Gaps Assessment and Impacts Document

(Version 3.0)

GAIA-CLIM
Gap Analysis for Integrated
Atmospheric ECV Climate Monitoring
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Work Package 6; Edited by Michiel van Weele (KNMI)

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Executive Summary

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. 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 (work packages) unfulfilled user needs ('gaps') are being identified. A key addition to this iteration includes the formulation of the gaps in a *SMART* fashion, i.e. specific or actionable, with a measurable outcome and clear relevance, with a cost estimate and for given time bounds.

User needs are further being obtained from the GAIA-CLIM user survey and the three user workshops. Furthermore, expert input on the public drafts is welcomed through a dedicated website for the GAID (http://www.gaia-clim.eu/page/gaid) suggesting additional gaps or updating our knowledge of the identified gaps' status. Specific important user communities for which the impact of the identified gaps would be most relevant include at least:

- Service providers (e.g. ECMWF for NWP, CAMS and C3S)
- Users of ECV climate data records (e.g. for IPCC/WMO assessments)
- Users of reference observations
- Users of baseline network observations
- Users of the 'Virtual Observatory

An on-line *Catalogue of Gaps* has been set up to support traceability of gaps and is further maintained at the GAIA-CLIM website http://www.gaia-clim.eu/page/gap-reference-list. This catalogue could be further enhanced with an interactive functionality that would enable the user to provide feedback via a wiki facility.

The purpose of the Gaps Assessment and Impacts Document (GAID) is to provide (i) the latest status of the on-line catalogue, and (ii) to provide an analysis of the list of gaps by taking different cross sections through the full catalogue. The catalogue is regularly updated during the project timeframe. Importantly, the catalogue is not limited solely to those gaps which are envisaged to be (partly) remedied within the project. Although some gaps may be (partly) remedied within the project (e.g. through developments related to the Virtual Observatory), for other gaps remedies will be out-of-scope for the GAIA-CLIM project. Part of the assessment includes an analysis of scientific and societal impacts of the gaps, identified potential remedies, and to begin to assess feasibility of resolution of the gap (remedies and gap prioritization).

The gaps assessment exercise is limited in scope to consider solely gaps relevant to the GAIA-CLIM project aims. Thus, it has a focus on the availability of, and ability to utilize non-satellite (reference) observations in support of the long-term sustained space-borne and non-satellite monitoring of a set of ECVs. The GAIA-CLIM primary atmospheric ECVs specifically are temperature, water vapour (H_2O), ozone (O_3), carbon dioxide (CO_2), methane (CH_4) and aerosols. Because these ECVs are being monitored through the EUMETSAT operational satellite programme, the Copernicus Space Segment and ESA research satellites, as well as by non-EU satellites, the relevance of the gaps and impact assessment is not limited to Europe. Nevertheless, some focus in the project is placed on the European infrastructure for climate monitoring.

In the GAID, cross sections through the catalogue of gaps are taken in various relevant aspects, e.g. per ECV and per instrument technique. The analysis aims to help identifying any inconsistencies, similarities and/or complementarities between gaps that e.g. might originate from different work packages. Also, potentially missing gaps might be found through such an analysis approach which can be incorporated in further iterations.

Further, to structure the analysis all identified gaps have been categorized into seven more generic 'gap types', including

- Gaps in Spatiotemporal Coverage
- Gaps in Vertical Domain and Vertical Resolution
- Measurement Uncertainty
- Comparator Uncertainty
- Technical Gaps
- Parameter Gaps
- Governance Gaps

The GAID is a living document and several versions of this document are to be produced throughout the lifetime of the GAIA-CLIM project. The list of gaps in the catalogue, the impacts, the (partial) remedies as well as preliminary cost assessments as presented in this version of the GAID are expected to further evolve.

From this GAID version 3 onward the GAID, as a living document, extracts the latest information from the website at specific points in time, more or less coinciding with the deliverable dates for each of the GAID versions. In the final year of the project, the GAID shall provide the basis for the drafting of a deliverable providing costed and prioritised recommendations for future work to improve our ability to use non-satellite data to characterise satellite measurements.

GAID versions 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 WP 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 WP 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 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 GAIDv3 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. Through WP6 an updated list of governance gaps has been included.	KNMI	31 August 2016

1 Introduction

A leading role in the global Earth Observation constellation has been taken by Europe with the development of its own operational space infrastructure. The growing European space infrastructure for climate monitoring is building on the existing 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). At time of writing in 2016, the first Sentinels are in orbit and the subsequent Sentinels are to be launched within the next 5-7 years. The long-term evolution of the CSS into its second generation during the next decade is currently under active development. In addition, ESA research satellites form an important component of Europe's space segment.

To maximise the return on investment, a sustained and high quality characterisation capability using non-satellite data is required. A multi-faceted and sustainable program could be foreseen which would facilitate regular satellite-to-satellite comparisons, intensive field campaigns, and dedicated calibration payload missions for sustained homogenized time series of Essential Climate Variables (ECVs).

For climate monitoring, the need for long-term sustained (> 30 years) homogenized time series of known high quality constitutes a huge challenge, both on the meteorological sensors and the CSS. The satellite observations need to be calibrated and validated to standards that enable them to be used with confidence for climate applications. 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 on the regional to global scale.

However, few, if any, of the non-satellite *'comparator measures'* – i.e. the value of a ECV to be compared with a satellite observation though having very different attributes – provide fully traceable robust uncertainty estimates. Without full traceability in the comparator measures, there is ambiguity in any non-satellite data segment comparison that ultimately limits its scientific value and utility for climate monitoring.

It is described in the Description of Action (DoA) of GAIA-CLIM that robust satellite instrument characterisation requires at least:

- Quantified uncertainty estimation***s*** for the non-satellite (reference) observations
- Understanding of the uncertainties in the non-satellite observations including apparent discrepancies between data sets through mismatches in spatiotemporal sampling, due to non-perfect colocation, and differences in the perception of the atmosphere of each measurement technique
- Dedicated user tools – which will primarily be served within GAIA-CLIM through the development of a 'Virtual Observatory'

The key challenges regarding the gap assessment in this document, the Gaps Assessment and Impacts Document (GAID), are then:

(i) To identify important limitations of the non-satellite monitoring segment for characterising space-based measurements for climate monitoring focusing on the user needs for selected atmospheric ECVs, the so-called '*gaps*',
(ii) To assess these gaps and to ascertain their impact, and
(iii) To prioritize the needs and to create a set of specific potential remedies to address the identified gaps

The GAIA-CLIM primary ECVs are temperature, water vapour (H_2O), ozone (O_3), carbon dioxide (CO_2), methane (CH_4) and aerosols. For this set of key atmospheric 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. The O_3 and aerosol precursors are being studied in the EU partner project QA4ECV and therefore discussion of user needs with respect to ECVs such as CO and NO_2 is given lower priority in GAIA-CLIM.

The GAID is a living document that shall benefit from broad stakeholder engagement and external input which is being solicited at various meetings and conferences and through a dedicated webpage (http://www.gaia-clim.eu/pages/gaid). At the General Assembly in Helsinki (10-11 February 2016) the suggestion was made to reorder the GAID outline per GAIDv3. An on-line Catalogue of Gaps has been set up and will be further maintained at the GAIA-CLIM website. The purpose of this GAID is to provide

(i) the latest status of the on-line catalogue at http://www.gaia-clim.eu/page/gap-reference-list

(ii) to provide an analysis of the list of gaps by taking cross sections through the catalogue.

Section 2 explains the approach to the collection and identification of the analysed gaps. In Section 3 we present an initial set of cross sections of the list of gaps and summarize their impacts, remedies and costs along these cross sections.

The most recent version of the catalogue is presented in Section 4. In the GAID only the list of gaps is presented with gap identifiers and short descriptions. Full gap descriptions are provided in the underlying project deliverables per work package, which for GAIDv3 include D1.4, D2.2, D3.3, D4.3 and D5.2, and also further in the on-line catalogue. In Section 5 we summarize the work and provide an overview of the past and further planned outreach activities related to this document. The Annex documents the input received through WP6 in preparation of the updated and completed list of governance gaps that is presented in Section 3.5.

2 The Identification of Gaps

2.1 User Communities and the Gap Collection Process

The gaps that are identified within GAIA-CLIM derive from both external users and communities and internal work packages in an iterative fashion. Because GAIA-CLIM is application driven, the impact(s) of each of the gaps is assessed from the (end-)user perspective, the service provider perspective (Numerical Weather Prediction (NWP), Copernicus Climate Change Service (C3S), Copernicus Atmospheric Monitoring Service (CAMS)), and in reference to the GCOS climate monitoring principles and general targets (Sections 2 and 3).

Different user communities can be distinguished including:

U1 Service providers (e.g. ECMWF for NWP, CAMS and C3S)
U2 Users of ECV climate data records (e.g. for IPCC/WMO assessments)
U3 Users of reference observations
U4 Users of baseline network observations
U5 Users of the planned ‘Virtual Observatory

In practice there might be some overlap between users in these user categories. Key users for the gap analysis in GAIA-CLIM are at least the data users that need non-satellite observations for climate monitoring in combination with spaceborne observations.

Task 6.1 has been providing external input to the GAID on user needs. A user survey has been undertaken and reported (Deliverable 6.1 ‘Report on results of user survey’,) and a first user workshop was held on 6 October 2015 in Rome, Italy (Deliverable 6.3 ‘Summary of first workshop with external users’). A second workshop is planned for November 2016 in Brussels and a final workshop is foreseen for month 33 (2017). These user workshops are intended to provide important additional information on user needs, potential gaps and anticipated impacts for users, which will feed further into the future versions of the GAID.

The results of the user survey presented in D6.1 indicate 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, while it was also recognised that it might be difficult to define the functionality such that it will be taken up by users. Another important gap that was clearly revealed in the survey was related to user familiarity with, and use of, uncertainties in non-satellite (reference) observations.

At the first user workshop in Rome – which has been summarized in D6.3 – some specific operational user needs e.g. for the CAMS operational validation were presented. Based on the user workshop a set of specific gaps related to TCCON and greenhouse gas monitoring have been added to the GAIA-CLIM catalogue.

Inputs to the GAID are potentially further derived from external sources, e.g., WMO / GCOS documents on ECVs, climate monitoring principles and (target) requirements and also the ESA Climate Change Initiative (CCI), EUMETSAT Satellite Application Facilities (SAF), and the Copernicus services. The ESA CCI programme aims to strengthen the climate monitoring contribution of the past and present-day space segment for atmospheric composition, and specifically includes in relation to GAIA-CLIM several primary ECVs as contributing projects Ozone_cci, GHG_cci and Aerosol_cci. The EUMETSAT SAF Network, in particular the Climate Monitoring SAF (CM SAF), provides temperature and humidity climate data records.

Specific input from external parties will be further invited through the upcoming user workshops and the above-mentioned GAID website. Apart from the latest approved version of the GAID a designated e-mail address (gaid@gaia-clim.eu) and a specific template for gap reporting is being provided at the website.

Inevitably, the materials that are brought together in the GAID will have a bias towards those gaps that are considered within the sphere of the GAIA-CLIM project. The impact assessment will be utilized for the prioritization in Task 6.3 (which is starting in month 24) of gap remedies, and improvements in the observation capability will be provided as a set of recommendations that both the European Commission and relevant national and international agencies can act on. Furthermore, complementarity is sought with e.g. the EU partner project QA4ECV for gaps related to the atmospheric ECV precursors *CO*, NO_2, and CH_2O.

2.2 Primary ECVs and Contributing Instrumental Techniques

The primary ECVs addressed in GAIA-CLIM include temperature, water vapour, ozone, aerosols, and the well-mixed greenhouse gases CO_2 and CH_4. The gap analysis for e.g. the precursor ECVs such as CO, NO2 is mostly left to the related EU project QA4ECV.

Table 1 provides, per primary ECV addressed in GAIA-CLIM, an overview of contributing surface networks and airborne observations, 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)
- ACTRIS/EARLINET (Aerosols, Clouds, and Trace gases Research InfraStructure Network/European Aerosol Research Lidar Network)
- The NOAA Global Greenhouse Gas Reference Network (GGGRN)
- Air Quality (AQ) national networks

Table 1. *Overview per GAIA-CLIM primary ECV of the contributions of surface networks and airborne observation programmes (incl. the applied instrumental techniques) to climate monitoring per atmospheric domains (PBL = planetary boundary layer; LT = lower troposphere < 6km); UT = upper troposphere (> 6km); LS = lower stratosphere (< 25 km); US+M (> 25 km) = upper stratosphere + mesosphere). Networks are denoted in italics, instrument techniques in plain text. Status per GAID Version 2.0. CFH = Cryogenic Frostpoint Hygrometer (see also the list of Acronyms)*

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* MW, ground GNSS, sondes, FTS	*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, MAX-DOAS	*NDACC* Brewer-Dobson, UV-VIS, MAX-DOAS, FTIR	*NDACC* sondes, FTIR *IAGOS* Aircraft in-situ	*NDACC* Sondes, FTIR *IAGOS* Aircraft in-situ	*NDACC* Lidar, FTIR, MWR, sondes *IAGOS* Aircraft in-situ	*NDACC* Lidar, FTIR, MWR, sondes (up to 30-35 km)
Aerosols	*AQ networks* Surface in-situ	*Actris/Earlinet* Lidar *Aeronet* Photometer, 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*

Per network, the specific instrument techniques used are indicated: These include: surface in-situ, lidar, FTIR, sondes, aircraft in-situ, balloon, and cryogenic frost point hygrometers (CFH). The information content of Table 1 partly has built on the mapping exercise being performed in WP1. The next iteration of the GAID will benefit from a consideration of D1.6 and D1.7 which given time constraints has not been possible for the current GAID version submitted contemporaneously with these.

