within a few years a quantitative idea of the importance of using lidar measurements in data assimilation

Expected viability for the outcome of success

High

Scale of work

Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

High cost (> 5 million)

Indicative cost estimate (exploitation)

Yes

Potential Actors

- National Meteorological Services
- Academia, individual research institutes

G2.08 Need for a metrologically rigorous approach to long - term water vapour measurements from Raman lidars in the troposphere and UT/LS

Gap Abstract

One of the paramount needs for developing long-term ECV datasets for atmospheric monitoring is to calibrate measurements using SI traceable standards. For water vapour measured with the Raman lidar technique, a solution is represented by the calibration of water vapour profiles using reference calibration lamps, which are traceable to NMIs standards. Another critical issue to ensure continuous water vapour Raman lidar measurement is due to the weakness of the Raman backscattering from water vapour molecules. During daytime, a few water vapour Raman lidars have already proven to be able to measure water vapour up to 3-4 km above ground level, but despite this only a few of them are operated on a continuous basis. Technological improvements or the effective integration with other techniques needs to be pursued.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

Secondary gap type

- Spatiotemporal coverage
- Vertical domain and/or vertical resolution

ECVs impacted

Water vapour

User category/Application area impacted

Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Lidar

Detailed description

A long-term data set for monitoring atmospheric water vapour using lidar techniques requires the calibration of Raman lidar water vapour profiles that vary randomly around some mean value (often addressed as a calibration constant that depends only on the instrument setup) and does not involve step jumps of unknown magnitude. Such step jumps in calibration increase the time required to detect atmospheric trends, which is already typically measured in decades [Weatherhead et. al., 1998; Boers and Meijgaard, 2009]. For this reason, it is important to carefully examine any calibration technique developed for ensuring stable and long-term calibrations. Absolute and relative, but also hybrid calibration methods have been developed. More recently, reference calibration lamps, which are traceable to NMIs standards, have proven to be robust for absolute calibration of water vapour Raman lidar to reduce systematic uncertainties and may represent a common reference for all the available systems.

Another challenge for Raman lidars to ensure the collection of water vapour long-term measurements for climate applications is to improve their daytime observing capability. Raman lidars have been shown to provide high resolution water vapour measurements in several experiments, but these measurements are typically restricted to night-time only, as Raman scattering is a weak physical process and the high solar background radiation during the day tends to mask these signals. During daytime, a few water vapour Raman lidars have already proven to be able to measure water vapour up to 3-4 km above ground level. Only DIAL systems can do better, but they do worse in the UT/LS at night compared to Raman lidar. Most of the water vapour Raman lidar systems are not operated during daytime and this generates a discontinuity in the water vapour monitoring in the troposphere in a climatological sense. The use of commercial systems, Raman lidar or DIAL, designed to operate on a continuous basis, can mitigate the gap but with moderate to high costs, though their performance needs to be carefully assessed in advance. Further technological improvements of lidar techniques for measuring water vapour are also expected but over the mid and long term. In addition, the improvement of synergy of water vapour Raman lidar with other measurements techniques represents an alternative solution upon which to invest. For example, the ACTRIS-2 and HD(CP) projects are working on this aspect to provide users with a synergetic lidar-radiometer water vapour product in both clear and cloudy sky conditions to cover the tropospheric range.

Operational space missions or space instruments impacted

- MetOp-SG
- Microwave nadir
- Infrared nadir
- Passive sensors
- GNSS-RO

Validation aspects addressed

Geophysical product (Level 2 product)

Gap Status after GAIA-CLIM

GAIA-CLIM has partly closed this gap.
GAIA-CLIM has contributed to addressing this gap under activities associated with the metrological characterisation of instrumentation.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Harmonization of water vapour measurements and reduction of biases in the satellite validation	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Improved capability to detect signals of climate change
Continuous monitoring of water vapor in the troposphere and in the UT/LS in support of satellite validation and assimilation models	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Improved weather and climate forecasts
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Lack of harmonization between water vapor Raman lidars globally.	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Inhomogeneities affecting water CDR in the troposphere and stratosphere to detect a signal of climate change.
Bias and lower performances in the intercomparison or in the retrieval of atmospheric state estimates from sensors synergy.	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	Biased, lower vertical and temporal resolution of atmospheric best estimate profile; partially compensated by potential sensor intercalibration.
Measurement and temporal biases affecting datasets used for satellite validation.	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	Limited quality and temporal resolution of lidar water vapour reference measurements available data for OSSE and satellite validation.

Part III Gap Remedies

Remedy 1 – Synergy between water vapour Raman lidar and other measurement techniques.

Primary gap remedy type

Laboratory

Proposed remedy description

The synergy of water vapour Raman lidar with other measurement techniques, like GPS/GNSS, optical and microwave radiometry, etc., provides complementary information on the water vapour structure to constrain, extend or simply improve the quality of the information provided by the lidar. In particular, synergy with passive microwave radiometers provides an robust solution to obtaining a low resolution profile of atmospheric water vapour during daytime also above the atmospheric altitude covered by the lidar enabling the characterization of the entire atmospheric column this could partially address this gap but this synergetic solution requires the development of new and more accurate algorithms to fully exploit the potential of the combined datasets. It also requires the co-location of these synergistic measurement techniques in close enough geographical proximity to be usable in this manner.

Relevance

Continuous measurements of water vapour observations with high spatial (vertical) and temporal resolution are needed to achieve a comprehensive understanding of the role of water vapour on climate at regional and global scales as well as to estimate its impact on OLR = outgoing long- wave radiation (OLR) at top of atmosphere. The availability of water vapour profiles in both cloud and clear sky conditions would largely enhance several activities related to the study of climate, to satellite retrievals, and radiative transfer modelling.

Measurable outcome of success

Success of any kind of synergetic products or joint retrieval performed using Raman lidar and microwave radiometry (or other measurement techniques) shall be assessed by using the data in the input data stream of the mesoscale models or by validating the water vapour model outputted profiles. Alternatively, a comparison with radiosoundings profiles from Reference networks (i.e. GRUAN) can represent another good way to assess the added values of this higher-level products though in this case the difference in the representativeness of the two different products (lidar+other vs radiosonde) must be quantified and taken in account.

Expected viability for the outcome of success

- Medium
- High

Scale of work

- Individually
- Single institution

Time bound to remedy

- Less than 5 years

Indicative cost estimate (investment)

- Low cost (< 1 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- Academia, individual research institutes
- SMEs/industry
- National measurement institutes

Remedy 2 – Further deployments and refinements of the GAIA-CLIM approach to metrological characterisation to Raman Lidar measurements

Primary gap remedy type

Laboratory

Proposed remedy description

Work within GAIA-CLIM has advanced the metrological characterisation of raman lidar water vapour products. Verification of the results generated in GAIA-CLIM is required prior to broad-scale adoption of the traceable measurement and processing approach by networks. At the same time work is required to improve the temporal coverage of measurements to increase their utility with a particular focus on advancing daytime measurements.

Relevance

For water vapour lidar calibration, the proposed remedy will dramatically improve the traceability of water vapour Raman lidar measurements and data consistency globally, and will help to manage changes in the system. The synergetic approach to improve water vapour measurement continuity is at present the only chance to improve daytime water vapour profiling capabilities.

Measurable outcome of success

Success would be, for example, if long term comparison between Raman lidar water vapour measurements and another traceable reference measurement technique (e.g. GRUAN radiosondes) would be compared over long term showing a reduction in the lidar calibration uncertainty using absolute techniques as well as the added value of synergetic lidar-radiometer products during daytime operations. Evidences of this improvement have been reported in literature but comparisons over long time periods have not been reported yet.

Expected viability for the outcome of success

- High

Scale of work

- Individually
- Single institution
- Large consortium

Time bound to remedy

- Less than 5 years

Indicative cost estimate (investment)

- Low cost (< 1 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- Academia, individual research institutes
- SMEs/industry
- National measurement institutes

References

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- Weatherhead, E. C., and coauthors, Factors affecting the detection of trends: Statistical considerations and applications to environmental data. J. Geophys. Res., 103, 17 149–17 161, doi:10.1029/98JD00995, 1998.

G2.10 Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions

Gap Abstract

Tropospheric ozone has an impact on air quality and acts as a greenhouse gas and therefore plays a role in public and environmental health, as well as climate change, linking the two subjects. Establishing processes and trends in tropospheric ozone, in particular in the free troposphere, above the mixed layer and below the stratosphere, is difficult due to a lack of data. Also, ozone soundings using balloon borne samplers are too scarce to capture the relatively high spatial and temporal variability in the troposphere. Contrary to stratospheric ozone, passive satellite observations have limited access to information about tropospheric ozone. However, new sensors on the next generation of satellite measurements shall have better tropospheric sensing capabilities, and shall require validation.

Part I Gap Description

Primary gap type

Spatiotemporal coverage

Secondary gap type

Vertical domain and/or vertical resolution

ECVs impacted

Ozone

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

- Ozonesonde
- Lidar

Detailed description

Tropospheric ozone has an impact on air quality and acts as a greenhouse gas and therefore plays a role in public and environmental health, as well as climate change, linking the two subjects. Establishing processes and trends in tropospheric ozone, in particular in the free troposphere, above the mixed layer and below the stratosphere, is difficult due to a lack of direct observational data. Tropospheric ozone is much more variable in space and time than stratospheric ozone due to transport and chemistry. The frequency and accuracy of the observations should ideally be adjusted to account for this elevated variability. In addition, the balloon borne ozone samplers are optimised for stratospheric observations, which implies sub optimal performance in the troposphere. Therefore, other observational techniques are needed fill the need for observations of tropospheric ozone from non-satellite sources that are more routinely operational. Contrary to stratospheric ozone, passive satellite observations have limited access to information about tropospheric ozone as the TOA down view is largely dominated by the much higher stratospheric loadings across the sensitive regions of the E-M spectrum. However, newer and planned missions are envisaged to have better tropospheric ozone sensing capabilities. Also, ozone soundings using balloon borne samplers are too scarce to capture the relatively high spatial and temporal variability in the troposphere.

Operational space missions or space instruments impacted

- Copernicus Sentinel 4/5
- MetOp
- MetOp-SG
- OMPS
- Polar orbiters
- Geostationary satellites
- UV/VIS nadir
- Passive sensors

Validation aspects addressed

- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Assimilated product (Level 4)
- Time series and trends
- Representativity (spatial, temporal)
- Calibration (relative, absolute)

Gap status after GAIA-CLIM

After GAIA-CLIM this gap remains unaddressed

Part II Benefits to resolution and risks to non-resolution

Identified benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Upcoming satellite missions will have improved capabilities for tropospheric ozone. Sub-orbital observation capacity will be used to assess the satellite data quality.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium Low	Improved knowledge of tropospheric ozone will reduce uncertainty in radiative transfer (climate) and improve results for chemistry.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Tropospheric ozone profile data is relatively scarce and limits applicability to range of activities including tropospheric ozone validation from satellites.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Remaining gap in appropriate data sources to optimally use new satellite data and to understand processes in the troposphere related to the linkage between air pollution and climate change.

Part III Gap Remedies

Remedy 1 – Expand coverage of differential absorption lidars to improve ability to characterise tropospheric ozone

Primary gap remedy type

Deployment

Secondary gap remedy type

Technical

Proposed remedy description

An increase in data on tropospheric ozone is expected from various space-borne platforms with increased capabilities, such as OMPS, TES and TROPOMI and the instruments proposed for Sentinel 4 and 5. However, a reinforcement of the ground based observational capacity is also required to validate these space borne observations and establish high-quality time series. An increase in the number of ozone balloon borne soundings is not likely due to the high costs involved (material and personnel). There is a potential for tropospheric ozone lidars (using the differential absorption lidar technique) to fill this gap. In the US, a network of tropospheric ozone lidars has been established (TOLNET). Similar initiatives could be pursued in Europe, where a latent tropospheric ozone lidar network could be revived. In Europe, such a network might become part of ACTRIS, the European Research Infrastructure which deals with short-lived greenhouse agents. Similar efforts are required in other areas of the globe to enable full characterisation of tropospheric ozone capabilities by future satellite missions.

Relevance

An increase in data on tropospheric ozone is expected from various space-borne platforms with increased capabilities, such as OMPS, TES and TROPOMI and the instruments proposed for Sentinel 4 and 5. However, a reinforcement of the ground based observational capacity is also required to validate these space borne observations and establish high-quality time series. The issue is relevant to understand the links between air pollution and climate change. Satellite data alone will likely not suffice to fill the gap.

Measurable outcome of success

A measure of success is the increase in the number of available tropospheric ozone profiles.

Expected viability for the outcome of success

Medium

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

High cost (> 5 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- National Meteorological Services
- WMO
- ESA, EUMETSAT or other space agency

G2.11 Lack of rigorous tropospheric ozone lidar error budget availability

Gap Abstract

Tropospheric ozone has an impact on air quality and acts as a greenhouse gas and therefore plays a role in public and environmental health, as well as climate change, linking the two subjects. In order to establish tropospheric ozone trends, more high-quality and high-frequency observations are needed (see G.2.10) and a rigorous error budget is required. Measurements of tropospheric ozone by means of the Differential Absorption Lidar (DIAL) Technique are close to reference quality and may meet this need if development of traceable products can be realised. The methodology of rigorous error-budget calculations is available, but needs to be implemented across available data sources.

Part I Gap Description

Primary gap type

Implementation of uncertainty budget and calibration

ECVs impacted

Ozone

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Lidar

Related gaps

G2.10 Tropospheric ozone profile data from non-satellite measurement sources is limited and improved capability is needed to characterise new satellite missions

Gag 2.10 relates to the provision of more observations. Gap 2.11 should thus be addressed at the same time or after closing G2.10.

Detailed description

Tropospheric ozone has an impact on air quality and acts as a greenhouse gas and therefore plays a role in public and environmental health, as well as climate change, linking the two subjects. In order to establish trends, more observations are needed (see G.2.10) and a rigorous error budget is needed for these observations to assure their quality. Tropospheric ozone profiles can be attained from lidar measurements (amongst others). Measurements of tropospheric ozone by means of the Differential Absorption Lidar (DIAL) technique are described in detail, metrologically characterised, and processed in a consistent comparable manner. Such data would greatly aid efforts at the characterisation of new and planned space missions which are envisaged to be capable of measuring tropospheric ozone changes and variability. Although these descriptions are now available, these should be more widely implemented across available data sources. In case of networked operation of tropospheric ozone DIAL instruments, this could be achieved by centralised data processing. However, not all available data sources are readily accessible and several rely on diverse, in-house developed processing and analysis techniques.

Operational space missions or space instruments impacted

- Copernicus Sentinel 4/5
- Meteosat Third Generation (MTG)
- MetOp
- MetOp-SG
- OMPS
- Polar orbiters
- Geostationary satellites
- Passive sensors

Validation aspects addressed

- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Assimilated product (Level 4)
- Time series and trends
- Representativity (spatial, temporal)
- Calibration (relative, absolute)

Gap status after GAIA-CLIM

GAIA-CLIM has partly closed this gap
GAIA-CLIM work on metrological characterisation has lead to a partial resolution of this gap.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Upcoming satellite missions will have improved capabilities for tropospheric ozone. Data available from existing tropospheric ozone DIAL instruments will be traceable.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Improved knowledge of tropospheric ozone will reduce uncertainty in radiative transfer (climate) and improve results for chemistry.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Lack of rigorous tropospheric O3 lidar error budget availability	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Reduced level of traceability of tropospheric ozone lidar measurements leading to ambiguity in downstream applications such as satellite cal/val.

Part III Gap Remedies

Remedy 1 – Create and disseminate a fully traceable reference-quality DIAL lidar product

Primary gap remedy type

Deployment

Secondary gap remedy type

- Technical
- Research
- Education/Training

Proposed remedy description

Work has been undertaken to attain a fully traceable product for DIAL lidar technique to measure tropospheric ozone profile data. A traceability chain has been fully documented. The uncertainty in each step in the processing chain has been quantified in a robust manner. Documentation as to how to undertake such traceable measurements has been published in the peer reviewed literature. Now these methods and calculations need to be implemented across potential networks and individual stations. This requires funding support to networks and individual sites to enable measurements to be undertaken in a comparable manner. It also requires support for centralised processing, archival and dissemination.

Relevance

The issue is highly relevant for any application that uses ground based tropospheric ozone lidar data as a reference. In particular to understand the tropospheric ozone budget and the reduction of the uncertainties in estimation of the resulting radiative forcing.

Measurable outcome of success

Established (published in peer reviewed journal) error budget calculation scheme.

Expected viability for the outcome of success

High

Scale of work

Single institution
Consortium

Time bound to remedy

Less than 1 year

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Yes, ongoing annual costs to maintain (low)

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- National Meteorological Services
- WMO
- ESA, EUMETSAT or other space agency

G2.12 Lack of rigorous pure rotational Raman temperature lidar error budget availability limits utility for applications such as satellite characterisation

Gap Abstract

Temperature lidars provide important information for trend detection in the middle atmosphere (connected to trends in the ozone layer). These are measured using lidar systems that often also measure the ozone layer. The lidar technique to measure temperature is sensitive to the presence of aerosol, which is an important contribution to the error budget. In addition, lidar techniques exist to measure temperature profiles in the troposphere using the pure-rotational Raman (PRR) technique that can be used in the presence of aerosol. For temperature measurements in the presence of aerosols using the PRR technique a rigorous error budget needs to be established to improve their utility for applications such as satellite characterisation.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

ECVs impacted

Temperature

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Lidar

Detailed description

Temperature lidars provide important information for trend detection in the middle atmosphere (connected to trends in the ozone layer). The temperature profiles in the middle atmosphere (12- 80 km altitude) are measured using lidar systems that often also measure the ozone layer. The temperature measurements are done using the Rayleigh-Mie technique. This lidar technique to measure temperature is sensitive to the presence of aerosol, which is an important contribution to the error budget. An additional lidar technique exists to measure temperature profile (in the troposphere) using the pure-rotational Raman technique (PRR) that can be used in the presence of aerosol. However, presently a metrologically traceable processing is unavailable for such measurements. Hence, for temperature measurements in the presence of aerosols using the PRR lidar technique a rigorous error budget needs to be established to improve their utility for applications such as satellite characterization.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

Time series and trends
Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Gap status after GAIA-CLIM

After GAIA-CLIM this gap remains unaddressed

Part II Benefits to resolution and risks to non-resolution

Identified benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
A traceable error budget for PRR temperature lidar will become available in addition to the existing RM temperature lidar used for the establishment of time series	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Better climate records will become available.
A traceable error PRR lidar budget will become available for the comparison to other techniques for temperature profile measurements.	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Redundancy in time series will improve confidence in data records.
PRR lidar error budgets will become available for users of data as auxiliary input.	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Improved uncertainty budgets for products relying on auxiliary input from lidar temperature profiles.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Lack of rigorous temperature PRR lidar error budget availability	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Reduced level of traceability of temperature lidar measurements leading to ambiguity in subsequent applications such as satellite Cal/Val.

Part III Gap Remedies

Remedy 1 – Create a fully traceable reference-quality temperature lidar product

Primary gap remedy type

Research

Secondary gap remedy type

- Technical
- Deployment
- Education/Training

Proposed remedy description

The existing traceability chain for temperature lidar measurements will need to be expanded with the necessary elements for the temperature measurements with the pure rotational Raman Lidar technique. The chain will describe all the processing steps in the PRR temperature lidar measurement system. Robust estimation of uncertainties shall be undertaken that appropriately codifies the knowledge of each step and its resultant uncertainty. These uncertainties shall be used to derive an error budget calculation scheme which will be compiled. It shall be accompanied by detailed documentation of the measurement technique, the instrumental aspects, the processing steps and auxiliary input to the algorithms. These results shall be published via the peer reviewed literature. Processing shall be enacted such that products meeting the detailed procedures are available for end-users.

Relevance

The issue is highly relevant for any application that uses ground based temperature lidar data as input or reference. In particular, to detect temperature trends in the middle atmosphere and aerosol-cloud-humidity interactions.

Measurable outcome of success

Established (published in peer reviewed journal) error budget calculation scheme that includes detailed documentation of the measurement technique, the instrumental aspects, the processing steps and auxiliary input to the algorithms.

Expected viability for the outcome of success

High

Scale of work

Consortium

Time bound to remedy

Less than 2 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

No

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- National Meteorological Services
- WMO
- ESA, EUMETSAT or other space agency

G2.13 Missing microwave standards maintained by national/international measurement institutes

Gap Abstract

The traceability of ground-based microwave radiometer (MWR) estimates and their uncertainty requires the traceability of MWR calibration to SI standards. Currently, no SI standard is available for MWR at any national/international measurement institute. Thus, full SI-traceability of ECVs from MWR is currently not feasible. However, at least one national measurement institute is currently developing SI standards for MWR. It is expected that SI-traceable standards for MWR will be available in the next few years. This will then allow the availability of transfer standards to MWR manufacturer and user communities.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

Secondary gap type

Uncertainty in relation to comparator measures
Governance (missing documentation, cooperation etc.)

ECVs impacted

- Temperature
- Water vapour

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Microwave Radiometer

Related gaps

- G2.36 Lack of traceable uncertainties in MWR measurements and retrievals

G2.13 should be addressed together with G2.36

The remedy of G2.13, i.e. the development of MW standards maintained at national/international measurement institutes and the availability of transfer standards, will set the basis for SI-traceability of MWR observations and retrievals. However, tools for evaluating the MWR total uncertainty budget can be developed independently of the solution of G2.13.

Detailed description

The traceability of the microwave radiometer (MWR) estimates and their uncertainty requires the traceability of MWR calibration to SI standards. This implies the use of certified black-body (BB) targets and temperature sensors (measuring the target physical temperature). Commercial BB targets have reached a mature state, but their characterization is usually limited. Despite this, many realizations of microwave brightness temperature standards exist in the form of heated or cooled calibration targets, although none are currently maintained as a standard by a national/international measurement institute (Walker, 2011). Thus, despite the efforts for fully characterizing the MWR absolute calibration, the traceability of any ECVs from MWR to national/international standards is currently not feasible. However, the development is ongoing (Houtz et al., 2015; 2016; 2017). This gap shall be addressed by national/international measurement institutes, and cannot be addressed within GAIA-CLIM.

Operational space missions or space instruments impacted

Microwave and Infrared temperature and humidity sounders

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Assimilated product (Level 4)
- Time series and trends
- Calibration (relative, absolute)
- Spectroscopy

Status after GAIA-CLIM

GAIA-CLIM has partly closed this gap:

This gap will be considered closed when MW standards are available in at least one national/international measurement institute for calibrating secondary standards to be used for MWR calibration. The role of GAIA-CLIM is to follow and report the technological developments at national/international measurement institutes (e.g. NIST) and to inform MWR users and manufacturers about these developments.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Traceable intra- and inter-MWR data characterization	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Traceable MWR characterization will allow proper reconciliation of historical time series of MWR observations at any given site as well as uniformly across the network
Increased confidence in MWR data quality	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Traceable MWR data characterization will yield increased confidence and utilization of MWR observations in reanalyses and climate research
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Non-traceable MWR-based validation for satellite ECVs	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Difficult to reconcile historical time series of MWR observations. Ground-based MWR will not reach the requirements for climate monitoring
Non-traceable MWR-based validation for satellite ECVs	All users and application areas will suffer from it.	High	No traceable validation for satellite boundary layer thermodynamical profiles

Part III Gap Remedies

Remedy 1 – Development and testing of MWR standards and secondary standards

Primary Gap remedy type

Technical ; TRL 4-6

Secondary gap remedy type

- Laboratory
- Deployment
- Research

Proposed remedy description

Metrology applicable to microwave remote sensing radiometry is currently under development at national/international measurement institutes (e.g. National Institute for Standards and Technology, USA). These efforts include the development of a standard radiometer and standard high-emissivity black body (BB) targets. It is expected that SI-traceable calibration for BB targets and transfer standards in the form of calibrated BB targets will be available at NIST in the next few years. The current status is presented in an open literature paper (Houtz et al., 2017). The uncertainty in the BB Tb is around 0.1 K (1-sigma), covering the frequency range from 10 to 200 GHz. NIST plans to be able to calibrate other BB targets against their standards, which could then be used as transfer standards. Thus, the primary gap remedy type is technical/technological (the development of MW standards), but it involves laboratory and research work (testing and characterization) as well as deployment (transfer standard to manufacturer and user communities).

Relevance

The remedy will make microwave standards available at least at one measurement institute (NIST). GAIA-CLIM aims at monitoring and effectively communicating the progress to MWR manufacturers and users, in order to promote the uptake of certified targets.

Measurable outcome of success

The successful outcome is to make MWR users and manufacturers aware of the above developments. The effective characterization of existing and/or new MWR units against microwave standards would be an additional measure of success, which is subject to the availability of the transfer standards before the end of GAIA-CLIM.

Expected viability for the outcome of success

Medium

Scale of work

Single institution

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

- Academia, individual research institutes
- SMEs/industry
- National measurement institutes

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G2.18 Better agreement needed on systematic and random components of the uncertainty in FTIR measurements and how to evaluate them

Gap Abstract

There is no clear agreement yet within the FTIR community on the distinction and characterisation of the random and systematic components of the uncertainty in FTIR measurements is. As a consequence, no common approach is available on how to evaluate these components appropriately leading to a degree of heterogeneity in the global FTIR network.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

Secondary gap type

Technical (missing tools, formats etc.)

ECVs impacted

- Temperature
- Water vapour
- Ozone
- Aerosols
- Carbon Dioxide
- Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

FTIR

Related gaps

- G2.37 Poorly quantified uncertainties in spectroscopic information
- G3.04 Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties
- G2.22 FTIR cell measurements carried out to characterize ILS have their own uncertainties

All these gaps deal with the characterisation of the data quality of FTIR. Thus they should all be considered at the same time as or prior to the resolution of the current gap.

Detailed description

Within the NDACC FTIR working group, the technical implementation of the uncertainty propagation (both random and systematic) is fully achieved within the EU QA4ECV and GAIA-CLIM projects. However, each PI must determine a good estimate of site-specific uncertainties on the parameters used as input to the retrieval setup. During the QA4ECV and GAIA-CLIM projects it was observed that there is not full agreement within the FTIR working group on how the estimation of random and systematic uncertainties for these input parameters should be done. Also there is no full agreement across the two main retrieval software packages SFIT4 and PROFFIT. Random and systematic uncertainty sources are often assumed differently for different sites/different retrieval software. Although the current data products generated during the QA4ECV and GAIA-CLIM projects are highly harmonzied across participating sites, the network will benefit from a further harmonisation of the uncertainty source assumption. A clear distinction between systematic and random uncertainties implemented network-wide, is important for determining accuracy and precision, e.g. when comparing to satellite data, and uncertainty of an average of data.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

Geophysical product (Level 2 product)

Gap status after GAIA-CLIM

GAIA-CLIM has partly closed this gap

Recipes to evaluate random and systematic parts of the uncertainty sources will be promoted, but that does not mean yet that they will be implemented at each FTIR site by the end of GAIA-CLIM.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Traceable and consistent error characterization of the FTIR data products	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	The agreement on the input data for the uncertainty calculations will assure that the error estimations are consistently traceable and comparable between different sites.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Incomparable uncertainty budgets for different sites within NDACC.	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Difficulty of a network-wide and consistent data usage by downstream applications that require network homogeneity.

Part III Gap Remedies

Remedy 1 – Improved traceability of uncertainties in FTIR measurements

Primary gap remedy type

Technical

Secondary gap remedy type

Education/Training

Proposed remedy description

Comparison and tuning of the uncertainty modules of the retrieval software packages. Write down a manual of how to estimate the uncertainties for all parameters that are part of the forward model in the retrieval software packages. Further, a recipe should be developed as to how a random and systematic uncertainty should be determined for each of the leading uncertainty contributions and this recipe should be promoted and implemented in both retrieval software packages at all NDACC FTIR sites. Ideally a centralized QC system or processing will remedy the online publication of FTIR data whose uncertainty budgets is not compliant with the proposed guidelines.

Relevance

Improved traceability of errors is a core objective of GAIA-Clim. Traceable ILS uncertainty will allow a traceable estimation of the FTIR product uncertainty due to ILS uncertainties.

Measurable outcome of success

Comparable and consistently traceable errors for all different sites.

Expected viability for the outcome of success

High

Scale of work

Consortium

Time bound to remedy

Less than 1 year

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost Estimate (exploitation)

No

Potential actors

Academia, individual research institutes

G2.22 FTIR cell measurements carried out to characterize Instrument Line Shape have their own uncertainties

Gap Abstract

For the retrieval of information about the vertical distribution of target species from FTIR spectra, it is important to know the FTIR instrument line shape (ILS). Therefore, regular cell measurements are carried out to characterize the ILS of the FTIR spectrometers. However these cell measurements have their own uncertainties since these are obtained using optimal estimation: an ILS retrieval comes along with an uncertainty and an averaging kernel. In particular the averaging kernel for an ILS retrieval is often not adequately considered (Hase, 2012). Inaccurate knowledge of the ILS mainly affects the retrieved vertical profile (e.g. for water vapour and ozone profile retrievals). The uncertainty on the ILS leads to larger uncertainties on the retrieved column-averaged concentrations of CH_4 and CO_2 (XCH_4, XCO_2). In other words, the uncertainties on the ILS retrieved from cell measurements will propagate to the total uncertainty budget of the retrieved species. Although the technical know-how is present within the NDACC IR working group, the actual implementation of the ILS uncertainty characterisation and propagation is not complete. In particular, further harmonization between the different FTIR retrieval software packages is required.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

ECVs impacted

- Temperature
- Water vapour
- Ozone
- Carbon Dioxide
- Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)

- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

FTIR

Related gaps

G2.18 Better agreement needed on systematic and random part of the uncertainty in FTIR measurements and how to evaluate each part

This gas should be considered at the same time as G2.18 as it is a contributing component to the broader uncertainty characterisation.

Detailed description

The retrieval of vertical profile information for target gases from ground-based high-spectral-resolution FTIR solar absorption spectra is based on the analysis of the observed shape(s) of the absorption line(s) of the target species in the recorded spectra. Since the observed shape is a convolution of the intrinsic absorption line shape with the instrument line shape (ILS), the analysis must account for the ILS. Therefore, the ILS must be known highly accurately. To this end, a cell filled with a known gas concentration at a known temperature and pressure is put into the FTIR instrument and a spectrum of the cell gas is taken. The cell spectrum allows the retrieval of the ILS using optimal estimation as described by Rodgers, and such a retrieved ILS comes with its uncertainty. The uncertainty on the retrieved ILS is a combination of the smoothing uncertainty, the noise, the forward model parameters, etc. This uncertainty will propagate into the total uncertainty budget of the retrieved target gas' profile and total abundance.

In summary, one can state that the cell measurement serves as a calibration of the target gas retrieval but that this calibration method is itself indebted with some uncertainty that must be accounted for in the total uncertainty budget of the retrieval result, which is the target gas vertical profile and total abundance.

Operational space missions or space instruments impacted

- Copernicus Sentinel 4/5
- MetOp
- MetOp-SG
- Polar orbiters
- Geostationary satellites
- Infrared nadir
- Other, please specify
  - All missions/instruments that use ground-based FTIR data for validation

Validation aspects addressed

Geophysical product (Level 2 product)

Gap status after GAIA-CLIM

GAIA-CLIM has partly closed this gap:

Progress has been made within GAIA-CLIM, to identify the contribution of the ILS uncertainty to the total uncertainty budget and to make it better traceable and better characterised. The uncertainty propagation routines that were developed during QA4ECV & GAIA-CLIM are such that the integration of the ILS uncertainty propagation is a straightforward extension. However the harmonization between the different retrieval software packages is not complete yet, and the implementation within at all FTIR stations should still be done consistently.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Better uncertainty characterization of the FTIR data products	All users and application areas will benefit from it	High	Better characterized ground-based FTIR data yield improved utilization as reference data
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Missing contribution to total uncertainty budget of the ground-based FTIR data products	All users and application areas will suffer from it.	High	Underestimation of total uncertainty associated with ground-based FTIR data products.
Inconsistent characterisation of FTIR data between different NDACC sites (not at all stations the quality of the cell retrievals is analysed in the same manner)	All users and application areas will suffer from it.	High	Reduced confidence in network wide data consistency.

Part III Gap Remedies

Remedy 1 – Regular cell measurements and ILS retrievals are to be performed in a consistent manner

Primary gap remedy type

Technical ; TRL6

Secondary gap remedy type

Education/Training

Proposed remedy description

Regular cell measurements have to be performed at all NDACC sites and ILS retrievals have to be performed in a consistent manner: both the technical setup of the retrieval (regularization, retrieval paramaters, cell measurement setup etc.) as the calculation of the total random and systematic uncertainty on the retrieved ILS. Ideally the random and systematic uncertainties on the retrieved ILS are expressed as full uncertainty covariance matrix, but it is unrealistic and a computational burden to determine and propagate such full covariance matrices. A good approach would be to characterise the leading ILS uncertainty contributions, smoothing/noise, random/systematic and accordingly work on a realistic and not oversimplifying approach to accurately estimate and propagate the ILS uncertainties towards the retrieved target gas.

