Gaps Assessment and Impacts Document

(Version 2.0)

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

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

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Executive Summary

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.

Work under GAIA-CLIM will address:

1. Defining and mapping existing the 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

The purpose of the Gaps Assessment and Impacts Document (GAID) is two-fold. First to identify and assess – through careful analysis against both existing and envisaged user requirements – as yet unfulfilled user needs ('gaps'). Important user categories for GAIA-CLIM include

(U1) Service providers such as e.g. ECMWF (NWP, CAMS, C3S);

(U2) Users of non-satellite observations for satellite data characterisation and validation;

(U3) (End-)users of non-satellite ECV data records (in support of climate monitoring)

The second purpose, next to gap identification, is to assess the scientific and societal impacts of the gaps, to identify potential remedies, and to begin to assess feasibility of resolution of the gap and gap prioritization.

Importantly, the full list of gaps as identified in the GAID is not limited to the gaps which are envisaged to be (partly) remedied within the project. During the project distinction is made between mostly specific gaps that are being (partly) remedied within the project (e.g. through developments related to the Virtual Observatory) and other either specific or generic gaps for which a remedy is out-of-scope for the GAIA-CLIM project.

The impact assessment 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.

Gaps in this GAID are regularly identified and updated from the project work packages. User needs are further obtained from the GAIA-CLIM user survey and user workshops, as well as through various pieces of (new) externally available documentation. Furthermore, expert input on the public drafts is welcomed through a dedicated web-site for the GAID (http://www.gaia-clim.eu/page/gaid) suggesting additional gaps or updating our knowledge of the identified gaps' status.

To aid comprehensibility, gaps per ECV have been categorized into seven generic 'gap types'. These gap types include gaps related to:

- spatio-temporal coverage
- vertical resolution
- uncertainty (uncertainty budget and calibration)
- uncertainty in relation to comparator measures
- missing parameters/auxiliary information
- pure technical issues
- governance

The gaps impact assessment and discussion of potential remedies is organised per gap type in order to identify, e.g., similarity and/or complementarity between the listed gaps that originate from different work packages. The GAID is a living document and several versions of this document will be produced throughout the lifetime of the project. Both the list of gaps, their (partial) remedies as well as the impact assessment are expected to evolve. Over time, efforts shall be made to more fully scope remedies including approaches such as a risk register based approach and providing costings estimates.

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 version history

Version	Principal updates	Owner	Date
0	Framework document	KNMI	9 April 2015
1.0	First version including the inputs received per work package by end of June 2015 through D1.1, D1.2, D1.3, D1.4, D1.5, and D6.1 and reviewed by 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

1 Introduction

1.1 The Scientific Challenge

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 2015, 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 e.g. future 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 estimations 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 the climate monitoring focusing on the user needs for selected atmospheric ECVs, the so-called '*gaps*',
(ii) to assess these gaps and to estimate 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. 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).

1.2 Approach to the GAIA-CLIM Gaps and Impact Assessment

In this document, gaps are identified 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 categories can be distinguished including at least:

- 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 is providing external input to the GAID on user needs. A user survey has been undertaken and reported (GAIA-CLIM 'Report on results of user survey', Deliverable D6.1) and a first user workshop was held on 6 October 2015 in Rome, Italy. A second workshop is planned for month 21 (autumn 2016) 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 feed into the GAID.

Inputs to the GAID are further derived from, 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 the GAIA-CLIM 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 is invited through the 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 are 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.

1.3 Document Outline

In Section 2 we identify the gaps in the integrated Climate Monitoring of Atmospheric ECVs. Up to the current version of the GAID the focus has been on section 2.1, on the gaps identified in the non-satellite ECV Climate Monitoring Segment, which is the focus on GAIA-CLIM. In Section 3 impacts and remedies are discussed for each of the identified gaps. At the General Assembly in Helsinki (10-11 February 2016) the suggestion was made to reorder the GAID outline per GAIDv3.