2.3 Version Control of Individual Gaps and the GAID

The GAID is a living document and several official versions shall be produced over the project lifetime. The current version is version 3 of the document. It documents gaps that arise from both internal and external input. To ensure the traceability and provenance of gaps between versions the following practices have been adopted:

- A gap once identified is given an unique identifier associated with the most logical WP or user community from which the gap derives, e.g. the GHG_CCI project
- A gap can have changed principal work package responsibility but its unique identifier remains
- A gap can be retired if felt by project participants either to be resolved or to be no longer relevant. If so, the gap identifier is also retired

A couple of gaps that had been identified in versions 1 and 2 of the GAID have been subsequently retired in GAID version 3. These gaps can still be found in the earlier versions of the GAID. The reasons for their retirement are articulated in the underlying deliverables D1.4, D2.2, D3.3, D4.3 and D5.2, including whether a new more specific gap has been added in its place. Because gaps are not being renumbered during the course of the project a few identifier numbers do not appear in the GAIA-CLIM Gap Catalogue (Section 4). For GAID version 3 a total number of 88 gaps have been identified.

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 (and hence deliverable) from which it arose. Taking cross sections through other dimensions such as ECV, instrument technique used, or generic gap type might help to further analyse the identified gaps and find e.g. potential inconsistencies, similarities, complementarities etc. Note that some of the 88 gaps in total might appear multiple times by taking cross sections. The excerpts are selected inclusive rather than exclusive to get the complete overview.

3.2 Gaps per Gap Type

Each of the identified gaps is being associated with one or more identified generic gap types. These provide another means of providing cross section on the identified gaps. Seven generic gap types are currently being distinguished by the GAID process:

- ***Spatiotemporal Coverage***: gaps in geographical and/or temporal coverage, i.e. a lack of measurements
- ***Vertical Domain and Vertical Resolution***: either limitations in altitude range or not resolving the vertical column sufficiently
- ***Measurement Uncertainty***: incomplete uncertainty budget, including calibration and e.g. spectroscopic uncertainties, i.e. all uncertainties intrinsic to one measurement
- ***Comparator Uncertainty***: uncertainties relating to comparator measures, i.e. uncertainties related to comparisons between measurements which have different attributes individually
- ***Technical***: user needs related to data dissemination, specific missing tools, formats, etc.
- ***Parameter***: missing parameter knowledge, missing auxiliary information related to the measurement of an ECV
- ***Governance***: user needs related to network governance and data policy, data access, gaps in

QA/QC methodologies/traceability/documentation/learning

In this subsection 3.2 the gaps are grouped in terms of their generic gap type for the first six types. For the seventh gap type, the governance gaps, containing the set of gaps identified by WP6 participants to specifically aid preparation of this release of the GAID is summarized separately in Section 3.5. Because these governance gaps are presented here for the first time we give the input provided for this version 3 of the GAID integral in the Annex to enable full traceability of their origin.

3.2.1 Gaps in Spatiotemporal Coverage

Gaps in coverage typically relate 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 include:

Gaps in Spatiotemporal Coverage	
G1.03	Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions
G1.04	Lack of a comprehensive review of current non-satellite observing capabilities for the study of ECVs in atmospheric, ocean and land domains
G1.07	Need for a scientific approach to the assessment of gaps in the existing networks measuring ECVs.
G1.08	Evaluation of the effect of missing data or missing temporal coverage of fully traceable data provided by ground-based networks
G1.09	Limited availability of quantitative CO profiles
G1.13	Uncoordinated lidar and microwave radiometer water vapour measurements
G1.14	Currently limited aircraft measurements in Eastern Europe
G1.15	Northern Hemisphere bias in NDACC and PANDORA network sites distribution
G2.01	Common lack of continuous operation of aerosol lidar measurement systems
G2.02	Lidar measurements missing vertical coverage in lowermost altitude range
G2.03	Incomplete collocation of sun and lunar photometers with day and night time aerosol lidars
G2.06	Need for more multi-wavelength Raman lidars
G2.10	Tropospheric O_3 profile data from non-satellite measurement sources is limited
G2.35	TCCON sites with high/low albedo and hot spot monitoring
G4.11	Limited geographical coverage of reference temperature and humidity radiosondes
G6.GHGCCI.03	No TCCON stations in Africa, large parts of Asia, S. America, Russia, Middle East, high/low surface albedo, and to validate important spatial gradients across large ecosystems

3.2.2 Gaps in the Vertical Domain or 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 surface / lower atmosphere observations 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 include:

Gaps in Vertical Domain or Vertical Resolution	
G1.09	Limited availability of quantitative CO profiles
G1.14	Currently limited aircraft measurements in Eastern Europe
G2.02	Lidar measurements missing vertical coverage in lowermost altitude range
G2.10	Tropospheric O_3 profile data from non-satellite measurement sources is limited
G6.GHGCCI.05	Very limited vertical profile reference measurements (TCCON)

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 include:

Gaps in Knowledge of the Uncertainty Budget and Calibration	
G1.10	Insufficiently traceable uncertainty estimates
G1.11	Traceable uncertainty estimates from baseline and comprehensive networks
G1.12	Propagate uncertainty from well-characterized locations and parameters to other locations and parameters
G2.04	Missing continued intercomparison of lidars with appropriate reference systems
G2.05	Lack of metrologically rigorous aerosol lidar error budget availability
G2.07	Need for assimilation experiments using lidar measurements
G2.08	Reducing water vapour lidar calibration uncertainties using a common reference standard
G2.09	Continuous water vapour profiles from Raman lidars limited during daytime
G2.11	Lack of rigorous tropospheric O_3 lidar error budget availability

G2.12	Lack of rigorous temperature lidar error budget availability
G2.13	Missing microwave standards maintained by National/International Measurement Institutes
G2.14	Lack of a comprehensive review of the uncertainty associated with MW absorption models used in MWR retrievals
G2.16	Missing agreement on calibration best practices and MWR instrument error characterization
G2.17	Lack of a common effort in homogenization of MWR retrieval methods
G2.18	Better agreement needed on systematic versus random part of the uncertainty in FTIR measurements and how to evaluate each part
G2.19	Line of sight and vertical averaging kernel are only approximations of the real 3D averaging kernel of a FTIR retrieval
G2.20	Substantial spectroscopic uncertainties in FTIR H_2O and CH_4 products
G2.21	Current spectroscopic databases contain uncertainties specifically effecting TCCON retrievals of CH_4 and CO_2
G2.22	FTIR cell measurements carried out to characterize ILS have their own uncertainties
G2.23	Possible SZA dependence in the FTIR CH4 retrievals during polar vortex overpasses
G2.24	Lack of in-situ calibration of CH_4 and CO_2 FTIR measurements
G2.26	Uncertainty in O_3 cross sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis
G2.27	Random uncertainty in total column O_3 retrieved by UV-vis spectroscopy dominated by instrumental imperfections impacting on the spectral fit calculations
G2.28	Uncertainty in a priori profile shape for AMF calculations for zenith sky O_3 retrievals
G2.29	Uncertainty in the vertical averaging kernels used for DOAS total column O_3 retrieval
G2.30	Lack of uncertainty quantification for Pandora O_3 measurements
G2.31	Lack of understanding of the information content of MAX-DOAS tropospheric O_3 measurements
G2.32	Better characterization of the different MAX-DOAS tropospheric O_3 retrieval methods needed
G2.33	Lack of in-depth understanding of random and systematic uncertainties of MAX-DOAS tropospheric O_3 measurements
G2.34	Uncertainties of ZTD for GNSS-PW, given by a 3rd party without full traceability
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and 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
G4.01	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances - relating to temperature
G4.02	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances - relating to humidity
G4.07	Error correlations for reference sonde measurements

G4.08	Ocean surface emissivity estimates in the microwave
G4.09	Land surface emissivity estimates in the microwave
G4.10	Land surface emissivity estimates in the infrared

3.2.4 Uncertainty Gaps 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 include:

Uncertainty Gaps in Relation to Comparator Measures	
G2.03	Incomplete collocation of sun and lunar photometers with day and night time aerosol lidars
G3.01	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and their co-location
G3.02	Limited quantification of the impact of different co-location criteria on comparison results
G3.03	Missing generic and specific standards for co-location criteria in validation work
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 error/uncertainty budget decomposition including errors/uncertainties due to sampling and smoothing differences

3.2.5 Technical Gaps

Technical gaps might include e.g. specific missing tools, data portal technicalities, etc. Specifically, gaps related to data policies, user training etc. are considered in this document as gaps in governance instead of pure technical gaps. The technical gaps which have been identified within GAIA-CLIM include:

Technical Gaps	
G1.02	Unknown suitability of measurement maturity assessment
G1.05	Lack of unified tools showing all the existing observing capabilities for measuring ECVs with respect to satellite spatial coverage

G1.06	Lack of a common effort in metadata harmonization
G2.15	Lack of unified tools for automated MWR data quality control
G5.01	Access to data in multiple locations with different user interfaces constitutes a barrier to usage and makes use in general difficult
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
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
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 Cal/Val data manipulations for atmospheric ECV validation systems prevents progress in the characterization of satellite products
G5.09	A readily accessible online tool is missing to perform radiative transfer calculations to transfer reference measurements of ECVs, including their uncertainty estimates, into the corresponding measurement space of a matching observation from space
G5.10	Characterisation of different types of uncertainty has not been systematically addressed per ECV
G5.11	Non-operational provision of reference measurement data and some (L2) satellite products may prevent use in Copernicus operational product monitoring
G6.GHGCCI.02	Data delivery too late for timely satellite data validation (TCCON)

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 in relation to the 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 O_3 profile. As another example: modellers might need additional parameters with the observed ECVs to verify their models, e.g., parameters related to Brewer-Dobson circulation, convective mixing, etc. The parameter gaps that have been identified within GAIA-CLIM include:

Parameter Gaps	
G4.08	Ocean surface emissivity estimates in the microwave
G4.09	Land surface emissivity estimates in the microwave
G4.10	Land surface emissivity estimates in the infrared

3.3 Gaps 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 more of general nature. These more generally applicable gaps are not repeated in these cross sections of gaps separated per instrument technique.

3.3.1 Gaps for Sondes

Gaps for Sondes	
G1.15	Northern Hemisphere bias in NDACC and PANDORA network sites distribution
G2.10	Tropospheric O_3 profile data from non-satellite measurement sources is limited
G4.07	Error correlations for reference sonde measurements

3.3.2 Gaps for Lidars

Gaps for Lidars	
G1.13	Uncoordinated lidar and microwave radiometer water vapour measurements
G2.01	Common lack of continuous operation of aerosol lidar measurement systems
G2.02	Lidar measurements missing vertical coverage in lowermost altitude range
G2.03	Incomplete collocation of sun and lunar photometers with day and night time aerosol lidars
G2.04	Missing continued intercomparison of lidars with appropriate reference systems
G2.05	Lack of metrologically rigorous aerosol lidar error budget availability
G2.06	Need for more multi-wavelength Raman lidars
G2.07	Need for assimilation experiments using lidar measurements
G2.08	Reducing water vapour lidar calibration uncertainties using a common reference standard
G2.09	Continuous water vapour profiles from Raman lidars limited during daytime
G2.11	Lack of rigorous tropospheric O_3 lidar error budget availability
G2.12	Lack of rigorous temperature lidar error budget availability

3.3.3 Gaps for FTIR

Gaps for FTIR	
G1.15	Northern Hemisphere bias in NDACC and PANDORA network sites distribution
G2.18	Better agreement needed on systematic versus random part of the uncertainty in FTIR measurements and how to evaluate each part
G2.19	Line of sight and vertical averaging kernel are only approximations of the real 3D averaging kernel of a FTIR retrieval
G2.20	Substantial spectroscopic uncertainties in FTIR H_2O and CH_4 products
G2.22	FTIR cell measurements carried out to characterize ILS have their own uncertainties
G2.23	Possible SZA dependence in the FTIR CH4 retrievals during polar vortex overpasses
G2.24	Lack of in-situ calibration of CH_4 and CO_2 FTIR measurements

3.3.4 Gaps for TCCON

Gaps for TCCON	
G2.21	Current spectroscopic databases contain uncertainties specifically effecting TCCON retrievals of CH_4 and CO_2
G6.GHGCCI.01	Lack of structural funding
G6.GHGCCI.02	Data delivery too late for timely satellite data validation
G6.GHGCCI.03	No TCCON stations in Africa, large parts of Asia, S. America, Russia, Middle East, high/low surface albedo, and to validate important spatial gradients across large ecosystems
G6.GHGCCI.04	Absolute calibration of TCCON to WMO standards is limited (height and frequency)
G6.GHGCCI.05	Very limited vertical profile reference measurements
G6.GHGCCI.06	Missing system for urban scale validation needed for high spatial resolution satellite data
G6.GHGCCI.07	No absolute calibration available (as is for TCCON), no traceability to WMO standards, no standardized procedures for NDACC retrievals

3.3.5 Gaps for UV-VIS / MAX-DOAS / Pandora

Gaps for UV-VIS / MAX-DOAS / Pandora	
G1.15	Northern Hemisphere bias in NDACC and PANDORA network sites distribution
G2.26	Uncertainty in O_3 cross sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis
G2.27	Random uncertainty in total column O_3 retrieved by UV-vis spectroscopy dominated by instrumental imperfections impacting on the spectral fit calculations
G2.28	Uncertainty in a priori profile shape for AMF calculations for zenith sky O_3 retrievals
G2.29	Uncertainty in the vertical averaging kernels used for DOAS total column O_3 retrieval
G2.30	Lack of uncertainty quantification for Pandora O_3 measurements
G2.31	Lack of understanding of the information content of MAX-DOAS tropospheric O_3 measurements
G2.32	Better characterization of the different MAX-DOAS tropospheric O_3 retrieval methods needed
G2.33	Lack of in-depth understanding of random and systematic uncertainties of MAX-DOAS tropospheric O_3 measurements

3.3.6 Gaps for MWR / GNSS

Gaps for MWR / GNSS	
G1.13	Uncoordinated lidar and microwave radiometer water vapour measurements
G2.13	Missing microwave standards maintained by National/International Measurement Institutes
G2.14	Lack of a comprehensive review of the uncertainty associated with MW absorption models used in MWR retrievals
G2.15	Lack of unified tools for automated MWR data quality control
G2.16	Missing agreement on calibration best practices and MWR instrument error characterization
G2.17	Lack of a common effort in homogenization of MWR retrieval methods
G2.34	Uncertainties of ZTD for GNSS-PW, given by a 3rd party without full traceability

3.3.7 Gaps for Aircraft Observations

Gaps for Aircraft Observations	
G1.14	Currently limited aircraft measurements in Eastern Europe

3.4 Gaps per ECV

In this section we include the gaps which are specific for one or maybe two ECVs only. There are of course many gaps which do not relate to one or two ECVs specifically. Such more generally applicable gaps are not repeated in these cross sections per ECV as presented here.