The second step in the proposal would be to implement this ILS uncertainty characterisation in both existing retrieval software packages PROFFIT and SFIT4. The outcome is a FTIR NDACC networkwide harmonized uncertainty budget that includes the propagated ILS uncertainty.

Relevance

Improved traceability of uncertainties is a core objective of GAIA-CLIM and shall benefit applications including but not limited to satellite characterisation by FTIR instruments.

Measurable outcome of success

Traceable ILS uncertainty will allow a traceable estimation of the FTIR product uncertainty due to ILS uncertainties.

Expected viability for the outcome of success

High

Scale of work

Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

Academia, individual research institutes

G2.24 Lack of calibrated in-situ vertical profiles of CH_4, CO_2 (and CO) for improving the accuracy of FTIR (partial) column measurements of CH_4, CO_2 (and CO)

Gap Abstract

This gap addresses the need for sustained calibration of the FTIR remote sensing data (essentially columns with some vertical information that enables to separate partial columns) for CO_2, CH_4 (and CO). This can be done by comparing the FTIR data with co-located or nearby in-situ soundings of the same species that are calibrated to community standards, in this case the WMO standards. At present however, there is not enough capacity to provide such in-situ data.

This gap also addresses the need for a European infrastructure for vertical greenhouse gas profiling in the troposphere for CO_2 and CH_4 There is a need for vertical profile information about these ECVs in the troposphere, among others to verify model results, and to validate remote sensing total and partial column data. The capabilities of the ground-based remote sensing observing systems are limited when it comes to vertical profile information, and are not sufficiently validated. Options for filling this gap are the facilitation of access to airborne in-situ measurement systems, like aircraft or UAV or Aircore for greenhouse gases.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

Secondary gap type

Spatiotemporal coverage

ECVs impacted

- Carbon Dioxide
- Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)

- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)
- Climate research *(research groups working on development, validation and improvement of ECV Climate Data Records)*

Non-satellite instrument techniques involved

FTIR

Detailed description

For the ECVs temperature, ozone, water vapour and aerosol, vertical profile information with relatively high vertical resolution (100m to a few km) in the troposphere is available from sonde and/or lidar measurements. For greenhouse gases (CO, CH_4, CO_2), the non-satellite observing system does not have sufficient capabilities. The FTIR measurements of these greenhouse gases have a low vertical resolution of the order of 5 to 8 km, if any, and this vertical information is difficult to validate. For example, measurements analysed so far within the GAIA-CLIM project have shown that CH_4 retrieval can be improved under polar vortex conditions as a result of applying new profile data. Also the modelling component in GAIA-CLIM has highlighted the deficiencies of the FTIR vertical profile information and the resulting needs for better in-situ vertical profiles.

One option to obtain in-situ vertical profiles is the use of the Aircore technique. This technique has been under development since 2000 and has the capability to obtain vertical profiles up to the middle stratosphere. Several Aircore sites exist in Europe, but the system is not yet a fully operational system. It is necessary to make the AirCore measurements easier for the users. Moreover, the Aircore cannot be launched at all sites, due to air traffic limitations and the fact that the Aircore must be recovered upon landing. The landing site cannot be pre-determined as long as the Aircore is launched with a balloon and descends with a simple parachute, thereby drifting with the wind and landing at a location which is not always suitable for retrieving the payload for performing the post-flight analysis of the air sample.

To solve the latter issue, some projects have investigated the design of a steered system to bring the Aircore down. A second option to obtain in-situ vertical profiles of GHG is to make use of aircraft spiral flights. The aircraft capacity in Europe is too limited to perform regular aircraft campaigns. Europe has no capability similar to the HIPPO campaigns in the USA. In any case, aircraft campaigns cannot cover vertical profiles higher than 12 km (a better calibration is possible if the profiles cover an altitude range from the ground up to the middle stratosphere), are very expensive, and are also difficult to organise above remote locations that are not situated on the European continent. High-altitude UAV or Aircore are required to cover higher altitudes. At present, high-altitude UAV are still largely in proof-of-concept stage.

However, although expensive, in-situ calibration of CH_4, CO_2 (and CO) columns/profiles measured by FTIR remote sensing instruments can be performed by aircraft overpasses equipped with in-situ instruments that are calibrated relative to the WMO standards. Such campaigns have been undertaken in the past, for example in Europe as part of the EU project IMECC. But, as mentioned above, new flight campaigns in Europe are currently not planned, the flights cover only an altitude up to about 12 km, and calibration flights are very costly and difficult over stations that are not situated in the European continent, like islands, S. America, Africa, Asia. Hence more regular verification of the calibration of the instruments is desirable, to ensure long-term and network-wide consistency with the standards as well as to ensure a better understanding and minimization of the biases across the networks when studying fluxes from e.g. hot spot regions.

Operational space missions or space instruments impacted

Current and future satellite missions, which have the capability to measure greenhouse gases from space include GOSAT, IASI, OCO-2, Tansat, S5P, GOSAT-2, Merlin, MicroCarb, OCO-3, Sentinel-5.

Validation aspects addressed

Geophysical product (Level 2 product)

Gap status after GAIA-CLIM

After GAIA-CLIM, this gap will remain.

New Aircore in-situ vertical profile data will be made available outside of GAIA-CLIM that can serve as calibration of FTIR GHG measurements and in support of modelling activities, however they are limited to only one site (Sodankyla) and with limited temporal coverage.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Increased accuracy of the measurements by ground-based network for validation/calibration purposes	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	High	Increases confidence in space borne measurements
Increased intra-network and inter-network (e.g., TCCON with ICOS) consistency	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Use of all network data without inconsistencies will increase the number of reliable data available for applications like flux inversions
Improved retrieval algorithms to be used by the sites	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	High	Retrieval algorithms will be improved, leading to better precision and accuracy of the measurements
Identified risk	**User category/Application area benefitted**	**Probability of occurrence if gap not**	**Impacts**
Inconsistencies in the network of FTIR data for the validation of satellite data	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	Medium	Reliable global validation of GHG satellites is at risk
Lack of traceability of remote sensing data leading to possible inconsistencies between remote sensing data and in-situ data due to erroneous or no calibration of remote sensing data	Copernicus programme ICOS	High	Possible benefits of synergic exploitation of in-situ and remote sensing data are lost; the ICOS internal consistency is at risk
Significant uncertainties about vertical distribution of GHG in the troposphere	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	High	Absence of data for verification/validation of models and satellite data, and of FTIR retrievals of vertical profile information of GHG

Part III Gap Remedies

Remedy 1 – Operationalise the Aircore technique

Primary gap remedy type

Technical

Secondary gap remedy type

Deployment

Proposed remedy description

Currently there is a limited availability of AirCore in Europe: only a few institutes have the required expertise to build and operate them, and to analyse the data. Moreover, the deployment of an AirCore depends on the availability of a suitable balloon launching site.

To enable operational use of the AirCore for providing vertical profiles of GHG over Europe and elsewhere on a regular basis, we need to have an Aircore system that is available 'off-the-shelf' and that can be used at many sites by non-expert users. Or we need a dedicated provider of Aircore data in Europe.

Moreover, we need an AirCore system that can be launched at many more sites, without meeting too many constraints about the site's environment. More specifically, we need an AirCore system that can descend in a steered way to a pre-determined landing site, and that complies with air traffic regulations. Currently carrier platforms are being studied for bringing the AirCore down to a pre-defined landing spot, based on the concept of a steerable glider or Unmanned Airborne Vehicle (UAV). The development of this kind of system should be further extended and such systems should become readily available to the community.

Relevance

The database of vertical profiles of GHG measured by Aircore will be used by the scientific community for verification and validation purposes, and for better calibration of the non-satellite and satellite remote sensing observing system to WMO standards (traceability). In the end, it will result in more reliable GHG products and trends, e.g., in Copernicus.

The remedy will also contribute to the network wide, more cost-effective calibration tool.

Measurable outcome of success

A much larger database of vertical profiles of GHG, with a better spatiotemporal spread.

Expected viability for the outcome of success

High

Scale of work

Consortium
Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Potential actors

- EU H2020 funding
- Copernicus funding
- WMO
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes
- SMEs/industry

Remedy 2 – Enhance the airborne infrastructure in Europe.

Primary gap remedy type

Deployment

Secondary gap remedy type

Technical

Proposed remedy description

Currently there is a limited availability of suitable aircraft in Europe that can carry in-situ analysers of Greenhouse gases (GHG) to high altitude and make spiral flights to obtain vertical profiles of the GHG. High-altitude UAV are still under development, but at the proof-of-concept phase and may have air traffic control restrictions that prove prohibitive.

We need an infrastructure and associated deployment programme that makes regular flights, especially over Europe but also over observation sites in other continents and the oceans, to obtain a good spatiotemporal sampling of the vertical distribution of GHG. This infrastructure can consist of aircrafts and/or UAV that can reach to high altitude. The scientific community should have easy access to this infrastructure for dedicated campaigns.

One option to realise this infrastructure is to engage more commercial airlines in the IAGOS RI such as to obtain a better spatiotemporal coverage of the profiles that are measured during take-off and landing of the aircrafts at the airports. Unfortunately, airports may not be representative for the background vertical profiles.

Relevance

Such an aircraft / UAV fleet will be very useful also for other research purposes (e.g., T/ H_2O observations in the UTLS).

Measurable outcomes of success

1. A much larger database of vertical profiles of GHG, with a better spatiotemporal spread. It will be used by the scientific community for verification and validation purposes, and for better calibration of the non-satellite and satellite remote sensing observing system to WMO standards (traceability). In the end, it will result in more reliable GHG products and trends, e.g., in Copernicus.
2. Better competitiveness with the US airborne capabilities

Expected viability for the outcome of success

High

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 10 years

Indicative cost estimate (investment)

High cost (> 5 million)

Potential actors

- EU H2020 funding
- Copernicus funding
- ESA, EUMETSAT or other space agency

Remedy 3 – Create a database of in-situ vertical profiles of CO_2 , CH_4, and CO with sufficient spatiotemporal coverage, possibly as part of the ICOS RI.

Primary gap remedy type

Deployment

Secondary gap remedy type

Governance

Proposed remedy description

To enable a regular and network-wide calibration of remote sensing measurements (ground-based FTIR), the community needs access to a database of in-situ vertical profiles from regular airborne observations at different locations in Europe and beyond – in which the in-situ observations are calibrated against a commonly adopted standard (e.g., the WMO standard). This requires a sufficient capacity of well-calibrated airborne sensors and sufficient spiral flight opportunities close to the ground-based FTIR observatories to collect such a database. In fact, this capacity should be part of the ICOS Research Infrastructure, to make it sustainable and fulfil the specific needs of the ICOS and ICOS-user communities. Hence, the proposed remedy is to create a database of in-situ vertical profiles of CO_2, CH_4 and CO with sufficient spatiotemporal coverage

Relevance

The remedy will contribute to the network wide, more cost-effective calibration- making it consistent with the in-situ networks. This is very relevant for the ICOS RI and the Copernicus services (CAMS and C3S).

Measurable outcome of success

The availability of an increased number of calibrated, in-situ vertical profile data of GHG with good spatiotemporal coverage would contribute to the next, improved version of the FTIR retrievals and to a better assessment of the seasonal cycle. It will lower the biases between sites in the network, and improve the consistency with surface in-situ measurements of the greenhouse gases as carried out in ICOS.

Expected viability for the outcome of success

High, as soon as the database exists

Scale of work

Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

High cost (< 5 million)

Potential actors

- EU H2020 and RI funding
- Copernicus funding
- National funding agencies
- WMO
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes
- National measurement institutes

G2.26 Poorly understood uncertainty in ozone cross-sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis

Gap Abstract

The uncertainty in the ozone absorption cross-sections is one of the main systematic error sources in the remote sensing of atmospheric ozone using UV-visible spectroscopy techniques. It is a structured random effect in that even though the uncertainty can be considered as primarily a systematic error source, the actual error is dependent on atmospheric temperature which varies across the annual cycle and with synoptic conditions. Presently the uncertainty in total column ozone due to uncertainty in absorption cross-sections is assumed to be around one to a few per cent but it is poorly quantified. If the same cross-sections are used in satellite observations and ground-based observations, one source for non-consistency can be excluded from the comparison allowing a relative rather than absolute comparison. In addition, when the uncertainties related to ozone cross-sections and their temperature dependencies are well characterized, this effect can be included in the error budget of ozone observations. It may be possible that this also improves the retrieval itself.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

Secondary gap type

Parameter (missing auxiliary data etc.)

ECVs impacted

Ozone

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)

- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

- UV/VIS zenith DOAS
- UV/VIS MAXDOAS
- Pandora

Related gaps

- G2.37 Poorly quantified uncertainties in spectroscopic information

This gap represents the top-level coordination and harmonisation activity required across the general spectroscopic measurement field, therefore G2.26 should be addressed in parallel with G2.37.

Detailed description

The ozone absorption cross-section is one of the main systematic error sources in the remote sensing of atmospheric ozone using UV-visible spectroscopy techniques. The uncertainty in the cross-sections can be considered as a systematic error source, although the actual error depends on atmospheric temperature, and thus it can be considered as a pseudo-random (or structured random) error, as mentioned in the deliverable D4.3 'Uncertainty Budget' of the EC FP7 project NORS . Presently the uncertainty in total column ozone due to uncertainty in absorption cross-sections is assumed to be around one to a few per cent (WMO GAW report 218 , NORS_D4.3_UB.pdf). In general, when the uncertainties related to ozone cross-sections and their temperature dependencies are well characterized, this effect can be included in the error budget of ozone observations. It is also possible that by including the (correlated) uncertainty to the retrieval algorithm, this would improve the retrievals as well.

The recent WMO IGACO-O3/UV activity ACSO (Absorption Cross Sections of Ozone) performed a thorough evaluation of the existing cross-sections and their impact on ground-based and satellite ozone retrievals. In particular, cross-sections studied were Bass and Paur (published in 1985), Brion, Daumont Malicet (published in 1995) and Serdyuchenko et al. (2014). The outcome of the ACSO study was that the latest Serdyuchenko et al. cross-sections are recommended to be used for ground-based Brewer and Dobson instruments. However, these cross-sections were not recommended to be used for satellite retrievals due to a deficiency in the signal-to-noise ratio close to 300nm. From the perspective of satellite validation, it would be beneficial if the same cross-sections were used by both satellites and ground-based instruments such that at a minimum a relative comparison were possible. However, if different absorption cross-sections are used in the satellite validation, it is important to understand what type of differences they cause in the validation. Related to

GAIA-CLIM, it is to be noted that neither Pandora nor any other DOAS or MAX-DOAS instruments were included in the ACSO study.

Operational space missions or space instruments impacted

- Copernicus Sentinel 5P, 4/5
- MetOp
- Polar orbiters
- Geostationary satellites
- UV/VIS nadir
- Passive sensors

Validation aspects addressed

- Geophysical product (Level 2 product)
- Time series and trends
- Calibration (relative, absolute)
- Spectroscopy

Gap status after GAIA-CLIM

After GAIA-CLIM this gap will remain.
A literature study leading to a summary of the findings including a recommendation of how this should be applied with regard to DOAS, MAX-DOAS and Pandora instruments has been undertaken in GAIA-CLIM but this does not close the gap.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Using the same cross-sections consistently with satellite and ground based instrumentation improves comparison by reducing the uncertainty in one critical factor.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	More reliable ozone products. Improved validation by improving the data consistency (removing one source of discrepancy in the respective data analyses).
Understanding the uncertainties of the cross-sections improves the error characterization of the ground based instrument.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	Improved error characterization of the ozone products
Understanding the uncertainties of the cross-sections may improve the retrieval results if correctly taken into account in the data processing (e.g. correlated errors).	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	Potentially improved ozone products and their uncertainties.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Error characterization is missing one component	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	Improved error characterization and potentially improved data quality.

Part III Gap Remedies

Remedy1 – Improved understanding of the effects of differences in Ozone cross-sections

Primary gap remedy type

Research

Secondary gap remedy type

Technical

Specify remedy proposal

It is necessary to study in-depth what impact the differences in the ozone cross-sections recommended for Dobson and Brewer instruments and the ones used for satellite retrievals have on the retrieved ozone amount when applied within the DOAS data analysis technique. This may best be achieved via a simulation study using the operational Pandora retrieval algorithm with alternative cross-sections of ozone. However, preliminary information can be obtained from a literature study in consultation with the Brewer and Dobson communities and some original quantitative analyses. The analysis may be expected to lead to recommendations for future processing of measurements to be taken up by those networks operating these instruments. The analysis may also require additional dedicated measurements at a small number of sites to support the characterisation.

Relevance

Starting from the results achieved within the ACSO study, the study proposed here will help to understand the uncertainties caused by different sets of ozone cross-sections used within the data analysis and how this impacts on the overall measurement uncertainty.

Measurable outcome of success

If the difference in the end product (total column ozone) is quantifiable with regard to which of the different ozone cross-sections have been used within the retrieval, then this can be applied to better compare the ozone data measured by satellites with ground-based data sets while both satellite and ground-based observations still use their preferred ozone cross-sections for the data analysis.

Expected viability for the outcome of success

Medium

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

No

Potential actors

- EU H2020 funding
- Copernicus funding
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

References

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G2.27 Lack of understanding of random uncertainties, air mass factor calculations, and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy

Gap Abstract

The uncertainties in the ozone slant columns retrieved with DOAS data analysis fitting procedures are predominantly caused by instrumental imperfections and by issues introduced within the analysis routines. Such uncertainties are often random and therefore can be estimated statistically from, e.g., the least-squares fit procedure. However, the fitting uncertainties derived from such analysis typically result in unrealistically small uncertainties and can lead to an underestimate by up to a factor of two. Further uncertainties are introduced during the calculation of air mass factors (AMFs) which are required to convert the measured ozone slant columns into vertical columns. The AMF uncertainties are dominated by errors in a priori profile shape effects with ozone and pressure/temperature a priori profiles being key input parameters for the AMF calculations. For further interpretation of the total column observations, averaging kernel information as part of the retrieval product plays an important role. However, currently vertical averaging kernels are only approximations of the real 3D averaging kernel and cannot fully account for the representativeness of the data.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

ECVs impacted

Ozone

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

- UV/VIS zenith DOAS
- UV/VIS MAXDOAS
- Pandora

Related gaps

- G2.37 Poorly quantified uncertainties in spectroscopic information

This gap represents the top-level coordination and harmonisation activity required across the general spectroscopic measurement field, therefore G2.27 should be addressed in parallel with G2.37

Detailed description

This gap addresses three of the major individual issues in our understanding of the analysis processing chain from the raw spectrum to the final total column ozone data product using the DOAS technique, and the interpretation of the actual final product.

The first aspect is the uncertainties in the ozone slant columns retrieved with the standard DOAS data analysis fitting procedures. They are to a large part caused by (1) instrumental imperfections such as detector noise, resolution change, etaloning (a fault that develops in thin charge-coupled devices when they behave as etalons) and other non-linearities of the detector, stray-light, and polarisation effects, as well as (2) by issues introduced within the analysis routine such as uncertainties in the Ring effect, unknown absorbers, and the wavelengths dependency of the AMF. Such uncertainties are mostly random in nature and therefore can be estimated statistically from the least-squares fit procedure. However, the fitting uncertainties derived from the least-squares analysis typically result in unrealistically small uncertainties and can lead to an underestimate of the measurement uncertainty by up to a factor of two. Results from intercomparison exercises (e.g. Van Roozendael et al., 1998, Vandaele et al., 2005, Roscoe et al., 2010) show that state-of-the-art instruments hardly ever agree to better than a few percent, even when standardised analysis procedures are used. This indicates that the actual accuracy in the ozone slant columns is at least to some degree limited by uncontrolled instrumental and/or analysis factors. And it leads to the question if something is not yet adequately addressed in the fitting procedures.

Further uncertainties are introduced during the calculation of air mass factors (AMFs) which are required to convert the measured ozone slant columns into vertical columns which means that the measured slant column density SCD is divided by the AMF to calculate the vertical column density (VCD) in molecules/cm2 which is then converted into Dobson Units. The NDACC UV-visible spectroscopy working group recommends the use of a generic look-up table of ozone AMFs which has been developed at BIRA-IASB (see NDACC UV-vis working group report) and accounts for the latitudinal and seasonal dependencies of the ozone vertical profiles. The NDACC recommendation is furthermore to average all retrieved vertical columns of ozone between 86° and 91° Solar Zenith Angle (SZA). The recommended approach is to apply a linear fit on vertical columns in the above SZA range and then derive the column value at the effective SZA (so far recommended to be 90° SZA). This range minimizes the measurement uncertainties arising during the fitting procedures and AMF calculation, and provides stratospheric ozone measurements with limited sensitivity to tropospheric ozone and clouds. Ozone and pressure/temperature *a priori* profiles are key input parameters for the AMF calculations and AMF uncertainties for zenith-sky twilight ozone retrievals are dominated by uncertainties in a priori profile shape effects. Hendrick et al. (2011) found that the uncertainty in the calculated AMFs based on uncertainties in the ozone profiles is around 1%. However, there is a lack of an adequate database of tropospheric ozone in particular and in regions where tropospheric or stratospheric ozone contents deviate from the climatological values, uncertainties of several percent can be introduced in total column ozone retrievals. Apart from uncertainties in the ozone a priori profiles, further sources of uncertainty are based on uncertainties in the aerosol and cloud information used. The typically small impact of clouds on zenith-sky ozone UV-vis measurements at twilight is due to the fact that the mean scattering layer is generally located at higher altitude than that of the clouds. However, AMFs calculated for cloudy conditions can be systematically larger than AMFs calculated for non-cloudy conditions.

The DOAS ozone total column retrieval is implicitly dependent on an a priori tracer profile. The radiative transfer calculation within the DOAS analysis accounts for the sensitivity of the measurement to tracer concentrations at all altitudes. These sensitivities are implicitly weighted with the assumed tracer profile to produce the retrieved column. The averaging kernel is proportional to this measurement sensitivity profile, and provides the relation between the retrieved quantities and the true tracer profile. The kernel therefore provides important information needed for a quantitative analysis of the satellite data (Eskes and Boersma, 2003 and references therein). The averaging kernel concept is by now well established in remote sensing. Applications are for instance the retrieval of profiles of atmospheric quantities like temperature and tracers like ozone from satellite measurements. Retrieval groups are increasingly including the kernel information in the profile data products disseminated to users. The look-up tables for total column ozone averaging kernels, provided by the NDACC UV-vis working group, have been developed based on the approach described by Eskes and Boersma (2003), i.e. the averaging kernel of a layer i can be approximated by the ratio of the box airmass factor of this layer i and the total airmass factor calculated from an O_3 profile climatology. The availability of averaging kernel information as part of the total column retrieval product is important for the interpretation of the observations, and for applications like chemical data assimilation and detailed satellite validation studies. However, vertical averaging kernels (when provided based on a climatology) are only approximations of the real 3D averaging kernel of a retrieval and cannot fully account for the representativeness of the data.

Operational space missions or space instruments impacted

- Copernicus Sentinel 4/5
- Meteosat Third Generation (MTG)
- MetOp
- Polar orbiters
- Geostationary satellites
- UV/VIS nadir

Validation aspects addressed

- Geophysical product (Level 2 product)
- Time series and trends
- Spectroscopy

Gap status after GAIA-CLIM

GAIA-CLIM has partly addressed this gap but it will not be closed within GAIA-CLIM.
An in-depth uncertainty analysis has been undertaken under GAIA-CLIM but closure requires its verification and implementation.

Part II Benefits to Resolution and Risks to Non-Resolution

Identified Benefit	User Category/Application area benefitted	Probability of benefit being realised	Impacts
If the source of the differences between fit uncertainty and expected uncertainty is better understood, this would lead to an improvement in the fit quality	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High Medium	Improvement in overall data quality & more realistic uncertainty partitioning between the components
Standardisation of AMFs will improve the overall uncertainty in the measured total O_3 columns retrieved from zenith sky UV-visible measurements	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High Medium	Will improve the overall accuracy of the measured total ozone column retrieved from zenith sky UV-visible measurements.
Improving the climatological databases of a priori ozone profiles will improve the accuracy of the RT model calculations of the respective AMFs	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High Medium	Will improve the overall accuracy of the measured total ozone column retrieved from zenith sky UV-visible measurements.
Including 3D averaging kernels for zenith-sky UV-visible ozone measurements	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High Medium	Improvement in the agreement between the different data sets (different sites as well as satellite/ground-based) Better agreement between observations at the edge of the polar vortex where the spatial and temporal gradients of the ozone field can be very large.
Identified risk	**User Category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**

If a distinct difference remains between realistic uncertainty estimates and the uncertainty calculated by the fitting routines, this will lead to undue confidence in reported data values.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High Medium	Higher and poorly quantified uncertainty in data products (such as ozone) measured with the DOAS technique leading to reduced utility in applications.
AMFs used by different groups are not standardized.	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High Medium	Ozone measurements provided by different groups are not homogenized and will likely show some unknown bias from site to site or group to group.
Including 3D averaging kernels for zenith-sky UV-visible ozone measurements	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High Medium	Improvement in the agreement between the different data sets (different sites as well as satellite/ground-based) & better agreement between observations at the edge of the polar vortex where the spatial and temporal gradients of the ozone field can be very large.

Part III Gap Remedies

Remedy 1 – Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error.

Primary gap remedy type

Research

Secondary gap remedy type

Technical

Specify remedy proposal

The proposed action is to improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error. This needs to be done, firstly, by evaluating all literature studies and other documentation available on this topic and, secondly, by using the results from the MAX-DOAS intercomparison campaign at Cabauw, the Netherlands, in September 2016, to provide more state-of-the-art data for further investigation specifically tailored to this issue. As part of GAIA-CLIM, we have developed a traceability chain for total column ozone measured by DOAS instruments and as part of this study we investigated, as a case study for two NDACC stations, the individual elements and their respective uncertainties leading up towards the DOAS fitting procedure and the uncertainties calculated within the fitting procedure. This is providing the first step for a quantitative investigation into the observed discrepancies which needs to be further extended e.g. with sensitivity studies of the uncertainties of the single components as well as an investigation of the potential of cancelling out of individual uncertainty components. The existing GAIA-CLIM work needs to be extended to be applicable across the full range of MAXDOAS instrumentation in usage globally.

Relevance

This remedy is specific for measurements using UV-visible spectroscopic measurement techniques and it will address the existing gap by providing a better understanding on what causes the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random uncertainty.

Measurable outcome of success

The success will be measured by how much we can improve our understanding of the difference between the individual uncertainty estimates versus the uncertainty provided by the data analysis fitting routines.

Expected viability for the outcome of success

Medium

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

No

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

Remedy 2 – Improvements to climatological databases of a priori ozone profiles for use in retrievals

Primary gap remedy type

Research

Specify remedy proposal

Improve climatological databases of a priori ozone profiles, with particular emphasis on tropospheric ozone are required to inform improved retrievals. It is necessary to test the quality/suitability of the databases of ozone profiles through a comparison with ozonesonde profiles at a selection of stations. Preferably this is to be done at the actual measurement site or station where also the UV-visible measurements are made. The vertically high resolved ozonesonde profiles can then be used to validate in particular the tropospheric part of the climatological ozone database. This would then specifically validate and improve the input parameters for the AMF calculation for that specific station. For NDACC stations, for example, which have both measurement techniques on site, this is a very feasible approach. Additionally, ozone profiles measured as part of ozonesonde networks, such as SHADOZ, provide this kind of validation for the currently used climatological database in a more global sense.

Relevance

Improving the climatological databases of a priori ozone profiles will improve the accuracy of the a priori data used within the respective RT model to calculate the AMFs and hence to improve the overall accuracy of the measured total ozone column retrieved from zenith sky UV-visible measurements.

Measurable outcome of success

If we can show that the updated and improved ozone database, when used as a priori for the ozone AMF calculations, leads to a smaller uncertainty in the calculation of ozone AMFs then we know that we have succeeded.

Expected viability for the outcome of success

Medium

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

Remedy 3 – Standardize AMF calculation methods and databases of a-priori information used in AMF calculations to improve the accuracy of the measured total column ozone

Primary gap remedy type

Research

Specify remedy proposal

Differences between AMFs can cause discernible discrepancies between the ozone data sets. For example, some NDACC UV-visible groups use their own individual DOAS settings and ozone AMFs calculated with different RTMs and sets of ozone, pressure and temperature profiles as input data, and with or without latitudinal and seasonal variations. The objective of the recommendations formulated by the NDACC UV-visible WG previously was thus to reduce these discrepancies through the use of standardized DOAS settings and ozone AMF look-up tables that account for the latitudinal and seasonal dependencies of the ozone vertical profile (see Hendrick et al., 2011).

The next step is to review, update and expand these existing tables further by initiating a targeted effort which also incorporates all relevant findings previously attained within projects such as NORS as well as investigations undertaken within GAIA-CLIM. Projects such as FRM4DOAS which are using centralised processing for the ozone data analysis also promote the use of more standardized AMF calculations and databases. With all this in mind, setting up a project to review and investigate the best routines and input variables for the AMF calculations, and to then recalculate and update the NDACC AMF LUTs to be used to homogenise the ozone total column data measured at different locations would be an efficient way forward.

Relevance

Standardized AMFs will improve the overall accuracy of the measured total ozone column retrieved from zenith sky UV-visible measurements.

Measurable outcome of success

Determine the difference between standardized AMFs and individually calculated ones and, in turn, the difference in the calculated vertical ozone columns. If the standardized AMF lead to smaller uncertainties in the total column ozone datasets we know that the remedy was successful.

Expected viability for the outcome of success

Medium

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Potential actors

- EU H2020 funding
- Copernicus funding

- National funding agencies
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

Remedy 4 – Evaluation of 3D averaging kernels for zenith-sky UV-visible ozone measurements

Primary gap remedy type

Research

Secondary gap remedy type

Technical

Specify remedy proposal

An evaluation of 3D averaging kernels for zenith-sky UV-visible twilight measurements based on AMF look-up tables is needed and a comparison with averaging kernels derived using a direct coupling of the retrieval with the output of a chemistry-transport model, in which the a priori profile used in the AMF calculation is replaced by a more realistic model-derived time and space dependent profile. To tackle this issue further, one or two specific retrieval algorithms coupled with chemistry-transport model output need to be selected to run an in-depth comparison with the averaging kernels retrieved based on the AMF LUTs. An important focus is that the averaging kernel calculated based on the AMF LUTs are representative enough to provide the information expected to add additional value to the actual measurements.

Relevance

Many research groups are not setup to run their retrieval code coupled with a chemistry-transport model and so it is essential to have a less computationally demanding approach which can then be used much more widely. Hence it is vital to understand how the uncertainties increase using the method based on the look-up tables and how representative the vertical averaging kernel climatology is of real measurement conditions.

Measurable outcome of success

Including 3D averaging kernels for zenith-sky UV-visible ozone measurements in satellite and model validation studies should improve the agreement between the different data sets, especially for UV-visible stations located in winter/spring at the edge of the polar vortex where the spatial and temporal gradients of the ozone field can be very large.

Expected viability for the outcome of success

Medium

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

No

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

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G2.30 Metrologically incomplete uncertainty quantification for Pandora ozone measurements

Gap Abstract

Pandora is a relatively new UV-VIS instrument for measuring total ozone and also ozone profiles in a similar way as MAX-DOAS instruments. So far only a few studies exist which describe measurement uncertainties or measurement validation. As a relatively inexpensive and automated instrument, there is a strong potential that a network of Pandora instruments could have a substantial role in the satellite validation in the future. A metrologically rigorous uncertainty quantification for the Pandora instrument is therefore needed.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

Secondary gap type

Governance (missing documentation, cooperation etc.)

ECVs impacted

Ozone

Non-satellite instrument techniques involved

Pandora

Related gaps

- G2.31 Incomplete understanding of the different retrieval methods, information content, and random and systematic uncertainties of MAX-DOAS tropospheric ozone measurements

There are similarities in filling this gap and Gap G2.31related to MAX-DOAS instruments even though there are not critical dependencies.

Detailed description

Pandora is a relatively new UV-VIS instrument for measuring total ozone and also ozone profiles in a similar way as MAX-DOAS instruments. The instrument is relatively small, inexpensive and automatic. The number of Pandora instruments has been growing during recent years and therefore it is possible that a network of Pandoras could have stronger role in satellite validation in the future. For example, the European Space Agency has recently supported the development of Pandora network called Pandonia

However, so far only a few studies exist which describe measurement uncertainties or measurement validation (see e.g. Herman et al. 2015, Tzortziou et al, 2012). This yields low confidence that the measurement uncertainties are currently either fully documented or rigorously quantified. For example, systematic uncertainty in Pandora direct-sun measurements are limited by temperature effects not corrected in current operational procedures. The neglect of temperature effects (related to the ozone spectroscopy in the Huggins bands) leads to seasonally dependent systematic biases and synoptic scale biases, of various amplitudes depending on the latitude of the site. This gap is partially addressed within GAIA-CLIM.

