GAIA-CLIM Report

Gap Analysis for Integrated Atmospheric ECV CLImate Monitoring:

Final review of and update to the GAID from the perspective of WP1

A Horizon 2020 project; Grant agreement: 640276

Date: 18/12/2017

Beneficiary: CNR

Nature: R

Dissemination level:

Work Package	WP 1
Deliverable	
Title	Final review of and update to the GAID from the perspective of WP1
Nature	R
Dissemination	PU
Beneficiary	CNR
Date	19/12/2017
Status	Final
Authors	Fabio Madonna, Peter Thorne, Anna Mikalsen, Michiel Van Weele, Martine De Maziere, Corinne Voces
Contacts	fabio.madonna@imaa.cnr.it
URL	http://www.gaia-clim.eu/

This document has been produced in the context of the GAIA-CLIM project. The research leading to these results has received funding from the European Union's Horizon 2020 Programme under grant agreement n° 640276.

Table of Contents

Introduction 4

1. Summary of existing gaps for WP1 6

2. Detailed update on traces for the gaps arising from WP1 7

3. Conclusions 8

4. Annex I Updated GAIA-CLIM Catalogue of gaps for WP1 8

Introduction

The GAIA-CLIM project aims to assess and improve global capabilities to use ground-based, balloon-borne, and aircraft measurements (termed non-satellite measurements henceforth) to characterise space-borne satellite measurement systems. The work under GAIA-CLIM encompasses the following tasks:

1. Defining and mapping 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 its work package 6, GAIA-CLIM performs an assessment of gaps in capabilities or knowledge relevant to the use of non-satellite data to characterise satellite measurements.

It is recognized that GAIA-CLIM shall provide progress in these application areas, but not necessarily close out all potential issues and challenges. Hence, in each of the project tasks outlined above, presently unfulfilled user needs ('gaps') have been identified through an iterative process throughout the project's lifetime. This gaps assessment exercise exclusively considers gaps identified as relevant to these GAIA-CLIM project aims. The identified key user communities for whom the impact of the identified gaps would be most relevant include:

- Service providers (e.g. ECMWF for NWP, CAMS and C3S)
- Users and providers of ECV climate data records (e.g. space agencies and satellite data user communities)
- Users of reference observations
- Users of baseline network observations
- Users of the 'Virtual Observatory'

The Gaps Assessment and Impacts Document (GAID) is a living document that summarises the outcome of this collection of gaps and their proposed remedies. It further describes the gap identification process, as well as the way these findings are presented and made accessible to users, stakeholders and actors. The current set of gaps and remedies captured under the living GAID document v4 provides a firm basis for providing costed and prioritised recommendations for future work to improve our ability to use non-satellite data to characterise satellite measurements. The first draft of recommendations document[1] builds upon this careful and meticulous collection and cataloguing process to produce a set of eleven overarching recommendations for future work to close the most critical gaps identified through the life of the project

This document provides a snapshot of the gaps status as per December 2017 in relation to work package 1. It provides a third, and final, formal delivery of WP1 input to the process. The on-line 'Catalogue of Gaps' provides the latest version of the full content of the gaps and their proposed remedies. The catalogue is available from: http://www.gaia-clim.eu/page/gap-reference-list.

[1] http://www.gaia-clim.eu/page/recommendations

Input from external parties continues to be invited through the GAID website. A designated e-mail address[2] and a specific template for gap reporting is provided at the website. Further user engagement shall be achieved through a series of visits to key stakeholders through the end of 2017. This user feedback will be important in refining the GAID and ensuring its usefulness to the broader scientific and policymaker communities, as well as space agencies, international organisations, and funding bodies.