3.4.1 Gaps for Temperature

Gaps for Temperature	
G2.12	Lack of rigorous temperature lidar error budget availability
G2.14	Lack of a comprehensive review of the uncertainty associated with MW absorption models used in MWR retrievals
G2.15	Lack of unified tools for automated MWR data quality control
G2.16	Missing agreement on calibration best practices and MWR instrument error characterization
G2.17	Lack of a common effort in homogenization of MWR retrieval methods
G4.01	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances - relating to temperature
G4.07	Error correlations for reference sonde measurements
G4.08	Ocean surface emissivity estimates in the microwave
G4.09	Land surface emissivity estimates in the microwave

3.4.2 Gaps for Water Vapour

Gaps for Water vapour	
G1.13	Uncoordinated lidar and microwave radiometer water vapour measurements
G1.14	Currently limited aircraft measurements in Eastern Europe
G2.08	Reducing water vapour lidar calibration uncertainties using a common reference standard
G2.09	Continuous water vapour profiles from Raman lidars limited during daytime
G2.14	Lack of a comprehensive review of the uncertainty associated with MW absorption models used in MWR retrievals
G2.15	Lack of unified tools for automated MWR data quality control
G2.16	Missing agreement on calibration best practices and MWR instrument error characterization
G2.17	Lack of a common effort in homogenization of MWR retrieval methods

G2.20	Substantial spectroscopic uncertainties in FTIR H_2O and CH_4 products
G2.34	Uncertainties of ZTD for GNSS-PW, given by a 3rd party without full traceability
G4.02	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances - relating to humidity
G4.07	Error correlations for reference sonde measurements
G4.08	Ocean surface emissivity estimates in the microwave
G4.09	Land surface emissivity estimates in the microwave

3.4.3 Gaps for Ozone

Gaps for Ozone	
G1.14	Currently limited aircraft measurements in Eastern Europe
G1.15	Northern Hemisphere bias in NDACC and PANDORA network sites distribution
G2.10	Tropospheric O_3 profile data from non-satellite measurement sources is limited
G2.11	Lack of rigorous tropospheric O_3 lidar error budget availability
G2.26	Uncertainty in O_3 cross sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis
G2.27	Random uncertainty in total column O_3 retrieved by UV-vis spectroscopy dominated by instrumental imperfections impacting on the spectral fit calculations
G2.28	Uncertainty in a priori profile shape for AMF calculations for zenith sky O_3 retrievals
G2.29	Uncertainty in the vertical averaging kernels used for DOAS total column O_3 retrieval
G2.30	Lack of uncertainty quantification for Pandora O_3 measurements
G2.31	Lack of understanding of the information content of MAX-DOAS tropospheric O_3 measurements
G2.32	Better characterization of the different MAX-DOAS tropospheric O_3 retrieval methods needed
G2.33	Lack of in-depth understanding of random and systematic uncertainties of MAX-DOAS tropospheric O_3 measurements

3.4.4 Gaps for Aerosols

Gaps for Aerosols	
G2.01	Common lack of continuous operation of aerosol lidar measurement systems
G2.02	Lidar measurements missing vertical coverage in lowermost altitude range
G2.03	Incomplete collocation of sun and lunar photometers with day and night time aerosol lidars
G2.04	Missing continued intercomparison of lidars with appropriate reference systems
G2.05	Lack of metrologically rigorous aerosol lidar error budget availability
G2.06	Need for more multi-wavelength Raman lidars
G2.07	Need for assimilation experiments using lidar measurements

3.4.5 Gaps for CO_2

Gaps for CO_2	
G2.21	Current spectroscopic databases contain uncertainties specifically effecting TCCON retrievals of CH_4 and CO_2
G2.22	FTIR cell measurements carried out to characterize ILS have their own uncertainties
G2.24	Lack of in-situ calibration of CH_4 and CO_2 FTIR measurements

3.4.5 Gaps for CH_4

Gaps for CH_4	
G2.20	Substantial spectroscopic uncertainties in FTIR H_2O and CH_4 products
G2.21	Current spectroscopic databases contain uncertainties specifically effecting TCCON retrievals of CH_4 and CO_2
G2.22	FTIR cell measurements carried out to characterize ILS have their own uncertainties
G2.23	Possible SZA dependence in the FTIR CH4 retrievals during polar vortex overpasses
G2.24	Lack of in-situ calibration of CH_4 and CO_2 FTIR measurements

3.5 Governance Gaps

Governance gaps could include user needs on e.g. coordination, funding, data policy (dissemination, free access), clarification of methodologies, missing traceability, missing documentation, lack of user training, etc. The governance gaps which have been identified within GAIA-CLIM include:

Governance Gaps	
G1.03	Missing evaluation criteria for assessing existing observing capabilities
G1.04	Lack of a comprehensive review of current non-satellite observing capabilities for the study of ECVs in atmospheric, ocean and land domains
G1.13	Uncoordinated lidar and microwave radiometer water vapour measurements
G1.14	Currently limited aircraft measurements in Eastern Europe
G1.15	Northern Hemisphere bias in NDACC and PANDORA network sites distribution
G2.03	Incomplete collocation of sun and lunar photometers with day and night time aerosol lidars
G2.04	Missing continued intercomparison of lidars with appropriate reference systems
G2.16	Missing agreement on calibration best practices and MWR instrument error characterization
G6.01	Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions
G6.02	Geographically dispersed observational assets reduce their utility for satellite Cal/Val
G6.03	Lack of dedicated funding for targeted observations to coincide with satellite overpass
G6.04	Mixed level of user experience with using uncertainty information
G6.05	Future support for GRUAN-processor
G6.06	a) Lack of dedicated funding for fast-delivery of targeted observations for satellite validation/calibration b) Lack of structural funding for station maintenance, data acquisition and initial analysis
G6.07	Different data policies in different networks harm the use of complementary data from different networks
G6.08	INSPIRE: a) Application of INSPIRE Implementing Rules to atmospheric and any other 3D/4D-data is not straightforward w.r.t. dimensionality, quality, etc. b) Where do data of one Member State end up which acquired in another Member State and/or is derived from satellite?
G6.09	Responsibility for observations in developing countries (Africa - Asia - S America)
G6.10	An unlimited growth of data portals, metadata standards and formats might make data discovery and access increasingly difficult
G6.11	The possible gradual loss of island radiosonde stations
G6.GHGCCI.08	Access to relevant ECMWF meteorological datasets is difficult or impossible for some researchers

4 GAIA-CLIM Catalogue of Gaps

In this section, we catalogue the present list of identified gaps per work package only through their short descriptions. The full description of each of the identified gaps, including their trace, the full discussion of the impacts and the suggested potential remedies, are provided online at the GAIA-CLIM project website.

The online gap catalogue at http://www.gaia-clim.eu/page/gap-reference-list will be maintained and updated further throughout the project. The copy of the GAIA-CLIM Catalogue of Gaps as provided here summarizes the content per August 2016. Retired gap numbers (see Section 2.3) include G1.01, G2.25, G4.03, G4.04., G4.05, G4.06, G5.04, G5.05.

GAIDv3, GAIA-CLIM

CATALOGUE of GAPS

http://www.gaia-clim.eu/page/gap-reference-list

31 August 2016

WP1 (Geographical capabilities mapping)

G1.02	**Unknown suitability of measurement maturity assessment** Ensure that the measurement maturity assessment prepared by GAIA-CLIM is readily applicable to all reference, baseline and comprehensive networks, and is beneficial to identify shortcomings in the practices applied by network operators. The maturity assessment involves assessing against 7 major strands such as metadata, uncertainty quantification and sustainability, as outlined in D1.3. This assessment, in the context of Task 1.2, has now been carried out for a number of target GAIA-CLIM networks and ECVs, but it should be applied more broadly to other ECVs and measurement domains if it is to extend its utility. Testing needs to be performed and may result in a subsequent need for revision of D1.3 accordingly either within or after the project.
G1.03	**Missing evaluation criteria for assessing existing observing capabilities** No effort has been made to define and broadly agree amongst global stakeholders the measurement and network characteristics underlying a system of systems approach to Earth Observation. As a result, this potentially inhibits realisation of the full benefits of an explicitly system of systems architecture (trickle down, calibration, characterisation etc.). It also places the burden of appropriate use of data squarely on the user, which is an unrealistic expectation in the majority of cases. Different domain areas use specific, but overlapping naming conventions, but often 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.

G1.04	**Lack of a comprehensive review of current non-satellite observing capabilities for the study of ECVs in atmospheric, ocean and land domains** Non-satellite observations support an increasingly wide range of applications in monitoring and forecasting of the atmosphere, and of the oceans and land surfaces, at different 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 new requirements have increasingly appeared with respect to these applications (and undoubtedly shall continue to do so). These observation systems provide the 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 European and global scale is needed for all the ECVs. This will also facilitate an identification of the existing geographical gaps in the global observing system. While a comprehensive review of space-based missions and needs has been put together within official documents of the international community (e.g. the CEOS Handbook and the “Satellite Supplement” to the 2nd GCOS Implementation Plan), in contrast the mapping of current non-satellite observing capabilities is piecemeal and poorly documented. 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 basis. Extensive reviews have been provided by WMO, GEOSS, GCOS, but they are limited to those networks and ECVs relevant for their institutional mission, and often disagree with one another.
G1.05	**Lack of unified tools showing all the existing observing capabilities for measuring ECVs with respect to satellite spatial coverage** A unified tool able to visualize all the sub-orbital observing capabilities for measuring ECVs at the global scale with respect to spatial and temporal coverage of space-based sensors has never been provided in the past by international bodies and agencies. Several tools have been implemented for specific networks of the global observing system, but all of them are designed on the basis of very specific needs, using different criteria/tools, and typically including just one ECV and only one or a small subset of the networks at the global scale. One of the most apposite examples is represented by the OSCAR system of the WMO and in particular for the surface based capabilities still under development. At its present state this tool is, focused on the WMO mission and does not include all the ECVs and all the existing networks. Moreover, satellite observing capabilities are collected separately and a unified tool able to show simultaneously all the existing non-satellite capabilities, along with the field of view of the satellite-based instruments can strongly help end-users in the design of new validation strategies and in the full exploitation of both ground-based and satellite data. This shall in turn help inform users on the available ECVs measurements within different domains (atmosphere, land, ocean) through a facilitated analysis of the geographical distribution of the system of networks at the global scale.
G1.06	**Lack of a common effort in metadata harmonization** Metadata is an increasingly central tool in the current web environment, 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. However, metadata standards have not been able to meet the needs of interoperability between independent

	standardization communities. 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. Several efforts have been undertaken to improve the harmonization of metadata across the networks and international programs, but this is still not sufficient. Harmonization effort in the atmospheric science community is related to the WIGOS standard, currently under development and subsequent implementation at the WMO, and by ESA CCI.
G1.07	**Need for a scientific approach to the assessment of gaps in the existing networks measuring ECVs.** Significant gaps in our observing capabilities limit our ability to provide a comprehensive characterization of the important physical parameters, and limit the accuracy of our predictive models and the satellite Cal/Val. Existing ground-based assets have not all been integrated into a coordinated observing network. Inadequacies include some large continental regions that are not monitored by any measurement stations or other assets. It is essential to understand the impacts of and, if scientifically necessary, reduce these gaps in the measurement data coverage, or at a minimum, to prevent these gaps from expanding if they would have deleterious impacts. Considering the importance of continuous, long-term observations for ECVs for many applications, an assessment of gaps on a scientifically sound basis is a necessary step for future improvements of the global observing system.
G1.08	**Evaluation of the effect of missing data or missing temporal coverage of fully traceable data provided by ground-based networks** Missing data are a common problem for geophysical data sets. For instrumental data sets obtained currently, the uneven spatiotemporal coverage arises for myriad reasons, depending on the type of instrumentation. For example, remote sensing is influenced by atmospheric conditions and can be hampered by clouds, aerosols, heavy precipitation, or extreme weather conditions. Alternatively, instrumentation may be limited to night-time or to periods when relevant staff are on-site or by similar factors. Missing data are, in particular, a source of problems in climate research, e.g., in the analysis and modelling of spatiotemporal variability. This is particularly so when the missing data is not entirely random such that there may arise a geophysical difference between the measured period and the potential fully sampled period. Analysing the full extent of the climate time series, with the missing points filled in, allows for greater accuracy and better significance testing in the spectral analysis. The full record can also improve our knowledge of the evolution of the oscillatory modes in the gaps, and provide new information on changes in climate. Spatiotemporal filling techniques have been developed, but there are only a few efforts at quantification of the effect of temporal sampling in the determination of atmospheric variability. This prevents full traceability of both the model and/or assimilation quantity and also the observational dataset.
G1.09	**Limited availability of quantitative CO profiles** Assess gaps in the observation system for CO vertical profiles and their impact on the evaluation of models and the derivation of top-down CO emissions. Source inversion techniques will help to evaluate how ground-based measurements can provide useful constraints in the derivation of top-down estimates for CO sources and sinks on the global scale. The impact of improved vertical resolution on the inversion of emissions, i.e. on posterior flux uncertainties and on the ability of the system to differentiate between different emission sources, will be determined.