Operational space missions or space instruments impacted

- Copernicus Sentinel 5P, 4/5
- MetOp
- MetOp-SG
- Polar orbiters
- Geostationary satellites
- UV/VIS nadir
- Passive sensors

Validation aspects addressed

- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Assimilated product (Level 4)
- Time series and trends

Gap status after GAIA-CLIM

After GAIA-CLIM this gap remains unaddressed.
A literature review has been undertaken on the uncertainties related to total ozone retrievals using the Pandora instrument. Based on this and additional information obtained during the CINDI-2 campaign, an analysis of selected types of uncertainties is currently being completed. We expect, in particular, that the outcomes of the CINDI-2 campaign held in September 2016 will provide additional input for this gap. Several Pandora instruments as well as MAX-DOAS instruments have participated in the campaign. Exercises and studies performed during this campaign will provide the community with relevant datasets and information about how to proceed most effectively.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Understanding of uncertainties related to Pandora instrument. In particular, understanding of systematic errors would be beneficial.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Improved validation possibilities by using a relatively inexpensive and (quasi-)autonomous instrument.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Potential systematic errors may limit satellite validation if not taken into account in the validation.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	Potential source of systematic errors that are correlated in time and space.

Part III Gap Remedies

Remedy1 – Instigate a reference quality measurement program for Pandora measurements

Primary gap remedy type

Research

Secondary gap remedy type

Technical

Specify remedy proposal

A literature review undertaken in consultation with the Pandora community will provide a better quantification of the measurement uncertainties. This literature review should be supported by findings from the CINDI-2 campaign. Potentially, sensitivity studies to simulate the effects of various uncertainties in the retrieval setup are also needed to fully characterize the uncertainties of the ozone observations. A substantive analysis is required in consultation with experts in metrology to ensure a fully traceable uncertainty can be quantified. This may require modifications to instrument protocols down the line. Key facets of a traceable measurement are Derivation of measurement equation and traceability diagrams, quantification of effect uncertainties, standardisation of measurement procedures and documentation of the methods deployed.

Within GAIA-CLIM, a detailed traceability chain has already been developed for total column ozone measurements made using UV-visible spectroscopic instruments and for this chain, each of the elements has been described in detail and the corresponding uncertainties have been quantified. Once this traceability chain together with the uncertainty details of the elements have been finalised, this information will be made available publicly and should provide a vital input towards the development of a metrologically rigorous uncertainty quantification for the Pandora instruments. Further work remains to have this processing adopted and the reference quality measurements provided on an operational basis to end-users.

Relevance

Given that the Pandora instruments will form the backbone of a new measurement network (PANDONIA) run in close collaboration with NDACC, any better understanding of and reduction in the measurement uncertainties will contribute to the homogenisation of the ozone data products available within these networks.

Measurable outcome of success

The aim is to reduce the total uncertainty of the final ozone data product and to understand the uncertainty budget and to quantify it in a metrological sense.

Expected viability for the outcome of success

High

Scale of work

Individually
Single institution

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

No

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- ESA, EUMETSAT or other space agency

G2.31 Incomplete metrological understanding of the different retrieval methods, information content, and random and systematic uncertainties of MAX-DOAS tropospheric ozone measurements

Gap Abstract

Retrieving tropospheric ozone from passive remote sensing observations is difficult because almost 90% of the total column ozone resides in the stratosphere. Pioneering studies have demonstrated that information on tropospheric ozone can be extracted using the so-called MAX-DOAS (Multi-Axis Differential Optical Absorption Spectroscopy) technique. The information content of such measurements, however, remains to be thoroughly explored. Furthermore, within these studies, different experimental retrieval methods have been applied and more research is needed to better characterize the different possible approaches for tropospheric ozone retrieval. In addition to the lack of understanding of the information content and consensus on retrieval approaches, the lack of uncertainty characterization of tropospheric ozone measurements from MAX-DOAS instruments restrains the potential for the assessment of network capabilities and the usage of these data for satellite and model validation purpose.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

Secondary gap type

Vertical domain and/or vertical resolution
Technical (missing tools, formats etc.)
Parameter (missing auxiliary data etc.)

ECVs impacted

Ozone

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)

Related gaps

- G2.26 Poorly understood uncertainty in ozone cross-sections used in the spectral fit for DOAS, MAX-DOAS, and Pandora data analysis
- G2.27 Lack of understanding of random uncertainties, air mass factor calculations, and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy
- G2.30 Metrologically incomplete uncertainty quantification for Pandora ozone measurements

All these related gaps deal with the characterisation and improvement of the data quality of UV-visible measurements and, hence, should be considered at the same time or prior to the resolution of this gap.

Detailed description

During the last decade, passive MAX-DOAS (Multi-Axis Differential Optical Absorption Spectroscopy) instruments have been deployed worldwide, focusing on the monitoring of air quality tropospheric trace gas species (NO_2 , HCHO, SO_2, CHOCHO) but also halogens (BrO, IO) and aerosols (through oxygen dimer (O_4) measurements). Because they have similar spatial domains, MAX-DOAS is widely used to validate satellite nadir observations of pollutants like NO_2 , HCHO, and SO_2 (see e.g. Hassinen et al. (2016) for the validation of the GOME-2 instruments on board of the METOP-A and B platforms). As for all UV-visible DOAS data products (see e.g. Platt and Stutz, 2008), the MAX-DOAS retrieval is based on a two-step approach: (1) a spectral inversion step using the differential optical absorption spectroscopy (DOAS) method and providing the slant column densities (SCD, which is the trace gas concentration integrated along the effective light path), and (2) a subsequent conversion step which ultimately provides the end products (tropospheric vertical columns and/or profiles).

Compared to other trace gases, tropospheric ozone retrievals are much more challenging since most of the ozone column (90%) is located in the stratosphere and therefore dominates the total ozone absorption, making difficult the separation between the tropospheric and stratospheric ozone absorption signals. Moreover, given the fact that for tropospheric ozone, the spectral fitting is usually done in the Huggins bands (i.e. 300-340 nm), the retrieval problem cannot be considered as linear as for other trace gases, because of the strong ozone absorption in this wavelength range. These difficulties explain why a limited effort has been made to date by the DOAS Community on this topic: so far only the exploratory studies of Liu et al. (2006) and Irie et al. (2011), both based on the Optimal Estimation Method (OEM; Rodgers et al., 2000), and of Gomez et al. (2014) have been reported in the literature.

In Liu et al. (2006), the atmosphere is modeled on an Umkehr-type grid with 22 layers from 0 to ~60 km, in steps of ~2.5 km for each of the bottom 20 layers and ~5 km for the top two layers. The total column ozone is also treated as one element of the measurement vector. The difference between the integrated total column from the ozone profile and the constrained total column estimated from zenith-sky or direct-sun observations is then minimized in the retrievals simultaneously with those between measured and simulated radiances at different elevation angles. The a priori ozone profile used in the retrievals and its standard deviations are extracted from the Total Ozone Mapping Spectrometer (TOMS) version-8 climatology. To extract more available information from the measurements, the *a priori* constraint is relaxed by increasing the original a priori standard deviations in the troposphere. A correlation length of 5 km is used to construct the a priori covariance matrix for the whole atmosphere. Tropospheric aerosols corresponding to a visibility of 50 km and background stratospheric aerosols from the LOWTRAN climatology are used. The temperature profile is taken from the US Standard Atmosphere.

In Irie et al. (2011), a more simple description of the troposphere is used and the state vector consists of VCD times a factor f_{clm} . VCD is defined as the vertical column density (VCD) for altitudes below 5 km. The ozone number density is fixed to 5.8×10^{11} molecules cm^{-3} at 5 km based on the US Standard Atmosphere and the vertical profile shape is assumed to be linear between 0 and 5 km. Then, the vertical profile of ozone below 5 km is determined depending on the VCD: a smaller VCD tends to yield a linearly increasing profile with altitude while a larger VCD produces a linearly decreasing profile. It is assumed that ozone concentrations are more variable in the Planetary Boundary Layer (PBL) than in the lower free troposphere, as the primary target of the Irie et al. (2006) study is to see variations in PBL concentrations. Above 5 km, the *a priori* profile has been set to the US Standard Atmosphere ozone profile. However, the profile above 5 km has been made multipliable by a factor, f_{clm} , in the retrieval in order to ensure a smooth matching between the profile parts below and above 5 km. For each 30-min interval, the *a priori* VCD value and the corresponding error are set to 20% and 100% of the maximum ozone DSCD values. The *a priori* f_{clm} (±error) is set to 1.0±1.0. Regarding the aerosols, a fixed AOD value (0.2) is assumed together with an exponentially decreasing with height profile shape.

In Gomez et al. (2014), a new approximation is proposed to estimate ozone mixing ratios from MAX-DOAS measurements at high-altitude sites. The proposed method uses O_4 slant column densities (SCDs) at horizontal and near-zenith geometries to estimate a station-level differential path. This modified geometrical approach (MGA) takes advantage of a very long horizontal path to retrieve ozone mixing ratios in the range of a few pptv (parts per thousand by volume). Moreover, measurements and retrieval approaches should be thoroughly characterized in terms of uncertainty budget and information content (vertical sensitivity, horizontal representativeness, dependency on measurement and solar geometries, and atmospheric visibility).

Although there have been these exploratory studies discussed above, there is still a clear need for a significant research effort to be undertaken by the DOAS Community in order to (1) develop reference methods/algorithms and recommendations for the retrieval of tropospheric ozone vertical profiles and columns from MAX-DOAS measurements, and (2) operationally apply these algorithms to all existing MAX-DOAS stations.

In particular, the following specific issues have been identified:

1. Lack of understanding of the information content of MAX-DOAS tropospheric ozone measurements. Although the studies discussed above have demonstrated the feasibility of tropospheric ozone measurements from UV-visible absorption measurements in both the Huggins and Chappuis bands (see Liu et al., 2006; Irie et al., 2011; Gomez et al., 2014), the information content of such measurements remains to be thoroughly explored in terms of vertical sensitivity, dependency on measurement geometry (in particular the number of viewing angles being sampled), dependency on atmospheric visibility (i.e. aerosol content), solar geometry, horizontal representativeness, etc. This current lack of knowledge of the information content of MAX-DOAS tropospheric ozone measurements restrains the usage of this technique for large scale ozone monitoring and satellite and model validation. A better characterization of this information content will contribute to the development of robust retrieval methods (see also Remedy #1).
2. Better characterization of the different MAX-DOAS tropospheric ozone retrieval methods needed. So far the retrieval methods applied are experimental and are either based on Optimal Estimation (OE) schemes (Liu et al., 2006; Irie et al., 2011) or on more simple approaches such as the modified geometrical approximation used in Gomez et al. (2014) to infer free-tropospheric ozone concentration from a high-altitude site. More work is necessary to better characterize the different approaches. Such characterization will, in turn, also contribute to a better understanding of the information content corresponding the MAX-DOAS tropospheric ozone measurements (see bullet 1) above and Remedy #2 below).
3. Lack of in-depth understanding of random and systematic uncertainties of MAX-DOAS tropospheric ozone measurements. A better characterization of these uncertainties will contribute to a more in-depth knowledge of the information content of the corresponding MAX-DOAS tropospheric ozone measurements. As for other trace gases, the main uncertainties are related to the estimation of the effective photon light path, which is dependent on the aerosol content and optical properties. Moreover, in the case of ozone, the interference with the strong ozone absorption taking place higher up in the atmosphere is potentially a significant source of systematic bias and a comprehensive error budget of tropospheric ozone retrieval from MAX-DOAS measurements is lacking (see also Remedy #3). The lack of

uncertainty characterization of tropospheric ozone measurements from MAX-DOAS instruments restrains the potential for network capabilities assessment and the usage of these data for satellite and model validation purpose.

Operational space missions or space instruments impacted

- Copernicus Sentinel 4/5
- Meteosat Second Generation (MSG)
- MetOp
- Geostationary satellites
- Infrared nadir
- UV/VIS nadir

Validation aspects addressed

- Geophysical product (Level 2 product)
- Time series and trends

Gap status after GAIA-CLIM

GAIA-CLIM has partly closed this gap.

This gap has been partly addressed by GAIA-CLIM, in particular through the work done by the CINDI-2 MAXDOAS Tropospheric Ozone Working Group. But many aspects of the gap remain.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
A better characterisation of the information content of MAX-DOAS tropospheric ozone measurements and retrievals will produce highly-relevant correlative data sets for model and satellite tropospheric ozone validation studies.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Copernicus research and operational tropospheric ozone data products better assessed and validated.
Highly-relevant (worldwide MAX-DOAS instruments deployment; measurement frequency: every 20 minutes during daytime) correlative data sets for model and satellite tropospheric ozone validation studies	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Copernicus research and operational tropospheric ozone data products better assessed and validated.
A better characterisation of the uncertainty budget of MAX-DOAS tropospheric ozone measurements and retrievals will produce highly-relevant (worldwide MAX-DOAS instruments deployment; measurement frequency: every 20 minutes during daytime) correlative data	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Copernicus research and operational tropospheric ozone data products better assessed and validated.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Sub-optimal validation of model and satellite tropospheric ozone data when using MAX-DOAS observations with corresponding information content not fully characterized or insufficiently understood and characterized uncertainty	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Potentially less confidence in satellite and model data due to the lack of highly relevant correlative tropospheric O_3 data sets

Part III Gap Remedies

Remedy 1 – Improved metrological understanding of potential for MAX-DOAS high-quality measurements and retrieval techniques of tropospheric ozone

Primary gap remedy type

Research

Secondary gap remedy type

Deployment

Specify remedy proposal

More studies are needed to investigate the potential of the MAX-DOAS remote-sensing technique for tropospheric ozone measurements.

In particular, the information content (vertical sensitivity, horizontal representativeness, dependency on measurement and solar geometries, and atmospheric visibility) and uncertainty budget of those measurements must be thoroughly characterized in different spectral ranges covering both Huggins and Chappuis ozone absorption bands and for a broad range of observation geometries and atmospheric conditions. Ideally, this should be conducted in a coordinated way, e.g. as part of an instrument intercomparison experiment such as the CINDI-2 intercomparison campaign which took place in Cabauw (The Netherlands) in September 2016. More in-depth studies are also needed to investigate and characterize the different possible methods for the retrieval of tropospheric ozone from MAX-DOAS observations. With most of the active MAX-DOAS research groups involved and the creation of a dedicated MAX-DOAS Tropospheric Ozone Working Group, this campaign provides an ideal framework for these tasks, and some of these tasks are already being addressed as part of the CINDI-2 campaign effort.

Relevance

A better characterisation of the information content and uncertainty budget of MAX-DOAS tropospheric ozone retrievals will improve the usability of MAX-DOAS observations for model and satellite validation studies, while an improved characterisation of the MAX-DOAS tropospheric ozone retrieval is fully aligned with the requirements of providing traceable and harmonized tropospheric ozone vertical columns and profiles for satellite and model validation.

Measurable outcome of success

To provide MAX-DOAS tropospheric ozone retrieval results with improved information content characterization and uncertainty assessment to Copernicus and Space Agencies (ESA, EUMETSAT), and to estimate the impact of these improvements on the interpretation of model and satellite validation studies.

To provide an in-depth characterisation of the different retrieval methods and their advantages and disadvantages for the retrieval of tropospheric ozone from MAX-DOAS measurements, and to select one of them for its operational application at all MAX-DOAS sites.

To provide the corresponding retrieval results to Copernicus and Space Agencies (ESA, EUMETSAT) for validation purpose.

Expected viability for the outcome of success

Medium

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

No

Potential actors

- Copernicus funding
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

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G2.36 Lack of traceable uncertainties in MWR measurements and retrievals

Gap Abstract

Ground-based microwave radiometers (MWR) provide continuous and unattended retrievals of atmospheric temperature and humidity profiles, as well as of vertically-integrated total column water vapour (TCWV) and cloud liquid water (TCLW). Despite the significant scientific advancements allowed by MWR observations over the last forty years, current operational MWR retrievals are still lacking a traceable uncertainty estimate. The characterization of the total uncertainty budget for MWR retrievals requires quantification of the contributions from the instrument hardware (including absolute calibration) and the retrieval method (including the radiative transfer model). These contributions have been quantified in open literature, but they often refer to one particular instrument and/or environmental condition, and thus are not able to be generalized. A systematic approach that dynamically evaluates the total uncertainty budget of MWR (i.e. as function of instrument/environment conditions) at the network level is lacking. Initiatives for mitigating this gap are being undertaken in Europe as well as in the United States.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

Secondary gap type

- Uncertainty in relation to comparator measures
- Technical (missing tools, formats etc.)
- Governance (missing documentation, cooperation etc.)

ECVs impacted

- Temperature
- Water vapour

User category/Application area Impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)

Non-satellite instrument techniques involved

Microwave Radiometer

Related gaps

- G2.13 Missing microwave standards maintained by national/international measurement institutes
- G2.13 should be addressed with G2.36

Argument: The remedy of G2.13, i.e. the development of MW standards maintained at national/international measurement institutes and the availability of transfer standards, will set the basis for SI-traceability of MWR observations and retrievals. However, tools for evaluating the MWR total uncertainty budget can be developed independently of the solution of G2.13.

Detailed description

The characterization of the total uncertainty budget for MWR retrievals requires quantification of contributions from the instrument hardware and the retrieval method. These contributions have been quantified in the open literature (e.g. Han and Westwater 2000; Hewison, 2006; Maschwitz et al., 2013; Stähli et al., 2013), but they often refer to one particular instrument and/or set of environmental conditions, and thus should not be generalized.

A proper uncertainty quantification for MWR retrievals shall result from the propagation of the uncertainty in calibration (transfer from raw voltages to the primary observable, the brightness temperature Tb) and the uncertainty in the retrieval method (transfer from Tb to atmospheric variables). As the uncertainty depends on the instrument and environmental conditions, the quantification shall be made dynamically, such that each measurement will be associated with one, generally different, uncertainty. The estimated uncertainty is thus time- and, for profiles, height-dependent. For a MWR network, the estimated uncertainty is also space-dependent, as it will depend on the instrument types deployed at various sites.

A systematic approach that dynamically evaluates the total uncertainty budget of MWR at the network level is lacking. In the following, the contributions to the total uncertainty are divided into four aspects: calibration and instrument characterization, retrieval method, radiative transfer and absorption model uncertainty, quality control.

Calibration and instrument characterization

Calibration and instrument characterization of MWR are to be performed regularly as they are time-dependent. Common procedures are applied by the operators to perform MWR calibration and instrument characterization. Currently, these procedures are usually provided by the manufacturers, and thus they are instrument-specific, or are based on user experience, and thus may be site-specific. Therefore, there is currently a lack of standardization in calibration procedures and uncertainty characterization. This in turn impacts negatively on the uniformity of products provided by a heterogeneous MWR network. This gap shall need to be addressed at both manufacturer and network levels.

Retrieval method

Different methods are currently applied for the retrieval of atmospheric variables from MWR observations. Different retrieval methods are adopted by different MWR manufacturers, operators, and users. Common retrieval methods include, but are not limited to, multivariate regression, neural networks and optimal estimation. This situation holds true for heterogeneous networks, such as the one currently establishing in Europe. The uncertainty of MWR retrievals depends partially on the used retrieval method. Documentation, versioning, and settings are usually not accessible nor maintained. Information on retrieval uncertainty is often completely missing. The traceability of software documentation and versioning is also not guaranteed. This lack of coordination impacts negatively on the harmonization and spatio-temporal consistency of products from a heterogeneous MWR network. This gap shall need to be addressed at the network level.

Radiative transfer and absorption model uncertainty

Most common MWR retrieval methods are based on radiative transfer simulations through the atmospheric medium. Thus, uncertainties in modelling the absorption/emission of microwave (MW) radiation by atmospheric gases and hydrometeors affect all the retrieval methods based on simulated MW radiances. Only retrieval methods based on historical datasets of MWR observations and simultaneous atmospheric soundings are not affected by absorption model uncertainties. Currently, the information on MW absorption model uncertainties are dispersed and not easily accessible. Most operational MWR operate in the 20-60 GHz range, where relevant absorption comes from water vapour, oxygen, and liquid water. A variety of models are available which combine the absorption of water vapour, oxygen, and liquid water, as well as other minor contributions. Absorption model uncertainties are currently estimated from the output difference of different models, while a more rigorous estimate is lacking. An attempt to mitigate this gap is currently being carried out within GAIA-CLIM.

Quality control

Quality control (QC) procedures are fundamental for providing users with tools for judging and eventually screening MWR data and products. Most operational MWRs apply QC procedures that are developed by either the MWR manufacturer or by the operators based on their experience. There are different levels of QC procedures, going from sanity checks of the system electronics, to monitoring the presence of rain/dew on the instrument window, to radio frequency interference detection, to monitoring calibration against independent reference measurements (usually by radiosondes). The nature of the QC procedures varies, as these may be applicable to all instruments or conversely be instrument and/or site specific. Therefore, there is currently a lack of harmonization and automation of MWR QC procedures. This impacts on the quantity and quality of the data delivered, as poor QC may result in either delivery of faulty data, or screening out of good data. This gap shall need to be addressed at both manufacturer and network levels.

Operational space missions or space instruments impacted

- Meteosat Third Generation (MTG)
- MetOp-SG
- Polar orbiters
- Geostationary satellites
- Microwave nadir
- Passive sensors
- GNSS-RO
- Other, please specify
    - Temperature and humidity sounders in general

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Assimilated product (Level 4)
- Time series and trends
- Calibration (relative, absolute)
- Spectroscopy

Gap status after GAIA-CLIM

GAIA-CLIM has partly closed this gap.

Attempts to mitigate this gap are currently being carried out within and outside of GAIA-CLIM. Within GAIA-CLIM, a review of state-of-the-art MW absorption models and associated uncertainty has started (Cimini et al., 2017a). The absorption model uncertainties need to be propagated through radiative transfer and inverse operator to estimate the total uncertainties affecting the simulated brightness temperatures and the retrieval methods. A review paper shall collect the outcome of this analysis.

Outside of GAIA-CLIM, attempts to mitigate this gap are currently being carried out in the framework of the EU COST Action TOPROF, specifically by the Microwave Radiometer Working Group (WG3). WG3 is actively tackling the above challenges by interacting with manufacturers and users. WG3 produced a report on calibration best practices. New developments on calibration target design have been stimulated through the interactions with manufacturers. Network-suitable retrieval methods are currently under development within TOPROF WG3 (De Angelis et al. 2016; 2017). The role of GAIA-CLIM is to follow the developments at TOPROF and report to GAIA-CLIM as well as MWR users/manufacturers.

The present overarching MWR gap will be considered closed when procedures for MWR calibration and instrument characterization and a unified retrieval method will be performed uniformly across the network.

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Availability of best practices for MWR calibration and instrument characterization	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High Medium	Best practices procedures will help operators in producing quality MWR observations and related uncertainty
Availability of a homogeneous and unified MWR retrieval method	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	A network-wide common retrieval method will make documentation, versioning, and maintenance easier. It will guarantee spatio-temporal consistency of retrieval across the network
Full characterization of the uncertainty related to microwave absorption model	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	The contribution to uncertainty due to microwave absorption model can be fully accounted in the uncertainty budget of MWR retrieved products and the associated time series and trends.
Availability of unified tools for automated MWR data quality control	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High Medium	Trustable and unified tools for automated MWR data quality control will make MWR observations less user-dependent and thus more uniform across the network
Increased confidence in MWR retrieved products	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	The following will yield increased confidence and utilization of MWR observations in reanalyses and climate research: - Instrument- and site-independent procedures for MWR calibration and characterization - Understanding absorption model uncertainties - Network-wide consistent retrieval method, with sustained versioning and documentation - Trustable MWR data quality control
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Continued non-uniform practices for MWR calibration and error characterization	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High	Higher probability of human error in MWR calibration and error characterization. Lack of network-harmonised MWR products which reduces their utility to applications requiring cross-network harmonised values such as satellite cal/val.
Lack of rigorous estimate for MW forward model	Climate research (research groups working on development, validation and improvement of ECV Climate Data	High	Uncertainty of ground-based MWR retrievals lacks the contribution of the absorption model, which potentially

uncertainty	Records)		affects time series and trend recognition
Quality of MWR products varying throughout a network	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Lack of network-harmonised MWR products leading to challenges for applications that require a harmonised network of measurements such as satellite cal/val
Continued lack of unified tools for automated MWR data quality control	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	MWR observations will continue to depend substantially on user experience. This can potentially introduce fake time/location differences. Quality uniform network products would be hampered.
Inspection by eye is recommended to detect suspicious data and faulty calibration	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High	Additional personnel costs, prone to human error
Decreasing trust in MWR data quality	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	High	MWR users at operational services may not necessarily be able to develop their own QC procedures. Features caused by quality uncontrolled data may impact the trustiness and use of MWR systems. Lack of harmonization across the MWR network may negatively impact the trustiness of MWR systems.
Non-traceable MWR-based validation for satellite ECVs	All users and application areas will suffer from it.	High	No traceable validation for satellite boundary layer thermodynamical profiles

Part III Gap Remedies

Remedy 1 – Adoption of an international approach to implement recommendations for addressing existing gaps in MWR operational products for climate monitoring utilization

Primary gap remedy type

- Technical ; TRL 5-7

Secondary gap remedy type

- Deployment
- Research
- Education/Training
- Governance

Specify remedy proposal

In order to close this overarching MWR gap, specific workplans should be developed to all the four aspects mentioned above: calibration and instrument characterization, retrieval method, radiative transfer and absorption model uncertainty, quality control. This may be best achieved via a collective set of actions which would be best achieved as a single project but could also be achieved via smaller distinct units of work as follows:

Calibration and instrument characterization

The currently available practices for MWR calibration and instrument characterization shall be reviewed. From these, the best practices should be defined and reported, and the documentation shall be made available to operators and users. Close collaboration with MWR manufacturers is desirable. The starting point is the outcome of the Microwave Radiometers Working Group (WG3) of the EU COST Action TOPROF, ended in October 2017. TOPROF WG3 produced a report on recommendations for operation and calibration of MWR within a network (Pospichal et al., 2016).

Retrieval method

The different types and flavours of retrieval methods currently exploited shall be reviewed and reported. A common retrieval method is recommended for MWR belonging to a network. The recommended retrieval method must produce explicitly and transparently the time-dependent estimated uncertainty of each atmospheric retrievals. A software package for a common retrieval method shall be developed and maintained. The starting point is the outcome of the TOPROF WG3 (Cimini et al. 2017b).

Radiative transfer and absorption model uncertainty

Modifications of absorption models are continuously proposed within the open literature based on laboratory data and MWR field observations. To estimate the total uncertainties affecting the MWR retrievals, the following activities are needed: (i) a review of the state-of-the-art and the associated uncertainty of MW absorption models; (ii) propagation of absorption model uncertainties through radiative transfer and inverse operator. Activities in this direction have started within GAIA-CLIM and shall eventually lead to a review paper (Cimini et al. 2017a).

Quality control

MWR quality control (QC) procedures shall be harmonized and automated to the maximum extent possible. A common network-wide data processing would be recommendable for the network products. Activities in this direction have started within TOPROF WG3, actively interacting with manufacturers for proposing ways for QC automation. Results of these activities shall be transferred as recommendations to users and manufacturers.

Activities contributing to the solution of the above issues have started within the COST action TOPROF and GAIA-CLIM. These two projects are ending in October 2017 and February 2018, respectively. Currently no plan is set for following up on these activities with research-oriented projects. The members of the TOPROF core group have submitted a proposal to the Policy and Finance Advisory Committee of EIG EUMETNET (grouping 31 European Meteorological Services) for including MWR into the next phase of their E-PROFILE project. If accepted, part of the above tasks may be accomplished in that framework, specially those concerning calibration and instrument characterization, and quality control. The next phase of E-PROFILE is scheduled for 2019-2023.

Relevance

Once the above issues are addressed, traceable MWR observations and retrievals will be available together with the estimate of the time-dependent uncertainty uniformly across the network. The remedies above will foster:

- The application of standardized calibration and uncertainty characterization procedures by MWR manufacturers and users;
- The use of a common network-suitable retrieval method. This will harmonise the MWR network products. Product harmonization leads also to more solid characterization of uncertainties;
- The consideration of MW forward model uncertainties in MWR retrievals, as quantifying the MW absorption model uncertainties will provide a common reference for MWR retrieval methods;
- The application of improved QC procedures by MWR manufacturers and users. Better QC leads to more solid characterization of MWR retrieval uncertainties, as it reduces the impact of suspicious data and faulty calibration.

Measurable outcome of success

The measurable outcome of success for the above specific remedies are the following:

- The number of MWR sites, users, and manufacturers adopting the proposed calibration and uncertainty characterization procedures;
- The number of MWR users and manufacturers considering the rigorous estimates of MW forward model uncertainties in their MWR retrievals;
- The number of MWR sites (i.e. network nodes) providing retrievals and associated uncertainty produced with the recommended uniform retrieval method;
- The number of MWR sites, users, and manufacturers adopting the proposed QC procedures.

Expected viability for the outcome of success

Medium

Scale of work

Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

- EU H2020 funding
- Copernicus funding
- National Meteorological Services
- Academia, individual research institutes
- SMEs/industry

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G2.37 Need for more complete metrological characterisation of spectroscopic information

Gap Abstract

Molecular spectroscopy provides the primary link between radiance and atmospheric gas composition. Full knowledge of the spectroscopic properties of a measurement could, in theory, provide a route to formal traceability for that measurement. The exact nature of the influence of spectroscopic uncertainties on the derived ECV products will vary according to the spectral region being measured and the specific details of the measurement technique being employed – and a series of related gaps have been identified. However, there would be a clear benefit in a top-level spectroscopic coordination activity that identifies and disseminates common issues and solutions, including a harmonised process for dealing with spectroscopic uncertainties and establishing spectroscopic traceability.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

Secondary gap type

Governance (missing documentation, cooperation etc.)

ECVs impacted

- Temperature
- Water vapour
- Ozone
- Carbon Dioxide
- Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

- Lidar

- Microwave Radiometer
- FTIR
- Brewer/Dobson
- UV/VIS zenith DOAS
- UV/VIS MAXDOAS
- Pandora

Related gaps

- G2.26 Poorly understood uncertainty in ozone cross-sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis
- G2.27 Lack of understanding of random uncertainties, Air Mass Factor calculations, and vertical averaging kernels in the total ozone column retrieved by UV-visible spectroscopy

This gap represents the top-level coordination and harmonisation activity required across the general spectroscopic measurement field. There are two gaps identified under this broad topic, G2.26 and G2.27 which address issues related to particular spectral regions and specific issues in individual measurement techniques. In both cases, this coordination activity should take place in parallel with the more specific gap assessments.

Detailed description

Molecular spectroscopy provides the primary link between radiance and atmospheric gas composition, and is a primary component of the theory of radiative transfer through the atmosphere. The spectroscopic properties of a gas are constant and therefore, if they are robustly characterised and all of the external and instrumental influence factors on a spectroscopic measurement method are assessed, then formal traceability could, in theory, be realised for any measurement using that method.

In addition to the spectroscopic issues relating to those techniques that directly use spectroscopic measurement methods to derive information on ECVs, spectroscopic parameters are also an integral part of radiative transfer (RT) codes. RT codes constitute the core of radiometric physical retrievals, such as optimal estimation methods. In addition, any data intercomparison/validation method that includes the use of RT codes will also be influenced by spectroscopic uncertainties. Such uncertainties will contribute to the overall uncertainty of the data intercomparison, and could be the source of, potentially unexpected, correlation between the different data sources.

The exact nature of the influence of spectroscopic uncertainties on the derived ECV products will vary according to the spectral region being measured and the specific details of the measurement technique being employed – and a series of related gaps have been identified that give examples of this. However, there would be a clear benefit in a top-level spectroscopic coordination activity that took an overview of the more detailed technical developments; identified and disseminated common issues and solutions; and potentially developed a harmonised process for dealing with spectroscopic uncertainties and establishing spectroscopic traceability. This final goal of formal traceability based purely on the spectroscopic assessment of the measurement is a very challenging one that is unlikely to be resolved in the short term. However intermediate steps to improve the knowledge of spectroscopic uncertainties and their impact on measurement methods and intercomparison results, will have immediate impact which will be enhanced through an overall spectroscopic coordination activity.

Historically, other sources of uncertainty have tended to be much larger than spectroscopic uncertainties such that spectroscopic uncertainty has tended to be seen as an ignorable effect. As satellite and non-satellite instrumentation become more stable and better characterised and understanding of collocation effects improves it is increasingly the case that spectroscopic uncertainties become important or even the limiting factor in the comparison, particularly as they are a potential source of long term correlation within individual measurement methods but also in comparisons between methods. It is thus increasingly important that spectroscopic uncertainties be considered afresh and better quantified.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments
This gap relates to all space instruments that rely on knowledge of spectroscopic parameters in their measurement procedure or could use a sub-orbital spectroscopic-based technique as a validation tool.