2 Integrated Climate Monitoring of Atmospheric ECVs

2.1 The Non-satellite ECV Climate Monitoring Segment

An overview has been made of the contributions per ECV of the networks that define the non-satellite segment for climate monitoring. Table 2.1 provides per primary ECV addressed in GAIA-CLIM an overview of contributing surface networks and airborne observations, split by altitude domain and network.

Table 2.1. *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*

The networks 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), as well as Air Quality (AQ) national networks. Some other networks of radiosondes include GUAN, ARSA or RAOB. Because, compared to GRUAN, for these networks fully traceable uncertainties do not yet exist nor could these be established in the foreseeable future, some focus is given to the GRUAN network in GAIA-CLIM.

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 in Table 2.1 provides a structure for the assessment of the gaps per ECV, per altitude domain, per network, and per instrument technique. The information content of Table 2.1 builds on the work in Task 1 and will be modified and improved accordingly.

Table 2.2 provides the current list of identified gaps from all work packages. Each of the identified gaps is associated with one or more of the generic gap types. The seven generic gap types that are currently being distinguished are related to respectively:

- ***Coverage***: gaps in geographical and/or temporal coverage, i.e. a lack of measurements
- ***Vertical Resolution***: either or not resolving the vertical column sufficiently
- ***Uncertainty***: uncertainty budget including calibration, i.e. uncertainties intrinsic to one measurement
- ***Comparator Uncertainty***: uncertainties relating to comparator measures, i.e. uncertainties related to comparisons between measurements which have different attributes
- ***Technical***: data dissemination, specific missing tools (specifically excluding governance)
- ***Governance***: data policy incl. (free) data access, unclear QA/QC methodologies, traceability/documentation/learning (specifically excluding pure technical gaps)
- ***Parameter***: missing parameter knowledge, missing auxiliary information for an ECV, etc.

Table 2.2. *Overview of the gaps that have been identified in GAIA-CLIM, organised per work package. Primary ECVs in GAIA-CLIM include H_2O, O_3, T, CO_2, CH_4 and aerosols. Secondary ECVs are denoted in italics. Dx.x refers to GAIA-CLIM project deliverables, n/a = not available. Status per GAID Version 2.0.*

Gap Identifier	Gap Type	ECV(s)	Gap Short Description	Gap owner(s)	Trace
G1.01	Technical Governance	H_2O, O_3, T, CO_2, CH_4, aerosols	Missing agreement on levels of data and associated names across domains	Peter Thorne (NUIG)	D1.3 GCOS AOPC Seidel et al., 2013
G1.02	Technical	H_2O, O_3, T, CO_2, CH_4, aerosols	Unknown suitability of measurement maturity assessment	Peter Thorne (NUIG)	D1.3
G1.03	Coverage Governance	H_2O, O_3, T, CO_2, CH_4, aerosols	Missing evaluation criteria for assessing existing observing capabilities	Peter Thorne (NUIG)	D1.1
G1.04	Coverage Governance	H_2O, O_3, T, CO_2, CH_4, aerosols	Lack of a comprehensive review of current non-satellite observing capabilities for all the study of ECVs in atmospheric, ocean and land domains	Fabio Madonna (CNR-IMAA)	D1.4, D1.6, D1.8
G1.05	Technical	H_2O, O_3, T, CO_2, CH_4, aerosols	Lack of unified tools showing all the existing observing capabilities for measuring ECVs with respect to satellite spatial coverage	Fabio Madonna (CNR-IMAA)	D1.4, D1.6, D1.8
G1.06	Technical	H_2O, O_3, T, CO_2, CH_4, aerosols	Lack of a common effort in metadata harmonization	Fabio Madonna (CNR-IMAA)	D1.4, D1.6, D1.8
G1.07	Coverage	H_2O, O_3, T, CO_2, CH_4, aerosols	Need for a scientific approach for the assessment of gaps in the existing networks measuring ECVs	Fabio Madonna (CNR-IMAA)	D1.9
G1.08	Coverage	H_2O, O_3, T, CO_2, CH_4, aerosols	Evaluation of the effect of missing data or missing in temporal coverage of full traceability data provided by ground-based networks	Fabio Madonna (CNR-IMAA)	D1.9 Whiteman et al., 2011
G1.09	Coverage Vert. resolution	*CO*	Limited availability of quantitative profiles; Insufficient verification of vertical information in satellite products	Jean-Francois Mueller (BIRA)	D1.2
G1.10	Uncertainty	H_2O, O_3, T, CO_2, CH_4, aerosols	Insufficiently traceable uncertainty estimates	David Tan (ECMWF) (moved to Fabio Madonna)	D1.3 Immler et al., 2010
G1.11	Uncertainty	H_2O, O_3, T, CO_2, CH_4, aerosols	Traceable uncertainty estimates from baseline and comprehensive networks	David Tan (ECMWF) (moved to Fabio Madonna)	D1.1, D1.4 Immler et al., 2010
G1.12	Uncertainty	H_2O, O_3, T, CO_2, CH_4, aerosols	Propagate uncertainty from well-characterized locations and parameters to other locations and parameters.	David Tan (ECMWF) (moved to Fabio Madonna)	n/a
G.1.13	Coverage Governance	H_2O	Water vapor measurements with the lidar and microwave radiometer are often provided in a sparse	David Tan (ECMWF) (moved to Fabio Madonna) or Arnoud Apituley, KNMI	D1.1, D2.1