G1.10	**Insufficiently traceable uncertainty estimates** Limited availability of traceable uncertainty estimates propagates to applications that use model or reanalysis fields. While a vast amount of data are available, the uncertainty of such data is - in a metrological sense - often only insufficiently specified, estimated or even unknown, which frequently limits the accuracy and thus the strict interpretation and use of atmospheric measurements. This concern has been raised by the NMIs participating in atmospheric networks (e.g. METEOMET). In order to achieve progress, it is critical to have data records that are stable over time, insensitive to the method of measurement, uniformly processed worldwide, and based on traceable references. This will allow us to establish the robust scientific basis for using such fields as a transfer standard in satellite dataset characterization and other activities, and for assessing the cost-effectiveness of potential observing system enhancements. Benefits will be logical rigour, reduction in ambiguity and better communication. A more informed use of data generated might allow large improvement in the accuracy of climate data records and might also allow to use a few satellites as reference data for calibration of models and re-analysis systems but, at present, potential users have low knowledge about the relative qualities of alternative datasets. Note: G1.10 is described in D2.2 (WP2).
G1.11	**Traceable uncertainty estimates from baseline and comprehensive networks** A baseline network provides a globally and regionally representative set of observations capable of capturing, at a minimum: global, hemispheric and continental-scale changes and variability. A comprehensive network provides observations at the detailed space and time scales required to fully describe the nature, variability and change of a specific climate variable, if analysed appropriately. As such, data provided by comprehensive networks but even more by baseline networks should be actively curated and retained. Datasets from baseline and comprehensive networks provide valuable spatiotemporal coverage, but often lack the metrological characteristics needed to facilitate traceable uncertainty estimates. It is therefore essential to identify the scope for baseline and comprehensive networks, leverage expertise from reference networks, including adopting elements of best practice from reference networks, and/or facilitating reprocessing that iteratively improves dataset quality. Note: G1.11 is described in D2.2 (WP2).
G1.12	**Propagate uncertainty from well-characterized locations and parameters to other locations and parameters** Reanalysis is a systematic approach to produce data sets for climate monitoring and research. Key limitations to reanalysis are (1) Observational constraints, and therefore reanalysis reliability, can considerably vary depending on the location, time period, and variable considered; and (2) The changing mix of observations, and biases in observations and models, can introduce spurious variability and trends into reanalysis output. It is clear that to fully exploit the value of ground-based remote sensing observations, they must provide traceable uncertainty estimates. On the other hand, the spatial coverage of ground-based measurements at the current state of the global observing system is often not sufficient for the satellite Cal/Val and climate monitoring and geographical gaps does not allow to have a sufficient representativeness in the observation available, to assess the NWP and reanalysis fields and the equivalent TOA radiances. In addition, there is a limited knowledge about how to propagate uncertainty from well-characterized locations and parameters to other locations and parameters. Note: G1.12 is described in D4.3 (WP4).

G1.13	**Uncoordinated lidar and microwave radiometer water vapour measurements** Water vapour and carbon dioxide (CO_2) are the principle greenhouse gases (GHGs). CO_2 is the main driver of climate change. Water vapour changes largely happen as a response to the change. Sustained observations of water vapour in the troposphere and UT/LS in the next decades will benefit from the integration of existing networks and observatories and the implementation of a coordinated effort at the global scale. Several stations are routinely performing water vapour measurements with microwave radiometers and with Raman lidars (column and profiles) often at the same site exploiting synergies, but they are often not coordinated thus losing their powerful observing capability at a large scale. However, the construction of such an integrated system will strongly depend on the creation of long-term sustainability of the research based observational initiatives. Long-term commitment of national and international funding agencies to maintain research and development efforts and funding for atmospheric observations is of fundamental importance. In this sense, the joint effort spent by ACTRIS and NDACC to have a common strategy in future, still under implementation, is worthwhile and could strongly improve this gap over the next 5-10 years.
G1.14	**Currently limited aircraft measurements in Eastern Europe** Missing aircraft information for many locations in Eastern Europe cause issues. Very few aircraft currently provide water vapour measurements over Europe, and even fewer O_3. Both of these parameters require additional sensors to be added to the aircraft. EUMETNET is funding available for a slow increase in the number of aircraft that carry humidity sensors, but currently there is planned for O_3.
G1.15	**Northern Hemisphere bias in NDACC and PANDORA network sites distribution** NDACC and PANDORA total column O_3 observation sites are concentrated in Europe and the US. There is definitely a strong bias towards Northern Hemisphere mid-latitudes and a lack of measurements in Asia, the tropics and Southern latitudes. (Note also that NDACC stations often include a variety of instruments measuring total column ozone such as UV/visible spectroscopy, MAX-DOAS, Brewer, Dobson, LIDAR, ozone sonde, FTIR). The lack of coverage in space and time limits the potential of the networks for e.g. latitudinal dependencies and global trend studies, climate change detection, satellite validation and long-term assessment of ECVs such as O_3. This gap is partially addressed within GAIA-CLIM.
WP2 (Measurement uncertainty quantification)	
G2.01	**Common lack of continuous operation of aerosol lidar measurement systems** Lidar profiling of atmospheric aerosol and cloud layers has become increasingly important for climate research during recent decades. More recently, the aircraft safety strategies followed after the volcanic eruption hazards of Eyjafjallajökull and Grimsvötn have increased the need for height-resolved monitoring of the aerosol concentration on continental scales. Most of the lidar measurements are not performed continuously (i.e. 24 hours/7 days a week). On the other hand, thousands of ceilometers and simple backscatter lidars are operating on a continuous basis all around the world, though the quality of their contribution to the characterization of

	aerosol impact on weather and climate as well as to satellite validation is limited compared to the more advanced multi-wavelength Raman lidar systems or HSRL. This is because of the strong assumptions needed to provide an estimate of the aerosol optical and microphysical properties. But, as a consequence of their complexity, higher-end lidar systems are quite expensive; thus their number is limited and many of them are operated by research institutes according to the local needs or to the protocols defined within research networks (e.g. EARLINET), or only occasionally during dedicated field campaigns. In principle, modern lidar instruments are capable of operating continuously, and several EARLINET stations can already provide continuous data. Continuous operation of aerosol lidars would dramatically increase the temporal coverage of lidar measurements for a continuous and sustained satellite validation program. Fully automated lidar systems would also decrease the high man-power costs involved in the operation of lidar systems, in particular during night-time measurements.
G2.02	**Lidar measurements missing vertical coverage in lowermost altitude range** Lidar profiling of atmospheric aerosol and cloud layers has become important for climate research during recent decades. Lidar systems have the technical limitation that they are limited in their coverage of the atmosphere close to the surface. The minimum altitude below which lidar can provide valid data depends on the particular configuration of the instrument and is in general different for each individual instrument even from a series-produced model as it is dependent on both, the optical design of the instrument, as well as the alignment of optical elements. The blind area close to the ground can pose a problem in the case that the atmospheric constituent is abundant in this domain and forms a substantial part of the total atmospheric column. Therefore, in cases where a lidar profile is being used to estimate a total column observation (for instance the aerosol extinction profile in relation to a satellite derived total aerosol optical thickness), considerable biases can occur that serve to complicate the analysis.
G2.03	**Incomplete collocation of sun and lunar photometers with day and night time aerosol lidars** Lidar profiling of atmospheric aerosols has become important for climate research during recent decades. Moreover, the synergy between lidar profiling and co-located total column aerosol properties provides additional insight into aerosol properties by using synergistic retrieval algorithms. For instance, using the synergy a distinction can be made between fine mode and coarse mode particles with height. This is important to understand radiative transfer in the atmosphere. In case a Raman lidar is collocated with a sun photometer and/or a lunar photometer, even more additional parameters can be derived. Hence, to fully exploit the synergy between lidars and photometers, collocation between both types of instruments at the various sites is needed.
G2.04	**Missing continued intercomparison of lidars with appropriate reference systems** Lidar profiling of atmospheric aerosol has become important for climate research during recent decades. Lidar systems cannot be independently calibrated. Therefore, the accuracy of aerosol lidar measurements can only be assured with internal instrumental quality checks, consistency of lidar observations with other instruments (e.g. total column aerosol observations), and through intercomparisons with lidar systems with a very well-known and well documented behaviour – so called reference systems. Such reference systems and comparisons are scarce (because they are expensive due to the need for experienced crew and extensive documentation of the system) and intercomparisons have to be done by collocating

	the reference systems with one or more lidar systems under consideration, which is a very time consuming and costly procedure. Ideally, intercomparisons with reference lidar systems should be done regularly, but time and funding are insufficient to make this happen.
G2.05	**Lack of metrologically rigorous aerosol lidar error budget availability** Lidar profiling of atmospheric aerosol has become important for climate research during recent decades. Lidar systems cannot be independently calibrated. Therefore, the accuracy of aerosol lidar measurements can only be assured with internal instrumental quality checks, consistency of lidar observations with other instruments (e.g. total column aerosol observations), and through intercomparisons with lidar systems with a very well-known and well documented behaviour – so called reference systems (see **G2.04**). In order to establish a rigorous aerosol lidar error budget, instrumental influence, as well as influence from ancillary information and calibration issues will have to be taken into account.
G2.06	**Need for more multi-wavelength Raman lidars** Raman lidars or multi-wavelength Raman lidars are undoubtedly the backbone of an aerosol global measurement infrastructure as they can provide quantitative range-resolved aerosol optical and microphysical properties. Whereas the detection of aerosol layers and their vertical extent requires only simple single wavelength backscatter lidars, the derivation of extinction coefficient profiles and a series of intensive aerosol properties requires advanced lidar concepts such as high-spectral resolution lidars (HSRL) or Raman lidars. The retrieval of aerosol microphysical properties and mass concentration requires at least a one-wavelength Raman lidar, but the error affecting these estimations can be dramatically reduced if a multi-wavelength lidar systems is used. This shows the relevance of having a large number of multi-wavelength lidar systems at the global scale; the relevance is also related to their potential role as anchor reference station to study of the impact of aerosols on weather and climate and for satellite validation. 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 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). Multi-wavelength Raman lidars could also 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 more dense 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 at the global scale is sufficient to carry out an accurate aerosol study.
G2.07	**Need for assimilation experiments using lidar measurements** Uncertainties associated with aerosol emissions, both 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. Data assimilation techniques are implemented to decrease these uncertainties, constraining models with available information from observations. Data assimilation is possible with horizontally sparse vertically dense data. In particular, lidar data can be effectively assimilated to greatly improve model skills. The use of ground-based lidar data allows us to anchor the bias correction for satellite lidar data using a variational bias correction scheme, in line with the growing interest by the global NWP community in using high-accuracy data from ground-based networks to constrain satellite data biases. 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 skills but, at the current stage, aerosol lidar data assimilation experiments are mainly limited to the assimilation of attenuated backscatter, which is a non-quantitative optical property of aerosol. Ground-based lidar networks can instead 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.
G2.08	**Reducing water vapour lidar calibration uncertainties using a common reference standard** One of the paramount needs for developing a long-term data set for monitoring atmospheric water vapour using lidar techniques is represented by 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. These step jumps in calibration increase the time required to detect atmospheric trends. 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, tools 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.
G2.09	**Continuous water vapour profiles from Raman lidars limited during daytime** Raman lidars have been shown to provide high-resolution 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. 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 improve the gap but with moderate to high costs, though their performance needs to be carefully assessed in advance. Synergy with other techniques, like passive microwave radiometry, provides an alternative solution to obtaining a profile of atmospheric water vapour during daytime over the entire investigated atmospheric column: this could partially address this gap but this synergetic solution requires the elaboration of new and more accurate algorithms to fully exploit the potential of the combined datasets.
G2.10	**Tropospheric O_3 profile data from non-satellite measurement sources is limited** Tropospheric O_3 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 O_3, in particular in the free troposphere, above the mixed layer and below the stratosphere, is difficult due to lack of data. Contrary to stratospheric O_3, passive satellite observations have limited access to information about tropospheric O_3. Also, ozone soundings using balloon borne samplers are too scarce to capture the relatively high spatial and temporal variability in the troposphere.

G2.11	**Lack of rigorous tropospheric O_3 lidar error budget availability** 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.
G2.12	**Lack of rigorous temperature lidar error budget availability** Temperature lidars provide important information for trend detection in the middle atmosphere (connected to trends in the ozone layer). These are detected using lidar systems that often also measure the O3 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 technique that can be used in the presence of aerosol. For both techniques a rigorous error budget needs to be established.
G2.13	**Missing microwave standards maintained by National/International Measurement Institutes** 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 metrology 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., 2014). This gap shall be addressed by national/international metrology institutes, and thus cannot be addressed within GAIA-CLIM.
G2.14	**Lack of a comprehensive review of the uncertainty associated with MW absorption models used in MWR retrievals** Most common MWR retrieval methods are based on the theory of radiative transfer 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. The intention is to address this gap within GAIA-CLIM.