[2] Email address for GAID feedback: gaid@gaia-clim.eu

1. Summary of existing gaps for WP1

Table 1.1. Overview of the gaps identified under work package 1 under GAID V4 and their identified remedies

Gap reference	Gap title	Remedies
G1.03	Lack of internationally recognised and adopted framework for assessment of fundamental observation capabilities	• (R1) Further deployments and refinements of the GAIA-CLIM approach • (R2) Adoption of measurement systems approach and assessment by international bodies
G1.04	Lack of a comprehensive review of current non-satellite observing capabilities for the study of ECVs across domains	• (R1) Extension and continuous update of a comprehensive review of existing geographical gaps for non-satellite observations
G1.05	Lack of integrated user tools showing all existing observing capabilities for measuring ECVs with respect to satellite spatial coverage	• (R1) Provision of mapping tools to match satellite and non-satellite observations
G1.06	Currently heterogeneous metadata standards hinder data discoverability and usability	• ((R1) Design and implementation of unified metadata format under a common data model
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	• (R1) Improved characterisation of high-quality instrumentation to increase the pool of reference quality observing techniques without necessitating new observational deployments. • (R2) Take steps to better realise the benefits of a system of systems approach to observing strategies • (R3) Improving quantification of the impacts of geographical gaps on ability to undertake user-driven activities such as to characterize satellite data

2. Detailed update on traces for the gaps arising from WP1

The changes made in the existing gaps identified as relevant for the WP1 activities are based on the following motivations:

- The need for an updated description of gaps and remedies linked to the timing and the progress of the activities carried out within GAIA-CLIM and other EU or international projects;
- The progress which contributed to the refinement of the gap analysis since the last version of the GAID;
- Improved knowledge of the motivation behind the gaps and an enhanced capability to clarify the description of gaps and remedies;
- Identified overlap between remedies to WP1 gaps and remedies to related gaps identified by other WPs.

Specific important content edits, beyond grammatical tidying, which have been applied in all cases per gap are as follows:

G1.03: "Lack of internationally recognised and adopted framework for assessment of fundamental observation capabilities"

Update to the gap description section to reflect the published status of Thorne et al., 2017. Addition of relevant Copernicus Climate Change Service (C3S) contract activities started since GAIDv4 to the first remedy. References to cited literature have been added.

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

Change in the title and the text of the remedy to reflect its broader scope. Reference in the remedy made to the recently initiated C3S (C3S 311a Lot 3) activity of relevance. Relationship with other gaps has been added.

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

Updates to reflect the final status of the Task 1.3 activities of relevance to this gap. Relationship with other gaps has been added.

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

Reordering of remedy proposal and addition of relevant information on C3S.

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"

The final remedy that was included in v4 of the GAID for this gap trace has been removed in response to substantial overlaps with gaps arisen by WP6.

3. Conclusions

This deliverable and the gap traces contained in the annexes constitute the third and final official input to the GAID process arising from WP1. Since the last version (v4) of the GAID, GAIA-CLIM activities related to WP1 are being followed up by the C3S Baseline and Reference Observation Networks (BARON, C3S 311a Lot 3), where, for a selected number of networks reviewed within GAIA-CLIM, the harmonization of the data and metadata format and structure shall be pursued. This exercise has been noted in the gaps related to this work package and supported the already outlined potential remedies.

4. Annex I Updated GAIA-CLIM Catalogue of gaps for WP1

Within this section, gaps that were detailed in section 1 are expanded to give full trace of the current understanding of the gaps, including a revision of its impacts and potential remedies.

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

Gap abstract:

There currently exists no universally recognised 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:

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:

- G1.04 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.

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 recognised 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 realisation of the full benefits of an explicitly system-of-systems architecture (trickle down calibration, characterisation, 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 recognised 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
Realising synergies between observational programs	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, 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

	International (collaborative) frameworks and bodies (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)		
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 realising 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 realised leading to degraded assessments of observational change
Full value of programs such as WIGOS not realised	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.)	High	Confusion to end-users on what different data streams constitute

	International (collaborative) frameworks and bodies (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)		

Part III: Gap remedies

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:

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.)

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
- G1.05 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**	**Impacts**

		being realised	
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 Data Records)	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 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

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

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

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

Technical readiness:

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

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

References:

- 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.