			way and under an uncoordinated effort		
G1.14	Coverage Governance	H_2O, O_3, T, *wind*	There is currently limited aircraft data, for example in Eastern Europe.	Ed Stone (Met Office)	n/a
G1.15	Coverage Governance	O_3 (total column)	Northern Hemisphere bias in NDACC and PANDORA network sites distribution	Karin Kreher (BKS)	D1.1, D2.1
G2.01	Coverage Governance	Aerosols	24/7 operation of lidar systems	Fabio Madonna, CNR-IMAA	n/a
G2.02	Coverage	Aerosols	Lidar incomplete altitude coverage	Arnoud Apituley, KNMI	D2.2, D2.4
G2.03	Comparator unc. Governance	Aerosols	Incomplete collocation of sun and moon photometers with day and night time aerosol lidars	Arnoud Apituley, KNMI	n/a
G2.04	Uncertainty Governance	Aerosols	Missing continued intercomparison with reference systems	Arnoud Apituley, KNMI	D2.2 Wandinger et al., 2015
G2.05	Uncertainty	Aerosols	Lack of rigorous aerosol lidar error budget availability	Arnoud Apituley, KNMI	D?.?; Earlinet
G2.06	Uncertainty Governance	Aerosols	Need of Raman lidars or better multi-wavelength systems	Fabio Madonna, CNR-IMAA	D2.2 Veselovskii et al., 2012
G2.07	Uncertainty	Aerosols	Need for assimilation experiments of lidar measurements	Fabio Madonna, CNR-IMAA	D2.2 EU project website ACTRIS2: www.actris.eu
G2.08	Uncertainty	Aerosols	Reducing calibration uncertainties using a common reference standard	Fabio Madonna, CNR-IMAA	D2.2
G2.09	Coverage	H_2O	Continuous operation of water vapor Raman lidars limited during daytime	Fabio Madonna, CNR-IMAA	n/a
G2.10	Coverage	O_3	Tropospheric O_3 profile data is limited	Arnoud Apituley, KNMI	n/a
G2.11	Uncertainty	O_3	Lack of rigorous tropospheric O_3 lidar error budget availability	Arnoud Apituley, KNMI	Leblanc et al., ISSI team report, http://www.issibern.ch/teams/ndacc/ISSI_Team_Report.htm (to be submitted to AMTD)
G2.12	Uncertainty	T	Lack of rigorous temperature lidar error budget availability	Arnoud Apituley, KNMI	Leblanc et al., ISSI team report, http://www.issibern.ch/teams/ndacc/ISSI_Team_Report.htm (to be submitted to AMTD)
G2.13	Uncertainty	T, H_2O (+column), *liquid H_2O*	Missing microwave standards maintained by National/International Measurement Institutes	Domenico Cimini, CNR-IMAA	D2.1 Walker et al., 2011
G2.14	Uncertainty	T, H_2O (+column), *liquid H_2O*	Lack of a comprehensive review of the uncertainty associated with MW absorption models used in MWR retrievals	Domenico Cimini, CNR-IMAA	D2.1 Rosenkranz, 2015
G2.15	Uncertainty Governance	T, H_2O (+column), *liquid H_2O*	Lack of unified tools for automated MWR data quality control	Domenico Cimini, CNR-IMAA	D2.1 EU Cost action TOPROF Report Löhnert & Maier, 2012