G2.15	**Lack of unified tools for automated MWR data 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 be addressed at both manufacturer and network levels. An attempt is currently being carried out within the EU COST action TOPROF. Progress will be reported within GAIA-CLIM.
G2.16	**Missing agreement on calibration best practices and MWR instrument error characterization** Common procedures are applied by the operators to perform MWR calibration and instrument error characterization. Currently, these procedures are for the most part provided by the manufacturers, and thus they are often instrument specific. Therefore, there is currently a lack of standardization in calibration procedures and uncertainty characterization. This in turn impacts negatively on the harmonization of products provided by a heterogeneous MWR network. This gap shall be addressed at both manufacturer and network levels. An attempt is currently being carried out within the EU COST action TOPROF. Progress will be reported on within GAIA-CLIM.
G2.17	**Lack of a common effort in homogenization of MWR retrieval methods** Different retrieval methods are applied 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 those currently establishing in Europe. The uncertainty of MWR retrievals depends partially on the retrieval methods used, and the documentation and versioning of different methods are not usually easily accessible. Information on retrieval uncertainty is often completely missing. The traceability of software documentation and versioning is also not guaranteed. This impacts negatively on the harmonization of products provided by an heterogeneous MWR network. This gap shall be addressed at the network level. An attempt is currently being carried out within the EU COST action TOPROF. Progress will be reported on within GAIA-CLIM.
G2.18	**Better agreement needed on systematic versus random part of the uncertainty in FTIR measurements and how to evaluate each part** There is no clear agreement yet on what is the systematic part of the uncertainty, and on what the random part of the uncertainty in FTIR measurements is, and how to evaluate each part. Random and systematic uncertainty sources are defined differently for the two main retrieval software distributions within the FTIR NDACC working group (PROFFIT and SFIT). To harmonize the uncertainty computation, a recipe should be developed as to how a random and systematic uncertainty should be determined for each of the leading uncertainty contributions

	in the target retrieval uncertainty budget. The distinction between systematic and random uncertainties is important for determining accuracy and precision, e.g. when comparing to satellite data, and uncertainty of an average of data.
G2.19	**Line of sight and vertical averaging kernel are only approximations of the real 3D averaging kernel of a FTIR retrieval** The line of sight (LOS) is an important "first order" characterization of the horizontal averaging for FTIR measurements. Tools exist to calculate the line of sight for individual FTIR measurements. The UVVIS GEOMS templates have introduced variables and can be transferred to the FTIR GEOMS template to store the LOS information. This is planned for the next FTIR GEOMS template update. Comparisons cannot yet account fully for the representativeness of the data, even though the LOS is used in such a comparison. To further characterize the horizontal averaging, a more detailed study of the 3D kernels should be issued.
G2.20	**Substantial spectroscopic uncertainties in FTIR H_2O and CH_4 products** The current spectroscopic databases contain too large uncertainties to model correctly the spectral windows used for H_2O and CH_4 retrievals. Meanwhile, the FTIR instruments (ground- and space-based high resolution spectrometers) are of such high quality that they cannot only reveal inconsistencies between the parameters of different lines but also of insufficient line shape parameterisations (Voigt line shape, speed dependent Voigt line shape, etc.). This gap causes an increase the uncertainty on the delivered H_2O and CH_4 products retrieved from high resolution and high quality measurements.
G2.21	**Current spectroscopic databases contain uncertainties specifically effecting TCCON retrievals of CH_4 and CO_2** The shape of the calculated absorption depends on the spectroscopic data and the line shape model used. Both, the spectroscopic data and the line shape model, have a direct impact on the retrieved dry mole fractions of CH_4 and CO_2. In the TCCON retrieval, isolated lines are assumed and the Voigt line shape, which is a convolution of a Gaussian (Doppler broadening) and a Lorentzian (pressure broadening), is used. The reason for the TCCON retrieval using the very basic Voigt line shape is that the spectroscopic databases provide almost all data needed for the calculation (not provided are the temperature dependence of the shift, self-broadening and H_2O broadening). The calculation of the shapes of isolated lines should include speed dependence and Dicke narrowing, but the spectroscopic databases do not provide any data in this regard. Hence, instead of isolated lines the line shape model should include line mixing, but also for this problem HITRAN does not provide the relevant data. A further refinement of the retrieval would be to add the calculation of speed dependent and Dicke narrowed line mixing profiles. Spectroscopic uncertainties are present in all spectral windows used for the TCCON retrieval and, more specifically, spectroscopic uncertainties are known to increase co-retrieved O_2, which serves as an internal standard to calculate XCO_2 (CO_2/O_2) and XCH_4, (CH_4/O_2), thus increasing the uncertainty of the CO_2 and CH_4 products.
G2.22	**FTIR cell measurements carried out to characterize ILS have their own uncertainties** Cell measurements carried out to characterize FTIR instrument line shape (ILS) have their own uncertainties. 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. For instance, in order to have ILS sensitivity for fine spectral signatures we need very low pressure cells. If the pressure is too high, the

	cell spectra will not contain information about the ILS at large optical path difference, which is important to understand the fine spectral signatures. This problem is reported by the averaging kernel of the ILS retrieval. Inaccurate knowledge of the ILS leads to larger uncertainties on the retrieved concentrations (XCH_4, XCO_2).
G2.23	**Possible SZA dependence in the FTIR CH_4 retrievals during polar vortex overpasses** Possible SZA (solar zenith angle) dependence in the retrieval during of CH_4 measured by polar vortex overpasses may influence CH_4 retrievals. During polar vortex overpasses, stratospheric profiles of CH_4 are expected to differ from those measured outside the polar vortex. This may influence some measurements at high latitudes in winter. Applying more accurate winter time a priori profiles would reduce residuals in the retrieval. Currently there is a lack of accurate CH_4 profile measurements under wintertime conditions.
G2.24	**Lack of in-situ calibration of CH_4 and CO_2 FTIR measurements** In-situ calibration of CH_4 and CO_2 can be performed by aircraft overpasses equipped with in-situ instruments. Such campaigns have been undertaken in the past at many sites, for example as part of IMECC. However, new flight campaigns in Europe are currently not planned and the flights cover only altitude up to about 12 km. Hence the AirCore technique is of great interest to many stations. Total gas column measured by an AirCore sampling system is directly related to the World Meteorological Organization in situ trace gas measurement scales. Therefore the measured AirCore data can be used to contribute to the FTIR calibration and will also provide in-situ data for a more regular validation of ground-based FTIR measurements. Since AirCore data cover the altitude range up to 30 km, they complement the aircraft campaigns in a very suitable way. Furthermore, the station-to-station bias, which is already quite small, will be further reduced by performing new validation exercises. Understanding and minimizing the bias is essential when studying fluxes from e.g. hot spot regions.
G2.26	**Uncertainty in O_3 cross sections used in the spectral fit for DOAS, MAX-DOAS and Pandora data analysis** The uncertainty in the O_3 absorption cross sections is one of the main systematic error sources in the remote sensing of atmospheric O_3 using UV-visible spectroscopy techniques. Even though the uncertainty can be considered as a systematic error source, the actual error depends on atmospheric temperature, and thus it can be considered as a pseudo-random error, as mentioned in the deliverable D4.3 ‘Uncertainty Budget’ of the EC FP7 project NORS (see http://nors.aeronomie.be/projectdir/PDF/NORS_D4.3_UB.pdf). Presently the uncertainty in total column O_3 due to uncertainty in absorption cross sections is assumed to be around one to a few percent (WMO GAW report 218, NORS_D4.3_UB.pdf). In general, when the uncertainties related to O_3 cross sections and their temperature dependencies are well characterized, this effect can be included in the error budget of O_3 observations. The recent WMO IGACO-O3/UV activity ACSO (Absorption Cross Sections of O_3, http://igaco-o3.fmi.fi/ACSO/), performed a thorough evaluation of the existing cross sections and their impact on ground-based and satellite O_3 retrievals. 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 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. 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. The uncertainties in the O_3 absorption cross sections are partially addressed in the GAIA-CLIM project.
G2.27	**Random uncertainty in total column O_3 retrieved by UV-vis spectroscopy dominated by instrumental imperfections impacting on the spectral fit calculations** The uncertainties in the O_3 slant columns retrieved with the standard DOAS data analysis fitting procedures 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 nonlinearities 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 (air mass factor). 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 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 O_3 slant columns is at least to some degree limited by uncontrolled instrumental and/or analysis factors.
G2.28	**Uncertainty in a priori profile shape for AMF calculations for zenith sky O_3 retrievals** AMFs are required to convert the measured O_3 slant columns into vertical columns with O_3 and pressure/temperature a priori profiles being key input parameters for the AMF calculations. AMF uncertainties for zenith-sky twilight O_3 retrievals are dominated by errors on a priori profile shape effects. There is a lack of an adequate database of tropospheric O_3 in particular and in regions where tropospheric or stratospheric O_3 contents deviate from the climatological values, uncertainties of several percent can be introduced in total column O_3 retrievals. Apart from uncertainties in the O_3 a priori profiles, further sources of uncertainty are based on uncertainties in the aerosol and cloud information used. There is also a lack of harmonization of the AMF calculation methods, which can introduce inconsistencies between the data sets measured at different locations within e.g. the NDACC network. This gap is to be partially addressed within GAIA-CLIM.
G2.29	**Uncertainty in the vertical averaging kernels used for DOAS total column O_3 retrieval** Within the NDACC UV-vis working group, look-up tables of total column O_3 averaging kernels have been developed based on the Eskes and Boersma (2003) approach, 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.

G2.30	**Lack of uncertainty quantification for Pandora O_3 measurements** Pandora is a relatively new UV-VIS instrument for measuring total O_3 and also O_3 profiles in a similar way as MAX-DOAS instruments. So far only a few studies exist which describe measurement uncertainties or measurement validation. 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 baselines. The neglect of temperature effects (related to the O_3 spectroscopy in the Huggins bands) leads to seasonally dependent systematic biases, of various amplitudes depending on the latitude of the site. This gap is partially addressed within GAIA-CLIM.
G2.31	**Lack of understanding of the information content of MAX-DOAS tropospheric O_3 measurements** Retrieving tropospheric O_3 from passive remote sensing observations is difficult because almost 90% of the total column O_3 resides in the stratosphere. However, it has been shown that information on tropospheric O_3 can be extracted from multi-angular observations of the sunlight scattered by the atmosphere, using the so-called MAX-DOAS technique or similarly designed instruments. Although these pioneering studies have demonstrated the feasibility of tropospheric O_3 measurements from UV-Visible absorption measurements in both the Huggins and Chappuis bands, the information content of such measurements remains to be explored in depth in terms of altitude range, 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 O_3 measurements limits the assessment of the usability of the technique for large scale O_3 monitoring. This gap is partially addressed within GAIA-CLIM.
G2.32	**Better characterization of the different MAX-DOAS tropospheric O_3 retrieval methods needed** The potential of MAX-DOAS and similarly designed instruments to measure tropospheric O_3 have only been demonstrated in a limited number of pioneering investigations. In these studies, experimental retrieval methods have been applied which are based on Optimal Estimation (OE) schemes or on more simple approaches such as the modified geometrical approximation to infer free-tropospheric O_3 concentration from a high-altitude site. More work is necessary to better characterize the different possible approaches to tropospheric O_3 retrievals from multi-axis scattered light measurements in both UV and visible wavelengths ranges. Similar to the lack of information content analysis (see **G2.31**), the lack of consensus on retrieval methods limits the assessment of the usability of the technique for large scale O_3 monitoring. This gap is partially addressed within GAIA-CLIM.
G2.33	**Lack of in-depth understanding of random and systematic uncertainties of MAX-DOAS tropospheric O_3 measurements** Although several studies have demonstrated the potential of multi-angular UV-Visible scattered light measurements of the MAX-DOAS and Pandora types to measure tropospheric O_3, the analysis of uncertainties and the validation of the resulting measurements has generally been limited in scope. As a result, a comprehensive error budget and validation of tropospheric O_3 retrieval from MAX-

	DOAS and Pandora measurements is currently lacking. Like for other MAX-DOAS measurements, the main uncertainties for O_3 are related to the estimation of the effective photon light path, which is dependent on the aerosol content and optical properties. In addition, for O_3, the interference with the strong O_3 absorption taking place higher up in the atmosphere is potentially a significant source of systematic bias. In addition to the lack of information content (**G2.31**) and consensus on retrieval approaches (**G2.32**), the lack of uncertainty characterization and validation of tropospheric O_3 measurements from MAX-DOAS and Pandora instruments analysis limits the potential for network capabilities assessment.
G2.34	**Uncertainties of ZTD for GNSS-PW, given by a 3rd party without full traceability** The Zenith Total Delay uncertainty is a key component of the total uncertainty in GNSS-PW measurements. If it is not handled in a proper way, it may drastically affect the GNSS-IPW uncertainty estimate. Fixing it equal to 4mm is just a compromise, excluding outliers from longer time series. When discussing GRUAN GNSS-IPW uncertainties, we only discuss data analysis using Precise Point Positioning (PPP) in the EPOS software package. While suggesting GRUAN GNSS-IPW uncertainties should be implemented by other data analysis centres, we talk about implementing the GNSS-IPW uncertainty analysis method in different software (i.e. not EPOS, solely used by GFZ and GRUAN data analysis). This task is not trivial; for example, the orbital error components are not delivered for end users like ZTDs from IGS (or simply obtainable from standard software for GNSS-data analysis). Preliminary analysis has been made (and is still in progress) on documentation and related articles published by the developers of Bernese and GAMIT/GLOBK software. ZTD uncertainty is known as a main contributor to the GNSS-IPW uncertainty budget. Therefore, it is essential to understand and to find recommendations when using uncertainty estimates obtained by different data processing software packages for undertaking GRUAN-type uncertainty analysis. The goal is to investigate at least two geodetic software packages using the same GNSS-data processing method, comparing the uncertainty definition and uncertainty handling, leading to (often remarkably) different numeric values of uncertainty estimates.
G2.35	**TCCON sites with high/low albedo and hot spot monitoring** So far, all TCCON sites are located in areas with good logistical support. Even sites like Ny-Aalesund or Ascension Island have a good infrastructure, although its time consuming and expensive to go there for maintenance. However, sites located in regions with high or low albedo are missing. Since retrievals could be biased by the albedo, observations at such sites would help investigating the existing biases in the satellite retrievals. Furthermore, future satellite missions will concentrate on hot spot sites, like large mega cities. A validation by ground-based instruments like within TCCON would require sites around the cities to detect the emission. This can be done by the mobile COCCON instruments, but TCCON instruments would have the advantage of for example long term coverage or the detection of more trace gases.