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Spectroscopy

Gap status after GAIA-CLIM

After GAIA-CLIM this gap will remain

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
A robust and consistent approach to the handling of uncertainties and traceability in spectroscopic measurements would significantly extend the availability of reference quality data across a wide range of techniques and ECVs.	All users and application areas will benefit from it	Medium	The provision of a formalised route to spectroscopic traceability would enable reference quality data to be realised in an efficient and consistent manner at any location. The contribution to uncertainty due to spectroscopic parameters can be fully accounted in the uncertainty budget of retrieved products and the associated time series and trends.
An improved understanding of the common issues in spectroscopic measurements would identify sources of correlated uncertainties between different measurement and modelling techniques	All users and application areas will benefit from it	High	Improved quality and understanding of the intercomparison between sub-orbital and satellite based measurements, and between measured and modelled atmospheric distributions. Understanding the spectroscopic uncertainties will yield increased confidence and utilization of observations in reanalyses and climate research.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
If a coordinated activity is not carried out then the situation will remain as a series of separate activities linked to individual techniques / instruments.	All users and application areas will suffer from it.	High	ECV retrieval uncertainty lacks a coordinated contribution of RT models, which may potentially affect time series and trend recognition. Intercomparison / validation activities remain inefficient with none of the synergistic benefits that a coordinated spectroscopic assessment could bring.
The potential effects of correlated uncertainties in the comparison of results from different techniques due to spectroscopic issues are not identified.	All users and application areas will suffer from it.	High	A key element in assessing the comparability and/or consistency of different measurements is not properly addressed, potentially undermining validation studies.

Part III Gap Remedies

Remedy 1 – Establish traceability of spectroscopic properties of Essential Climate Variables

Primary gap remedy type

Research

Secondary gap remedy type

Education/Training
Governance

Specify remedy proposal

Establishment of a top-level cooperation and networking activity to coordinate and review spectroscopic uncertainty activities across the range of spectral regions and measurement techniques, with the long-term goal of developing harmonised processes to establish spectroscopic traceability in ECV determination. This may be achieved either by a large-scale coordinated project or piecemeal for specific cases. A large-scale coordinated project approach would benefit from synergies and commonality of approaches and may be preferred. Experts in laboratory and theoretical spectroscopy, metrology and the instruments would be required, and would need to link to the exiting collaborative activities involved in the development of spectroscopic reference databases such as HITRAN and GEISA. A key aspect of this work will be the introduction of metrological traceability in the determination of new spectroscopic data, covering both the target gas concentrations and path lengths being measured but also the ancillary parameters such as temperature, pressure and matrix gas composition that are crucial in derivation of spectroscopic model parameters and their uncertainties. The top level project should include a focus on the development of common procedures and robust methods that could be deployed across the wider spectroscopic community, to ensure consistency and comparability amongst data providers in the generation of the spectroscopic parameters, and understanding amongst data users in the application of the parameters and related uncertainties.

Relevance

The proposed coordination activity is required to ensure a harmonised approach to addressing specific gaps in spectroscopic knowledge. This will lead to the efficient development of an improved understanding of spectroscopic uncertainties and a unified methodology in establishing traceability in spectroscopic measurements.

Measurable outcome of success

Successful outcome of the activity will be demonstrated in the short term through transfer of knowledge from one area of spectroscopic research to another, and through the development of common processes and procedures. An additional measure of success would be the implementation of the estimated uncertainties in the retrieval methods exploited by the satellite and ground-based user community.

Expected viability for the outcome of success

Medium

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

More than 10 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

Other: European funding mechanisms such as COST or EMPIR.

G3.01 Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and of their co-location

Gap Abstract

The atmospheric concentration of nearly all ECVs varies in space and time at the scale of the individual measurements, and at the scale of their co-location in the context of data comparisons (e.g., for the purpose of satellite validation, data merging, and data assimilation). However, the amplitude and patterns of these variations are often unknown on such small scales. Consequently, it is impossible to quantify the uncertainties that result from sampling and smoothing properties of the measurements of the variable, structured atmospheric field. This gap thus concerns the need for a better quantification of atmospheric spatiotemporal variability at the small scales of individual measurements and co-locations.

Part I Gap Description

Primary gap type

Uncertainty in relation to comparator

Secondary gap type

- Knowledge of uncertainty budget and calibration
- Parameter (missing auxiliary data etc.)

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Independent of instrument technique

Related gaps

- G3.04 Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties
- G3.06 Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences

G3.04. To be addressed after G3.01

Argument: To estimate the additional uncertainties on a measurement that result from spatiotemporal atmospheric variability at the measurement sampling and smoothing scales, a quantification of that spatiotemporal variability is a prerequisite.

G3.06. To be addressed after G3.01

Argument: Understanding the uncertainty budget of a comparison (in a validation context) requires a quantification of the impact of co-location mismatch. This cannot be done without an estimate of the spatiotemporal variability of the ECV under study.

Detailed description

Spatiotemporal variability of the atmosphere at the scale of the airmass being measured or - in the case of a measurement intercomparison - at the scale of the co-location, leads to additional uncertainties, not accounted for by the uncertainty budget reported with an individual measurement (Lambert et al., 2012). To quantify these additional uncertainties (cf. gaps G3.04 and G3.06), or to ensure that they remain negligible through the use of appropriate co-location criteria (cf. G3.02), a prerequisite is a proper understanding of atmospheric variability of the targeted ECV on those scales.

While scales above approx. 100km and 1h are relatively well captured for several GAIA-CLIM target ECVs in model or satellite gridded data (e.g., Verhoelst et al., 2015, for total ozone), information on smaller scales is most often restricted to results from dedicated campaigns or specific case studies, e.g., Sparling et al. (2006) for ozone profiles, Hewison (2013) for meteorological variables, and Pappalardo et al. (2010) for aerosols. Due to the exploratory nature of these studies, neither global nor complete vertical coverage is achieved. For instance, information on small-scale variability in the ozone field is limited to altitudes and regions probed with dedicated aircraft campaigns. The validation of satellite data records with pseudo global networks of ground-based reference instruments on the other hand requires an appropriate quantification of atmospheric variability in very diverse conditions, covering all latitudes, altitudes, dynamical conditions, degrees of pollution etc.

This gap therefore concerns the need for a better, more comprehensive, quantification of the spatiotemporal variability of the ECVs targeted by GAIA-CLIM.

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Assimilated product (Level 4)
- Time series and trends
- Representativity (spatial, temporal)
- Calibration (relative, absolute)
- Spectroscopy
- Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Gap status after GAIA-CLIM

GAIA-CLIM explored and demonstrated potential solutions to close this gap in the future:
Within GAIA-CLIM, a work package (WP3) was dedicated to research on co-location mismatch in an inhomogeneous and variable atmosphere. In the context of this work package, some studies were performed that quantified spatiotemporal variability for a few ECVs at a limited scale domain (e.g. temperature and water vapour temporal variability at 6-hour scale from radiosonde inter-comparisons, and aerosol optical depth variability at the scale of a satellite-ground co-location in the North-East US). Although this work was limited to a few ECVs, scales, geographical coverage etc. owing to the limited resources and data availability, GAIA-CLIM has demonstrated use cases / case studies which may permit a more exhaustive approach in future. Fully addressing this gap requires significant observational and modelling work, far beyond the scope of GAIA-CLIM, as described in detail in the remedies.

Part II Benefits to resolution and risks to non-resolution

Identified Benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Improved understanding of single measurement uncertainty, including the impact of the instrument smoothing and sampling properties	All users and application areas will benefit from it.	High	More reliable uncertainty estimates allow for more confidence in the data and optimized use in e.g. assimilation and other applications.
Improved definition of appropriate co-location criteria for validation work, minimizing errors due to co-location mismatch	All users and application areas will benefit from it.	High	Lower uncertainty due to co-location mismatch will result in tighter constraints on the products from validation work, supporting further instrument and algorithm development.
Improved interpretation of comparison results because co-location mismatch errors can be quantified.	All users and application areas will benefit from it.	High	Improved quantification of the uncertainty due to co-location mismatch will allow more stringent tests of the reported measurement uncertainties, supporting further instrument and algorithm development.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Incomplete uncertainty budget for single measurements and derived products	All users and application areas will suffer from it.	High	Poor confidence in data and services; potential over-interpretation; difficult/unreliable generation of higher level data products (through data assimilation and/or merging).
Incomplete uncertainty budget for data comparisons	All users and application areas will suffer from it.	High	Sub-optimal feedback from data comparisons, in particular in the context of satellite validation. Potential of both EO and ground segments not fully realized.

Part III Gap Remedies

Remedy 1 – Improved high-resolution modelling to quantify mismatch effects

Primary gap remedy type

Research

Secondary gap remedy type

Technical

Proposed remedy description

A first remedy to gain better insight in the small-scale spatiotemporal variability of atmospheric ECVs is by high-resolution modelling studies at the global scale, resulting in comprehensive data sets of atmospheric fields, at high horizontal, vertical, and temporal resolution, based not solely on higher-resolution grids but also including the relevant physics and (photo) chemistry at those scales.

Improved spatiotemporal resolution in atmosphere models is a much broader scientific goal, with great computational and theoretical (e.g. convection and turbulence treatment) challenges. As such, this remedy probably requires a level of effort and resources beyond what can be justified solely by the need for satellite data validation. The technological/ organizational viability is therefore considered medium and the cost estimate high.

Relevance

If successful, this remedy would largely close the gap, and it would facilitate remedies for most other gaps related to comparator uncertainties through the use of OSSEs (Observing System Simulation Experiments) based on these modelled fields.

Measurable outcome of success

The quality of the model output at its finest resolution can be estimated by comparison with high-resolution measurement data sets, preferably those with limited horizontal, vertical, and temporal smoothing effects, e.g. from balloon-borne sondes. Ideally, an agreement is found within the combined model and measurement uncertainties.

Expected viability for the outcome of success

Medium

Scale of work

Single Institution, Consortium

Time bound to remedy

Less than 10 years

Indicative cost estimate (investment):

High cost (> 5 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- National Meteorological Services

Remedy 2 – Use of statistical analysis techniques based upon available and targeted additional observations

Primary gap remedy type

Research

Secondary gap remedy type

Technical

Proposed remedy description

This remedy concerns the statistical analysis of existing and future satellite and non-satellite high-resolution data sets, which allows us to separate the contribution of atmospheric variability from the total uncertainty budget of a data comparison, e.g. using so-called 'structure functions' or heteroskedastic functional regression. Within the geographical and temporal coverage of the data set, these methods produce an estimate of the variability (or auto-correlation) of the field. Note that, as for Remedy G3.01(1), the scientific interest for higher resolution in the data sets is much broader than only the validation needs, e.g. for the identification of emission sources in an urban environment.

The technological and organizational effort required to make step changes in the spatiotemporal resolution of the observational data sets is in general very large, and comes with a large financial cost (more than 5M euro), in particular if global coverage is aimed for. Hence, such developments need a much larger user base and the use proposed here should be considered secondary to the scientific objectives of such new missions. Nevertheless, smaller dedicated campaigns with for instance aircraft or Unmanned Aerial Vehicles (UAVs) can offer great insight at particularly interesting sites (e.g. at ground stations with a multitude of instruments observing a particular ECV), and this at medium cost (between 1M and 5M euro).

Relevance

This remedy directly addresses the gap, as already illustrated for instance with aircraft data for ozone by Sparling et al. (2006).

Measurable outcome of success

The primary outcome would be publications describing for the different ECVs and various atmospheric regimes, locations and altitude ranges the atmospheric variability at scales ranging from those of in-situ measurements (e.g. 10s of meters for balloon sonde measurements) to that of a satellite pixel (several 10s to 100s of kilometres). These can be based either on existing data sets, or represent an exploitation of newly designed campaigns and missions.

Expected viability for the outcome of success

High

Scale of work

Single institution

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- National Meteorological services

References

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G3.02 Missing standards for, and evaluation of, co-location criteria

Gap Abstract

The impact of a particular choice of co-location criterion is only rarely studied in the scientific literature reporting on satellite validation results. However, without some quantification of the impact of the co-location criterion that was adopted, it is virtually impossible to assess the contribution of natural variability to the total error budget of the data comparisons. As such, this gap impacts significantly the potential interpretation of the data comparison result in terms of data quality. Some in-depth studies do exist, but testing multiple criteria, or using criteria based on the latest results of such exploratory work, is far from common (indeed, often arbitrary) practice(s). This gap thus concerns the need for more awareness among validation teams, for more detailed studies comparing the (dis-)advantages of various co-location criteria, and for community-agreed standards on co-location criteria that are broadly adopted in the context of operational services.

Part I Gap Description

Primary gap type

Uncertainty in relation to comparator

Secondary gap type

Governance (missing documentation, cooperation etc.)

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus services (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Independent of instrument technique

Related gaps

- G3.04 Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties
- G3.06 Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences
- G6.03 Lack of sustained dedicated periodic observations to coincide with satellite overpasses to minimise co-location effects

G3.04. To be addressed before G3.02
Argument: Ideally, co-location criteria take into account the smoothing and sampling properties of the measurements. Consequently, studies on co-location criteria can benefit from a proper characterization of these smoothing and sampling properties.

G3.06. To be addressed before G3.02
Argument: The merit of certain co-location criteria can best be assessed when the uncertainty budget of the comparisons is decomposed in measurement and co-location mismatch uncertainties.

G6.03. To be addressed after G3.02
Argument: Deciding on the best time and location for targeted reference observations should be informed by information on the optimal co-location criteria.

Detailed description

Co-location criteria should represent an optimal compromise between the obtained number of co-located measurements (as large as possible to have robust statistical results) and the impact of natural variability on the comparisons (as low as possible to allow a meaningful comparison between measured differences and reported measurement uncertainties). Hitherto, only a few ground-based satellite validation studies explored the impact of the adopted co-location criteria on the comparison results (e.g. Wunch et al., 2011, and Dils et al., 2014, for CO_2 , Verhoelst et al., 2015, for O_3, Pappalardo et al., 2010, for aerosols, Lambert et al. 2012, for water vapour, Van Malderen et al. 2014, for integrated water vapour). Still, atmospheric variability is often assumed –or even known- to impact the comparisons, but without detailed testing of several co-location criteria (or by extensive model-based simulations), this impact is hard to quantify. Besides the need for dedicated studies, this gap also concerns the “community practices” regarding co-location approaches, which are neither consistent across different studies, nor optimal as they often rely on historical co-location criteria, which are not necessarily fit-for-purpose for the accuracy and spatiotemporal sampling properties of current measurement systems. Consequently, to ensure reliable and traceable validation results, as required in an operational context, community-agreed standards for co-location criteria should be developed, published, and adopted.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Assimilated product (Level 4)
- Time series and trends
- Representativity (spatial, temporal)
- Calibration (relative, absolute)
- Spectroscopy
- Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Gap status after GAIA-CLIM:

GAIA-CLIM explored and demonstrated potential solutions to close this gap:

Two activities within GAIA-CLIM targeted this gap to some extent:

Within GAIA-CLIM, a dedicated task (T3.2 in WP3) dealt with data intercomparison studies, focusing on a closure of the comparison uncertainty budget and including an exploration of different co-location criteria, see for instance the results on total ozone columns published by Verhoelst et al. (2015, their Fig. 11).

The Virtual Observatory developed within GAIA-CLIM offers the user the possibility to adjust co-location criteria and to visualize the resulting impact on the comparison results.

However, no attempt has been made within GAIA-CLIM to produce an authoritative analysis and resulting documentation on this matter.

Part II Benefits to resolution and risks to non-resolution

Identified Benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Greater awareness of the impact of natural variability on the comparison results;	All users and application areas will benefit from it	High	More reliable feedback on data quality, in particular on the reported uncertainties. This in turn increases confidence in the data for the end user and allows more meaningful use in a variety of applications.
Improved definition of appropriate co-location criteria for validation work, minimizing errors due to co-location mismatch.	All users and application areas will benefit from it	High	Lower uncertainty due to co-location mismatch will result in tighter constraints on the products from validation work, supporting further instrument and algorithm development.
Facilitates intercomparison of different validation studies	All users and application areas will benefit from it	High	More reliable comparisons between different products (each having its own validation report) to better assess their fitness-for-purpose for a specific user application.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Poor feedback on data quality (in particular on the reported uncertainties) from validation studies due to unknown/unquantified influence of atmospheric variability.	All users and application areas will suffer from it.	High	Poor confidence in data and services; potential over-interpretation; difficult/unreliable assimilation; Potential of both EO and ground segments not fully realized.
Difficulty to compare validation results on similar products performed by different teams	All users and application areas will suffer from it.	High	Sub-optimal choice of data product for a given application.

Part III Gap Remedies

Remedy 1 – Systematic quantification of the impacts of different co-location criteria

Primary gap remedy type

Research

Secondary gap remedy type

Governance

Proposed remedy description

Dedicated studies are required which explore in detail the advantages and disadvantages of several co-location methods and criteria. Dedicated working groups or activities could/should be set up within the framework of the ground-based observing networks, as already initiated for meteorological variables at a GRUAN-GSICS-GNSSRO WIGOS workshop on Upper-Air Observing System Integration and Application, hosted by WMO in Geneva in May 2014. Dissemination among, and acceptance by, the key stakeholders may be challenging and can probably best be achieved in the context of overarching frameworks such as the CEOS Working Group on Calibration & Validation (WGCV). The financial cost should be very low. Also, the space agencies and service providers could/should insist on sufficient attention for (and analysis of) the adopted co-location criteria in the validation protocols followed by their validation teams.

Relevance

These studies and the proposed associated governance support target this gap directly. They will provide stakeholders with a traceable, authoritative reference on which to base their validation requirements and protocols regarding co-location criteria. It will also facilitate meta-analysis of different validation studies without the need to take into account differences in results due to differences in the impact of co-location mismatch on the results.

Measurable outcome of success

Peer-reviewed publications or widely distributed technical notes on the subject, from an authoritative body; Explicit inclusion of requirements on the co-location methodology and criteria in validation protocols.

Expected viability for the outcome of success

High

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

No

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- National Meteorological Services
- WMO
- ESA, EUMETSAT or other Space agency
- Academia, individual research institutes

References

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G3.04 Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties

Gap Abstract

This gap concerns the need for a more detailed characterization of the actual spatiotemporal smoothing and sampling properties of both satellite-based EO measurements and ground-based in-situ or remote-sensing measurements. Indeed, EO measurements are most often associated with single locations, or at best pixel footprints, while in fact the actual measurement sensitivity covers a larger spatiotemporal extent, due for instance to the radiative transfer determining the measured quantities, or the actual measurement geometry (choice of line-of-sight, trajectory of a weather balloon, etc.). In an inhomogeneous and variable atmosphere, this leads to additional errors and uncertainties that are not part of the reported measurement uncertainties, but still need to be quantified, in particular when performing comparisons with other types of measurements, with different smoothing and sampling characteristics. For several ECVs and measurement techniques, significant work is needed to (1) determine/model the actual spatiotemporal smoothing and sampling properties, and (2) quantify the resulting uncertainties on the measurements of the variable atmosphere.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

Secondary gap type

Uncertainty in relation to comparator measures

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus services (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

- Radiosonde

- Ozonesonde
- Lidar
- FPH/CFH
- Microwave Radiometer
- FTIR
- Brewer/Dobson
- UV/VIS zenith DOAS
- UV/VIS MAXDOAS

Related gaps

- G3.01 Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and of their co-location
- G3.06 Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences

- G6.03 Lack of sustained dedicated periodic observations to coincide with satellite overpasses to minimise co-location effects

G3.01. To be addressed before G3.04
Argument: A quantification of the uncertainties that result from the specific sampling and smoothing properties of an instrument requires information on the spatiotemporal variability of the atmospheric field.

G3.06. To be addressed after G3.04
Argument: Error/uncertainty budget decomposition of a comparison requires a proper understanding of the smoothing and sampling properties of the instruments involved, i.e. requires G3.04 to be remedied.

G6.03. To be addressed after G3.02
Argument: Deciding on the best time and location for targeted reference observations should be informed by information on the actual sampling and smoothing properties of the measurement systems.

Detailed description

Remotely sensed data are often considered as column-like or point-like samples of an atmospheric variable, associated for instance with the location of a ground-based instrument. This is also the general assumption for satellite data, which are assumed to represent the column or profile above the satellite field-of-view footprint in case of nadir sounders, and atmospheric concentrations along a vertical set of successive tangent points in the case of limb and occultation sounders. In practice, the quantities retrieved from a remote-sensing measurement integrate atmospheric information over a tri-dimensional airmass and also over time. E.g., ground-based zenith-sky measurements of the scattered light at twilight integrate stratospheric UV-visible absorptions (by O_3, NO2, BrO etc.) over several hundreds of kilometres in the direction of the rising or setting Sun (Lambert et al., 1997). A satellite limb measurement will actually be sensitive to the atmosphere along the entire line-of-sight towards the photon source, depending on the specific emission, absorption, and scattering processes at play (e.g. von Clarmann et al., 2009). Similarly, in-situ measurements of atmospheric profiles cannot be associated with a single geo-location and time stamp, due for instance to balloon drift for ozone- and radiosondes. In a variable and inhomogeneous atmosphere, this leads to additional uncertainties not covered in the 1-dimensional uncertainties reported with the data (e.g. Lambert et al., 2011, 2012).

A prerequisite for quantifying these additional uncertainties of multi-dimensional nature is not only a quantification of the atmospheric variability at the scale of the measurement (c.f. G3.01), but also a detailed understanding of the smoothing and sampling properties of the remote sensing system and associated retrieval scheme. Pioneering work on multi-dimensional characterization of smoothing and sampling properties of remote-sensing systems and associated uncertainties was initiated during the last decade (e.g. in the EC FP6 GEOmon project and in the current EC H2020 GAIA-CLIM project), but in the context of integrated systems like Copernicus and GCOS, appropriate knowledge of smoothing and sampling uncertainties, which is still missing for several ECVs and remote sensing measurement types, has to be further developed and harmonized.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Assimilated product (Level 4)
- Time series and trends
- Representativity (spatial, temporal)
- Calibration (relative, absolute)
- Spectroscopy
- Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Gap status after GAIA-CLIM

GAIA-CLIM explored and demonstrated potential solutions to close this gap

Addressing this gap was a major objective of GAIA-CLIM, within which specific tasks were dedicated to the characterisation of smoothing and sampling properties of selected instruments and for selected ECVs. Results have been obtained for total ozone columns, for ozone, temperature, and humidity profiles, and for aerosol columns and profiles from a diverse set of ground-based instruments. Regarding satellite data, only a selection of current missions were explored. Results were made available in technical notes, namely D3.4 ("Report on measurement mismatch studies and their impact on data comparisons") and D3.6 ("Library of (1) smoothing/sampling error estimates for key atmospheric composition measurement systems and (2) smoothing/sampling error estimates for key data comparisons"), and through the 'Virtual Observatory'. In the long term, this gap will require continued efforts to fully characterize the spatiotemporal smoothing and sampling properties of both new ground-based instruments and upcoming satellite sensors. Hence the gap requires constant re-evaluation as technology and observing programs evolve.

Part II: Benefits to resolution and risks to non-resolution

Identified Benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
More complete assessment of the impact of natural variability on the measurements;	All users and application areas will benefit from it	High	Better uncertainty characterization. This in turn increases confidence in the data for the end user and allows more meaningful use in a variety of applications.
Improved definition of appropriate co-location criteria for validation work, taking into account the actual sampling and smoothing properties, and ultimately minimizing errors due to co-location mismatch.	All users and application areas will benefit from it	High	Lower uncertainty due to co-location mismatch will result in tighter constraints on the products from validation work, supporting further instrument and algorithm development.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Incomplete total uncertainty budget for a single measurements.	All users and application areas will suffer from it.	High	Incomplete data characterization and potentially limited or flawed interpretation, whatever the use type.
Incomplete uncertainty budget for measurement comparisons, e.g. for validation.	All users and application areas will suffer from it.	High	Flawed validation results: missing uncertainty components lead to failed consistency checks, and a less performant validation system.

Part III: Gap Remedies

Remedy 1 – Comprehensive modelling studies of measurement process.

Primary gap remedy type

Research

Proposed remedy description

Detailed modelling of the measurement process, including multi-dimensional radiative transfer if applicable, to quantify the 4-D measurement sensitivity. An example are multi-D averaging kernels for retrieval-type measurements. This work requires a significant effort from the instrument teams, for which dedicated, though still relatively low (per instrument), resources are required, in particular for code modifications and additions. If appropriate, the results from these detailed calculations can be parametrized for easy and efficient use when calculating the resulting errors and uncertainties for large amounts of data. This uncertainty calculation is done by combining the quantification of the measurement sensitivity with knowledge on the spatiotemporal variability of the atmospheric field (cf. G3.01). When these detailed modelling studies are out of reach, a similar estimate of the multi-D measurement sensitivity can be made in a more pragmatic way based on the measurement principle and physical considerations (e.g. Lambert et al. 2011), or it can in some cases be estimated with empirical methods by comparing data sets with differing resolution. Note that an essential prerequisite is the availability of all required metadata with the measurements, such as viewing angles or GPS trajectories.

Relevance

This remedy will provide a description for every instrument and measurement type of the full 4-D measurement sensitivity, and the errors and uncertainties resulting from the assumption that a measurement can be associated with a nominal geo-location and time.

Measurable outcome of success

Publications and technical notes describing for every instrument and measurement type the full 4-D measurement sensitivity, and the errors and uncertainties resulting from the assumption that a measurement can be associated with a nominal geo-location and time.

Expected viability for the outcome of success

High

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

No

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- National Meteorological Services

- ESA, EUMETSAT or other Space agency
- Academia, individual research institutes

Remedy 2 – Empirical determination of true resolution by comparison with high-resolution data

Primary gap remedy type

Research

Proposed remedy description

If temporally coinciding data with higher spatial resolution are available, the true horizontal resolution of a measurement system can be determined empirically by comparing the measurements of the two instruments as obtained on the same scene. This approach was for instance demonstrated by Sihler et al. (2017) for satellite and ground-based DOAS-type measurements. It is empirical in the sense that it does not require extensive modelling of the measurement process. Rather, it requires some basic assumptions on the actual footprint and the sensitivity therein of each measurement, which is then further optimized by comparison with the high-resolution data set, if necessary over a large set of diverse scenes. This approach was also explored within GAIA-CLIM, where it was used to estimate the true vertical resolution and weighting function of temperature and humidity soundings, as described in D3.4.

Relevance

This remedy addresses the gap partially (since it only deals with the resolution aspects) and it requires an independent, high-resolution data set of sufficient quality. As such, it is not universally applicable, but it does provide a valuable resolution estimate, independent of any classical metrological modelling

Measurable outcome of success

Publications and technical notes describing for every instrument and measurement type the full 4-D measurement sensitivity, and the errors and uncertainties resulting from the assumption that a measurement can be associated with a nominal geo-location and time.

Expected viability for the outcome of success

High

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Non- applicable

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- National Meteorological Services
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

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G3.05 Representativeness uncertainty assessment missing for higher-level data based on averaging of individual measurements

Gap Abstract

Level-3 data are, by definition, constructed by averaging asynoptic level-2 data over certain space-time intervals, so as to arrive at a (regularly) gridded data product. However, the (global) sampling pattern of the sounder(s) that produced the original level-2 data is never perfectly uniform, nor are revisit times short enough to guarantee dense and homogeneous temporal sampling of e.g. a monthly mean at high horizontal resolution. Consequently, the averages may deviate substantially from the true average field that would be obtained if complete spatiotemporal coverage were possible. These so-called representativeness errors are only rarely investigated, and almost never provided with a product, in spite of their importance in interpreting the data.

Part I: Gap description

Primary gap type

Knowledge of uncertainty budget and calibration

Secondary gap type

- Uncertainty in relation to comparator measures
- Governance (missing documentation, cooperation etc.)

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus services (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

- Radiosonde
- Ozone sonde
- Lidar
- FPH/CFH
- Microwave Radiometer
- FTIR

- Brewer/Dobson
- UV/VIS zenith DOAS
- UV/VIS MAXDOAS
- Pandora
- GNSS-PW

Related gaps

- G3.01 Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and of their co-location

G 3.01. To be addressed before G3.05

Argument: A quantification of representativeness uncertainties requires an adequate representation of the atmosphere at the scale of the measurements.

Detailed description

The creation of level-3 data by averaging non-uniformly distributed level-2 measurements inevitably leads to representativeness errors, see e.g. Coldewey-Egbers et al., (2015) for the case of a level-3 (gridded monthly means) total ozone data set. The resulting representativeness uncertainty can be larger than the formal uncertainty on the mean. In the best case this would represent an additional random uncertainty term. If the sampling pattern of the sounder changes in time, this may give rise to systematic, time-dependent representativeness errors that affect for example trend analyses for climate research (see e.g. Damadeo et al., 2014). However, estimates of these representativeness uncertainties are rarely included with the data product. Also, the representativeness of the ground-based network should be taken into account when validating such data sets, i.e. the sparse spatial and temporal sampling of the ground network leads to significant representativeness uncertainties in for instance derived monthly (zonal) means.

Note that also in the context of validation of level-2 data, measurements are sometimes averaged after co-location (e.g. Valks et al., 2011; Schneising et al.,2012) without explicit calculation of the representativeness errors and resulting uncertainty.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

- Gridded product (Level 3)
- Time series and trends
- Representativity (spatial, temporal)

Gap status after GAIA-CLIM

After GAIA-CLIM this gap will remain as it was not addressed within the project (level-3 and level-4 data were in general not addressed within the project).

Part II: Benefits to resolution and risks to non-resolution

Identified Benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
More complete uncertainty quantification on the reported data.	All users and application areas will benefit from it	High	Better uncertainty characterization. This in turn increases confidence in the data for the end user and allows more meaningful use in a variety of applications.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Underestimated uncertainty on the reported data (averages)	All users and application areas will suffer from it.	High	Incomplete data characterization and potentially limited or flawed interpretation, whatever the use type.

Part III: Gap Remedies

Remedy1 – Quantification of representativeness of averages using modelling, statistical and sub-sampling techniques

Primary gap remedy type

Research

Secondary gap remedy type

Governance

Proposed remedy description

Studies are required quantifying the representativeness of averages, e.g. by model-based simulations of averages based on either the limited real sampling or on an ideal, complete sampling. This approach was followed for instance by Coldewey-Egbers (2015) for a total ozone L3 product. More pragmatically, representativeness uncertainties can also be computed as a function of parametrized measurement inhomogeneity and climatological field variability (for instance Sofieva et al., 2014). Note that the demand for such studies is also a governance issue: service providers and overarching frameworks should insist that any L3 data set comes with such a quantification of representativeness uncertainties.

The effort required to address this gap depends on the particular product and on whether atmospheric variability is well understood for that ECV (c.f. gap G3.01). For most of the ECVs targeted by GAIA-CLIM, an estimate of the representativeness uncertainty should be achievable at a low cost. The additional validation required to assess the quality of this representativeness uncertainty estimate may –in absence of existing reference data sets at sufficiently high spatial and temporal sampling– require a more significant investment, e.g. to conduct intensive field campaigns.

Relevance

This remedy directly addresses and fills the gap.

Measurable outcome of success

Success is achieved when level-3 data sets include not only the formal uncertainty on the mean and the variance around that mean, but also an estimate of the representativeness uncertainty on that mean. The reliability of this reported representativeness uncertainty must than also be validated or verified.

Expected viability for the outcome of success

High

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- National Meteorological Services
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

References:

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G3.06 Missing comparison (validation) uncertainty budget decomposition including uncertainty due to sampling and smoothing differences

Gap Abstract

A data validation study is meant to check the consistency of a given dataset with respect to a reference dataset within their reported uncertainties. As such, the uncertainty budget of the data comparison is crucial. Besides the measurement uncertainties on both data sets, the discrepancy between the two datasets will be increased by uncertainties associated with data harmonization manipulations (e.g. unit conversions requiring auxiliary data, interpolations for altitude regridding) and with co-location mismatch, i.e. differences in sampling and smoothing of the structured and variable atmospheric field. In particular, the latter term is hard to quantify and often missing in validation studies, resulting in incomplete uncertainty budgets and improper consistency checks.

Part I: Gap description

Primary gap type

Uncertainty in relation to comparator

Secondary gap type

- Knowledge of uncertainty budget and calibration
- Governance (missing documentation, cooperation etc.)