G2.16	Uncertainty Governance	T, H_2O (+column), *liquid* H_2O	Missing agreement on calibration best practices and instrument error characterization	Domenico Cimini, CNR-IMAA	D2.1 EU Cost action TOPROF Report Löhnert & Maier, 2012
G2.17	Uncertainty Governance	T, H_2O (+column), *liquid* H_2O	Lack of a common effort in homogenization of retrieval method	Domenico Cimini, CNR-IMAA	D2.1 EU Cost action TOPROF Report Cimini et al., 2011
G2.18	Uncertainty	H_2O, O_3, CH_4	Agreement on systematic vs. random part of the uncertainty and how to evaluate each part	Bavo Langerock Mathias Schneider	NORS_D4.3_UB.pdf
G2.19	Uncertainty	H_2O, O_3, CH_4	Line of sight and vertical averaging kernel are only approximations of the real 3D averaging kernel of a retrieval	Bavo Langerock	NORS_D4.2_DUG.pdf
G2.20	Uncertainty	H_2O, CH_4	Spectroscopic uncertainties	Mathias Schneider	Hase et al., 2012 Frankenberg et al., 2011
G2.21	Uncertainty	CO_2, CH_4	Current spectroscopic databases contain uncertainties	?	Wunsch et al., 2011
G2.22	Uncertainty	O_3, CO_2, CH_4	Cell measurements carried out to characterize ILS have their own uncertainties	Mathias Schneider	Hase et al, 2012 Hase et al., 2013
G2.23	Uncertainty	CH_4	Possible SZA dependence in the retrieval during polar vortex overpasses	Rigel Kivi (FMI)	n/a
G2.24	Uncertainty	CO_2, CH_4	In-situ calibration can be verified by involving new data	Rigel Kivi (FMI)	Wunsch et al., 2011
G2.25	Uncertainty	H_2O (column), O_3 (column), CH_4 (column)	TCCON calibration w.r.t. standards	?	n/a
G2.26	Uncertainty	O_3 (column)	Uncertainty of the O_3 cross section used in the spectral fit	Johanna Tamminen (FMI)	NORS_D4.3_UB.pdf NDACC_UVVIS-WG_O3settings_v2.pdf
G2.27	Uncertainty	O_3 (column)	Random uncertainty in total column O_3 retrieved by UV-vis spectroscopy dominated by instrumental imperfections impacting on the spectral fit calculations	Karin Kreher (BKS)	NORS_D4.3_UB.pdf NDACC_UVVIS-WG_O3settings_v2.pdf
G2.28	Uncertainty	O_3 (column)	Uncertainty in AMF calculations for zenith sky ozone retrievals	Karin Kreher (BKS)	Hendrick et al., 2011
G2.29	Uncertainty	O_3 (column)	Uncertainty in vertical averaging kernels	Karin Kreher (BKS)	Eskes and Boersma, 2003
G2.30	Uncertainty	O_3 (column)	Uncertainty in PANDORA measurements	Johanna Tamminen (FMI)	Herman et al., 2015
G2.31	Uncertainty	O_3 (tropospheric column)	Information content of MAX-DOAS tropospheric O_3 measurements	Francois Hendrick (BIRA)	D2.1; Liu et al., 2006 Irie et al, 2011 Gomez et al., 2014
G2.32	Uncertainty	O_3 (tropospheric column)	MAX-DOAS tropospheric O_3 retrieval method	Francois Hendrick (BIRA)	Same as for G2.31