WP3 (Comparison error budget closure – Quantifying metrology related uncertainties of data comparisons)	
G3.01	**Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the measurements and their co-location** 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. 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. **G3.03**), a prerequisite is a proper understanding of atmospheric variability of the targeted ECV on those scales. While scales above approx. 100km/1h are relatively well captured for several GAIA-CLIM target ECVs in model or satellite gridded data, information on smaller scales is most often restricted to results from dedicated campaigns or specific case studies. 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. Closely related to **G4.06**, which deals with the impact of natural variability on measurement-model comparisons, and with **G1.07**, dealing with the assessment of gaps in the existing networks.
G3.02	**Limited quantification of the impact of different co-location criteria on comparison results** 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 confrontation between measured differences and reported measurement uncertainties). Hitherto, only a limited set of ground-based satellite validation studies explored the impact of the adopted co-location criteria on the comparison results. 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, from which clear recommendations could be formulated (cf. gap **G3.03**), this gap also concerns the “community practices” regarding validation approaches, which often rely on a set of default (historical) co-location criteria, which are not necessarily fit-for-purpose for the accuracy and spatiotemporal sampling properties of current measurement systems.
G3.03	**Missing generic and specific standards for co-location criteria in validation work** Different validation exercises on the same ECV/instrument combinations are often performed using different (sub-optimal) co-location criteria, ranging for instance from fixed maxima imposed on spatial and temporal distance, over criteria based on the state/dynamics of the atmosphere or on representativeness areas derived from

	models, to airmass matching techniques that take into account the actual 3D/4D sensitivity of each measurement. This makes an intercomparison of the validation results difficult and it limits optimal use of the ground-based networks. To ensure reliable and traceable validation results, as required in operational validation work, community-agreed standards for co-location criteria should therefore be developed and published. Moreover, the optimal co-location strategy depends heavily on specifics such as user requirements, network coverage, instrument properties, atmospheric regimes etc. and standards should thus be diversified accordingly. As such, resolution of this gap depends to a large extent on a corresponding effort regarding gap **G3.02**.
G3.04	**Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties** Remotely sensed data are often considered as column-like or point-like samples of an atmospheric variable, e.g., column and vertical profile measurements of ozone, water vapour at the vertical of the station. This is also the general assumption for satellite data, which are assumed to represent the column or profile at the vertical of the satellite field-of-view footprint in case of nadir sounders, and atmospheric concentrations along a vertical suite 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 three-dimensional airmass and also over time. Ground-based zenith-sky measurements of the scattered light at twilight integrate stratospheric UV-visible absorptions (by O_3, NO_2, BrO, ..) over several hundreds of kilometres in the direction of the rising or setting Sun. 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. Similarly, in-situ measurements of atmospheric profiles cannot be associated with a single geo-location and time stamp, due for instance to balloon drift. In a variable and inhomogeneous atmosphere, this leads to additional uncertainties not covered in the 1-dimensional uncertainties reported with the data. 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 (cf. **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, but in the context of integrated systems like Copernicus and GCOS, appropriate knowledge of smoothing and sampling uncertainties, still missing for several ECVs and remote sensing measurement types, has to be further developed and harmonized.
G3.05	**Representativeness uncertainty assessment missing for higher-level data based on averaging of individual measurements** The creation of level-3 (and level-4) data by averaging non-uniformly distributed measurements inevitably leads to representativeness errors. The resulting representativeness uncertainty can be larger than the formal uncertainty on the mean. 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 the derived monthly (zonal) means. Also, in the context of validation of level-2 data, measurements are sometimes averaged after co-location without explicit calculation of the representativeness errors and

	resulting uncertainty.
G3.06	**Missing comparison error/uncertainty budget decomposition including errors/uncertainties due to sampling and smoothing differences** Ideally, every validation exercise 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, only in a few particular cases is it 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. Some pioneering work has been published. However, no such studies have hitherto been performed for most other ECVs and/or instruments.
WP4 (Assessment of reference data in global data assimilation systems and characterisation of key satellite datasets)	
G4.01	**Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances - relating to temperature** Numerical Weather Prediction (NWP) models are already routinely used in the validation and characterisation of EO data, but a lack of robust uncertainties associated with NWP model fields and related 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. The aim is to assess uncertainties in NWP fields through systematic monitoring, using GRUAN data, as part of WP4.
G4.02	**Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances - relating to humidity** This gap is closely related to G4.01 relating to temperature. See the text for G4.01.
G4.07	**Error correlations for reference sonde measurements** Full characterisation of error correlations for GRUAN measurements. In the context of WP4, GRUAN reference sonde measurements are being used to estimate the uncertainties in NWP model fields through routine comparisons between the two. Additionally, both GRUAN measurements and NWP model fields are being projected to TOA brightness temperatures. This projection requires an estimate of the error correlations in the GRUAN measurements (ideally represented by a full error covariance matrix). This is an active area of research within GAIA-CLIM and within the GRUAN community, but no estimates of the error correlations are available to date.

G4.08	**Ocean surface emissivity estimates in the microwave** Lack of uncertainty estimates associated with ocean surface emissivity models. Ocean surface emissivity models are used to estimate ocean surface emissivity based on ocean surface wind fields, temperature and salinity. Several 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 ECV's listed above from satellite-based microwave imager observations. These models lack traceable estimates of the uncertainties associated with the computed emissivities in the 10-250 GHz range. Improved uncertainties associated with emissivity estimates could be developed through targeted campaigns using, for example, airborne radiometers.
G4.09	**Land Surface emissivity estimates in the microwave** Lack of uncertainties associated with land surface emissivity estimates. Land surface emissivity atlases in the microwave region (10-250 GHz) have been developed in recent years and these are widely used as starting points for dynamic retrievals of land surface emissivity within retrieval and assimilation schemes, which exhibits significant spatial and temporal variability in snow and ice covered regions. The validation of microwave imaging instruments over land requires independent, well characterised, dynamic atlases of land surface emissivity, with traceable uncertainty estimates based on validation campaigns using, for example, well calibrated airborne radiometers.
G4.10	**Land surface emissivity estimates in the infrared** Land surface emissivity atlases in the infrared region (2-16 μm) are required for the validation of infrared satellite sounding measurements over land. Work is underway to develop dynamic atlases of spectral emissivity in this part of the spectrum, based on measurements from polar-orbiting hyper-spectral infrared observations, however these new dynamic atlases need to be validated to ensure the estimates have robust uncertainties associated with them.
G4.11	**Limited geographical coverage of reference temperature and humidity radiosondes** A comparison between NWP and reanalysis model fields and satellite observations reveals biases that vary geographically, particularly for the temperature and humidity sounders. Some or all of this geographical variation could be due to errors in the NWP or reanalysis model background and reference in-situ temperature and humidity radiosondes are needed to establish this. However, the available reference radiosondes that could provide estimates of uncertainties in NWP and reanalysis model fields are limited to a small number of locations. Work is on-going in work package 1 to better understand the geographical limitations of the reference in-situ data.
WP5 (Creation of a virtual observatory visualisation and data access facility)	
G5.01	**Access to data in multiple locations with different user interfaces constitutes a barrier to usage and makes use in general difficult** The task of characterizing satellite measurements by means of comparison to reference measurements needs access to and documentation of various reference measurements needed 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.
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** The comparison of satellite data and reference measurements is complicated, partly because data are provided in multiple data formats, e.g., HDF, NetCDF, BUFR, ASCII, etc, and in different structures (granules vs. global datasets, level 1 vs. level 2 data). In particular, the granularity of available data may differ between data sources. The inclusion of data into a common data base that allows geographical and temporal sub-setting and the reliable use of data analysis tools requires format conversion modules for each format used on the input side. Format conversions always bring with them the danger of destroying information, in particular in the accompanying meta-data. Different granularity of the data creates work to collect and resample data until they represent the same area and time. Then, to perform a comparison, data need to be co-located using specific criteria. Work to achieve correct co-locations are repeated by users many times, which is a gross redundancy in effort and prone to processing errors.
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** Several sources for co-located data sets exist but most of them are specialized to compare mapped fields, e.g., obs4mips ESG data provisions, reference and other non-satellite data against models or satellite data, e.g., the NORS project. But most of these 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 EUMETSAT to monitor data quality in real time. The effect of this gap is that many validation activities are performed, but do not use the available uncertainty information in an optimal way which has general effects on the quality of the research and the robustness of any conclusions drawn from such validation exercises. 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.
G5.06	**Extraction, analysis and visualization tools to exploit the potential of reference measurements are currently only rudimentary** Services that provide data extraction, analysis and visualization tools are currently only rudimentary. In particular, analysis capabilities that for instance allow analysis at different time or spatial scales are missing. E.g. to display uncertainty of the comparison results due to differences in sampling and so called smoothing error. The GAIA-CLIM User Survey indicated a clear need for such a capability to be developed, but challenges remain because whatever analysis / visualization 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.
G5.07	**Incomplete development and/or application and/or documentation of an unbroken traceability chain of Cal/Val data manipulations for atmospheric ECV validation systems prevents progress in the characterization of satellite products** 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 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 dedicated to atmospheric ECVs are developed in projects like ESA's CCI. 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. The impact of not adopting a traceable end-to-end validation approach is diverse. Firstly, important quality indicators may be missing in the analysis, e.g. information on spatiotemporal coverage, resolution, dependences of the data quality on particular physical parameters (e.g. solar zenith angle, could cover, thermal contrast) etc. Secondly, results may be incoherent between several validation exercises on the same data set, and the origin of the discrepancies 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.
G5.09	**A readily accessible online tool is missing to perform radiative transfer calculations to transfer reference measurements of ECVs, including their uncertainty estimates, into the corresponding measurement space of a matching observation from space** The GAIA-CLIM User Survey highlighted the need to have an online radiative transfer capability available in the planned 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 impact of not comparing in measurement space is the need for uncertainty estimates for one or several retrieved geophysical parameters, which is usually more complex compared to assessing the uncertainty of a measured satellite count or radiance. This is because the forward calculation from the geophysical profile is unique, whereas the inverse calculation is non-unique in that several distinct geophysical profiles can be satisfied by a single radiative measurement.

G5.10	**Characterisation of different types of uncertainty has not been systematically addressed per ECV** For some ECVs a full measurement uncertainty chain has been established, but smoothing uncertainty has not been considered or vice versa. This prevents and potentially delays inclusion of various instrument/ECV combinations into the Virtual Observatory. The development work of the Virtual Observatory was addressing the selection of reference data, available uncertainty estimates (measurements and smoothing) and the satellite data that shall be characterized. This exercise revealed that certain different types of uncertainty are not addressed systematically resulting in some cases in reference measurements that have quantified uncertainty but for which no means exist to address smoothing uncertainties and vice-versa. This leads to delays in integrating the full QA and validation chain into the Virtual Observatory. It can be expected that for other ECVs in atmospheric but also oceanic and terrestrial domains similar issues exist.
G5.11	**Non-operational provision of reference measurement data and some (L2) satellite products may prevent use in Copernicus operational product monitoring** Currently, some reference measurements are provided with specific delays due to requirements for certain quality control measures to be applied. The usage scenario for a Virtual Observatory within a Copernicus Service would likely need a close to real time availability of such data 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 cannot be operationalized leading to faster delivery, quality assessment at short time scales shall remain of limited nature reducing the value of the data for applications.
Governance Gaps (WP6)	
G6.01	**Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions** Non-satellite data sources identified as reference and baseline quality within GAIA-CLIM have greatly dispersed governance. This dispersed governance leads to decisions which, although sensible on a network basis, are sub-optimal on a more holistic basis. This fractured governance also results from but also augments a diversity in funding support and observational priorities as discussed in G6.02 and G6.03. Different networks take different approaches to data processing and serving which reduces comparability of the resulting data.
G6.02	**Geographically dispersed observational assets reduce their utility for satellite Cal/Val** Related to ***G6.01*** but also several gaps in the underlying WPs, a result of the fractured governance of observational networks is that instruments are very frequently not co-located. That is to say that an FTIR may belong to network X and be located 100 km distance from a suite of complimentary observations belonging to network Y. Because the measurements are geographically dispersed this serves to reduce their value for numerous applications including, but not limited to, satellite characterization.