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus services (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

- Radiosonde
- Ozonesonde
- Lidar
- FPH/CFH
- Microwave Radiometer

- FTIR
- Brewer/Dobson
- UV/VIS zenith DOAS
- UV/VIS MAXDOAS
- Pandora
- GNSS-PW

Related gaps

- G3.01 Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and of their co-location
- G3.04 Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties

G3.01. To be addressed before G3.06
Argument: To quantify the additional errors and uncertainties in a comparison due to co-location mismatch, it is advantageous to have external information on the atmospheric variability on the scale of the co-location mismatch.
G3.04. To be addressed before G3.06
Argument: To quantify the additional errors and uncertainties in a comparison due to co-location mismatch, it is important to know the smoothing and sampling properties of the individual instruments

Detailed description

Ideally, every validation study based on comparisons with ground-based reference data should investigate whether the comparison statistics (bias or mean difference, spread on the differences, drift, etc.) are compatible with the reported random and systematic measurement uncertainties, while taking into account the additional uncertainties due to spatiotemporal sampling and smoothing differences, i.e. non-perfect co-location of the airmasses sensed by both instruments. Indeed, it is only in a few particular cases possible to adopt co-location criteria that result in a sufficiently large number of co-located pairs, while at the same time keeping the impact of atmospheric variability on the comparisons (due to spatiotemporal mismatches) well below the measurement uncertainties. In all other cases, the discrepancy between two data sets will contain non-negligible terms arising from sampling and smoothing differences, which need to be taken into account. In fact, such an analysis is essential to fully assess the data quality and its fitness-for-purpose, but in practice, it is rarely performed, as this co-location mismatch is hard to quantify reliably. Some pioneering work was published by Cortesi et al. (2007) on uncertainty budget closure for MIPAS/ENVISAT ozone profile validation, by Ridolfi et al. (2007) for the case of MIPAS/ENVISAT temperature profiles validation, by Fasso et al. (2013) in the context of radiosonde intercomparisons, by Lambert et al. (2012) on water vapour comparisons, and by Verhoelst et al. (2015) for GOME-2/MetOp-A total ozone column validation. However, no such studies have hitherto been performed for most other ECVs and/or instruments. This gap therefore concerns the need for (1) further research dealing with methods to quantify co-location mismatch, and (2) governance initiatives to include in the common practices among validation teams dedicated efforts to construct full uncertainty budgets, and use these in the consistency checks.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Assimilated product (Level 4)
- Time series and trends
- Representativity (spatial, temporal)
- Calibration (relative, absolute)
- Spectroscopy
- Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Expected gap status after GAIA-CLIM

GAIA-CLIM explored and demonstrated potential solutions to close this gap
Dedicated studies within GAIA-CLIM aimed for full error (or uncertainty) budget decomposition for representative comparison exercises, involving all non-satellite measurement types targeted by GAIA-CLIM and several current satellite sounders. Moreover, some of these results were transferred into the Virtual Observatory to allow end users to also decompose the uncertainty budget of their comparisons. Nevertheless, further work is required to quantify comparison error budgets in many cases, to operationalise comparison error budget calculations in operational satellite validation and production of higher level services, and to increase awareness in the community of the need for comparison error budget closure.

Part II: Benefits to resolution and risks to non-resolution

Identified Benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Improved feedback on data quality from the validation work, including on the reported uncertainties.	All users and application areas will benefit from it	High	Optimized use of the data, avoiding over-interpretation but potentially also allowing greater detail to be extracted.
Tighter constraints from validation work support product development	All users and application areas will benefit from it	High	Shortcomings in products are more easily identified, driving further development and ultimately ensuring better, more reliable data products.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Incomplete –or even incorrect- feedback from a validation exercise on the data quality.	All users and application areas will suffer from it.	High	Poorly quantified data quality, affecting all use types. Sub-optimal feedback to data providers slows product development. The potential of the EO system is not fully realized.

Part III: Gap Remedies

Remedy 1 – Use of Observing System Simulation Experiments (OSSEs)

Primary gap remedy type

Research

Proposed remedy description

This remedy concerns Observing System Simulation Experiments (OSSEs), such as those performed with the OSSSMOSE system by Verhoelst et al. (2015) on total ozone column comparisons. These are based on a quantification of the atmospheric field and its variability (c.f. gap G3.01), e.g. in the shape of reanalysis fields, and on a detailed description of the sampling and smoothing properties of the instruments that are being compared (c.f. gap G3.04). The aim is to calculate the error due to spatiotemporal mismatch for each comparison pair, and to derive the mismatch uncertainties from these, so that they can be added to the measurement uncertainties to derive the full uncertainty budget.

The technological and organizational challenges are mostly related to the underlying gaps G3.01 and G3.04. When these are properly addressed, the calculation of the full uncertainty budget of a comparison exercise requires only a low investment in time and resources. Integrating this into an operational validation context does constitute an additional challenge requiring dedicated effort and funding.

Relevance

This remedy addresses directly the gap.

Measurable outcome of success

At a high level, success is achieved when validation (and other comparison) results are published including a full uncertainty budget decomposition, taking into account spatiotemporal mismatch uncertainties. Or when they include a convincing demonstration that mismatch uncertainties are well below the measurement uncertainties and are negligible.

At a lower level, success is achieved if the OSSE allows one to close the uncertainty budget, i.e. the measured differences (or their statistics) are compatible with the sum of all uncertainty sources. Note that this requires reliable measurement uncertainties as well.

Expected viability for the outcome of success

High

Scale of work

- Single institution

- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- National Meteorological Services
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

Remedy 2 – Statistical estimation of typical co-location mismatch effects

Primary gap remedy type

Research

Proposed remedy description

An alternative to estimating co-location mismatch (the main missing term in the uncertainty budget decomposition of a comparison) from model simulations, is to employ statistical modelling on the differences, for instance with a heteroskedastic functional regression approach, (as implemented for instance in the STAT4COLL software package). In certain applications, this approach also allows one to disentangle measurement uncertainties from co-location mismatch, at least for the random components. GAIA-CLIM will have employed such an approach for a subset of specific cases (spatial domains and ECVs / measurement techniques). Further efforts are required to generalise the approach and tools to enable broader exploitation, including integration into an operational validation context.

Relevance

Employ statistical modelling on the differences, for instance with a heteroskedastic functional regression approach. Efforts are required to generalise the GAIA-CLIM approach and tools to enable broader exploitation.

Measurable outcome of success

At a high level, success is achieved when validation (and other comparison) results are published including a full uncertainty budget decomposition, taking into account spatiotemporal mismatch uncertainties. Or when they include a convincing demonstration that mismatch uncertainties are well below the measurement uncertainties and are therefore negligible.

At a lower level, success is achieved if the statistical modelling allows one to close the uncertainty budget, i.e. the measured differences (or their statistics) are compatible with the sum of all uncertainty sources. Note that this requires reliable measurement uncertainties as well.

Expected viability for the outcome of success

High

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- National Meteorological Services
- ESA, EUMETSAT or other Space agency
- Academia, individual research institutes

References

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G4.01 Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity

Gap Abstract

Numerical Weather Prediction (NWP) models are already routinely used in the validation and characterisation of Earth Observation (EO) data. However, a lack of robust uncertainties associated with NWP model fields and related top-of-atmosphere (TOA) radiances prevent the use of these data for a complete and comprehensive validation of satellite EO data, including an assessment of absolute radiometric errors in new satellite instruments. Agencies and instrument teams, as well as key climate users, are sometimes slow (or reluctant) to react to the findings of NWP-based analyses of satellite data, due to the current lack of traceable uncertainties.

Part I Gap Description

Primary gap type

Uncertainty in relation to comparator

Secondary gap type

Knowledge of uncertainty budget and calibration

ECVs impacted

- Temperature
- Water vapor

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)

Non-satellite instrument techniques involved

Radiosonde

Related gaps

- G4.08 Estimates of uncertainties in ocean surface microwave radiative transfer
- G4.09 Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer
- G4.10 Incomplete estimates of uncertainties in land surface infrared emissivity atlases
- G4.12 Lack of reference-quality data for temperature in the upper stratosphere and mesosphere

G4.08 and G4.09 are concerned with uncertainties in microwave surface radiative transfer for respectively the ocean and land surfaces. This gap (G4.01), being concerned with modelled TOA radiances, is partially dependent on a knowledge of uncertainties in the surface microwave radiative transfer. G4.08 should be addressed with the current gap and G4.09 can be addressed independently

G4.10 is concerned with uncertainties in infrared land surface emissivity atlases. This gap (G4.01), being concerned with modelled TOA radiances, is partially dependent on a knowledge of surface emissivity uncertainties. G4.10 can be addressed independently of the current gap.

G4.12 is concerned with the lack of reference measurements for the higher atmosphere (pressures less than 40 hPa). This gap (G4.01) cannot be closed for this part of the atmosphere without first addressing G4.12.

Detailed description

Numerical Weather Prediction (NWP) models and reanalysis systems possess a number of key attributes for the comprehensive assessment of observational datasets. These models routinely ingest large volumes of observations within the framework of data assimilation and, combined with model data, produce optimal estimates of the global atmospheric state. The model fields are constrained to be physically consistent, and have continuous coverage in time and space. NWP fields exhibit sufficient accuracy in their representation of temperature and humidity fields to enable the characterisation of subtle biases in monitored satellite data. Examples include the evaluation of SSMIS (Bell et al., 2008), FY-3A sensors (Lu et al., 2011) and AMSU-A (Lupu et al., 2016).

However, robust uncertainty estimates for NWP fields are still lacking. Space agencies and instrument teams, as well as key climate users, are sometimes slow (or reluctant) to react to the findings of NWP-based analyses of satellite data due to the current lack of traceable uncertainties. Reliable estimates for the uncertainty of NWP fields, and modelled TOA radiances, would allow an assessment of absolute radiometric errors in satellite instruments. The aim is to assess uncertainties in NWP fields, through systematic monitoring, using reference-quality data,

The aim of GAIA-CLIM activities is to assess uncertainties in NWP fields through systematic monitoring, using data from the GCOS Reference Upper-air Network (GRUAN) radiosonde network. Difference statistics evaluated by Noh et al. (2016) for three institutes' models indicated good agreement with GRUAN profiles for temperature (biases not exceeding 0.1-0.2 K throughout the troposphere, with root-mean-square (RMS) differences within 1 K). Models were found to be less skilful at representing relative humidity (RH) fields, with biases cf. GRUAN sondes of up to 5% RH and RMS differences up to 15% RH. This illustrates the particular need to quantify NWP humidity uncertainties, as a means of improving the assessment of satellite EO data, which are sensitive to atmospheric water vapour.

GAIA-CLIM has developed a 'GRUAN processor' as a software tool, which enables the routine comparisons of NWP fields with reference radiosonde data. Importantly, these comparisons can be conducted both in terms of geophysical variables (temperature, humidity) and TOA radiances or brightness temperatures. It is estimated that significant progress can be made in establishing this routine monitoring within the timescale of GAIA-CLIM, although maintenance of the processor is not guaranteed beyond the lifetime of the project.

The complexity of NWP and reanalysis systems is such that a complete error budget is unattainable. However, progress can be made in accounting for spatial, seasonal, diurnal, and weather regime factors that affect uncertainties. This can be achieved through comparisons with recognised reference measurements, such as GRUAN radiosondes, complemented by 'near-reference' measurements with greater global coverage.

Operational space missions or space instruments impacted

- Meteosat Third Generation (MTG)
- MetOp
- MetOp-SG
- Polar orbiters
- Microwave nadir
- Infrared nadir
- Passive sensors

- US Joint Polar Satellite System (JPSS): ATMS, CrIS instruments
- Chinese Fengyun (FY) weather satellites: MWTS, MWHS, MWRI instruments

Validation aspects addressed

- Representativity (spatial, temporal)
- Calibration (relative, absolute)

Gap status after GAIA-CLIM

GAIA-CLIM partly closed this gap
Significant progress has been made in the development of a 'GRUAN processor' for the routine comparison of NWP fields with reference data. It is likely that components of the uncertainty budget relating to the comparisons will need further investigations beyond GAIA-CLIM.

GAIA-CLIM has further established the value of NWP in the validation of microwave temperature sounding instruments (e.g. Meteor-M N2 MTVZA-GY), microwave humidity sounders (e.g. FY-3C MWHS-2) and microwave imagers (e.g. GCOM-W AMSR-2).

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Through lower cost, effective and timely validation of new microwave missions, of which there are >10 planned over the next 2 decades.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	High	More timely integration of new, validated satellite data sets into reanalyses.
Broader C3S user base	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High	Improved confidence in, and established quantitative uncertainties for, ERA temperature and humidity analyses. Improved confidence in projected impacts.

Identified risk	User category/Application area benefitted	Probability of benefit being realised	Impacts
Sub-optimal validation of EO data	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Continued uncertainty on the value of NWP for the validation of (primarily temperature sounder and humidity sounder and imager) satellite data. Motivates more costly Cal/Val campaigns based on airborne measurements (a large and recurring cost for each new mission). Data users have less confidence in findings based on observational data of uncertain quality. Slower evolution of the community's understanding of the quality of EO data sets, particularly for new missions. Failure to recognise defects in instruments and/or processing chains may result in sub-optimal satellite data being used in downstream applications (e.g. reanalyses or climate studies).
Unknown uncertainties associated with NWP temperature and humidity fields	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	While model biases and uncertainties remain unquantified, NWP centres cannot respond by targeting model performance improvements. Users of NWP and reanalysis data want reliable uncertainty estimates rather than taking the data on trust. While uncertainties are lacking, this limits the confidence in, and societal impact of, NWP forecasts and reanalyses.

Part III Gap Remedies

Remedy 1 – Development of tools to propagate geophysical profile data and attendant uncertainties to TOA radiances and uncertainties

Primary gap remedy type

- Technical
- Technology Readiness Level (TRL) 6

Proposed remedy description

Develop a 'GRUAN processor' as a software deliverable from GAIA-CLIM. The GRUAN processor consists of a platform that enables the visualisation and exploitation of co-locations between GRUAN observed profiles and NWP fields. The processor enables visualisation both in geophysical space and as TOA radiance equivalents for a range of temperature and humidity sensitive satellite sensors. GAIA-CLIM has produced the processor in a demonstration capability. Further efforts would be required to operationalise its availability and generalise the processor to include other reference-quality measurements from further non-satellite measurement techniques.

Relevance

The software is open-source and enables users (by which we mean reasonably knowledgeable users) to compare NWP fields from both ECMWF and Met Office (in the first instance) with GRUAN data. This includes a comparison of temperature and humidity, as well as TOA brightness temperatures for all sensors supported by the (publicly available) RTTOV radiative transfer model.

Measurable outcome of success

- Statistics available on the comparison, for all GRUAN sites, with respect to ECMWF and Met Office NWP fields.
- A web page displaying these statistics.
- An open-source GRUAN processor available to the wider community.
- Integration of the GRUAN processor into the GAIA-CLIM Virtual Observatory.

Expected viability for the outcome of success

High

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Minor costs associated with hosting, upkeep and periodic reviews for updates

Potential actors

- EU H2020 funding
- National Meteorological Services

Remedy 2 – Evaluate quality of NWP and reanalysis fields through comparisons with reference data as a means of establishing direct traceability.

Primary gap remedy type

- Technical ; TRL 6

Proposed remedy description

The GRUAN processor developed for GAIA-CLIM offers the means of traceable evaluation of the quality of NWP fields at the GRUAN-site locations. Due to the scarcity of reference measurements for comprehensive evaluation of NWP data, it will be necessary to determine additional 'near-reference' measurements for which defensible uncertainty estimates can be provided. It is proposed to extend the assessment of NWP fields using other data of demonstrated quality, such as selected GUAN radiosondes and GNSS radio occultations, in order to sample a larger subspace of NWP regimes. Additionally, NWP and reanalysis systems now make use of ensembles (multiple forecasts to represent error growth from uncertain initial conditions and stochastic physics perturbations). Uncertainties as estimated from ensembles should be evaluated using available NWP minus reference-data differences. It is also desirable to extend the assessment to include atmospheric composition, for which reference composition measurements and their uncertainties are required.

Relevance

NWP and reanalysis fields and products are very widely used for the validation and characterisation of EO data, although associated robust uncertainties are lacking. Traceable uncertainties will engender more confidence from users.

Measurable outcome of success

Published uncertainties should be available for widely used NWP and reanalysis model fields such that the uncertainties and associated correlation structures are traceable to underlying reference data.

Expected viability for the outcome of success

High

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- EU H2020 funding
- National Meteorological Services

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G4.08 Estimates of uncertainties in ocean surface microwave radiative transfer

Gap Abstract

Several passive microwave missions (operating in the 1-200 GHz range) make measurements in spectral regions where the atmosphere is sufficiently transmissive so that the surface contributes significantly to measured radiances. The calibration/validation of microwave satellite data to reference standards is hampered, for some instruments and channels, by a lack of traceable estimates of the uncertainties in the modelled ocean surface contribution. This is particularly important for microwave imagers, sensitive to total column water vapour, which are routinely assessed within numerical weather prediction (NWP) frameworks. It also affects the lowest peaking channels of microwave-temperature sounders such as channel 5 of AMSU-A. The accuracy of retrievals of atmospheric temperature and humidity over the ocean is also dependent on the accuracy of ocean surface microwave radiative transfer. The dominant source of uncertainty for ocean surface microwave radiative transfer is expected to be ocean emissivity estimates.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

Secondary gap type

Parameter (missing auxiliary data etc.)

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Radiosonde (through use of the GRUAN processor)

Related gaps

- G4.01 Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity
- G4.09 Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer
- G4.10 Incomplete estimates of uncertainties in land surface infrared emissivity atlases

Gap 4.01 is concerned with the use of NWP fields for the validation of observations relating to temperature and humidity. This gap (G4.08) identifies one component of the challenge described in G4.01, and affects temperature sounding measurements in the boundary layer and lower troposphere. It also covers humidity sounding (and imaging) in the boundary layer and lower troposphere
G4.08 is related to, but can be addressed independently of, G4.09 and G4.10

Detailed description

Passive microwave observations from satellite radiometers are widely used to make remote-sensing measurements of the Earth's atmosphere and surface characteristics. Current missions operate in the spectral range of 1 – 200 GHz but this will be extended in the future to 229 GHz for the EPS-SG MWS instrument and to frequencies over 600 GHz for the ICI mission. Total column water vapour, cloud liquid water path, ocean surface wind speed and direction, sea-surface temperature and salinity, and profiles of humidity and temperature, are all derived from microwave observations. The top-of-atmosphere (TOA) spectral signals in this spectral range can, depending on the state of the atmosphere, comprise a significant component due to emission and reflection from the ocean surface. This is particularly true of microwave imagers (where data quality assessment and operational use at NWP centres rely on radiative transfer modelling including surface terms) and the surface-sensitive channels of microwave temperature and humidity sounders (e.g. AMSU-A channel 5 and window channels). It is therefore critical that uncertainties in the ocean surface microwave radiative transfer are accurately calculated. This requirement spans applications ranging from the assimilation of Level-1 products (for example) in reanalysis efforts, to the generation of Level-2 (and higher) products at all levels of maturity, ranging from near-real-time operational products to climate data records.

Several emissivity models have been developed over the last two decades to support the assimilation of microwave-imager data at operational NWP centres and to support applications based on retrievals of the ECVs listed above from satellite-based microwave imager observations. These models account for several processes influencing the emissivity of the ocean surface, including: polarised reflection of the ocean's (dielectric) surface derived from the Fresnel equations, large scale roughness due to wind-driven waves, small scale roughness due to capillary waves, and the radiative effect of foam at progressively higher wind speeds. An ocean surface emissivity model, which is widely used in the remote sensing and operational NWP community, is the Fast Ocean Emissivity Model (FASTEM), which forms part of the RTTOV fast radiative transfer model. Following the initial formulation by English and Hewison (1998), FASTEM has been developed over the last 20 years, with many recent developments guided and informed by an analysis of biases observed between satellite observations and simulations based on NWP models (Bormann et al (2011); Bormann et al (2012); Meunier at al (2014); and Kazumori et al (2015)). The current version of FASTEM (version 6) includes the dielectric constant model and wind speed terms developed by Liu et al (2011), the foam parameterisations of Stogryn (1972) and O'Monahan and Muircheartaigh (1986), and the wind-direction dependence terms developed by Kazumori et al (2015).

A number of studies have been carried out to estimate the uncertainties of ocean emissivity models (e.g. Guillou et al 1996; Guillou et al; 1998, Greenwald et al; 1999). However, most studies which estimated uncertainties were carried out before the latest versions of FASTEM, which include considerable updates made by Liu et al (2011) and Kazumori et al (2015), and also tended to focus on one aspect of the model or one frequency. Therefore, despite a number of studies being carried out to validate the FASTEM model, it still lacks traceable estimates of the uncertainties associated with the computed emissivities in the 1-200 GHz range. This gap has been identified as an important deficiency in using NWP-based simulations for the validation of new satellite missions.

FASTEM is an approximate (fast) parameterisation of an underlying reference model (English et al., 2017). Such a reference model has three main components: (i) the dielectric model predicting the polarised reflection and refraction for a flat water surface (Lawrence et al. 2017); (ii) the roughness model which represents the ocean roughness due to large scale swell and wind-induced waves; and (iii) the foam model which commonly parameterises the ocean foam coverage as a function of wind speed and assigns a representative emissivity to the foam fraction. For a true reference model, each of these components should be associated with traceable uncertainties.

Operational space missions or space instruments impacted

- Copernicus Sentinel 3
- MetOp
- MetOp-SG
- Copernicus Sentinel 3: Microwave Radiometer (MWR) instruments. MetOp (2006-2025): Advanced Microwave Sounding Unit (AMSU); Microwave Humidity Sounder (MHS). MetOp-SG: Microwave Imager (MWI); Microwave Sounder (MWS); Ice Cloud Imager (ICI)

Other:

- S-NPP / JPSS (2012-2030): Advanced Technology Microwave Sounder (ATMS)
- Feng-Yun 3 (2008-2030): Microwave Radiation Imager (MWRI); Microwave Temperature Sounder (-1 and -2); Microwave Humidity Sounder (-1 and -2).
- Global Change Observation Mission (GCOM-W1, 2012-2020): Advanced Microwave Scanning Radiometer-2 (AMSR-2)
- Special Sensor Microwave Imager / Sounder (SSMI/S, F-16 - F-19: 2003-2020)
- Meteor-M (2009-2030): MTVZA
- GPM (2014-): Microwave Imager (GMI)
- Megha-Tropiques (2011-): Microwave humidity sounder (SAPHIR)
- Coriolis (2003-): microwave radiometer Windsat
- Jason (2001-2021): microwave radiometers JMR and AMR

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Gap status after GAIA-CLIM

After GAIA-CLIM this gap remains unaddressed

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Lower cost, effective and timely validation of new microwave missions, of which there are >10 planned over the next 2 decades.	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	High	More timely integration of new, validated, satellite datasets into reanalyses.
Broader C3S user base	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High	Improved ERA humidity analyses, improved consistency in-time and geographically and in different phases of the satellite era, through improved homogenisation of datasets. Improved regionally resolved analyses and improved confidence in projected impacts

Identified risk	User Category/Application area benefitted	Probability of benefit being realised	Impacts
Sub-optimal validation of new EO data	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Continued uncertainty on the value of NWP for the validation of imager data drives a requirement for more costly Cal/Val campaigns for each new system based on airborne measurements or equivalent. This will be a large and recurring cost for each new mission Less confidence in findings based on observational data of unknown quality. Sub-optimal (slower) evolution of the community's understanding of the quality of key measured datasets
High uncertainties associated with surface emissivity modelling	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	The error component associated with surface emission modeling remains large and dominates the error budget for these observations, thereby limiting the weight given to these observations in climate reanalyses. Consequently limiting the accuracy of NWP and reanalysis based analyses of lower tropospheric humidity over ocean. This will have knock-on effects on attempts to predict regionally resolved impacts of climate change.

Part III Gap Remedies

Remedy 1 – Intercomparison of existing surface emissivity models

Primary gap remedy type

- Technical ; TRL 4

Proposed remedy description

Undertake an in-depth intercomparison of available microwave ocean surface emissivity model outputs, for a carefully defined set of inputs (ocean state, atmospheric state). An intercomparison of emissivity models, in itself, will not achieve a validation of emissivity models, but the differences identified and quantified can shed light on the sources of bias in any given emissivity model. Such an intercomparison exercise is, therefore, a useful step towards a full validation of emissivity models. In many cases, however, such an intercomparison yields valuable insights into the mechanisms, processes, and parameterisations that give rise to biases. This approach thus constitutes a useful first step in the validation of (in this case) ocean surface emissivity estimates. The measurable output of success therefore, for this activity, will be a documented quantitative comparison of FASTEM (various versions) with another, independent, emissivity model, for a realistic sample of global ocean surface conditions. The probability of a successful outcome is high if the exercise can be coordinated through the appropriate international working groups (e.g. International TOVS Working Group, International Precipitation Working Group, GSICS, X-Cal), and is supported by national and/or international agencies.

Relevance

An intercomparison exercise is a useful step towards a full validation of emissivity models. In many cases, such an intercomparison yields valuable insights into the mechanisms, processes and parameterisations that give rise to biases.

Measurable outcome of success

Documented quantitative model inter-comparison: intercomparisons of non-traceable estimates, in this case outputs from independent ocean surface emissivity models, in themselves will not constitute a validation of any individual estimate. For example, independent estimates can be biased in the same sense. This motivates the need for the additional remedies associated with this gap.

Expected viability for the outcome of success

High

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- National funding agencies
- National Meteorological Services
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

Remedy 2 – The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz

Primary gap remedy type

Deployment

Proposed remedy description

Typically, validation of ocean emissivity models has been carried out using airborne campaigns. However, to date these campaigns have not used traceably calibrated radiometers, since there have been no primary reference standards available. However, primary reference standards are beginning to be developed and there are now some capabilities in China, Russia, and the USA. We propose using these traceably calibrated radiometers for field campaigns as well as airborne campaigns. It would be useful to exploid this type of radiometers in laboratory experiments using wave tanks and field campaigns with radiometers mounted on oil rigs. A combination of different techniques should lead to more robust estimates of the uncertainties in the emissivity models. Note that the determination of emissivity will be reliant on sufficiently accurate co-located estimates (from models) or in-situ measurements, of ocean surface skin temperature, salinity, and ocean surface wind speed.

Relevance

A combination of different techniques should lead to more robust estimates of the uncertainties in the emissivity models.

Measurable outcome of success

Documented, quantitative, evaluation of ocean surface emissivity models with respect to measurements of ocean surface emissivity obtained during experimental campaigns with traceably calibrated radiometers, for a globally representative range of ocean surface wind speeds, temperatures, and salinity.

Expected viability for the outcome of success

Medium

Scale of work

Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- National funding agencies
- National Meteorological Services
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

Remedy 3 – Establish an ocean emissivity reference model in the spectral region 1 – 200 GHz

Primary gap remedy type

- Technical; TRL 4

Proposed remedy description

Undertake the necessary research and modelling to establish a reference emissivity model where the constituent parts have associated robust traceable uncertainties. This should include a re-calibration of the dielectric constant model to new reference laboratory measurements of the dielectric constant of seawater (see Remedy 4). A roughness model which, incorporates information from a wave model (large scale ocean swell) and surface wind speed (influencing small scale ripples and waves) is also needed to predict scattering characteristics. Similarly, the contribution of foam can be derived in principle from a wave model and full radiative transfer (rather than assuming a nominal emissivity value for the foam fraction). These activities will require coordination. Traceable uncertainty estimation must be assured at each step, the documented code should be freely available, and the final reference model should be maintained and supported.

Relevance

Current fast emissivity models lack traceable uncertainty estimates which is a key source of uncertainty in the radiative transfer modelling of surface-sensitive microwave satellite observations over ocean in the 1-200 GHz range.

Measurable outcome of success

Documented and freely available software for the prediction of microwave ocean emissivity. The reference model constituent parts should have rigorous uncertainty estimates attached. The underlying basis of the model should be peer reviewed. The expertise for undertaking the necessary laboratory and modelling activities exists, but in disparate institutions that will require coordination. Establishing a fully characterised reference model would close this gap.

Expected viability for the outcome of success

Medium

Scale of work

Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Non-applicability

Potential actors

- National funding agencies
- National Meteorological Services
- Academia, individual research institutes

Remedy 4 – Reference-quality dielectric constant measurements of pure and saline water for the frequency range 1 – 200 GHz

Primary gap remedy type

Research

Proposed remedy description

Ocean emissivity models rely on accurate measurements of the dielectric constant of water and seawater for a range of temperatures and frequencies. However, there are inconsistencies between measurements available in the literature (Lawrence et al 2017) and none have SI-traceable uncertainties. Measurements should be taken that are reference quality, i.e. SI-traceable and with validated uncertainty estimates. The uncertainties should include a calculation of the correlation between measurements of the real and imaginary components of the dielectric constant, so that the uncertainties can be properly transformed into radiance space. As well as ocean emissivity, this would also support dielectric constant models for cloud radiative transfer (e.g. the dielectric constant of super-cooled liquid water).

Relevance

This will support a reference ocean emissivity model, allowing for cal/val of microwave imagers and surface sensitive channels of microwave sounders to reference standards.

Measurable outcome of success

Documented and freely available measurements of the dielectric constant of seawater and pure water for a range of frequencies (1 – 200 GHz) and temperatures (-5 to +35 °C) with traceable uncertainty estimates.

Expected viability for the outcome of success

Medium

Scale of work

PhD or post-doctoral student

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- National funding agencies
- Academia, individual research institutes

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G4.09 Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer

Gap Abstract

There is a lack of traceable uncertainties associated with the contribution of land surface microwave radiative transfer to Top of the Atmosphere (TOA) brightness temperatures for microwave imaging and sounding instruments. The land surface emission exhibits significant spatial and temporal variability, particularly in snow- and ice-covered regions. There are a number of sources of uncertainty in the approaches currently used to estimate the land-surface contribution, including the emissivity and skin temperature prior, ineffective cloud and precipitation screening and errors introduced by the simplification of the radiative-transfer equation for practical computations. The accuracy of simulated radiances using Numerical Weather Prediction (NWP) models is limited, for some applications, by the uncertainty in modelled surface emission. Solving this gap will require a combination of different approaches, including the use of experimental campaigns which are useful to validate the overall contribution of the land surface.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

Secondary gap type

Parameter (missing auxiliary data etc.)

ECVs impacted

- Temperature
- Water vapour

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Independent of instrument technique

Related gaps

- G4.01 Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity
- G4.08 Estimates of uncertainties in ocean surface microwave radiative transfer
- G4.10 Incomplete estimates of uncertainties in land surface infrared emissivity atlases

G4.01 should be addressed with G4.09
Argument: Gap 4.01 is concerned with the use of NWP fields for the validation of observations relating to temperature and humidity. This gap (G4.09) identifies one component of the challenge described in G4.01, and affects temperature sounding measurements as well as humidity sounding (and imaging) measurement in the boundary layer and lower troposphere over land.

G4.08 and G4.10 can be addressed independently.

Detailed description

Passive microwave observations from satellite radiometers operating in the spectral range from 1-200 GHz are widely used to make remote-sensing measurements of the Earth's atmosphere and surface characteristics. Observations in this frequency range are sensitive to atmospheric humidity and temperature, as well as to emission and reflection from the surface. Microwave instruments, which are primarily used to estimate atmospheric temperature and humidity profiles (e.g. AMSU-A, MHS, AMSR-2), can also have a significant contribution from the surface, depending on atmospheric conditions. Currently the calibration/validation (cal/val) of these instruments tends to be carried out only over ocean due to more trustworthy estimates of the surface contribution, but in the future, this should be extended to the land so that cal/val can be performed over the full dynamic range of the instruments. To do this, it is necessary to validate the estimated land-surface contribution to the TOA radiances, and to calculate the associated uncertainties in radiance space.

The calculation of the land-surface contribution to the TOA radiances relies on simplified radiative-transfer equations, and estimates of the surface 'skin' temperature and emissivity. It is assumed that the land surface represents a homogeneous body with an emission equal to the skin temperature multiplied by an emissivity. An additional contribution to the TOA brightness temperature is calculated as the atmospheric emission reflected off the surface, which can be assumed to be either a specular or Lambertian reflection (Lambertian for snow-covered surfaces, specular for many other surfaces). In reality, the surface emission is more complex, due to multi-layers with heterogeneous dielectric properties (varying both vertically and horizontally), particularly for snow cover, and the reflection is likely to be not entirely specular or Lambertian. Furthermore, microwave emissions come from layers deeper than the surface (depending on frequency and dielectric properties) and so the use of a skin temperature estimate may not be appropriate for some conditions, particularly over deserts where the penetration depth is higher (see e.g. Norouzi et al; 2012).

As with the ocean surface, physically-based models have been developed to allow the estimation of land surface emissivity (e.g. Wang and Choudhury, 1981; Njoku and Li, 1999; Weng et al., 2001) for different surface types and different frequencies. Methods to estimate the surface type from satellite observations have also been developed (e.g. Grody, 1988). However, in order to accurately calculate the emissivity using physically-based models, a large number of input parameters are required that are difficult to estimate accurately over the spatial scales needed for satellite measurements. Progress in this area is still ongoing, but as a result, it has become necessary to rely on retrievals from satellite observations, following the methods developed by Karbou et al (2006; 2010). At the Met Office, for example, the microwave skin temperature and emissivity values are retrieved simultaneously in a 1D-Var system from the window channels of temperature and humidity sounders. At ECMWF and Meteo-France, the emissivity is also calculated from window channel observations, but with the skin temperature taken from the NWP model values.

Uncertainties in the land-surface contribution to the TOA radiances are a combination of uncertainties in: the emissivity values used, skin-temperature estimates, and the simplified radiative-transfer equations. The individual uncertainties of each of these contributions should be accurately estimated. As well as validating the individual components, the overall contribution can also be validated using experimental campaigns with ground-truth data, as well as comparisons to the TOA brightness temperatures from satellite instruments. It is likely that a combination of approaches will be needed to close the gap on uncertainty.

Estimates of uncertainties in retrieved land-surface emissivity have been calculated by Prigent et al (1997, 2000) and Karbou et al. (2005a), from the standard deviations of values retrieved from the satellite observations of different instruments. The authors provided gridded maps of uncertainties, which were shown to be around 2% on average. However, these uncertainties are indicative rather than robust, and are likely to be underestimates since they do not account for uncertainties due to: the calibration of the satellite instruments used in the retrievals, the temperature-humidity profiles used to calculate the channel transmittances, cloud screening, and surface temperature data. Ruston et al (2004) also carried out emissivity retrievals from SSM/I satellite observations over the USA and estimated the uncertainties in retrieved emissivity by randomly perturbing the input parameters. The authors concluded that errors were around 2% for frequencies less than 85 GHz. Their methods did not include possible errors in the atmospheric component due to the water-vapour continuum, however.