G2.33	Uncertainty	O_3 (tropospheric column)	Random and systematic uncertainties of MAX-DOAS tropospheric O_3 measurements	Francois Hendrick (BIRA)	D2.1; Liu et al., 2006 Irie et al, 2011
G2.34	Uncertainty	H_2O (column)	Uncertainties of ZTD, given by a 3rd party (IGS)	Kalev Rannat (TUT)	Ning, 2012
G3.01	Comparator unc.	H_2O, O_3, T, CO_2, CH_4, aerosols	Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the inter-comparisons	Tijl Verhoelst	D3.1 (incl. Annex 1, 2 and 3)
G3.02	Comparator unc.	H_2O, O_3, T, CO_2, CH_4, aerosols	Limited quantification of the impact of different co-location criteria on comparison results	Tijl Verhoelst	D3.1 (incl. Annex 1, 2 and 3)
G3.03	Comparator unc.	H_2O, O_3, T, CO_2, CH_4, aerosols	Missing generic and specific standards for co-location criteria in validation work	Tijl Verhoelst	D3.1 (incl. Annex 1, 2 and 3)
G3.04	Comparator unc.	H_2O, O_3, T, CO_2, CH_4, aerosols	Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties	Tijl Verhoelst	D3.1 (incl. Annex 1, 2 and 3)
G3.05	Comparator unc.	H_2O, O_3, T, CO_2, CH_4, aerosols	Representativeness uncertainty assessment missing for higher-level data based on averaging of individual measurements	Tijl Verhoelst	D3.1 (incl. Annex 1, 2 and 3)
G3.06	Comparator unc.	H_2O, O_3, T, CO_2, CH_4, aerosols	Missing comparison error budget decomposition including errors due to sampling and smoothing differences	Tijl Verhoelst	D3.1 (incl. Annex 1, 2 and 3)
G4.01	Uncertainty	T	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances.	W. Bell	Bell et al., 2008 Bohrmann et al., 2013 Doherty et al., 2015 Geer et al., 2010 Lu et al., 2011
G4.02	Uncertainty	H_2O	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances	W. Bell	Same as for G4.01
G4.03	Coverage Parameter	T, H_2O	Where traceable uncertainty estimates exist for a model or reanalysis quantity, it is often limited to a few locations and parameters where reference datasets are available. Compre-hensiveness is lacking for extension to locations and parameters where reference datasets are not available	Tbc	n/a