G6.03	**Lack of dedicated funding for targeted observations to coincide with satellite overpass** Many high-quality observational assets do not operate 24/7. For some instruments there are geophysical limitations as to when measurements can be undertaken e.g. an FTIR requires direct line of sight to the sun. But for many others it is for financial or logistical reasons that measurements are solely episodic. For example, radiosonde launches tend to be twice-daily or at best four times daily. Similarly, lidar operations may be made only when staff are available. Because funding for these observations typically is not concerned with satellite characterization the sampling strategy is sub-optimal for satellite characterization.
G6.04	**Mixed level of user experience with using uncertainty information** The user survey highlighted a mixed level of maturity in individual's self-assessment of the ability to use measurement uncertainties appropriately. This is an impediment potentially to uptake of the use of reference quality data in applications such as satellite characterization.
G6.05	**Future support for GRUAN-processor** GAIA-CLIM provides 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 measured (GRUAN) and modelled (NWP) state estimates. Originally envisaged to run as part of the operational systems at ECMWF and Met Office, a decision was made early in the project to develop the processor as a standalone capability that would be available effectively as 'open-source' software. The GRUAN-processor is built around several core capabilities that are likely to be supported longer-term by EUMETSAT, nevertheless there is a foreseen governance gap beyond the term of GAIA-CLIM regarding the ongoing development priorities and support for the GRUAN-processor.
G6.06	**a) Lack of dedicated funding for fast-delivery of targeted observations for satellite validation/calibration** **b) Lack of structural funding for station maintenance, data acquisition and initial analysis** For satellite validation, fast delivery of the independent non-satellite network data is often requested by the satellite agencies. This generally is not foreseen in the network protocols and cannot be afforded by the network partners without additional dedicated funding. It turns out to be difficult to find the funding authority that is willing to provide the necessary resources: in several cases, the funding authorities defer the responsibility to provide the funding to one another. Several applications (e.g., validation efforts) and services (e.g., Copernicus) take the availability of observational non-satellite data for granted and only support the better access / use / harmonisation of the data. Networks like NDACC and ACTRIS (and to a lesser extent TCCON) have been developed through the coordination of ongoing individual observations with similar objectives and implementation methodologies. The coordination has been formalised as a network with clearly outlined objectives, and guidelines for the implementation of the observations by the individual partners; these guidelines include protocols and directives for the observation hardware and operating procedures, the data analysis and archiving, the data quality control, etc. However the organisation of the network does not imply

	any coordinated funding for the partners. Therefore, the partners have to search for their own funding, often with the national funding agencies, to comply with the network protocols on a best effort basis. Today, it turns out to be difficult to find the necessary funding, and even more so when it comes to structural funding. Any additional requirement requires additional resources.
G6.07	**Different data policies in different networks harm the use of complementary data from different networks** Networks have grown bottom-up and each one has established its own data policy. The consequence hereof is that portals providing access to data from several networks, or users who combine data from different networks in a study or application, must deal with different data policies. This makes the combined use of complementary data quite tedious.
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?** INSPIRE is a legal EU framework for reporting geospatial data. Each Member State (MS) is supposed to report the geospatial data located in its own territory. However, because INSPIRE has been conceived for the reporting of 2D-data like the data of the land register or cadastre, atmospheric data from satellite and other platforms typically have 3 (space) or 4 (space and time) dimensions and might not fit well with some INSPIRE rules. An appropriate representation of atmospheric data requires an extension of the INSPIRE conventions and rules and there is a need to also harmonise these extensions. Furthermore, it is common in the atmospheric and Earth Observations community that one MS (MS A) carries out observations and acquires data in another MS (MS B). In INSPIRE, however, MS A has no obligation to archive/report the data acquired in MS B because they do not pertain to its own territory. MS B is however not the owner of the data acquired by MS A so it has no right to archive/report these data. Consequently, such data might not end up in the INSPIRE databases. Finally, specific metadata entries like ‘quality’ in INSPIRE may be not the same as used in the atmospheric and Earth Observations communities.
G6.09	**Responsibility for observations in developing countries (Africa - Asia - S America)** It is evident that non-satellite data are missing in developing countries, mainly in Central Africa and South America, and to a lesser extent in South-east Asia, despite the fact that the availability of data in these regions is crucial for satellite and model validation and in the context of global changes. Many existing observations have been realised on the basis of fortuitous bilateral agreements. Since 2007 there has been the GMES-Africa initiative, now ‘Copernicus-Africa cooperation’ in the wider context of the Europe-Africa partnership, but little has been realised as to the development and maintenance of a non-satellite observations infrastructure for atmospheric observations. In October 2015 a new funding support was approved by the European Commission for the new phase of the European-African initiative. In the initial implementation phase of the initiative (2016 – 2020) three priority topics will be addressed: long term management of natural resources, marine and coastal areas monitoring and water resources management. Nevertheless, non-satellite atmospheric observations are urgently needed in Africa and arrangements must be

	made to overcome the political and economic barriers.
G6.10	**An unlimited growth of data portals, metadata standards and formats might make data discovery and access increasingly difficult** *A detailed gap description is not available.*
G6.11	**The possible gradual loss of island radiosonde stations** *A detailed gap description is not available.*
Gaps Provided Through GAIA-CLIM User Workshop #1 (WP6)	
G6.GHGCCI.01	**Lack of structural funding** *A detailed gap description is not available. Some background information through the presentation by I. Aben at the 1st User Workshop in Rome (Oct. 2015)*
G6.GHGCCI.02	**Data delivery too late for timely satellite data validation** *See the comments at* G6.GHGCCI.01
G6.GHGCCI.03	**No TCCON stations in Africa, large parts of Asia, S. America, Russia, Middle East, high/low surface albedo, and to validate important spatial gradients across large ecosystems** *See the comments at* G6.GHGCCI.01
G6.GHGCCI.04	**Absolute calibration of TCCON to WMO standards is limited (height and frequency)** *See the comments at* G6.GHGCCI.01
G6.GHGCCI.05	**Very limited vertical profile reference measurements** *See the comments at* G6.GHGCCI.01
G6.GHGCCI.06	**Missing system for urban scale validation needed for high spatial resolution satellite data** *See the comments at* G6.GHGCCI.01
G6.GHGCCI.07	**No absolute calibration available (as is for TCCON), no traceability to WMO standards, no standardized procedures for NDACC retrievals** *See the comments at* G6.GHGCCI.01
G6.GHGCCI.08	**Access to relevant ECMWF meteorological datasets is difficult or impossible for some researchers** *See the comments at* G6.GHGCCI.01

5 Summary and GAID Outreach Activities

In summary, in this Gaps Assessment and Impacts Document (GAID) Version 3.0 a compilation and analysis has been made of the gaps that have been formulated by the project team from project start through the end of July 2016. So far a total number of 88 gaps has been identified and maintained. In this GAID some initial cross sections of the gaps are presented, e.g. by grouping the gaps into a set of generic gap types, and a catalogue is given of the currently identified gaps including a short description. The impacts of the gaps and suggested remedies are presented per cross section.

Note that following the suggestions made at the General Assembly in Helsinki (10-11 February 2016) the outline of GAID Version 3.0 has been modified drastically in comparison to GAID Version 1.0 and GAID Version 2.0. An important new element was the recommendation to make the gaps '*SMART*' in support of further assessment of the gaps and also to facilitate listing of prioritised recommendations for the next version and to support traceability through the on-line catalogue of gaps.

For the different GAID versions a range of outreach activities has been undertaken so far.

- 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 in 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 will be 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.

This user interaction is key in refining the GAID and ensuring its usefulness to the broader scientific, technical and policymaker communities.

List of Acronyms

ACSO	Absorption Cross Section of Ozone (IGACO activity)
AQ	Air Quality
AMF	Air Mass Factor
ASCII	American Standard Code for Information Interchange
BB	Black Body
BUFR	Binary Universal Form for the Representation of Meteorological Data
C3S	Copernicus Climate Change Service
Cal/Val	Calibration and Validation
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CAMS	Copernicus Atmospheric Monitoring Service
CCI	Climate Change Initiative (ESA)
CEOS	Committee on Earth Observation Satellites
CF(-compliant)	Climate and Forecast
CFH	Cryogenic Frost point Hygrometer
COST	Cooperation in Science and Technology (EU)
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
ESFRI	European Strategy Forum on Research Infrastructures
EUMETNET	European Meteorological Network
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
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
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GHG	GreenHouse Gas
GNSS-(I)PW	Global Navigation Satellite Systems (Integrated) Precipitable Water
GRUAN	GCOS Reference Upper-Air Network
GUAN	GCOS Upper-Air Network
HDF	Hierarchical Data Format
HITRAN	HIgh resolution TRansmission molecular AbsorptioN database

HSRL	High Spectral Resolution Lidar
IAGOS	In-service Aircraft for a Global Observing System
IGACO	Integrated Global Atmospheric Chemistry Observations
ILS	Instrument Line Shape
IMECC	Infrastructure for Measurements of the European Carbon Cycle
IR	Infrared radiation
LIDAR	LIght Detection And Ranging
LOS	Line Of Sight
LS	Lower Stratosphere
LT	Lower Troposphere
MAX-DOAS	Multi-Axis Differential Optical Absorption Spectroscopy
METEOMET	Metrology for Meteorology
MW	Microwave radiation
MWR	Microwave Radiometer/try
NDACC	Network for the Detection of Atmospheric Composition Change
netCDF	Network Common Data Form
NMI	National Meteorological Institute
NWP	Numerical Weather Prediction
OSCAR	Observing Systems Capability Analysis and Review Tool
PBL	Planetary Boundary Layer
PPP	Precise Point Positioning
QA/QC	Quality Assurance / Quality Control
QA4EO	Quality Assurance Framework for Earth Observation
QA4ECV	Quality Assurance for Essential Climate Variables
QI	Quality Indicators
SZA	Solar Zenith Angle
TCCON	Total Carbon Column Observing Network
TOA	Top of Atmosphere
TOPROF	Towards Operational ground based PROFiling with ceilometers, doppler lidars and microwave radiometers for improving weather forecasts (COST ES1303)
US+M	Upper Stratosphere and Mesosphere
UT	Upper Troposphere
UT/LS	Upper Troposphere / Lower Stratosphere
UV-VIS	Ultraviolet-Visible radiation
VO	Virtual Observatory
WIGOS	WMO Integrated Global Observing System
WMO	World Meteorological Organization
WP	Work Package
ZTD	Zenith Total Delay

ANNEX Full Descriptions of Identified Governance Gaps through WP6

The following information on governance gaps has been identified in June/July/August 2016 through a coordinated action as part of Work Package 6 in preparation of this GAID Version 3.

G6.01: Dispersed governance of high-quality measurement assets leading to gaps and redundancies in capabilities and methodological distinctions

Gap Detailed Description

Non-satellite data sources identified as reference and baseline quality within GAIA-CLIM have greatly dispersed governance. This dispersed governance leads to decisions which, although sensible on a network basis, are sub-optimal on a more holistic basis. This fractured governance also results from but also augments a diversity in funding support and observational priorities as discussed in G6.02 and G6.03. Different networks take different approaches to data processing and serving which reduces comparability of the resulting data.

Activities within GAIA-CLIM related to this gap

Indirectly GAIA-CLIM addresses this gap to the extent that it brings together actors from many of the high-quality networks. However, there is no single activity which specifically addresses this point.

Gap Remedy / Remedies

Two remedies are foreseen.

In the short-term efforts should be made to strengthen cross-network governance representation to improve coordination. In the longer-term it may be advisable to seek to merge networks where possible and where aims overlap sufficiently so that non-satellite high quality measurement systems have a stronger and more unified voice globally.

<u>Specific remedy proposed (#1):</u>

Strengthen existing efforts to ensure meaningful collaboration through cross-governance group representation, network memoranda of understanding and involvement in joint research and infrastructure activities.

<u>Measurable outcome of success:</u>	Demonstrable increase in collaboration between networks through joint projects, publications, and participation in network meetings
<u>Technological viability:</u>	High
<u>Indicative cost estimate:</u>	Low (<1 million)
<u>Relevance:</u>	The remedy would improve visibility of all high quality networks and their relevance.
<u>Time bounds:</u>	Within the GAIA-CLIM project timeframe.

<u>Specific remedy proposed (#2):</u>

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. Mergers should be on a no regrets basis and should not be enforced if funding support or other essential support would be weakened as a result.

Measurable outcome of success:	Reduction in complexity of the ecosystem of onbserving networks through time while retaining and enhancing observational capabilities
Technological viability:	High
Indicative cost estimate :	Medium (<5 million)
Relevance:	The remedy would make it easier for funding and research communities to interact with the high-quality measurement networks.
Time bounds:	Long-term – at least five to ten years

Gap Risks to Non-Resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Continued fractured governance leading to sub-optimal management and development of high-quality measurement networks	High	Reduced utility of observational data assets through fractured decision-making
Reduction in funding opportunities for high-quality measurements owing to fractured and competing demands	Medium	Reduced value of observations

G6.02: Geographically dispersed observational assets reduce their utility for satellite Cal/Val

Gap Detailed Description

Related to G6.01 but also several gaps in the underlying work packages, a result of the fractured governance of observational networks is that instruments are very frequently not co-located. That is to say that an FTIR may belong to network X and be located 100Km distance from a suite of complimentary observations belonging to network Y. Because the measurements are geographically dispersed this serves to reduce their value for numerous applications including, but not limited to, satellite characterisation.

Activities within GAIA-CLIM related to this gap

There are no specific activities within GAIA-CLIM that directly address this gap.

Gap Remedy / Remedies

The most obvious remedy is to rationalise on national / regional levels observational assets to ensure maximum scientific value. This rationalisation needs to account for both measurement heritage and the range of observational application areas.

Specific remedy proposed:

National and/or regional assessments of high quality observational assets leading to reviews of strategies which may lead to consolidation of facilities where a clear benefit to multiple data stakeholders is identified.

Measurable outcome of success:	Evidence of more strategic decision-making and long-term planning in research infrastructure investments
Technological viability:	High
Indicative cost estimate:	High (>5 million) globally but likely medium or low nationally
Relevance:	Increasing the utility of high-quality measurements would benefit multiple application areas
Time bounds:	Long term, at least five to ten years

Gap Risks to Non-Resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Continued lack of strategic placement of research infrastructure leading to diminished scientific value across the range of application areas.	High	Reduced quality of data services provided

G6.03: Lack of dedicated funding for targeted observations to coincide with satellite overpass

Gap Detailed Description

Many high-quality observational assets do not operate 24/7. For some instruments there are geophysical limitations as to when measurements can be undertaken e.g. an FTIR requires direct line of sight to the sun. But for many others it is for financial or logistical reasons that measurements are solely episodic. For example, radiosonde launches tend to be twice-daily or at best four times daily. Similarly, lidar operations may be made only when staff are available. Because funding for these observations typically is not concerned with satellite characterisation the sampling strategy is sub-optimal for satellite characterisation.