A number of experimental campaigns have been carried out to evaluate land surface emissivities over different surface types. For example, Harlow (2011) demonstrated how airborne microwave measurements can be used to validate the emissivity of snow-covered ice, relating to snow depth and snow pack characteristics, and quasi-Lambertian reflectance behaviour. Comparisons of different emissivity models have also been carried out. Ferraro et al. (2013) attempted an inter-comparison of several EO land emissivity data sets over the USA. The authors found differences of around 10 K in radiance space (emissivity x skin temperature) for frequencies up to 37 GHz and greater differences up to around 20 K for higher frequencies. These differences appeared to be generally systematic rather than random, with similar seasonal trends captured by the different datasets. Tian et al (2014) estimated uncertainties in retrieved emissivity values by comparing retrievals from different satellite sensors. They estimated similar uncertainties to Ferraro et al (2013), with systematic differences around 3 – 12 K over desert and 3 – 20 K over rainforest (with largest differences at the higher frequencies above 80 GHz). Random errors were estimated to be around 2 – 6 K.

As well as estimating uncertainties in the emissivity values retrieved, it is important to also consider uncertainties due to assumptions made in the simplified radiative transfer equations. For example, Karbou and Prigent (2005b) estimated the uncertainties in emissivity due to the specular assumption by performing emissivity retrievals from brightness temperatures simulated, using both the specular and Lambertian assumptions. They concluded that the errors in retrieved emissivities due to the specular assumption were less than 1% for most surfaces.

While to date there have been considerable efforts to validate the calculation of the surface contribution to TOA microwave radiances at frequencies between 1 – 200 GHz, none of the uncertainty estimates have been traceable or complete. This is in part due to the complexity of the problem and it is likely to take a combination of a number of approaches before the gap can be fully closed. However, in part 3 below we suggest two areas of development which could contribute to the estimation of uncertainties in the land surface radiative transfer to reference standards.

Operational space missions or space instruments impacted

- MetOp
- MetOp-SG
- Polar orbiters
- Microwave nadir
- Passive sensors
- Other, please specify:
    - MetOp (2006-2025): Advanced Microwave Sounding Unit (AMSU); Microwave Humidity Sounder (MHS)
    - MetOp-SG: Microwave Imager (MWI); Microwave Sounder (MWS); Ice Cloud Imager (ICI)
    - S-NPP / JPSS (2012-2030): Advanced Technology Microwave Sounder (ATMS)
    - Feng-Yun 3 (2008-2030): Microwave Radiation Imager (MWRI); Microwave Temperature Sounder (-1 and -2); Microwave Humidity Sounder (-1 and -2)
    - Global Change Observation Mission (GCOM-W1, 2012-2020): Advanced Microwave Scanning Radiometer-2 (AMSR-2)
    - Special Sensor Microwave Imager / Sounder (SSMI/S, F-16 - F-19: 2003-2020)
    - Meteor-M (2009-2030): MTVZA

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Gap status after GAIA-CLIM

After GAIA-CLIM this gap remains unaddressed

Part II Benefits to resolution and risks to non-resolution

Identified benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Resolution of this gap will enable greater use of surface-sensitive satellite observations over land in NWP data assimilation systems (either by permitting the use of extra channels, or giving greater weight to existing observations).	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	Potential improvements in ERA near-surface analyses; improved confidence in projected impacts. Greater confidence in ECV parameters derived from passive microwave sensors, such as soil moisture.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Sub-optimal validation of new EO data	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Less confidence in findings based on observational data of unknown quality over land. Sub-optimal (slower) evolution of the community's understanding of the quality of key measured datasets
High uncertainties associated with surface emissivity modelling	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	Medium	The error component associated with surface emission modeling remains large and dominates the error budget for these observations, thereby limiting the weight given to these observations in climate reanalyses - consequently limiting the accuracy of NWP and reanalysis based analyses of lower tropospheric humidity over land. This will have knock-on effects on attempts to predict regionally resolved impacts of climate change.

Part III Gap Remedies

Remedy 1 – The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based).

Primary gap remedy type

Deployment

Secondary gap remedy type

Research

Proposed remedy description

This remedy concerns the use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based). Such campaigns can be used to validate both the (combined) emissivity and skin temperature estimates calculated from window-channels observations for temperature and humidity sounders, and emissivity models. Such campaigns would need to be undertaken across a sufficiently diverse set of land-surface types and meteorological seasons to provide representative results that enabled broad applicability. There is also a need for robust ground-truth activities in such campaigns to minimise the uncertainty.

Relevance

It is proposed to use traceably calibrated radiometers in land surface measurements campaigns (both airborne and ground-based. Such campaigns can be used to validate both the (combined) emissivity and skin temperature estimates calculated from window-channels observations for temperature and humidity sounders, and emissivity models.

Measurable outcome of success

Documented, quantitative evaluation of land surface radiative transfer contributions with respect to measurements obtained during airborne campaigns for a globally representative range of land surfaces.

Expected viability for the outcome of success

Medium

Scale of work

Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- National funding agencies
- National Meteorological Services
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

Remedy 2 – Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables

Primary gap remedy type

Research

Proposed remedy description

While retrievals of emissivity and surface-skin temperature are currently used for microwave atmospheric sounding and imaging instruments over land, as a long-term goal, it would be beneficial to move towards the use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables. Uncertainties should also be estimated. We therefore suggest, as long-term goals:

- The development of emissivity models over a wide range of frequencies (1-200 GHz) that rely on remotely-sensed parameters and/or atlases of land-surface characteristics; and are validated with ground-based or airborne radiometer measurements for different surface types.
- Inter-comparisons of available emissivity models, in particular physically based (e.g. multilayer) and simplified models.

Relevance

There is a need to establish traceable uncertainties for NWP fields and radiances calculated from them.

Measurable outcome of success

Documented, quantitative, evaluation of land surface emissivity values estimated from models with respect to measurements of land-surface emissivity obtained during experimental campaigns, for a globally representative range of surfaces.

Expected viability for the outcome of success

Medium

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- National funding agencies
- National Meteorological Services
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

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G4.10 Incomplete estimates of uncertainties in land surface infrared emissivity atlases

Gap Abstract

Land surface emissivity atlases in the infrared region (3-17 µm) are required for the validation of infrared satellite sounding measurements over land. Work is underway, outside of the GAIA-CLIM project, to develop dynamic atlases of spectral emissivity in this part of the spectrum, based on measurements from polar-orbiting hyper-spectral infrared observations and using a rapidly updating Kalman Filter. However, these new dynamic atlases need to be validated to ensure the estimates have robust uncertainties associated with them.

Part I Gap Description

Primary gap type

Knowledge of uncertainty budget and calibration

Secondary gap type

Parameter (missing auxiliary data etc.)

ECVs impacted

- Temperature
- Water vapour

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Independent of instrument technique

Related gaps

- G4.01 Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity
- G4.08 Estimates of uncertainties in ocean surface microwave radiative transfer
- G4.09 Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer

G4.10 should be addressed with G4.01

Argument: Gap 4.01 is concerned with the use of NWP fields for the validation of observations relating to temperature and humidity, This gap (G4.10) identifies one component of the challenge described in G4.01, and affects temperature and humidity sounding measurements in the boundary layer and lower troposphere over land.
G4.08 and G4.09 can be addressed independently of G4.10

Detailed description

Passive-infrared observations from satellite radiometers operating in the spectral range from 17-3.3 µm are widely used to make remote-sensing measurements of the Earth's atmosphere and surface characteristics. Vertical profiles of humidity and temperature and surface properties such as skin temperature are derived from measurements in this spectral region. The top-of-atmosphere (TOA) spectral signals in this range can, depending on the state of the atmosphere, comprise a significant component due to emission and reflection from the land or ocean surface. It is therefore critical that validated models of (ocean and land) surface emissivity are available for the analysis of these infrared observations. This requirement, for validated models of emissivity, spans applications ranging from the assimilation of Level-1 products (for example) in reanalysis efforts, to the generation of Level-2 (and higher) products at all levels of maturity ranging from near-real-time operational products to climate data records.

There are particular challenges to representing the emissivity of land surfaces. In contrast to the ocean, where the physical mechanisms governing the surface emission can be parameterised, the infrared land surface emission is highly dependent on properties such as land-surface coverage (vegetation, bare soil, snow and so on), roughness and moisture content. These properties may change slowly (seasonally) or rapidly (daily). As a result, it has become necessary to rely on infrared land surface emissivity atlases, which characterize in a gridded fashion the global variations in emissivity at different frequencies.

There are several notable examples of publicly available atlases. The ASTER Global Emissivity Dataset has been compiled using cloud free scenes from the Advanced Spaceborne Thermal Emission and Reflection Radiometer on the Terra satellite. Monthly emissivity maps at 5 km spatial resolution are available for the years 2000-2015 (Hulley et al., 2015). Validation with laboratory spectra from four desert sites resulted in an absolute error of approximately 1%.

Capelle et al. (2012) applied a multispectral method for the retrieval of emissivity and surface temperature from IASI clear sky fields of view. They obtained a high spectral resolution product over the tropics for the period 2007-2011. The product was validated against emissivity spectra retrieved with an airborne interferometer (Thelen et al., 2009) to within an absolute accuracy of 2%.

Borbas et al. (2007) developed the UWIREMIS global land surface emissivity atlas for the 3.7 to 14.3 µm range. The atlas was derived by regressing the MODIS operational land surface emissivity product against laboratory emissivity spectra. At the Met Office, the UWIREMIS atlas is used as a first guess in the 1-D variational retrieval of surface emissivity for IASI observations over land.

The use of infrared emissivity atlases in NWP models is evolving. At the Met Office, work is underway to incorporate emissivity estimates derived from sounders such as IASI into a dynamically updated atlas (Gray, 2016). By using a Kalman filter approach, it is intended that the atlas can be updated in near-real-time as new observations become available. Thus, it would be able to capture short term emissivity variations in a way that static atlases cannot. This methodology is promising; however, such atlases need to be validated to make sure the retrieved values have robust uncertainties associated with them.

Operational space missions or space instruments impacted

- MetOp
- MetOp-SG
- Polar orbiters
- Geostationary satellites
- Infrared nadir
- Passive sensors
- AIRS on Aqua; CrIS on NOAA JPSS satellites; HIRAS, GIIRS on Chinese Feng-Yun series; IRS on future Meteosat Third Generation satellites

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)

- Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Expected gap status after GAIA-CLIM

After GAIA-CLIM this gap remains unaddressed

Part II Benefits to resolution and risks to non-resolution

Identified Benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Resolution of this gap will enable greater use of surface-sensitive satellite observations over land in NWP data assimilation systems (either by permitting the use of extra channels, or giving greater weight to existing observations).	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	Medium	Potential improvements in ERA near-surface analyses; improved confidence in projected impacts.
Broader usability of ECV parameters	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	Greater confidence in ECV parameters derived from passive infrared sensors, such as land surface radiation budget.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Sub-optimal validation of new EO data	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Less confidence in findings based on observational data of unknown quality over land. Sub-optimal (slower) evolution of the community's understanding of the quality of key measured datasets
High uncertainties associated with surface emissivity modelling	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	Medium	The error component associated with surface emission modeling remains large and dominates the error budget for these observations, thereby limiting the weight given to these observations in climate reanalyses - consequently limiting the accuracy of NWP and reanalysis based analyses of lower tropospheric humidity and temperature over land This will have knock-on effects on attempts to predict regionally resolved impacts of climate change.

Part III Gap Remedies

Remedy 1 – Provision of validated land surface infrared emissivity atlases

Primary gap remedy type

- Technical ; TRL4

Secondary gap remedy type

- Deployment
- Research

Specify remedy proposal

There is a need to establish a comprehensive set of dynamic land surface infrared emissivity atlases. It is first required to perform an intercomparison of available emissivity models to ascertain their potential strengths and weaknesses and highlight where the greatest uncertainties exist. It is then necessary to coordinate airborne campaigns to validate land-emissivity models in the infrared-spectral region with a special focus on those domains where current models are most uncertain. The resulting improved infrared emissivity atlases should be made openly available in usable formats and broadly advertised. Peer-reviewed publications are likely to be required to build confidence in and raise awareness of these products.

Relevance

There is a need to establish a comprehensive set of dynamic land surface infrared emissivity atlases. The resulting improved infrared emissivity atlases should be made openly available in usable formats and broadly advertised.

Measurable outcome of success

Publicly available, open-source, dynamic (daily) spectral emissivity atlases in the infrared (3-17 μm). Documented, quantitative evaluation of infrared land surface emissivity atlases and models with respect to measurements of land-surface emissivity obtained during airborne campaigns, for a globally representative range of surfaces.

Expected viability for the outcome of success

Medium

Scale of work

Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

No

Potential actors

- National funding agencies
- National Meteorological Services
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes

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G4.12 Lack of reference-quality data for temperature in the upper stratosphere and mesosphere

Feedback

Gap Abstract

The GCOS Reference Upper Air Network (GRUAN) provides reference in-situ data for temperature and humidity with traceable estimates of uncertainty. This network can be used to validate NWP short-range forecasts for temperature and humidity to reference standards (see gap G4.01). The NWP temperature and humidity forecasts can then be used to perform satellite Cal/Val of new instruments, with improved knowledge of the associated uncertainties. However, there are very few GRUAN data above 40 hPa and none above 5hPa. We therefore identify a gap in reference-quality observations in the upper stratosphere and mesosphere, which particularly affects the calibration/validation of microwave and infrared temperature sounding channels at these heights, particularly AMSU-A channels 12 – 14, ATMS channels 13 – 15, CrIS channels at 667.500 cm^{-1}, 668.125 cm^{-1}, and 668.750 cm^{-1}, IASI channels at 648.500 - 669.750 cm^{-1} and AIRS channel numbers 54 - 83.

Part I Gap Description

Primary gap type

Vertical domain and/or vertical resolution

Secondary gap type

Knowledge of uncertainty budget and calibration

ECVs impacted

Temperature

User category/application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)

Non-satellite instrument techniques involved

Radiosonde

Related gaps

- G4.01 Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity
- G6.03 Lack of sustained dedicated periodic observations to coincide with satellite overpasses to minimise co-location effects

G4.01 should be addressed after G4.12.
Gap 4.01 concerns about the lack of validation of NWP fields to reference standards. Validating NWP fields at 20 – 0.01hPa cannot be done without reference-quality data at these heights.
G6.03 should be addressed with G4.12
The colocation of GNSS-RO with a GRUAN sonde is in principle forecastable at least two weeks into the future. Potential ‘golden overpass’ times, when the GRUAN site is coincident with a polar orbiter measure and a radio occultation measure, are therefore predictable.

Detailed description

The direct assimilation of microwave and infrared temperature sounders into Numerical Weather Prediction (NWP) and reanalysis systems improves estimates of the atmospheric state, directly improving both the NWP weather forecasts, as well as the long-term monitoring of atmospheric temperature by reanalysis systems, such as Copernicus C3S reanalysis (ERA-5 and later). When data from new temperature sounders (e.g. ATMS, AMSU-A, IASI, AIRS, CrIS) become available, it is important to assess the quality of the observations before they can be assimilated. Short-range temperature forecasts from NWP systems provide a good reference for validating new temperature-sounding satellite instruments due to the high accuracy of these forecasts, particularly in the troposphere. For example, estimates of the uncertainties of tropospheric temperature forecasts for the ECMWF system indicate that they are around 0.1K in radiance space (Bormann et al, 2010). Using NWP forecasts as a reference also facilitates the inter-comparison of satellite data, since differences in time and space of the measurements can be accounted for with the use of a forecast model. This allows to estimate inter-satellite biases (e.g. Bormann et al 2013; Lu et al 2015).

While NWP temperature fields are very useful as a reference for satellite Cal/Val, this method does not currently lead to fully traceable estimates of uncertainty (see gap G4.01), since the uncertainties in the NWP background, the uncertainties in the radiative-transfer model, and the spatial-mismatch uncertainties are not known to fully traceable standards. This first point can be addressed by using reference in-situ data such as from GRUAN for assessing the uncertainties in the ECMWF and Met Office NWP short-range forecasts of temperature and humidity. To do this, a tool known as the 'GRUAN processor' has been developed based on the EUMETSAT NWP Satellite Application Facility (NWP SAF) Radiance Simulator (see https //www.nwpsaf.eu/GProc_test/ins.shtml). This tool can be used to calculate the differences between GRUAN-temperature measurements and NWP forecasts in both geophysical space (temperature and humidity as a function of height) and radiance space (radiances as a function of channel for different satellite instruments) and compare these differences to the GRUAN uncertainties.

GRUAN reference temperature measurements are available from the surface to an atmospheric height of up to 5 hPa. However, less radiosonde data are available in the stratosphere than the troposphere and none above 5 hPa. In the upper reaches balloon-burst propensity leads to potentially biased sampling of solely warmer tail conditions. The lack of reference data in the upper stratosphere and mesosphere affects the assessment of uncertainties in NWP temperature fields to reference standards, leading to a poorer assessment at heights around 40 – 5 hPa and no assessment being possible above 5 hPa. In turn, this affects the calibration/validation of new temperature sounding data, which are sensitive to this portion of the atmosphere. This is particularly true of AMSU-A channel 14, whose weighting function peaks around 2 – 3 hPa, but it also affects channels 12 – 13 (peaking at 10 and 5 hPa respectively). The equivalent channels on ATMS are also affected, and there are also a number of infra-red temperature sounding channels on hyperspectral infrared sounders which are affected, including CrIS channels at 667.500 cm^{-1}, 668.125 cm^{-1}, and 668.750 cm^{-1}, IASI channels at 648.500 - 669.750 cm^{-1} and AIRS channel numbers 54 - 83. Furthermore, the weighting functions for most satellite sounding channels have a stratospheric tail with some small sensitivity to the stratospheric temperature, so that this will contribute to the uncertainty of the Cal/Val for all channels, although with less of an impact for the channels peaking lower in the atmosphere.

The gap identified here is twofold – a lack of reference observations at 40 – 5 hPa, and no reference observations above 5 hPa. The first part could be solved by supplementing the GRUAN-reference dataset with GNSS Radio Occultation (GNSS-RO) observations and products, including sets of bending angles and temperature retrievals. GNSS-RO bending angles have a high vertical resolution and uncertainties have been calculated both for these observations and for the derived temperature profiles with a high accuracy (Kursinski et al 1997). This makes GNSS-RO observations potentially very valuable as references for the calibration/validation of new satellite temperature-sounding data. We propose, therefore, including both the bending angles and derived temperature profiles, along with their estimated uncertainties, in the GRUAN processor in future work. This requires efforts to co-locate GRUAN profiles and GNSS-Radio Occultations. Such work will benefit where GRUAN sites in future make use of an EUMETSAT simulator that predicts up to two weeks in advance coincidence of polar orbiter overpasses and GNSS-RO occultations.

It should be noted that there are some known drawbacks to using GNSS-RO temperature profiles as a reference, however. Firstly, since the observations are directly sensitive to pressure/temperature rather than temperature, there is a so-called null space, in which the observations are blind to combined mean errors in temperature and pressure, which cancel each other out. Because of this, it is important to keep using reference radiosondes such as the GRUAN observations. Secondly, the temperature profiles at higher altitudes are less accurate since the observations rely on the bending by the atmosphere and in thin atmosphere the signal-to-noise ratio becomes very low. This makes it difficult to use GNSS-RO observations as a reference at altitudes above around 5 hPa (Healy and Eyre, 2000; Collard and Healy, 2003). The use of GNSS-RO measurements would therefore not help the lack of observations about 5hPa, but it would increase global coverage, improving the cal/val of new satellite temperature sounding data at heights of 40 – 5 hPa.

There is a clear need to develop instrumentation capable of measuring temperature routinely above 40 hPa (and in particular above 5hPa) in a traceable manner with metrologically well characterised uncertainties. The remedy defined here (using GNSS-RO temperature profiles as a reference dataset) only partially closes this gap and does not obviate the need for technological developments in upper atmosphere profiling.

Operational space missions or space instruments impacted

- MetOp
- MetOp-SG
- Other, please specify:

All instruments with temperature sounding channels whose weighting functions include a significant contribution from 40 – 0.01 hPa. This includes:

- All AMSU-A instruments (NOAA, MetOp and Aqua satellites)
- Special Sensor Microwave Imager/Sounder instruments (F-16 to F-19)
- ATMS instruments (Suomi-NPP, JPSS-1 and later)
- MWTS-2 instruments (FY-3 satellite series)
- MWHS-2 instruments (118 GHz channel 2) on FY-3 satellite series
- MTVZA-GY instrument on Meteor-M
- IASI instruments (MetOp series)
- AIRS instruments (Aqua)
- CrIS instruments (Suomi-NPP and JPSS satellite series)
- HIRAS instruments (FY-3D and later satellites)
- GIRSS (FY-4E and later)
- MTG (Meteosat Third Generation) IRS

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)

Gap status after GAIA-CLIM

After GAIA-CLIM this gap remains unaddressed

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Space Agencies	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	High	Better calibration/validation of stratospheric and mesospheric temperature sounding data
Numerical Weather Prediction	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High	Improved assimilation of AMSU-A and ATMS higher peaking channels (particularly channel 14 AMSU-A and channel 15 ATMS) Improved assimilation of the higher peaking channels on infra-red hyperspectral sounders (AIRS, IASI, CrIS) Quantitative assessment of the biases in short-range forecasts in the upper stratosphere and mesosphere
Copernicus C3S Reanalysis	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Improved assimilation of temperature sounding channels sensitive to the upper stratosphere and mesosphere (see above)
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Sub-optimal Cal/Val of atmospheric sounding data at heights of 40 – 5 hPa, due to very little available reference data.	All users and application areas will suffer from it.	High	Less confidence in the validation of NWP data to reference standard for these atmospheric heights, given the smaller number of available reference data.
No Cal/Val to reference standard possible for atmospheric sounding data strongly sensitive to heights above 5 hPa (e.g. AMSU-A channel 14).	All users and application areas will suffer from it.	High	The ‘true biases’ of upper stratospheric and mesospheric temperature sounding channels cannot be known due to a lack of reference data. Consequentl,y there is a larger uncertainty associated with the mean forecast and analysis values in the upper stratosphere and mesosphere This uncertainty is supported by jumps observed in the long-term time series of stratospheric/mesospheric temperature analyses from reanalysis, associated with the AMSU-A data available at the time.

Part III Gap Remedies

Remedy 1 – Use of GNSS-RO temperature profiles as a reference dataset for satellite Cal/Val

Primary gap remedy type

- Technical ; TRL 5 – technology development / demonstration

Secondary gap remedy type

Research

Proposed remedy description

As a first step, we propose the inclusion of GNSS-RO bending angles and derived temperature profiles and their uncertainty estimates in the GRUAN processor. It is important to keep the bending angles, as well as the temperature profiles, since the latter have additional sources of uncertainty due to the need for prior information in the retrievals. This first step would involve some technical work. It would also require work by GRUAN sites to improve scheduling to match with GNSS-RO profiles within reasonable colocation criteria. EUMETSAT has developed a tool that has been shown to be able to forecast occultation positions with >98% skill up to two weeks in advance. This can forecast optimal launch times to create a full profile from the surface to 5hPa that coincides with a polar orbiter overpass.

A second step would be to carry out a research study comparing the NWP forecasts with GNSS-RO bending angles and derived temperature profiles and evaluate whether the mean differences fall within the uncertainty estimates. This would lead to an indication of the uncertainties in NWP temperature fields, as indicated by comparison with GNSS-RO observations.

The final step would be to evaluate these uncertainties in radiance space for different satellite instruments. The proposal here follows the procedure that is currently being used for GRUAN data in the GAIA-CLIM project.

Relevance

The solution proposed here addresses the lack of reference observations for temperature at atmospheric heights 40 – 5hPa. This is important for the calibration/validation of stratospheric temperature sounding channels. An additional benefit would be increased global coverage of reference temperature-sensitive observations.

Measurable outcome of success

Firstly, development of the GRUAN processor to include GNSS-RO observations and uncertainties. Secondly, a documented study of the comparison between GNSS-RO temperature profiles and NWP temperature fields in both geophysical space (temperature-height) and radiance space (radiances by channel) for different satellite instruments.

Expected viability for the outcome of success

High

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 1 year

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Non-applicable

Potential actors

- EU H2020 funding
- National Meteorological Services
- WMO
- ESA, EUMETSAT or other space agency

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G5.01 Vast number of data portals serving data under distinct data policies in multiple formats for fiducial reference-quality data inhibits their discovery, access, and usage for applications, such as satellite Cal/Val

Gap Abstract

Presently, access to high-quality reference network data and satellite data is obtained through a variety of portals, using a broad range of access protocols, and the data files are available in an array of native data formats that lack interoperability (see Gap 1.06). There also exists a broad range of data policies from open access through delayed mode restricted access. To make effective usage of the full range of reference-quality measurements, e.g., for the characterisation of satellite data, therefore presently requires substantial investment of time and resources to instigate and maintain a large number of data-access protocols and data read/write routines, as well as to fully understand and adhere to a broad range of data policies and timeliness. This is a substantial impediment to the effective usage of data for applications, such as the GAIA-CLIM Virtual Observatory or similar application areas.

Part I: Gap description

Primary gap type

- Technical (missing tools, formats etc.)

Secondary gap type

- Parameter (missing auxiliary data etc.)
- Governance (missing documentation, cooperation etc.)

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Independent of instrument technique

Related gaps

- G1.06 Currently heterogeneous metadata standards hinder data discoverability and usability

Gap 1.06 pertains to unifying metadata format and discovery metadata, which would naturally form a component of resolving the current gap. This critical dependent gap should be addressed with this gap.

Detailed description

The task of characterizing satellite measurements by means of comparison to reference measurements needs consistent and reliable access to data and documentation of various “fiducial” reference measurements for the analysis of the quality of satellite measurements and/or derived geophysical data products. This task can be massively complicated and time-consuming arising from the need to collect data from multiple locations also often offering the data on various types of user interfaces with which a user needs to become familiar. In many cases, data downloads do not follow specific data exchange standards, which makes it difficult to automate access to them. In addition, the available bandwidth at the provider side might be too small to serve many customers, which can result in extended waiting times for the data. This applies even more when co-located ground based and satellite data are to be offered to the user. The range of data policies that a user needs to adhere to further complicates the issue. These include timeliness of the data exchange.
A common source that integrates several reference-data networks with satellite data considering traceable uncertainty does not exist but is needed according to the GAIA-CLIM user survey. A key first step to this is consistent access to reference quality measurement systems in a harmonised data format that contains requisite discovery metadata and for which the data usage policy and restrictions are clearly articulated. Many of the existing data policies can be very different, e.g.,

- Completely open access for all users including commercial users;
- Open access for research purposes only;
- Open access after a set time delay;
- Access only upon request to PI.

Several sources for co-located data sets exist, but most of them are specialized to very particular use cases. Most are not fully utilizing the potentially available information on uncertainty or including uncertainty arising from spatiotemporal mismatch of the compared data streams. Some of the existing datasets are publically available via the internet, while others are run internally to organizations like space agencies to monitor data quality in real time. While many validation activities are performed, they do not use the available uncertainty information in an optimal way, which has resulting impacts on the quality of the research and the robustness of any conclusions drawn from such validation exercises.
In summary, the issues over data discovery and access are pervasive and inhibit their effective usage in a broad range of application areas, including satellite Cal/Val activities. The recently instigated Copernicus Climate Change Service contract C3S311a Lot3 which is concerned with access to data from baseline and reference networks may go a considerable length towards addressing this gap for non-satellite reference measurements and is discussed under remedy G5.01(R1).

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Assimilated product (Level 4)
- Time series and trends
- Representativity (spatial, temporal)
- Calibration (relative, absolute)

Gap status after GAIA-CLIM

GAIA-CLIM explored and demonstrated potential solutions to close this gap in the future
Some of the work within GAIA-CLIM provided unified access to a range of reference quality data products via the Virtual Observatory facility. However, this access shall not be operational and substantive further work would be required. It also will not permit universal access for other applications to integrated holdings.

Part II: Benefits to resolution and risks to non-resolution

Identified Benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Access to reference measurements organised via a brokering system service as envisioned by Copernicus makes discovery and access easier.	All users and application areas will benefit from it	High to Medium	The one-stop-shop for the described data would become the central platform where several scientific and service oriented communities would search for such data. This can lead to significant cost reductions for research and development activities that count on the availability of such data.
Access to reference measurements co-located to satellite measurements through the GAIA-CLIM Virtual Observatory in operational mode, in particular at level 1, could boost satellite-retrieval development and comparison.	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	Individual satellite retrieval developers, international retrieval round robin activities for retrieval analysis and selection, as well as climate data record quality assessments, as performed by WCRP, would save significant effort in setting up data bases like the ones contained in the Virtual Observatory.
An operational Virtual Observatory could be exploited as real-time Cal/Val facility for new satellite instruments at space agencies.	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	Medium	The Virtual Observatory may provide a basic structure for real-time satellite data Cal/Val that can be reused and further developed with new programmes. This system would for the first time consider the full uncertainty budget involved in such a data comparison at the operational level.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
The use of multiple locations with different set ups for data access continues to complicate work on data comparison and increases cost to delivery and analysis / exploitation of data.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	The limited number of users who are able to fully exploit available observations to undertake activities, such as satellite Cal/Val, reduces the intrinsic value of these data and related investments into infrastructure.
Non-satellite reference measurements will have limited value for the characterisation of satellite measurements.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High	Negative impacts on funding support for non-satellite measurements. Poorer quality assessments of satellite measurement programs.

Part III: Gap Remedies

Remedy 1 – Successful implementation of the Copernicus Climate Change Service activity on baseline and reference network data access via the Climate Data Store

Primary gap remedy type

Deployment

Secondary gap remedy type

- Technical
- Governance

Proposed remedy description

The C3S 311a Lot 3 contract, concerned with access to baseline and reference network data, shall make considerable strides in making harmonised access to reference- and baseline-network data available under a common data model and with clear articulation of data policies that enables appropriate and seamless usage. Work is envisaged to cover aspects of data access brokering, data harmonisation, and data provision and builds upon aspects of work within GAIA-CLIM. Data shall be served via the Climate Data Store (CDS) facility of C3S. However, it is limited to accessing data from a subset of atmospheric networks and ECVs, so in the longer-term, extension to remaining atmospheric ECVs and oceanic and terrestrial ECVs would be required were these to be used for satellite cal/val.

Relevance

The remedy would provide single point of access to harmonised data products served under a common data model. Note that rapid access, e.g. for satellite validation in the commissioning phase, is not being addressed through this remedy.

Measurable outcome of success

Data available via the CDS and used in applications such as the GAIA-CLIM Virtual Observatory

Expected viability for the outcome of success

High

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

Copernicus funding

Remedy 2 – Operationalization and extension of the Virtual Observatory facility developed within GAIA-CLIM

Primary gap remedy type

Deployment

Secondary gap remedy type

Technical

Proposed remedy description

The diverse sources of reference-quality data could be integrated with data made available through operational exploitation platforms, which could be developed for different user communities. GAIA-CLIM provides this as part of the Virtual Observatory for a set of atmospheric ECVs and the specific application of characterising satellite measurements. As a major part of the Virtual Observatory, a co-location database has been developed. The first step is to identify all pertinent satellite and non-satellite reference datasets that are of interest for a comparison to a given satellite sensor data. This could either be via a forward modelling approach to derive an estimate of the satellite-sensor data or a comparison to geophysical variables derived from the satellite data or both. The provided data need to be complemented by as complete as possible metadata and traceable uncertainty information, including comparison mismatch uncertainties that need to be derived from the comparison setting and the variability of the geophysical variable to be compared.

The Virtual Observatory has been developed to demonstrate the use of non-satellite reference data and NWP model data for the characterisation of satellite data. The Virtual Observatory integrates the different measurements, their metadata, quantified uncertainty for the measurements, and the uncertainty arising from the comparison process. Many other ECV reference measurements – satellite data combinations, e.g., for terrestrial and oceanic ECVs, are outside the scope of the GAIA-CLIM project and have not been addressed by this project. But these could be accommodated via operationalisation and extension of the service in the future. Such an operational service should involve unified access to the underlying reference quality non-satellite measurements used benefitting from proposed Remedy 1 to this gap.

Relevance

An operational and extended Virtual Observatory facility would provide unified access to non-satellite reference-quality measurements and specific co-located data under its purview via the Copernicus CDS.

Measurable outcome of success

Operational access to relevant measurements and colocations

Expected viability for the outcome of success

High

Scale of work

- Single institution
- Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

- ESA, EUMETSAT or other space agency

G5.06 Extraction, analysis, and visualization tools to exploit the potential of fiducial reference measurements are currently only rudimentary

Gap Abstract

Climate research and services have an increasing need to consider a large amount of observational data and model outputs simultaneously in applications. Because the data volumes provided by satellite observations and ensemble model runs have increased to levels that prevent easy download to local compute environments, there is an enhanced need for tools that provide functionality for data extraction, analysis, and visualisation at source or on cloud compute resources. At the same time, "fiducial" reference measurements are needed to provide evidence for the quality of satellite observations and models, but the aforementioned tools to exploit the potential of such reference measurements are currently only rudimentary. This in particular includes tools to analyse and display uncertainty of comparison results due to differences caused by mismatches in space and time of data used in comparisons.