G4.04	Governance	T, H_2O	Datasets from baseline and comprehensive networks provide valuable spatiotemporal coverage, but often lack the characteristics needed to facilitate traceable uncertainty estimates	Tbc	WPs 1,2,3
G4.05	Uncertainty	T, H_2O	Limited knowledge about how to propagate uncertainty from well-characterized locations and parameters to other locations & parameters	Tbc	WP4 (+Task 1.4/1.5)
G4.06	Comparator unc.	T, H_2O	Difficulty to assess the importance of natural variability in the total model-observation error budget.	Tbc	WP4 (+Task 1.4/1.5)
G5.01	Technical Governance	H_2O, O_3, T, CO_2, CH_4, aerosols	Access to data in multiple locations with different data policies and accessibility (e.g. speed of retrieving and unpacking, passwords)	Tbc	**http://www.gruan.org** **http://tccon.ornl.gov/** **http://www.ndsc.ncep.noaa.gov/data/**
G5.02	Technical	H_2O, O_3, T, CO_2, CH_4, aerosols	Access to data in multiple data format and structure (e.g. granularity of data). Lack of standardized metadata	Tbc	http://www.ucar.edu/tools/applications_desc.jsp
G5.03	Technical	H_2O, O_3, T, CO_2, CH_4, aerosols	Efficient data management to collocate observations needs to be improved	Tbc	CCI toolbox Giovanni GSICS
G5.04	Technical	H_2O, O_3, T, CO_2, CH_4, aerosols	Usability of reference data needs to be improved: high functionality in subset selection	Tbc	WP5
G5.05	Technical Governance	H_2O, O_3, T, CO_2, CH_4, aerosols	Usability of reference data needs to be improved: format	Tbc	WP5
G5.06	Technical	H_2O, O_3, T, CO_2, CH_4, aerosols	Need for analysis tools to exploit reference database (visualization, intercomparison, statistics, etc.)	tbc	(Partly) addressed in GAIA-CLIM in the form of a demonstrator Virtual Observatory
G5.07	Technical Governance	H_2O, O_3, T, CO_2, CH_4, aerosols	Incomplete development and/or application and/or documentation of an unbroken traceability chain of Cal/Val data manipulations for atmospheric ECV validation systems	tbc	D5.1 Keppens et al., 2015 (traceability chain) QA4ECV: http://www.qa4ecv.eu/ QA4EO: http://qa4eo.org/
G5.08	Comparator unc	H_2O, O_3, T, CO_2, CH_4, aerosols	Missing quantification of additional uncertainties introduced in the comparison results due to differences in (multi-dimensional) sampling and smoothing of atmospheric inhomogeneity	Tijl Verhoelst	D5.1, D3.1 Lambert et al., 2012 Verhoelst et al., 2015 Fasso et al., 2014 Ignaccolo et al., 2015 ?EU FP6 GEOmon Technical Notes D4.2.1 and D4.2.2 (2008-2011)?

Table 2.3. *Overview of the gaps that have been identified through users external to GAIA-CLIM through the GAIA-Clim user workshop and project website designated to the GAID. Primary ECVs in GAIA-CLIM include H_2O, O_3, T, CO_2, CH_4 and aerosols. Secondary ECVs are denoted in italics. Dx.x refers to GAIA-CLIM project deliverables, n/a = not available. Status per GAID Version 2.0.*

Gap Identifier	**Gap Type**	**ECV(s)**	**Gap Short Description**	**Gap owner(s)**	**Trace**
G6.GHGCCI.01	Governance	CO_2, CH_4, *CO*	Lack of structural funding	Ilse Aben	GHG_CCI
G6.GHGCCI.02	Technical	CO_2, CH_4, *CO*	Data delivery too late for timely satellite data validation	Ilse Aben	GHG_CCI
G6.GHGCCI.03	Coverage	CO_2, CH_4, *CO*	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	Ilse Aben	GHG_CCI
G6.GHGCCI.04	Uncertainty	CO_2, CH_4, *CO*	Absolute calibration of TCCON to WMO standards is limited (height and frequency)	Ilse Aben	GHG_CCI
G6.GHGCCI.05	Coverage, Vert. resolution	CO_2, CH_4, *CO*	Very limited vertical profile reference measurements	Ilse Aben	GHG_CCI
G6.GHGCCI.06	Coverage	CO_2, CH_4, *CO*	Missing system for urban scale validation needed for high spatial resolution satellite data	Ilse Aben	GHG_CCI
G6.GHGCCI.07	Uncertainty	CH_4, *CO*	No absolute calibration available (as is for TCCON), no traceability to WMO standards, no standardized procedures for NDACC retrievals	Ilse Aben	GHG_CCI
G6.GHGCCI.08	Technical, governance	CO_2, CH_4, *CO*	Access to relevant ECMWF meteo datasets is difficult or impossible for some researchers	Ilse Aben	GHG_CCI

3 Impact Assessment per Gap Type per ECV for the Non-Satellite Climate Monitoring Segment

3.1 Introduction

In this section, the impacts of each of the gaps are being discussed from the (end-)user perspective, including the service provider perspective (NWP, C3S, CAMS), and in reference to the GCOS climate monitoring principles and general targets. Also, if possible, indications are being provided on envisaged remedies, time schedule and cost estimates. Gaps with potential remedies envisaged within the GAIA-CLIM timeframe and scope are highlighted. The initial list of gaps at the start of the project has been documented in GAID Version 1.0 and was based on the input on gaps received through the first deliverables of work packages 1 through 6 (D1.1, D2.1, D3.1, D4.1, D5.1, and D6.1). Full discussions for each of the identified gaps, impacts and potential remedies reference have been made in the individual project deliverables and these are not repeated here. In particular, each of these deliverables has a traceable account that underpins each gap identified herein.