Activities within GAIA-CLIM related to this gap

None.

Gap Remedy / Remedies

Funding mechanisms need to be assured that optimise the observational scheduling for satellite characterisation if the full utility of these measures is to be realised.

Specific remedy proposed:

Space agencies to work with relevant observational networks to support targeted observations to maximise their utility for satellite characterisation through targeted support for observations concentrating upon the highest-quality observational assets.

Measurable outcome of success:	Increased number of high-quality non-satellite data co-locations with satellite measurements on a sustained basis
Technological viability:	High
Indicative cost estimate:	High (>5 million) globally but likely medium or low nationally
Relevance:	Increasing the number of co-locations available would improve the ability to undertake robust satellite characterisation.
Time bounds:	Long term, at least five to ten years. Sustained

Gap Risks to Non-Resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Paucity of high quality co-locations in the future.	High	Reduced ability to independently characterise the data quality of satellite missions

G6.04: Mixed level of user experience with using uncertainty information

Gap Detailed Description

The user survey highlighted a mixed level of maturity in individual's self-assessment of the ability to use measurement uncertainties appropriately. This is an impediment potentially to uptake of the use of reference quality data in applications such as satellite characterisation.

Activities within GAIA-CLIM related to this gap

Some limited activity via publications, outreach and documentation of the virtual observatory.

Gap Remedy / Remedies

Specific remedy proposed:

Training and outreach is likely required on a sustained basis involving a range of mechanisms such as hands-on training, development of course materials, online worked examples, publications, manuals etc.

Develop a range of materials and approaches to help train users in the appropriate usage of uncertainty information in applications. Several approaches should be pursued to cater for the range of user experiences to date and the range of way users learn.

Measurable outcome of success:	Improved usage of the Virtual Observatory tools by end-users
Technological viability:	High
Indicative cost estimate:	Medium (1- 5 million)
Relevance:	Increasing the expertise of end users to use appropriately the uncertainty information would increase the value of the data for multiple applications
Time bounds:	Long term, at least five to ten years. Sustained

Gap Risks to Non-Resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Lack of user ability to use the uncertainty information provided appropriately	Low to High (user dependent)	Lack of uptake of data leading to continued lack of use of best practices

G6.05: Future support for GRUAN-processor

Gap Detailed Description

The current plans for WP4 & WP5 anticipate 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 measured (GRUAN) and modelled (NWP) state estimates. Originally envisaged to run as part of the operational systems at the WP4 partner institutions (ECMWF and Met Office), a decision was made early in the project to develop the processor as a standalone capability that would therefore be available to a wider user base - including the developers of the GAIA-CLIM Virtual Observatory - effectively as 'open-source' software. 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 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 (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.

Activities within GAIA-CLIM related to this gap

- The ongoing development of the GRUAN processor is based around freely available component software that has been developed (in the case of RTTOV) over several decades and will continue to be maintained and enhanced as part of other programmes, thereby minimising the maintenance and development effort for the processor longer-term, beyond the GAIA-CLIM project.
- The processor is being integrated into the GAIA-CLIM Virtual Observatory, one of the main portals for the GAIA-CLIM project.

Gap Remedy / Remedies

To establish an engaged user-base for the processor, through:

- Maximising the uptake and impact of the processor, through a focus on: the usability of the system and; the accuracy of outputs.
- Publicising the processor (and the scientific value of the outputs) and establish healthy links with key stakeholder groups during the course of the GAIA-CLIM project;

<u>Specific remedy proposed:</u>

Maximise uptake and impact of the processor by optimising the scientific integrity of the results and through a focus on the usability of the system during its development, followed by activities aimed at publicising the capabilities of the processor.

<u>Measurable outcome of success:</u> Successful integration of the processor and/or outputs into the Virtual Observatory, successfully demonstrated during the end of project User Workshop. Preparation and acceptance of a publication detailing the quantitative comparisons of GRUAN versus NWP for both Met Office and ECMWF models, and including an estimate of uncertainties in NWP TOA radiances/brightness temperatures

Technological viability:	High
Indicative cost estimate:	low (<0.5 million)
Relevance:	The remedy proposed here would document the capabilities of the GAIA-CLIM GRUAN processor and provide a basis for subsequent efforts to promote uptake by key stakeholder groups. This would thereby enhance the chances of fostering a coordinated effort to provide a longer term development path for the processor
Time bounds:	Within the GAIA-CLIM project timeframe + 12 months.

Gap Risks to Non-Resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Lack of penetration, and acceptance, of proposed methodology (NWP, coupled to GRUAN, for the validation of meteorological EO data) into wider user community	High	Sub-optimal (slower !) evolution of the community's understanding of the quality of key measured datasets

G6.06a) Lack of dedicated funding for fast-delivery of targeted observations for satellite validation/calibration
G6.06b) Lack of structural funding for station maintenance, data acquisition and initial analysis

Gap Detailed Description

Several applications (e.g., validation efforts) and services (e.g., Copernicus) take the availability of observational non-satellite data for granted and only support the better access / use / harmonisation of the data. There is still a lack of structural funding for the station maintenance, data acquisition and initial analysis.

Networks like NDACC and ACTRIS (and to a lesser extent TCCON) have been developed through the coordination of ongoing individual observations with similar objectives and implementation methodologies. The coordination has been formalised as a network with clearly outlined objectives, and guidelines for the implementation of the observations by the individual partners; these guidelines include protocols and directives for the observation hardware and operating procedures, the data analysis and archiving, the data quality control, etc. However, the organisation of the network does not imply any coordinated funding for the partners. Therefore, the partners have to search for their own funding, often with the national funding agencies, to comply with the network protocols on a best effort basis. Today, it turns out to be difficult to find the necessary funding, and even more so when it comes to structural funding. Any additional requirement requires additional resources.

For satellite validation, fast delivery of the independent non-satellite network data is often requested by the satellite agencies. This generally is not foreseen in the network protocols and cannot be afforded by the network partners without additional dedicated funding. It turns out to be difficult to find the funding authority that is willing to provide the necessary resources: in several cases, the funding authorities defer the responsibility to provide the funding to one another.

Activities within GAIA-CLIM related to this gap

The harmonisation tasks in WP2 will, in the end, support the partners to develop commonly agreed data analysis tools – which can then be more easily automated and distributed among the network partners – therefore minimizing the individual efforts by each partner.

This will however not completely remedy the funding gap.

Gap Remedy / Remedies

Specific remedy proposed:

The satellite agencies should provide the additional resources needed to satisfy the fast delivery and specific requirements. However, this does not completely solve the problem, because it only helps if the basic support for maintaining the observations compliant with the network protocols is available. As long as the basic network observations are not considered 'mandatory', as is for example the case for air quality measurements in the frame of the national environmental reporting requirements, there will always be funding gaps.

Measurable outcome of success:	EU opens discussion with Member States and ESA. Awareness of the various funding agencies for the structural funding problem and high-level agreements among them about each other's responsibilities for funding the non-satellite 'routine' network observations and for funding the additional specific requirements (e.g., fast-delivery, specific format, etc.)
Indicative cost estimate:	Low
Relevance:	Guarantee long-term continuation of non-satellite observations with internationally recognised quality and relevance for air quality, climate, and the ozone layer, and enable delivery of the data for validation applications (satellite, Copernicus services, downstream applications, …) with specific requirements such as fast delivery.
Time bounds:	Initiate high-level discussions within GAIA-CLIM timeframe – with outcomes on the mid-term

Gap Risks to Non-Resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Not enough data available in due time for satellite data validation. Waste of effort in the satellite products developments	High	Lack of quality assessments of the downstream products based on satellite observations

G6.07: Different data policies in different networks harm the use of complementary data from different networks

Gap Detailed Description

Networks have grown bottom-up and each one has established its own data policy. The consequence hereof is that portals providing access to data from several networks, or users who combine data from different networks in a study or application, must deal with different data policies. This makes the combined use of complementary data quite tedious.

Activities within GAIA-CLIM related to this gap

None

Gap Remedy / Remedies

Specific remedy proposed

- Propose a harmonised data policy to NDACC, TCCON, GRUAN and ACTRIS networks as a starting point
- Propose the harmonisation of data policies to ENVRI+

Measurable outcome of success:	The adoption of a single harmonised data policy is put on the agenda of ENVRI+. Adaptation of different data policies to a single one for networks dealing with the atmospheric environment.
Indicative cost estimate:	Almost none
Relevance:	Facilitates the data access in data portals and for data users – stimulating the (combined) use of complementary data from different networks, hence a more beneficial use of the networks data.
Time bounds:	Mid-term

Gap Risks to Non-Resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
- Network data less well used, i.e., a loss of benefit versus cost - Users do not comply with individual data policies e.g., in publications	High	

G6.08a) INSPIRE : Application of INSPIRE Implementing Rules to atmospheric and any other 3D/4D-data is not straightforward w.r.t. dimensionality, quality, etc.
G6.08b) INSPIRE: Where do data of one Member State end up which acquired in another Member State and/or is derived from satellite?

Gap Detailed Description

INSPIRE is a legal EU framework for reporting geospatial data. Each Member State (MS) is supposed to report the geospatial data located in its territory.

There are several related gaps:

(i) Typically INSPIRE has been conceived for the reporting of 2D-data like the data of the land register or cadastre. The EO data from satellite and other platforms, and in particular the atmospheric observations, typically have 3 (space) or 4 (space and time) dimensions and don't fit well with the INSPIRE rules. An appropriate representation of the EO data requires an extension of the INSPIRE conventions and rules and there is a need to also harmonise these extensions.

(ii) It is common in the atmospheric and EO community that one MS (MS A) carries out observations and acquires EO data in another MS (MS B) . MS A has no obligation to archive/report the data acquired in MS B in INSPIRE because they do not pertain to its territory, and MS B is not the owner of the data acquired by MS A so it has no right to archive/report these data. Therefore, when applying the INSPIRE rules, these data will not necessarily end up in the INSPIRE database.

(iii) Several questions arise when MS A is responsible for the derivation of a satellite product linked to an ESA (NASA/JAXA/…) satellite, and a fortiori covering different territories:

a. who is the owner of the data?

b. who is responsible for reporting/archiving the data in the INSPIRE database?

c. what is the geospatial boundary of the data?

d. The metadata entry 'quality' in INSPIRE doesn't have the same meaning as we are used to in the EO community

Activities within GAIA-CLIM related to this gap

None

Gap Remedy / Remedies

Specific remedy proposed:	Adapt INSPIRE rules and conventions
Measurable outcome of success:	INSPIRE committees are aware of the problems. INSPIRE conventions for 3D (4D) atmospheric EO data are commonly agreed and applied. INSPIRE EO data are reported / archived according to these rules. All relevant geospatial data are reported/archived.
Indicative cost estimate:	Not estimated
Relevance:	Guarantee availability of geospatial data for EU in INSPIRE database
Time bounds:	Long-term (beyond the GAIA-CLIM timeframe)

Gap Risks to Non-Resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
INSPIRE database far from complete and not completely harmonised	High	

G6.09: Responsibility for observations in developing countries (Africa - Asia - S America)

Gap Detailed Description

It is evident that non-satellite data are missing in developing countries, mainly in Central Africa and South America, and to a lesser extent in South-east Asia, despite the fact that the availability of data in these regions is crucial for satellite and model validation and in the context of global changes. Many existing observations have been realised on the basis of fortuitous bilateral agreements.

Since 2007 there has been the GMES-Africa initiative, now 'Copernicus-Africa cooperation' in the wider context of the Europe-Africa partnership, but little has been realised as to the development and maintenance of a non-satellite observations infrastructure for atmospheric observations. In October 2015 a new funding support was approved by the European Commission for the new phase of the European-African initiative. In the initial implementation phase of the initiative (2016 – 2020) three priority topics will be addressed: long term management of natural resources, marine and coastal areas monitoring and water resources management. Nevertheless, non-satellite atmospheric observations are urgently needed in Africa and arrangements must be made to overcome the political and economic barriers.

Activities within GAIA-CLIM related to this gap

WP1 can address the observations gap in Africa (and other developing countries) more explicitly.

Gap Remedy / Remedies

Specific remedy proposed:	Add in-situ atmospheric observations in Africa among the priority topics in the Copernicus-Africa work programme 2016-2020
Measurable outcome of success:	Report to the EU about the existing observations in Africa to highlight the gaps, including priority setting for filling the gaps. Sustainable infrastructure for atmospheric observations set up in Africa
Indicative cost estimate:	Not estimated
Relevance:	Better validation of satellite and model data above the African continent
Time bounds:	Long-term, beyond GAIA-CLIM timeframe

Gap Risks to Non-Resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Large areas without any data for validation of satellites and models	High	Negative impact on ability to establish science-based climate change mitigation and adaptation measures in Africa and other developing countries

G6.10: An unlimited growth of data portals, metadata standards and formats might make data discovery and access increasingly difficult

This gap has some significant overlap with the technical G1.06 (cf. the G1.06 gap short description) but here relates to the subsequent user needs on governance specifically. No further gap description has been made.

G6.11: The possible gradual loss of island radiosonde stations

This gap relates to radiosonde stations, mostly at remote islands only?) which are gradually diminishing recently. Examples include at least Ascension Island and the W. Tropical Pacific ARM site. A potential closure of Gough Island is also under discussion. No further gap description has been made.