Part I: Gap description

Primary gap type

Technical (missing tools, formats etc.)

Secondary gap type

- Knowledge of uncertainty budget and calibration
- Uncertainty in relation to comparator measures

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Independent of instrument technique

Related gaps

- G5.07 Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems

The tools to be developed to address this gap in the context of validation work should be based on the traceability principles and Cal/Val best practices referred to in G5.07. Hence G5.07 should be addressed before G5.06 as it represents a contribution to the latter.

Detailed description

Services that provide data extraction, analysis, and visualization tools exist for comparisons of gridded data, but are currently only rudimentary for comparisons of satellite and non-satellite fiducial reference measurements based on data co-locations, which are needed for the validation of satellite measurements and derived products. In particular, analysis capabilities that for instance allow analysis at different time or spatial scales are missing. While measurement uncertainties are at least displayed by some existing services, e.g., the FP7 NORS project, the visualisation of uncertainty arising from differences in spatiotemporal sampling is generally not included, but is needed to fully understand the uncertainty budget of a specific comparison.

The user survey undertaken by GAIA-CLIM indicated a clear need for such a capability to be developed. But challenges remain, because whatever analysis / visualisation tool can be provided, it will not necessarily match all individual needs. The GAIA-CLIM user survey also indicated that the analysis of the co-locations provided by the Virtual Observatory may not solely be used to evaluate satellite measurements but also vice-versa, the satellite measurements may be used to evaluate the quality of the reference measurements, e.g., their temporal consistency. Such a flexible tool does not exist to date.

Operational space missions or pace instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Assimilated product (Level 4)
- Representativity (spatial, temporal)

Gap status after GAIA-CLIM

GAIA-CLIM explored and demonstrated potential solutions to close this gap in the future:

GAIA-CLIM WP5 has developed a Virtual Observatory that addresses this gap partly for a limited set of ECVs and with several limitations concerning the representation of the mismatch errors. At the end of the GAIA-CLIM project, there will be a prototype tool that can be developed further in the future.

Part II: Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
The existence of the GAIA-CLIM Virtual Observatory allows quality assessment for satellite data and derived products with a high potential to be made operational. It can also be extended to more GCOS ECVs.	All users and application areas will benefit from it	High	The GAIA-CLIM Virtual Observatory can be used in different contexts such as validation tool for products contained in the C3S CDS, as baseline for satellite-retrieval studies and comparisons, and as a satellite Cal/Val tool in space agencies that have the capability to deal with many different sensors. These usages increase the visibility of the value of non-satellite reference measurements and make sustained funding more viable.
The data extraction capability of the Virtual Observatory allows the export of data from the Virtual Observatory in user-friendly formats.	All users and application areas will benefit from it	High	The provision of a data extraction and visualisation capability considering the uncertainty aspects of data comparison can make further developments of retrieval schemes for considered variables easier. This usage increases the visibility of the value of non-satellite reference measurements and makes sustained funding more viable.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Lack of the described tools prevents optimal use of reference measurements leading to potential issues with the justification of the measurements in the future.	All users and application areas will suffer from it.	High	Derived global products from satellite may suffer in quality from inadequate evaluation of the measurements and retrieval schemes used to generate them. This can hamper applications supporting decision and policymaking.

Part III: Gap Remedies

Remedy 1 – Operationalization of a satellite – non-satellite match-ups facility with appropriate discovery and user tools

Primary gap remedy type

Technical

Secondary gap remedy type

- Research
- Education/Training
- Governance

Proposed remedy description

The Virtual Observatory contains a still rudimentary data extraction capability that allows the export of co-located data from it in user-friendly, self-descriptive NetCDF format. The format also allows comparison data being amended by meta-data of the comparison, e.g., the used co-location criteria, etc., but this has not been realised within the lifetime of the GAIA-CLIM project. Such a format also supports analysis of the data in ways that may not be enabled, at least initially, in the final demonstrator version of the Virtual Observatory. Data extraction tools also are capable of sub-setting each data source contained in the co-location data base by ECV, time and location, observing system, and other boundary conditions such as surface type.
To exploit the co-location data base proposed as remedy 2 for gap G5.01, analysis tools must be developed to provide statistics and various indicators for a comparison that meet user needs as indicated by the GAIA-CLIM user survey outcomes. These analysis tools must have some flexibility, such as interchanging the reference in a comparison and the ability to perform analysis at different time and eventually space scales.
Visualisation tools need to be capable of displaying multiple co-located parameters to circumvent the complexity of comparing datasets of varying type and geometries, e.g. time series and instantaneous, spatially localised and large spatial extent observations, column-integrated observations, and vertical profiles, etc. Special attention must be paid to the specification of graphical representation of individual parameters and various uncertainty measures, including the smoothing uncertainty.
Tool development should look to benefit from existing elements and capabilities whenever possible. All developed tools need to be accessible via a GUI that also needs to be developed. GAIA-CLIM has developed a demonstrator facility with a limited number of static examples. Further development and operationalisation of the facility would be required to enable reliable near-real-time and delayed mode exploitation for a broader range of satellite instruments and ECVs.

Relevance

The GAIA-CLIM Virtual Observatory could serve as the basis for the development of an operational tool for the Evaluation and Quality Control pillar of the C3S, if being made available after the end of the GAIA-CLIM project. Such an implementation represents an important step towards an easily accessible comparison tool that considers all kinds of uncertainty relevant for data comparisons.

Measurable outcome of success

Developed tools for data extraction and display for co-located satellite and non-satellite measurements being accessible via an operational graphical user interface.

Expected viability for the outcome of success

- Medium
- High

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

- Copernicus
- ESA, EUMETSAT or other space agency
- SMEs/industry

G5.07 Incomplete development and/or application and/or documentation of an unbroken traceability chain of data manipulations for atmospheric ECV validation systems

Gap Abstract

Recently established quality assurance and validation guidelines and systems are not sufficiently well recognised or understood in the global community, where validation purposes, methodologies, and results can differ significantly from one report to another. Harmonised practices should now be advertised and applied more universally across the community to avoid (1) missing quality indicators, (2) incoherent results between different validation exercises, and (3) unreliable results or additional methodological uncertainties due to sub-optimal data manipulations. Moreover, there is room for further improvement in validation methodologies, taking advantage of the ever-increasing breadth of measurement, modelling, and data analysis techniques.

Part I: Gap description

Primary gap type

Technical (missing tools, formats etc.)

Secondary gap type

- Uncertainty in relation to comparator measures
- Governance (missing documentation, cooperation etc.)

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)

Non-satellite instrument techniques involved

Independent of instrument technique

Related gaps

- G5.06 Extraction, analysis, and visualization tools to exploit the potential of fiducial reference measurements are currently only rudimentary

The tools to be developed to address G5.06 in the context of validation work should be based on the traceability principles and Cal/Val best practices referred to in G5.07. In this sense, G5.06 should be addressed first, as it represents a contribution to the remedy for G5.07 (see G5.07 gap remedy #1).

Detailed description

In the context of sustainable Earth Observation data services, such as those in development for the Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), Quality Assurance (QA) and geophysical validation play a key role in enabling users to assess the fitness of available data sets for their purpose. User requirements, e.g., those formulated for the Global Climate Observing System (GCOS), have to be identified and translated into QA and validation requirements. In turn, QA and validation results must be formulated in the form of appropriate Quality Indicators (QI) to check and document the compliance of the data with the user requirements. Metrology practices recommend the development and implementation of traceable end-to-end QA chains, based on the Système International d'Unités (SI) and community-agreed standards (as identified for instance in the GEO-CEOS QA4EO framework).
Generic guidelines for such QA systems applicable virtually to all atmospheric and land ECVs are being developed within the EU FP7 QA4ECV project (2014-2018), while more specific guidelines developed in projects like ESA's Climate Change Initiative (CCI) and dedicated to atmospheric ECVs are being published. Generic and specific QA systems and guidelines established in those recent projects are not sufficiently well recognized or understood in the global community, where validation purposes, methodologies, and results can differ significantly from one report to another. Harmonised practices should now be advertised and applied more universally across the community.
The impacts of not adopting a traceable end-to-end validation approach are diverse. Firstly, important quality indicators may be missing in the analysis, e.g. information on spatio-temporal coverage, resolution, dependences of the data quality on particular physical parameters (e.g. solar zenith angle, cloud cover, thermal contrast, etc.). Secondly, results may be incoherent between several validation exercises on the same data set and the origin of the discrepancies be unclear due to insufficient traceability. Thirdly, methodological uncertainties in, e.g., geographical mapping, in the use of vertically averaging kernels, or in unit conversions using auxiliary data, may lead to unreliable results. Finally, all this may imply sub-optimal use of the true validation capabilities of the ground-based reference network, which means that the full potential value is not being extracted from these measurement system assets.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Assimilated product (Level 4)
- Time series and trends
- Representativity (spatial, temporal)
- Calibration (relative, absolute)
- Spectroscopy
- Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Gap status after GAIA-CLIM

GAIA-CLIM explored and demonstrated potential solutions to close this gap in the future:

The GAIA-CLIM project adds to other EU projects with respect to more ECVs and disseminates results via the "Virtual Observatory" facility but does not close the gap.

Part II: Benefits to resolution and risks to non-resolution

Identified benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Completeness of the QA and validation reports, addressing all Quality Indicators relevant for the envisaged use.	All users and application areas will benefit from it	High	Users will have access to more and better information on which to judge the fitness-for-purpose of a particular product for their application.
Homogeneity in adopted Quality Indicators and processing chains allows intercomparison of different validation studies and their results.	All users and application areas will benefit from it	High	Users can easily compare different products based on their performance in validation exercises that were performed along the same principles and with comparable metrics.
Improved reliability and minimal methodological uncertainties related to the Cal/Val processing chain.	All users and application areas will benefit from it	High	Optimal use of the reference data to gauge the quality of the satellite data sets, without unnecessary additional methodological uncertainties; Improved feedback on satellite data production, with greater detail and differentiation.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Difficulty to judge the fitness-for-purpose of satellite data products because of missing or poorly-defined Quality Indicators.	All users and application areas will suffer from it.	Medium	Users of satellite data products may refrain from using these products when they are not sufficiently characterised. This constitutes sub-optimal use of the EO system and may lead to non-realised performance of the services.
Difficulty to compare different validation exercises, e.g. of different products for a particular ECV.	All users and application areas will suffer from it.	High	Users are often faced with the question “which is the best data set for my application?”. Without comparable validation methods and Quality Indicators applied to all candidate data sets, no reliable, informed choice can be made. This leads to sub-optimal use of the EO system and impacts negatively the application(s) envisaged by the user.

Part III: Gap Remedies

Remedy 1 – Propagation and adoption of metrological best practices in sustained validation activities

Primary gap remedy type

Governance

Secondary gap remedy type

- Technical
- Research
- Education/Training

Proposed remedy description

The remedy proposed here consists in the composition of expert consortia under the umbrella of (and potentially with funding by) overarching bodies and initiatives (WMO, EC, space agencies). These consortia should look into the following highly related aspects of the gap:

- The development of (new) best-practice validation protocols and the corresponding documentation framework;
- The application of these protocols and guidelines in (operational) validation platforms;
- The advertising (including peer-reviewed papers, handbooks, training and courses) to validation teams and service providers.

Some efforts are already ongoing in this direction, for instance in the EC FP7 project QA4ECV (definition of a traceable validation chain and application in the "Atmosphere Validation Server" for a few ECVs), in ESA's CCI, and in ad-hoc initiatives such as the recent ISSI team "EO validation across scales" (which included GAIA-CLIM and CEOS representatives). Still, these only partially address the gap, and a much wider effort (in terms of ECVs, methods, platforms, and outreach) is required to extend, implement, and operationalise these QA4EO-compliant practices.

Relevance

The integrated concept of the proposed remedy (including research, technical developments, education, and governance) ensures that the gap is broadly addressed. For optimal acceptance by the scientific community and the major stakeholders, the composition of the expert teams is key.

Measurable outcome of success

Published protocols and guidelines, endorsed by the large stakeholders, and referred to in the scientific literature. Implementation of these protocols in the validation platforms supported by the space agencies, the Copernicus programme, etc.

Expected viability for the outcome of success

- Medium
- High

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Potential actors

- EU H2020 funding
- Copernicus funding
- WMO
- ESA, EUMETSAT or other space agency

G5.09 Need to propagate various fiducial reference quality geophysical measurements and uncertainties to TOA radiances and uncertainties to enable characterisation of satellite FCDRs

Gap Abstract

Presently, the evaluation of the quality of Fundamental Climate Data Records (FCDR) (observations at radiance level that serve as key inputs for model-based reanalyses and retrievals of GCOS ECVs) is based mainly on isolated activities by individual research groups. Given the importance of FCDRs for all downstream data records, there is an important and evolving requirement to improve the assessment of FCDRs by utilising non-satellite reference measurements and model fields, among other means, for validation. The utilisation of non-satellite reference measurements for this purpose requires the use of observation operators (often in the form of radiative transfer models) to transfer the reference measurements into the measurement space of the satellite instrument. There is currently no readily accessible, maintained, online tool (except for the 'GRUAN processor' as part of GAIA-CLIM) that would enable the broader scientific and operational communities to contribute to the quality evaluation of FCDRs.

Part I: Gap description

Primary gap type

Technical (missing tools, formats etc.)

Secondary gap type

Uncertainty in relation to comparator measures

ECVs impacted

- Temperature
- Water vapour

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

- Radiosonde
- Microwave radiometer
- Lidar

Detailed description

The GAIA-CLIM user survey highlighted the need for a readily accessible radiative-transfer capability available as part of the Virtual Observatory to allow the transfer of reference measurements into the measurement space of satellite instruments. Such a tool would enable a more direct characterisation of the satellite measurements. The validation of satellite measurements in terms of the measured radiance is more straightforward than a validation of retrieved (or analysed) quantities. This is because the forward calculation from the geophysical profile is unique, whereas solutions to the inverse problem are non-unique in that several distinct geophysical profiles can be consistent with a given radiance measurement. As part of this, the uncertainty information in reference measurements needs to be appropriately transformed in the mapping (e.g. from reference measurements to top-of-atmosphere (TOA) brightness temperatures). In turn, this requires knowledge of the vertical and / or horizontal correlation structures present in the reference measurement.

The GAIA-CLIM project realised the development and demonstration of a GRUAN-processor, which is able to monitor Numerical Weather Prediction (NWP) model temperature and humidity fields relative to GRUAN radiosonde observations, and to monitor the differences in computed TOA radiances for a wide range of meteorological satellite sensors from both measured (GRUAN) and modelled (NWP) state estimates. The GRUAN-processor is built around several core capabilities that are likely to be supported longer-term by EUMETSAT (the fast RT modelling capability [RTTOV] and the flexible interface to NWP model fields [the Radiance Simulator]), nevertheless there is a foreseen governance gap beyond the term of GAIA-CLIM regarding the ongoing development priorities and support for the GRUAN-processor.

The key stakeholders include: satellite agencies (engaged in assessing the quality of long term satellite datasets and implementing Cal/Val plans for forthcoming missions); NWP centres (with an interest in determining traceable uncertainties in model fields); GRUAN governance groups and site operators (with an interest in assessing the value of NWP for cross–checking GRUAN-data quality); and the wider climate-research community (also with an interest in assessing the quality of long term satellite datasets). The future governance of the processor would ideally take account of the priorities of this group of stakeholders.

Associated with this top-level requirement for a flexible observation operator is a specific requirement, related to the need for comprehensive information on the error characteristics of reference measurements. In the context of reference radiosonde measurements, this includes estimates of the error correlations between measurements. Other ground-based data sources such as microwave radiometers and Lidar systems could be developed into reference measurements, including the full assessment of uncertainty.

GRUAN was established with the goal of creating a network of sites around the world where reference measurements of atmospheric vertical profiles are performed (Seidel et al., 2009). Data processing for GRUAN sondes attempts to account for all known sources of systematic and random error affecting the temperature and humidity sensors (Dirksen et al., 2014). However, although vertically resolved best-estimate uncertainties are available, the error correlation structure (i.e. between vertical levels) in the sonde measurements is not presently available, constituting a current gap.

Many applications of reference radiosonde measurements require an estimate of error correlations. For example, as part of the comparison of reference-sonde measurements and NWP fields in terms of TOA brightness temperatures, it is necessary to have realistic estimates of these error covariances. Only then is it possible to estimate realistically, using a radiative-transfer model, the uncertainty in TOA brightness temperature that propagates from sonde profile uncertainty.

Calbet et al. (2017) performed a study into the calibration-traceability chain for forward modelling of the Infrared Atmospheric Sounding Interferometer (IASI), using collocated GRUAN sondes and the LBLRTM radiative transfer model. They found the propagation of uncertainties from sonde profiles was hampered by the lack of covariance information between levels. They resorted to analysing two extreme cases: where the level-by-level sonde profile uncertainties are perfectly correlated or perfectly uncorrelated. The uncertainty in modelled TOA radiances was assumed to lie between the two extremes.

The vertical error correlation structure in GRUAN-sonde profiles is the subject of current research. Such uncertainties are envisaged to be reported in the version 3 GRUAN product (correlated, partially correlated and random terms) being developed by the GRUAN Lead Centre.

A tractable means of representing vertical error covariances is by parametrisation. If the measurement variance at each vertical level is known, the correlated errors between levels can be represented by Gaussian statistics assuming a characteristic correlation length (see e.g. Haefele and Kämpfer, 2010). The correlations should be based on physical constraints where these are known.

Operational space missions or space instruments impacted

- Meteosat First, Generation (MFG)
- Meteosat Second Generation (MSG)
- Meteosat Third Generation (MTG)
- MetOp and MetOp-SG
- Other agencies comparable missions in polar and geostationary orbit

Validation aspects addressed

- Radiance (Level 1 product)
- Spectroscopy

Gap status after GAIA-CLIM

GAIA-CLIM has partly closed this gap.

The GAIA-CLIM Virtual Observatory has partly closed this gap at the conceptual demonstrator level by addressing the ECVs upper-air temperature and humidity for the HIRS satellite instruments measuring in the infrared spectral ranges. The Virtual Observatory contains results obtained by an offline forward modelling capability to transfer GRUAN radiosonde measurements into the measurement space of the satellite instruments using a radiative transfer model that is sustained in operational mode within the EUMETSAT Numerical Weather Prediction Satellite Application Facility.

The gap is only partly closed, because more GCOS ECVs and associated satellite instruments need to be considered in the future and because the capability is not available online and operationally, which would require additional funding. In addition, more sophisticated radiative transfer models could be coupled with the Virtual Observatory to address eventual shortcomings of the operational fast model and more reference measurement techniques could be added.

With respect to the requirement for comprehensive knowledge of the error characteristics of reference data (specifically, error correlations for GRUAN data), initial estimates have been generated and tested within the timeframe of GAIA-CLIM, but it is expected that this activity will need to continue beyond the end of the GAIA-CLIM project in part because further information is expected from GRUAN ,but not yet available on the specific correlation structures apparent in the radiosonde profiles.

Part II: Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Integration of a forward radiative transfer capability into the GAIA-CLIM Virtual Observatory enables direct comparison of satellite radiances to non-satellite reference measurements.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	The realization will lead to the use of the GAIA-CLIM Virtual Observatory for the validation of Fundamental Climate Data Records forming the basis for GCOS ECV climate data records via the use of FCDRs in NWP-model based reanalysis and retrieval schemes.
The forward radiative transfer capability in the Virtual Observatory provides the potential for a further development of the Virtual Observatory into a general satellite Cal/Val facility.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	Medium Low	The quality of satellite data is monitored in real time using various, often mission specific, tools. Non-satellite reference data play only a marginal role. The Level-1 capability of the GAIA-CLIM Virtual Observatory makes it viable to be considered to become part of a real time monitoring system.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Limited uptake of Virtual Observatory as comparisons not possible at level-1b radiance space.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	Value of reference-quality measurements for satellite-data characterization not realized with the consequence that the Virtual Observatory has no potential for satellite Cal/Val activities. On the long term, justification for non-satellite reference measurements may fade.
Lack of penetration and acceptance of proposed methodology (NWP, coupled to GRUAN, for the validation of meteorological EO data) into wider user community.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High	Sub-optimal (slower !) evolution of the community’s understanding of the quality of key measured datasets.

Part III: Gap Remedies

Remedy 1 – Implement means to provide the community with a forward radiative transfer capability or results of computations

Primary gap remedy type

Technical

Secondary gap remedy type

Deployment

Proposed remedy description

GAIA-CLIM has developed the GRUAN processor that is able to simulate measurements for many satellite instruments operating in the infrared and microwave spectral ranges consistent with GRUAN-profile measures and their uncertainties. Here, it is proposed to integrate the GRUAN processor into the Virtual Observatory and make it accessible online to create simulated measurements for any satellite instrument for which co-locations with the GRUAN-reference measurements exist in the Virtual Observatory database. This could then provide a working model that would enable development of similar operators for measurements arising from other non-satellite reference quality measurements. In particular, many of the modules in the GRUAN processor could be extended to enable the use of additional measurements in future.
Alternatively, potentially at lower cost, a service could provide online results of radiative transfer calculations for ground-based reference measurements that can form an element of match-up data bases and GUI such as the Virtual Observatory.

Relevance

Implementing the proposed remedy would help to satisfy a clear user need expressed by the GAIA-CLIM user survey. The remedy presents an important step forward towards the validation of Fundamental Climate Data Records that can be evaluated for many instruments using non-satellite reference measurements available within the GAIA-CLIM VO.

Measurable outcome of success

The measurable outcome of success for the specific remedy proposed is the accessible online radiative transfer capability, available as part of the Virtual Observatory, and provision for the long-term maintenance and development of the capability, in accordance with the evolving requirements of stakeholders.

Expected viability for the outcome of success

High

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Yes, in case a service is established that provides results from forward calculations or co-located data.

Potential actors

- EU H2020 funding
- Copernicus funding
- ESA, EUMETSAT or other space agency

Remedy 2 – Improved characterization of error covariances in GRUAN measurements

Primary gap remedy type

Technical

Proposed remedy description

Uncertainty-covariance information needs to be made available and used appropriately within applications that convert from geophysical-profile data to TOA radiances. Firstly, the profile information needs to contain the uncertainty and the correlation structure in a usable format. Within GAIA-CLIM, simple parametrised versions of the vertical error covariances have been developed and tested as part of the significance testing in the GRUAN processor. Further work could refine approaches to more robustly utilising the uncertainty covariance information available.

Alternative approaches based on methods (Desroziers et al, 2005) routinely used to characterise errors in data assimilation systems should also be tested. This method requires that observations are actively assimilated. Initial estimates could be obtained from sub-selecting from the larger set of GUAN data currently assimilated in operational NWP systems, where the selection is based on those GUAN stations exhibiting gross-error characteristics similar to those of GRUAN measurements.

Relevance

The solution proposed here is fully aligned with the requirement (to establish traceable uncertainties for NWP fields and radiances calculated from them).

Measurable outcome of success

Parametrised error covariances, developed and tested in consultation with experts from the GRUAN community.

Expected viability for the outcome of success

High

Scale of work

- Single institution
- Consortium

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

- EU H2020 funding
- National Meteorological services

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G5.11 Non-operational provision of fiducial reference-measurement data and some satellite-derived products reduces their utility for monitoring and applications

Gap Abstract

Copernicus Services, including the Climate Change Service (C3S), will provide information in close to real time using global and regional reanalysis outputs, as well as satellite L2 products. These outputs are not always consistent with their own climatology, because input data are not produced with the same quality at real-time as they are in elaborated climate data records. The availability of so-called "Climate Data Record Interim Products" would remedy this problem by producing products with as high as possible consistency with the climatology, being based on automated satellite inter-calibration and careful quality control. These types of data records are emerging from operational satellite agencies, but lacks optimal means for validation due to non-availability of many non-satellite reference measurements in close to real-time.

Part I: Gap description

Primary gap type

Governance (missing documentation, cooperation etc.)

Secondary gap type

Technical (missing tools, formats etc.)

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (SDGs, space agencies, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Independent of instrument technique

Related gaps

- G1.10 Relative paucity and geographical concentration of reference-quality measurements, with limited understanding of uncertainty in remaining measurements, limits ability to formally close satellite to non-satellite comparisons

Gap 1.10 where the remedy of it would enable the networks of reference measurements with better geographical distribution that can become candidate for operational quality control and data dissemination.
The remedies of Gap 1.10 and this gap can be realised in parallel.

Detailed description

Copernicus Services, including the Climate Change Service, will provide information in close to real-time using global and regional reanalysis outputs, as well as satellite-derived products. For the validation of these products, both delivered with high timeliness, it is essential to have non-satellite reference measurements available for use in near-real-time, which is rarely the case today. There is a need to operationalise quality control and delivery of such data in the future to realise the potential benefits that fiducial reference measurements with characterised uncertainty offer.

Currently, many reference measurements are provided with specific delays due to requirements for certain quality-control measures to be applied. But in many other cases, delayed mode provision relates solely to network data policies and / or to data transmission protocols. The usage scenario for a Virtual Observatory within a Copernicus Service would likely need a close to real time availability of reference quality data streams to enable the assessment of very recent satellite-data products and the close to real time performed reanalysis. If the quality analysis and data provision for non-satellite fiducial reference measurements cannot be operationalised, leading to faster delivery, quality assessments of Copernicus products at short time scales shall remain of limited nature, reducing the value of the data for applications.

In addition, the timely operational delivery of satellite Climate Data Record Interim Level 2 products that are consistent with their long-term climatology also needs to be fostered to improve close to real-time reanalysis products and their validation. The validation of the Interim products could enhance the needs for non-satellite reference measurements as part of an operational validation set up.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments
The gap addresses the timeliness of validation that is needed for close to real-time outputs of Copernicus Services.

Gap status after GAIA-CLIM

After GAIA-CLIM this gap remains unaddressed

The GAIA-CLIM project is not addressing this gap and it is likely to remain after the end of the project.

Part II: Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Operational quality control and delivery of non-satellite reference measurements would allow for better characterisation of satellite and reanalysis products offered in close to real time. This would most likely generate a higher demand for operationally produced reference measurements where the operational delivery requires also a sustained funding of the needed measurement devices and associated data services.	All users and application areas will benefit from it	Medium	Quality analysis for time-critical services of Copernicus could be significantly increased by providing reference measurements closer to real time.
Operational production of L2 Climate Data Record Interim satellite products would allow for more consistent reanalysis outputs and its validation.	All users and application areas will benefit from it	Medium	Quality analysis for time-critical services of Copernicus could be significantly increased by providing CDR Interim L2 products for assimilation and validation of reanalysis. The validation of such products requires the first benefit to be realised.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
If the remedy on non-satellite reference measurements is not started, the use of non-satellite reference measurements remains limited.	All users and application areas will suffer from it.	Medium	Reference measurements may play only a minor role in the validation of Copernicus service outputs with potential long-term consequences for the network maintenance. This also applies to their use in the validation of emerging CDR Interim L2 products.
If the remedy on the satellite CDR Interim is not started, reanalysis outputs and other Copernicus satellite-based products suffer from temporal inconsistencies.	All users and application areas will suffer from it.	Medium	Quality assurance for CDR Interim L2 products would be far from optimal and financial support of reference-measurement systems may fade also endangering the validation of long-term data records.

Part III: Gap Remedies

Remedy 1 – Operationalize processing and delivery for non-satellite reference measurements and satellite CDR Interim L2 products.

Primary gap remedy type

Technical

Secondary gap remedy type

Governance

Proposed remedy description

A first step would be to assess the current procedures for quality control and delivery mechanism for non-satellite reference measurements, and to work out a proposal to further automate them. Depending on the needs, specific projects could be established to operationalise the processes and associated software. The dissemination of such data could be included into operational dissemination mechanisms used for operational data provisions such as over the WMO Information System.
In addition, entities producing GCOS ECV climate data records from satellite measurements should be encouraged to develop a mechanism that continues the data processing by keeping high consistency with the produced CDR. This involves automated inter-satellite calibration for input data to retrieval schemes and a strongly automated quality control, using non-satellite reference measurements that produces statistics in particular related to the temporal consistency with the long term CDR, e.g., stability and trend estimates with uncertainty. Such data shall be disseminated with high timeliness (~2-3 days delay).

Relevance

The remedy has the potential to significantly increase the use of non-satellite fiducial reference data in Copernicus Services. The operational character of quality control and delivery mechanism for such data and their subsequent operational use would potentially lead to a funding of measurement systems from operational sources that would sustain the measurement systems and associated data services rather long-term. This could be realised in conjunction with the already emerging generation of CDR Interim L2 products that need reliable reference measurements for their validation, which may increase the chance for funding.

Measurable outcome of success

Close to real-time availability of non-satellite reference measurements and their use in the continuation of GCOS ECV climate data records with high timeliness to Copernicus Services.

Expected viability for the outcome of success

- Medium
- High

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 10 years

Indicative cost estimate (investment)

Very high cost (> 10 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

- Copernicus funding
- National funding agencies
- National Meteorological Services
- ESA, EUMETSAT or other space agency
- SMEs/industry

G6.01 Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions

Gap Abstract

Current governance of high-quality measurement programs is highly fractured. Numerous networks exist at national, regional, and global levels that have been set up and funded under a variety of governance models. This fractured management of observational capabilities can lead to, amongst others: redundancies, spatiotemporal gaps, varied data policies and formats, varied data processing choices, and fractured provision of data. The gap thus contributes to various other more specific gaps identified in the gaps-assessment process undertaken within GAIA-CLIM.

Part I Gap description

Primary gap type

Governance (missing documentation, cooperation, etc.)

Secondary gap type

- Spatiotemporal coverage
- Vertical domain and/or vertical resolution
- Knowledge of uncertainty budget and calibration

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (space agencies, EU institutions, WMO programmes/frameworks etc.)

Non-satellite instrument techniques involved

Independent of instrument technique

Related gaps

- G6.02 Analysis and optimisation of geographical spread of observation assets to increase their utility for satellite Cal/Val and research.

- G6.03 Lack of sustained dedicated observations to coincide with satellite overpass to minimise co-location effects
- G5.01 Vast number of data portals serving data under distinct data policies in multiple formats for fiducial reference-quality data inhibits their discovery, access, and usage for applications, such as satellite Cal/Val

The G6.01 gap is an effect multiplier on many of the gaps identified in the GAID. As such, its resolution would facilitate resolution of numerous other gaps. Solely a handful of important dependencies are noted here.
The gap identified in G6.02 arises as a result of G6.01. One of the key benefits of resolution of G6.01 would be the potential to rationalise dispersed observational assets.
The resolution to G6.03 will be simpler if a more unified governance of non-satellite measurement networks is achieved and the data is provided from these networks in a more unified manner.
The data policy landscape is a direct result of the fractured governance of observational assets identified in the current gap. Resolving the current gap would aid steps to address the issues detailed in G5.01.

Detailed description

Non-satellite data sources identified as "reference" and "baseline" quality within GAIA-CLIM have greatly dispersed governance structures. There are numerous national, regional, and global networks, which aim to measure GAIA-CLIM target ECVs to a high standard. This dispersed governance leads to decisions, which, although sensible on an individual network basis, are sub-optimal on a more holistic basis.
This fractured governance both results from but also augments a diversity in historical and present-day funding support, authority, and observational program priorities. Inevitable deleterious results accrue from a fractured governance and support mechanism, which include:

- Geographical dispersal of capabilities
- Unintended and undesirable competition between otherwise synergistic activities
- Different networks take different approaches to data acquisition (measurement practices), data processing and serving, which reduces both accessibility to and comparability of the resulting data.

As such, many of the remaining gaps identified within the GAIA-CLIM GAID are symptoms of the effects of G6.01 remaining unaddressed (see prior section). Although the gap has been identified and articulated here solely for GAIA-CLIM target ECVs, it is symptomatic of broader issues that pervade the governance of all but perhaps for a small handful of non-satellite observational assets and programs. The norm is for multiple parties to be interested in measuring given ECVs and other variables. These parties inevitably undertake a diverse range of approaches, which reduces their comparability and interoperability.

Validation aspects addressed

- Radiance (Level-1 product)
- Time series and trends
- Representativity (spatial, temporal)
- Calibration (relative, absolute)

Gap status after GAIA-CLIM

After GAIA-CLIM this gap remains unaddressed

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/application area benefitted	Probability of benefit being realised	Impacts
More unified voice for non-satellite data management	International (collaboration) frameworks (space agency, EU institutions, WMO programmes/frameworks etc.)	High	Improved ability to engage in strategy planning. Improved responsiveness in a unified fashion to identified user and stakeholder needs.
Rationalisation of observational assets	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	Medium	Closer to optimal co-location of high-quality instrumentation leading to better characterisation of atmospheric properties.
Consistency of data provision	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	Medium	More consistent provision of data (reduction in variety of portals and / or formats) leading to better ability to utilise the data.
More efficient use of resources	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High Medium	Greater value to funders
Identified risk	**User category/application area benefitted**	**Probability of risk being realised**	**Impacts**
Reduction in funding opportunities for high-quality measurements owing to fractured and competing demands.	International (collaboration) frameworks (space agency, EU institutions, WMO programmes/frameworks etc.)	Medium	Reduced value of observations.
Continued fractured governance leading to sub-optimal management and development of high-quality measurement networks.	International (collaboration) frameworks (space agency, EU institutions, WMO programmes/frameworks etc.)	High	Reduced utility of observational data assets through fractured decision-making.