Gaps in the GAID are enumerated such that the first number denotes the Work Package (and hence deliverable) from which it arose. In Table 2.2, the complete list of identified gaps has been grouped into seven generic gap types (categories), which provides the structure for the discussion in this section on impacts and remedies. Note that some gaps are cross-cutting and thus might appear under more than one generic gap type or gap category (clear reference is made to other occurrences of a certain gap to limit unnecessary duplications). The initial list of gaps, as well as the discussion on impacts and potential remedies, is being modified and further improved through each next version of the GAID.

Results from the 2015 user survey

The results of the user survey in 2015 (‘Report on results of user survey’, deliverable D6.1) implicated 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 need for functional match-up facilities was clear, while it might be difficult to define the functionality in such a way that it will be taken up by users. Another important gap that was clearly revealed by the user survey was related to user familiarity with, and use of, uncertainties in the non-satellite observations.

3.2 Gaps in Coverage

(G1.03; G1.04; G1.07; G1.08; G1.09; G1.13; G1.14; G1.15; G2.01; G2.02; G2.09; G2.10; G4.03: 13 gaps in total)

Key aspects, which might be expected here are user needs related to missing non-satellite (reference) observations. Gaps in coverage could be temporal (i.e. insufficient time sampling), geographical (i.e. missing network locations), and also vertical (observations which are missing atmospheric domains).

The gaps in coverage which have been identified and that are being addressed within GAIA-CLIM include:

<u>All ECVs:</u>

- ***Missing evaluation criteria for assessing existing observing capabilities (G1.03)***

- 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.

  Impacts: Firstly, it inhibits realising the benefits of an explicitly system of systems architecture (trickle down, calibration, characterisation etc.). Secondly, it 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 very many use cases.

  Remedy: GAIA-CLIM has developed D1.3 which provides a potential framework in which to initiate discussions. But this is the limit of how far GAIA-CLIM alone can proceed on this gap. D1.3 shall be shared at the upcoming WIGOS management meeting in early 2015 for consideration. WIGOS is likely the appropriate body to get broader buy-in and enhanced coordination amongst global stakeholders. We shall also write-up a version of D1.3 for peer-review to gain greater exposure and buy-in (submission foreseen Q2 2016). Success would be if the system of systems approach and maturity assessment is adopted by WIGOS (likely modified) and used to instigate a system of systems approach across atmospheric, oceanic and terrestrial domains and that approach yields demonstrable scientific, technological and financial benefits. In the interim uptake in other projects would be a demonstrable outcome.

  Timescale and cost estimate: Financial cost (direct costs) is likely to be low. Timeline to adoption by WIGOS is likely to be at earliest the next WMO Congress in 2019 but much discussion within WIGOS and WMO Technical Commissions shall occur in the interim. GCOS shall ensure consideration by appropriate bodies.

– ***Lack of a comprehensive review of current non-satellite observing capabilities for the study of ECVs in atmospheric, ocean and land domains (G1.04)***
  - 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. These activities support an increasing range of services with high socio-economic benefits. User requirements have become more stringent and new requirements have appeared with respect to these applications. More observation systems serve needs for real-time, near-real-time and non-real-time availability.