Part III Gap Remedies

Remedy 1 – Undertake short-term cross-network governance improvements

Primary gap remedy type

Governance

Specify remedy proposal

Strengthen existing efforts to ensure meaningful collaboration between potentially synergistic or complementary networks. This could be achieved via several means. Improved cross-governance group representation could be implemented between networks that have similar aims / remits which may start to enforce a degree of collaboration and cross-fertilisation of best practices. A more formal approach, which may be relevant in certain cases, is a more formal network memoranda of understanding. On a more practical and working level, synergies can be realised through involvement in joint research and infrastructure activities such as EU Research Infrastructures, Horizon 2020, and Copernicus grants and service contracts or similar activities outside of Europe. Networks should be actively encouraged to participate in such funding opportunities. Funders should explicitly advertise such opportunities and consider targeted research funding opportunities that aim to build synergies between observational networks.

Relevance

The remedy would lead to improved cross collaboration and understanding between networks of potential synergies and serve to improve the visibility of activities between synergistic groups.

Measurable outcome of success

Demonstrable increase in collaboration between networks through joint projects, publications describing joint research outcomes, and participation in network meetings.

Expected viability for the outcome of success

High

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

- EU H2020 funding
- national funding agencies
- Copernicus funding
- WMO
- ESA, EUMETSAT or other space agency

Remedy 2 – Longer-term rationalization of observational network governance

Primary gap remedy type

Governance

Specify remedy proposal

Take steps to assess and as necessary rationalise the number of networks involved in taking high-quality measurements by merging, where possible, leading to more unified governance and planning for these measurement programs, both regionally and globally. To undertake this robustly requires an analysis of the current observational capabilities and governance structure, which should take account of funding, geopolitical remit, and other relevant factors. This may include in-depth survey interviews and other means to fully understand the role, support-model, and uses of each network. Then a rationalisation plan would need to be produced, circulated, and gain broad buy-in amongst the affected networks and associated global oversight bodies. Mergers should only proceed on a no-regrets basis and should not be enforced, if funding support or other essential support would be weakened as a result of the decision. Merged entities must be scientifically more robust, complete, and sustainable as a result of any merger.

Relevance

The remedy would make it easier for funding and research communities to interact with the high-quality measurement networks.

Measurable outcome of success

Reduction in complexity of the "ecosystem" of observing networks through time while retaining and enhancing observational capabilities.

Expected viability for the outcome of success

Medium

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

More than 10 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

No

Potential actors

- EU H2020 funding
- Copernicus funding
- National funding agencies
- National Meteorological Services
- WMO
- ESA, EUMETSAT or other space agency

G6.02 Analysis and optimisation of geographical spread of observational assets to increase their utility for satellite Cal/Val, research, and services

Gap Abstract

As a result of fractured governance along with historical funding decisions, the geographical spread of observation systems, which may, in principle, be synergistic, are not presently sufficiently optimised in order to realise the potential benefits for numerous research applications, including, but not limited to, satellite cal/val. For example, a twice-daily radiosonde program may currently be undertaken 100km from a facility with lidars and an FTIR. This dispersion of observational capabilities may substantially reduce their overall value to the user community for multiple uses.

Part I Gap description

Primary gap type

Spatiotemporal coverage

Secondary gap type

Governance (missing documentation, cooperation etc.)

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (space agencies, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques Involved

Independent of instrument technique

Related gaps

- G1.10 Relative paucity and geographical concentration of reference-quality measurements, with limited understanding of uncertainty in remaining measurements, limits ability to formally close satellite to non-satellite comparisons

- G6.01 Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions

Part of the closure of G1.10 may include a rationalisation of the dispersed observational capabilities in data-sparse regions to maximise both their value and their long-term sustainability.
G6.02 arises as a direct result of G6.01, which is the fractured governance of measurement systems. Addressing G6.01 will strongly facilitate closing G6.02.

Detailed description

A direct result of the fractured governance of observational networks is that instruments that could derive synergistic analysis benefits are very frequently not geographically co-located. That is to say that an instrument may belong to network or operator X and be located 100km distance from a suite of potentially complimentary instruments belonging to network or operator Y. Because the measurements are geographically dispersed, this serves to reduce their value for numerous applications, including, but not limited to, satellite characterisation. This arises either because they measure complementary ECVs that enable fuller understanding, or measure distinct aspects of the same ECV such that, when combined, a fuller understanding of the measurand accrues. This is especially important for certain satellite instruments such as hyperspectral sounders, which, across the sensed channels, are sensitive to a broad range of ECVs such that to adequately characterise them requires quasi-coincident measures of a broad number of ECVs with an overpass.

In a worst-case scenario of a catastrophic space weather event, there remains a risk that multiple satellites are simultaneously unavailable. To bridge such an event from a climate perspective requires the persistence of a set of in-situ sounding capabilities that can measure what is sensed by the satellite instrumentation across the gap. For the more complex instruments, there is value to this being achieved by a set of super-sites that measure multiple ECVs simultaneously and to high quality.

However, in some cases, there may be good reasons to not co-locate measurements (1) if long time series already exist, it would be counterproductive to climate monitoring to disrupt the time series by re-locating the instrument to another site; (2) the atmospheric variability may be different from one target species to another, justifying their observation at different sites, and (3) the benefits of a site for satellite validation are not necessarily the same as for other research purposes. For example, a mountain site may be very appropriate for stratospheric observations, but is much less appropriate for satellite validation.

Therefore, a careful scientific analysis should be carried out before implementing a new observation site, and before deciding to re-locate an instrument, taking into account the existing data, the existing sites in the neighbourhood, and the main scientific objectives of the (new) observations. Funding authorities and network coordinators should take these scientific analyses into account before taking decisions about the implementation of new observations or moving existing capabilities.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

- Radiance (Level 1 product)
- Representativity (spatial, temporal)
- Calibration (relative, absolute)
- Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Improved characterisation of state of atmospheric column characteristics at co-located sites	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High	Better ability to characterise processes and undertake vicarious calibration of satellites and other instrumentation
Development of novel products combining information from multiple instruments	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	Medium	Improved understanding of relevant processes, new products, and services
Cooperation between investigators, networks, and funders	International (collaboration) frameworks (space agency, EU institutions, WMO programmes/frameworks etc.)	Medium	Better planning and deployment of future observational capabilities
Cost reduction	all application areas	High	Larger benefit/cost ratios
Identified risk	**User category/Application area benefitted**	**Probability of risk being realised**	**Impacts**
Continued lack of strategic placement of research infrastructure, leading to diminished scientific value across the range of application areas.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) International (collaboration) frameworks (space agency, EU institutions, WMO programmes/frameworks etc.)	High	Reduced quality of data services provided by dispersed instruments. Potential research insights arising from co-located observational strategy not realised.
Threat to instrument long-term continuity arising from not realising full value of assets.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High Medium	Reduction in overall non-satellite measurement constellation capabilities.
Reduced ability to bridge across catastrophic satellite failure.	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium Low	Many satellite instruments take measurements that are sensitive to multiple parameters. To bridge the effect of catastrophic failure requires surface assets capable of sufficiently mimicking the measurement series.
Observational needs cannot be satisfied because of too high cost	All application areas	Medium	Non-optimised deployment of research infrastructures leads to instruments not working effectively, which reduces available data for many applications

Part III Gap Remedies

Remedy 1 – Reviews of capabilities leading to action plans for rationalization of current non-satellite observational capabilities

Primary gap remedy type

Deployment

Secondary gap remedy type

Governance

Proposed remedy description

Undertake reviews of high-quality observational assets to assess potential value of different reconfigurations of capabilities to address multiple potential applications. These assessments may be carried out nationally, regionally, or internationally. The assessments must be guided to the extent available by quantitative research and well-formulated stakeholder needs. The reviews would lead to steps towards consolidation of facilities where a clear overall benefit to multiple data stakeholders is identified in doing so. The analysis may be facilitated by activities such as OSSEs, short period field campaigns or other activities, which permit a quantitative assessment of the benefits of collocating capabilities. It may also make use of a number of existing instrument-rich sites such as the US department of energy's Atmospheric Radiation Measurement (ARM) Southern Great Plains site, Ny Alesund, Lindenberg, Lauder, and others. It may build on work assessing the observational entropy of different measurement configurations (Madonna et al., 2014)

Relevance

The remedy would lead to rationalisation of observing capabilities to selected super-sites where justified.

Measurable outcome of success

Evidence of more strategic decision-making and long-term planning in research infrastructure investments and progressive creation of more co-located facilities.

Expected viability for the outcome of success

Medium

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

High cost (> 5 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

- Copernicus funding
- National funding agencies
- National Meteorological Services
- WMO
- ESA, EUMETSAT or other space agency

References

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G6.03 Lack of sustained dedicated periodic observations to coincide with satellite overpasses to minimize co-location effects

Gap Abstract

There are many non-satellite measurement systems that, in principle, could be used for the purposes of satellite characterization on a sustained basis. Such measurements are metrologically well characterized and understood. They often measure variables, which are measured or measurable from space. However, many of the measurement systems are discontinuous (discrete) in time and their measurement scheduling is typically made with no regard to satellite-overpass times. This considerably diminishes their value for satellite Cal/Val activities. Better scheduling would increase their intrinsic value for satellite programs.

Part I Gap description

Primary gap type

- Governance

Secondary gap type

- Spatiotemporal coverage
- Uncertainty in relation to comparator measures

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (space agencies, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

- Radiosonde
- Ozonesonde
- Lidar
- FPH/CFH

Related gaps

- G6.01 - Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions
- G6.06 - Provision of reference-quality measurements on a sustained and continuous basis to maximise opportunities for the validation of satellite and derived products

G6.01 - To be addressed with G6.03
Argument: The resolution to the current gap will be simpler if a more unified governance of non-satellite measurement networks is achieved and the data is provided from these networks in a more unified manner.
G6.06 To be addressed with G6.03
Argument: Operationalising instruments that can be operated 24/7 removes the current gap for the instruments affected.

Detailed description

For some non-satellite instruments, there are geophysical limitations as to when measurements can be undertaken, e.g. an FTIR requires direct line of sight to the sun or a MAX-DOAS can only measure at sunrise/sunset.

Other instruments can and do operate 24/7 and therefore could always capture a co-location, if the satellite passes overhead. For example, both GNSS-PW and microwave radiometers, in principle, operate on a 24/7 basis. G6.06 discusses issues around their continuous operation where this is not yet assured.

But for many non-satellite measurement techniques, it is for financial or logistical reasons that measurements are solely episodic. For example, operational radiosonde launches tend to be twice-daily or at best four times daily at fixed local times. Similarly, for many instrument configurations, lidar operations may be made only when staff are available. These types of considerations effect very many non-satellite measurements, which could, in principle, be better targeted to support EO-sensor characterization by taking measurements much closer to satellite-overpass time. This would reduce the co-location mismatch and thus the attendant mismatch uncertainties. Because funding for these observations typically is not concerned with satellite characterisation, the current sampling strategy ends up being sub-optimal for satellite characterisation. Better aligning sampling strategies with times of satellite overpass, which are predictable a substantial time in advance, would increase their utility to satellite Cal/Val activities.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Time series and trends
- Representativity (spatial, temporal)
- Calibration (relative, absolute)
- Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Gap status after GAIA-CLIM

After GAIA-CLIM this gap remains unaddressed

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Better intra-satellite and inter-satellite data characterization using the ground (non-satellite) segment through increased pool of co-locations to common non-satellite tie-points	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Better characterized satellite data will yield improved utilization in derived products, including reanalyses products and resulting services.
More robust funding support for ground-based observations continuity, recognising that ground-based products may have unique value in, e.g., providing vertically resolved profiles to characterise satellites.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) International (collaboration) frameworks (space agency, EU institutions, WMO programmes/frameworks etc.)	Medium	Increased diversity and quality of tools and data available to support service providers to develop bespoke products.
Identified risk	**User category/Application area benefitted**	**Probability of risk being realised**	**Impacts**
Insufficient number of high-quality co-locations in the future that meet co-location match-up criteria to meaningfully constrain (at least some) satellite missions.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Reduced confidence in satellite measurements and products and services derived therefrom.
Inability to use non-satellite segment to effectively bridge across any unplanned gap in spaceborne EO capabilities	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Low	Reduced colocations reduces the opportunity to use the non-satellite series to bridge the effects of any gap and yield a homogeneous series. This reduces the value of the satellite record for monitoring long-term environmental changes.
Reduction in perceived utility and value of measurements leading to reduction in funding	International (collaboration) frameworks (space agency, EU institutions, WMO programmes/frameworks etc.)	Low	Diversifying the usage base of the high-quality measurements increases their intrinsic value and helps support widespread adoption.

Part III Gap Remedies

Remedy 1 – Optimization of scheduling to enhance capability for satellite Cal/Val activities

Primary gap remedy type

Deployment

Secondary gap remedy type

Governance

Proposed remedy description

Sustained funding and governance mechanisms need to be instigated and assured that optimise the observational scheduling of relevant high-quality non-satellite periodic (non-continuous) measurements and their provision in NRT for satellite characterisation, if the full potential value of these measures is to be realised. To be effective, space agencies and non-satellite high-quality observing networks need to work together to design, instigate, and fund a sustained program of targeted measurements that optimise collection and dissemination of non-satellite data in support of the space-based observational segment. The scientific benefits will be maximised if a strategy can be devised, which optimizes the ability of the non-satellite data segment to characterize satellite instrument performance across time, across platforms and across instrument types. This, in turn, points to individual non-satellite observational segments being tasked with helping to characterise across multiple missions from multiple agencies from multiple countries to maximise the scientific value of the cal/val exercise rather than this support being extended and decided on a per mission basis. The strategy should include recourse to other measurements. For example, EUMETSAT have recently introduced a forecasting tool, which can, with high probability, forecast colocations of radio-occultation measurements with a ground-based instrument and any given polar orbiter mission. Finding such occurrences potentially enhances the value of co-locations substantially by making them multi-point comparisons.

Care must be taken for any changes in scheduling not to impact deleteriously upon existing functions and purposes of the non-satellite segment. This implies that, in at least some cases, the remedy will need to involve funding support commensurate with taking new or additional measurements at sites. The most obvious solution would be to instigate an international measurements support program, which would administer and disperse funding support for sustained satellite cal/val with reference-quality data from operators who optimise spending decisions and have as active stakeholders space agencies, non-satellite data providers, and end-users.

Relevance

Better scheduling would increase the number of co-locations available for measurement systems that are discontinuous in time and increase the intrinsic value of the non-satellite observations for satellite Cal/Val.

Expected viability for the outcome of success

High

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

- Copernicus funding
- National funding agencies
- WMO
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes
- SMEs/industry
- National measurement institutes

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Remedy 2 – Operationalize use of double-differencing techniques in co-location matchups to minimize the effects of scheduling mismatch

Primary gap remedy type

Deployment

Secondary gap remedy type

Research

Proposed remedy description

In some circumstances, competing demands make it impossible to better align scheduling of non-satellite measurements to satellite measurements. In other cases, the measurement itself is constrained by the measurement technique. Thus, efforts are required to quantify and reduce the impacts of scheduling mismatches if these cannot be avoided. Within GAIA-CLIM, much effort has been made on quantifying mismatch effects, but there are also potentially tools and techniques to effectively remove the effects, at least to first order. One potential way to do so, which has shown promise for ECVs amenable to data assimilation in NWP models, is double differencing (Tradowsky et al., 2017). This involves the calculation and comparison of the pair of differences to a model estimate between observations that are relatively proximal in space and time under the assumption that the model biases are either negligible or constant. In theory, the technique could be applied to a broad range of ECVs and problems although work would be required to develop such approaches using chemistry models or similar models. Work is additionally required to operationally produce such estimates and tag the co-locations with these estimates, if they are to prove useful in reducing the impact of unavoidable mismatch effects arising from conflicting scheduling requirements.

Relevance

Reduces the potential impact if a scheduling mismatch is unavoidable by removing a first order dynamical estimate of the effects of the differences in the sensed air mass.

Expected viability for the outcome of success

High

Scale of work

Single institution
Consortium

Time bound to remedy

Less than 5 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

- National meteorological services
- Academia, individual research institutes
- National measurement institutes
- SMEs/industry

References

Tradowsky J S, C P Burrows, S B Healy and J Eyre, 2017: A new method to correct radiosonde temperature biases using radio occultation data. J. Appl. Meteor. Climatol., 56, 1643-1661, https://doi.org/10.1175/JAMC-D-16-0136.1

G6.06 - Provision of reference-quality measurements where technically feasible on a continuous basis, to maximize opportunities for the validation of satellite and derived products

Gap Abstract

Many non-satellite reference measurements have the potential to be operated on a continuous basis, or can at least be made available to operate at any time, even if in practice they cannot take uninterrupted observations, e.g. because the measurement technique requires certain geophysical conditions. Providing continuous observations to the extent possible would maximise opportunities for the validation of satellite-based measurements, as well as higher level data products derived from them. For various reasons - including scientific, technical, operational, organisational, and financial reasons - this potential has not been fully realised to date as many reference observations are obtained only intermittently or are discontinuous because of the lack of funding. This gap sets out the general and overarching case for 'operationalising' and sustaining key reference measurements.

Part I Gap description

Primary gap type

Spatiotemporal coverage

Secondary gap type

Technical (missing tools, formats etc.)

ECVs impacted

Temperature, Water vapour, Ozone, Aerosols, Carbon Dioxide, Methane

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- International (collaborative) frameworks and bodies (space agencies, EU institutions, WMO programmes/frameworks etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

- Lidar
- Microwave Radiometer
- GNSS-PW
- FTIR
- Brewer/Dobson
- UV/VIS zenith DOAS
- UV/VIS MAXDOAS
- PANDORA
- Other non-GAIA-CLIM targeted instrument techniques: sunphotometer

Related gaps

- G6.03 Lack of sustained dedicated periodic observations to coincide with satellite overpasses to minimize co-location effects

To be addressed with G6.06.
Argument: Operationalizing and maintaining instruments that can possibly be operated 24/7 increases the number of dedicated observations to coincide with satellite overpass.

- G5.11 Non-operational provision of fiducial reference-measurement data and some (L2) satellite products may prevent use in Copernicus operational product monitoring

To be addressed with G6.06.
Argument: Provision of reference-quality streams to users in near-real-time increases their utility to numerous applications, including satellite Cal/Val

Detailed description

The ECVs addressed in the GAIA-CLIM project (temperature, water vapour, aerosols and atmospheric composition) are measurable by a diverse range of instruments. For some non-satellite instruments, there are geophysical limitations as to when measurements can be undertaken, e.g., FTIR requires direct line of sight to the sun under clear-sky conditions. However, other instruments (e.g., GNSS-PW and microwave radiometers) can, in principle, operate on a continuous basis.
The primary benefits of sustained and continuous operations are two-fold: Firstly, the opportunities to achieve spatiotemporal match-ups with satellite measurements - if this is the primary approach to validation - are maximized; and secondly the validation of higher level data products (spanning the full range from retrieved products, through gridded products, to global reanalysis-based products) is enhanced through the use of continuous, or almost continuous, datasets.
The measurement techniques potentially available to serve as reference measurements for the relevant ECVs include: ground-based microwave radiometry and infrared spectrometry; differential optical absorption spectroscopy (DOAS and Pandora), lidar (including Rayleigh, Raman, rotational Raman and differential absorption lidar), Brewer/Dobson spectrometers, and sunphotometers. There are a number of reasons why, in practice, many measurements are not made on a continuous basis:

- Technical - instruments may require frequent maintenance, adjustment, calibration, or retuning requiring manual intervention, which may not be available on a continuous basis; data acquisition and analysis may still require too many manual interventions;
- Scientific – particular site-specific conditions may prevent measurements being made. For example, cloud conditions may preclude certain measurements (e.g., FTIR – for composition measurements, or for passive measurements of temperature and humidity, also rotational Raman lidar for temperature).
- Operations / logistics – the site may not be manned continuously and instruments cannot, as yet, operate in an automated way; also, the data analysis may not be sufficiently automated.
- Financial - funding authorities often neglect the importance of the non-satellite observing system, whereas it is indispensable for ca/val of the space segment of the observing system and as a transfer standard between successive satellites.

Funding, clearly, plays a key role in determining the capacity for a given instrument to make (continuous) measurements and to rapidly deliver the data. Targeted funding support to meet multiple stakeholder needs including, but not limited to satellite cal/val, could ensure that a station/instrument is capable of more continuous operations and more rapid delivery of the data through higher levels of manning. Funding could also support technical development work to improve the degree of automation of the instrumentation across entire national or international networks and of subsequent data analysis, thereby lowering the cost for continued operations and rapid data delivery.
The purpose of this gap is to recognize this general deficiency in many observing networks, and to encourage support to rectify these deficiencies. A funding mechanism (or mechanisms) needs to be instigated that recognizes the costs to be covered by those communities which shall benefit from such sustained operational capabilities (including but not only satellite applications). Such targeted support would ensure sustainability, recognizing the substantial diversity of competing demands on resources of in-situ measurement assets.

Operational space missions or space instruments impacted

Independent of specific space mission or space instruments

Validation aspects addressed

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Assimilated product (Level 4)
- Time series and trends
- Calibration (relative, absolute)
- Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Gap Status after GAIA-CLIM

After GAIA-CLIM this gap will remain

Part II Benefits to resolution and risks to non-resolution

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Better intra-satellite and inter-satellite data characterization using the ground segment through increased pool of co-locations to common non-satellite tie-points.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Better characterized satellite data will yield improved utilization in derived products, including reanalyses products and resulting services.
More robust funding support for ground-based observations continuity, recognizing that ground-based products may have unique value in, e.g., providing vertically resolved profiles, serving cal/val purposes and being a transfer standard between successive satellites.	International (collaboration) frameworks (space agency, EU institutions, WMO programmes/frameworks etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	Diversity of tools and data available to support service providers to develop bespoke products.
More rapid availability of the data to detect possible problems with the satellite and derived products	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	medium	Faster turn-around between observations and data availability; more rapid dissemination of reliable satellite and derived products.

Identified risk	User category/Application area benefitted	Probability of risk being realised	Impacts
Insufficient number of high-quality co-locations in the future that meet co-location match-up criteria to meaningfully constrain (at least some) satellite missions.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Reduced confidence in satellite measurements and products and services derived therefrom.
Inability to use non-satellite segment to effectively bridge across any unplanned gap in spaceborne EO capabilities.	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium Low	Reduced co-locations reduces the opportunity to use the non-satellite series to bridge the effects of any gap and yield a homogeneous series. This reduces the value of the satellite record for monitoring long-term environmental changes.
Reduction in perceived utility and value of measurements leading to reduction in funding.	International (collaboration) frameworks (space agency, EU institutions, WMO programmes/frameworks etc.)	Medium Low	Diversifying the usage base of the high-quality measurements increases their intrinsic value and helps support widespread adoption.

Part III Gap Remedies

Remedy 1 – Operationalize measurements to be 24/7 on an instrument-by-instrument and site-by-site basis.

Primary gap remedy type

Technical

Secondary gap remedy type

Laboratory

Specify remedy proposal

The precise remedy will be specific to individual cases. But, in general, it requires an assessment on a per-instrument and per-site basis of the current impediments to continuous operation of the asset and to rapid data delivery. Once the reason(s) underlying are known, then work can be undertaken to address them. Generally, these reasons may fall into several categories:

- Technical innovations or modifications to the instrumentation to enable continuous operations;
- Modifications to instrument housing;
- Modifications to data analysis system
- Funding increases to maintain the instrumentation and operations (data acquisition and analysis) and to enable more continuous operation and more rapid data analysis and dissemination.

Automation of observations and data analysis are key to achieving an optimised non-satellite observing system. Another path to more rapid data delivery is centralisation of the data processing in a network, with the condition that the central facility has the required expertise, maintains contacts with the network partners to evolve as the state-of-the-art evolves, and has sustained funding support. Amongst others, resolution of these issues shall require the participation of instrument scientists, site operators, networks, and funding agencies.

Relevance

Remedy will be specific to individual cases. But, in general, it requires an assessment on a per-instrument and per-site basis of the current impediments to continuous operation of the asset.

Measurable outcome of success

Increased number of high-quality non-satellite data available, providing a sufficient number of co-locations with satellite measurements on a sustained and more continuous basis, and providing the possibility to bridge successive satellite missions.

Expected viability for the outcome of success

High

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 10 years

Indicative cost estimate (exploitation)

Yes

Potential actors

- National funding agencies
- National Meteorological Services
- WMO
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes
- SMEs/industry
- National measurement institutes

Remedy 2 – Ensuring sustained funding of the non-satellite observing system

Primary gap remedy type

Governance

Specify remedy proposal

Providing the resources to enable operationalizing the non-satellite observing system is key to the viability of the above remedy 1. Currently several funding agencies do not sufficiently recognize the importance of sustaining the non-satellite long-term observing system. The stakeholder communities that benefit from the provision of non-satellite reference data should also take the responsibility to provide continued funding support that enables the operators of the system to maintain it to ensure compliance with state-of-the-art quality specifications, and to increase the benefit/cost ratio by proper automation and operationalisation. This could be achieved, e.g., by including the provision of support to the non-satellite observing system in the mandate of relevant funding agencies. Without the perspective of sustained support, the system operators cannot engage in system maintenance and optimization.

Relevance

Remedy 2 underpins remedy 1.

Measurable outcome of success

Increased long-term availability of continuous (where technically feasible) high-quality non-satellite data series, providing appropriate sampling of the atmosphere, a sufficient number of co-locations with satellite measurements and providing the possibility to bridge successive satellite missions.

Expected viability for the outcome of success

High

Scale of work

Programmatic multi-year, multi-institution activity

Time bound to remedy

Less than 10 years

Indicative cost estimate (exploitation)

Yes

Potential actors

- National funding agencies
- National Meteorological Services
- WMO
- ESA, EUMETSAT or other space agency
- SMEs/industry
- National measurement institutes
- Copernicus funding
- EU H2020 funding

G6.12 Under - capacity of workforce to exploit satellite data and satellite characterization

Gap Abstract

While it is necessary to address technical and organizational gaps that reduce the availability, effectiveness, and quality of satellite characterization data, such improvements need be exploited by a sufficient workforce capacity to develop and deliver products and services to the marketplace. There is a shortage of skilled personnel to enable activities from the development and deployment of high-quality non-satellite instrumentation, through its processing to its exploitation, in order to successfully provide high-quality data products merging satellite and non-satellite data. If Copernicus services are to realize their full potential, additional training through formal and informal routes is required to train the next generation of data providers, analysts, and users that can fully exploit the substantive investment in space-based and non-space based observational assets and tools and, hence, deliver the envisaged step-change in capabilities and services to the marketplace.

Part I Gap description

Primary gap type

Governance (missing documentation, cooperation etc.)

User category/Application area impacted

- Operational services and service development (meteorological services, environmental services, Copernicus Climate Change Service (C3S) and Atmospheric Monitoring Service (CAMS), operational data assimilation development, etc.)
- Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)

Non-satellite instrument techniques involved

Independent of instrument technique

Related gaps

Underpins many other gaps but not any critical relationship per se.

Detailed description

European and global space agencies are investing substantially in improved satellite based remote-sensing capabilities. At the same time, numerous national and trans-national networks are performing high-quality non-satellite measurements. To realise a return on investment on these observational assets requires a skilled workforce capable of understanding and exploiting these data to their full potential. Experience within the GAIA-CLIM project, which aims to develop a set of tools and approaches to highlight potential applications of non-satellite data to better characterise satellite observations, has highlighted the relatively limited pool of available expertise at the present time. This expertise deficit pertains to varying degrees to all aspects of the end-to-end chain from instrument experts through practitioners capable of delivering products to end-users. Without addressing the educational / training deficit highlighted, it will be impossible to fully realise the value of the substantive investments to date in the space and non-space observational segments. A range of training needs are envisaged from formal educational routes that train the next generation of instrument specialists, data analysts and product developers through to more informal training of those professionals delivering user services and advice. For example, training should be a mandatory service provided by the Environmental European Research Infrastructures.

Validation aspects addressed

Generic education gap underpins all aspects but is not directly related to any single other gap.

Gap status after GAIA-CLIM

After GAIA-CLIM this gap remains unaddressed

Part II Benefits to resolution and risks to non-resolution

Identified benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Innovative research	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High	New products, analyses, improved observations, and approaches, innovations to research infrastructures
Increase in practitioners capable of delivering user services	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High	Better provision of service and advice to users
Identified risk	**User category/Application area benefitted**	**Probability of risk being realised**	**Impacts**
Lack of capacity to uptake and use Copernicus data services	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	Medium	Lack of competition in marketplace, incorrect provision of advice and / or services to end users, non-utilisation of observational data to support decision making
Long-term observational operation compromised	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High Medium	Observational capabilities not sustained leading to critical gaps in service / information provision.
Long-term management of observational capabilities and programs compromised	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	Medium Low	Next generation of science and service leaders not available leading to reductions in service quality and / or provision.

Part III Gap Remedies

Remedy 1 – Undergraduate, masters, and doctoral training in Copernicus-relevant programs

Primary gap remedy type

Education/Training

Proposed remedy description

The exploitation of Copernicus data and services requires the training of a competent workforce of data providers, analysts, managers, and service provision experts. This requires a substantial increase in the number of relevant degree programs at undergraduate, masters and PhD levels. Via the Copernicus academy system, ERASMUS+, national programs, or other avenues, innovative teaching courses should be developed and shared to help develop competency in use of Copernicus data to derive products and services, including the use of satellite and non-satellite data and their appropriate synthesis / fusion / merging.

Perhaps most acute is training at the doctoral level, which provides the next generation of expert scientists capable of maintaining and improving the observational program and driving innovative analysis approaches. In many countries within Europe, there is very limited, if any, access to doctoral funding program support specifically targeted at Copernicus-relevant activities. Increasingly within H2020 / FP, and national projects, work seems shifted to postdoctoral and senior staff at the expense of doctoral training. There, hence, exists a looming capability capacity issue as the existing EO expert workforce is likely not being adequately replaced in time. The Copernicus program, along with other relevant stakeholders (a.o. ESA, EUMETSAT, national bodies), through the Copernicus Academy or other means, should facilitate a dedicated doctoral training program to questions relevant to Copernicus and dispersed via member states. This would enhance the ability of academic institutions within Europe to engage with Copernicus activities, while simultaneously training potential future researchers to support the sustained operation of Copernicus services. Such doctoral candidates and their supervisors would naturally act as champions of Copernicus within their institutions, potentially aiding uptake within the academic sector, and acting as a force multiplier.

Doctoral studentships are relatively inexpensive and offer an opportunity to explore issues in depth. Many of the gaps and remedies identified by both GAIA-CLIM are amenable to doctoral thesis type work. A targeted doctoral program addressing questions of mutual interest to host institutions and Copernicus would facilitate the provision of a sustainable programmatic capability while simultaneously better engaging academia within the programmatic structure of Copernicus.

Relevance

The exploitation of Copernicus data and services requires the training of a competent workforce of data providers, analysts, managers, and service provision experts.

Measurable outcome of success

Increase in range of qualified individuals supporting the Copernicus program provision.

Expected viability for the outcome of success

High

Scale of work

- Individually
- Single institution

Time bound to remedy

Less than 10 years

Indicative cost estimate (investment)

Low cost (< 1 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

- Copernicus funding
- National funding agencies

Remedy 2 – Instigate professional training, including formal qualification of competency in provision of Copernicus services

Primary Gap remedy type

Education/Training

Specify remedy proposal

The effective provision of services from Copernicus data requires users to have confidence about the quality of the service provider. This would be greatly aided by a program of training and certification of competency targeted at professionals working in the field who deliver user services and advice. This would assure that a basic level of service provision in the use and analysis of satellite and non-satellite data was attained by the party offering the service. This may result from a combination of proof of prior service engagement with users and / or formal training course(s) attendance. Service providers should show competency in accessing relevant observational data and products, their appropriate fusion, and the provision of advice to the user. A Copernicus service provision certificate could be provided by one or more accredited institutions offering training in required competencies with appropriate assessment. Training should be provided in a range of languages and need not be limited to European domain.

Relevance

Ensure that users can be confident of competency of service provider to deliver relevant information services.

Measurable outcome of success

Increased uptake of Copernicus services by end-users.

Expected viability for the outcome of success

High

Scale of work

- Individually
- Single institution

Time bound to remedy

Less than 3 years

Indicative cost estimate (investment)

Medium cost (< 5 million)

Indicative cost estimate (exploitation)

Yes

Potential actors

- Copernicus funding
- National funding agencies
- National Meteorological Services
- ESA, EUMETSAT or other space agency
- Academia, individual research institutes
- SMEs/industry
- National measurement institutes