    In order to allow EO providers and users to maximize the value of existing observations and implement user friendly mapping facility, a comprehensive review of the current observing capability at European and global scale for all the ECVs is needed. This will facilitate also an identification of the existing geographical gaps in the global observing system. While a comprehensive review of space-based mission and needs has been put together within official document of the international community (like the CEOS Handbook and in the "Satellite Supplement" to the updated GCOS Implementation Plan), the mapping of current observing capabilities has been carried out by each network under an uncoordinated effort across the community measuring ECVs. Extensive review have been already provided by WMO, GEOSS, GCOS, but they are limited to a sub-set of network or to a subset of ECVs, often drive by the mission of each single program of international institution.
  - Remedy: GAIA-CLIM will spent a huge effort in putting together one of the more extensive review of the existing capabilities for the measurement of a multitude of ECVs according to those listed within the GAIA-CLIM project. Results will be delivered on September 2016 (deliverable D1.6).This task will be considered for being established over long term as a service activity regularly updated starting from

the end of GAIA-CLIM, after March 2018.
Timescale: uncertain; Cost estimate: for this activity is low but the importance of keeping this service alive over long term is critical to avoid the fragmentation already experienced in the past. It is obvious that the review might be reinforced by a capillary exchange of information resulting from an enhanced coordination amongst global stakeholders like the WMO Commission on Basic Systems, GCOS, GEOSS, GAW, and the federated networks adhering to this programs. This final task has an uncertain scenario and requires further plans and a cost assessment.

- ***Need for a scientific approach to the assessment of gaps in the existing networks measuring ECVs (G1.07)***
  - 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 station. It is essential to reduce these big gaps in the measurement data coverage, or at least, to prevent these gaps from expanding. Considering the importance of continuous, long-term observations for ECVs for many applications, an assessment of gaps on a scientific sound basis is a mandatory step over future improvements of the global observing system.
    Remedy: a comprehensive scientific approach assessing the gaps in the current observing capabilities of the system of systems does not exist. This assessment are commonly performed without a scientific basis or using an ad hoc approach never applied in an extensive and systematic way. Often this is done on the basis of the experience gained by the international experts in the frame of research projects. GAIA will start addressing this gap, proposing an assessment of the geographical gaps in the current surface-based and sub-orbital observing capabilities for a few variable like water vapour and aerosol on the basis of two different techniques (functional regression technique, Markov chain Monte Carlo).
    Timescale and cost estimate: GAIA-CLIM results will be delivered before the end of the project (D1.9). Anyhow, more studies are needed and this can accomplished only through a closer cooperation between measurement community, geo-statisticians and modellers to design different solutions to assess the gaps and then to inter-compare the elaborated approach to provide robust and reliable solutions. This scenario is uncertain and need the support of global stakeholders, though the cost are moderately low and likely sustainable.

    Risk: the risk is obviously related to the lacking on interdisciplinary approach that might generate and under or a less efficient exploitation of the available data.
- ***Evaluation of the effect of missing data or missing temporal coverage of full traceability data provided by ground-based networks (G1.08)***
  - Missing data are a common problem for geophysical data sets. For instrumental data sets obtained in modern times, the uneven spatio-temporal coverage arises because of the way the measurements are obtained. Depending on the type of instrumentation, remote sensing is influenced by atmospheric conditions and can be hampered by clouds, aerosols, heavy precipitation, or extreme weather conditions. Missing data are, in particular, a source of problems in climate research, e.g., in the analysis and modelling of spatio-temporal variability. Analyzing 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 on the evolution of the oscillatory modes in the gaps, and provide new information on changes in climate. Spatio-temporal filling techniques

have been developed (Kondrashov et al., 2006) 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/assimilation quantity and also the observational dataset.
Remedy: the use of geo-statistical approaches to assess this effect; Research should characterize model-observation differences with focus on enhancing representation of "observation operators". GAIA-CLIM will initiate this work in the frame of task 1.4, in the frame of the study of the geographical gaps, but more research is needed on this topic.
Timescale and cost estimate: uncertain.
Risk: less efficient exploitation of the available data with large impact on the global observing system that running under an uncoordinated effort might generate dataset (whose cost is significant) that will be never intensively used due to the presence of missing data or missing temporal coverage.

<u>O_3 (total column):</u>

- ***Northern Hemisphere bias in NDACC and PANDORA network sites distribution (G1.15)***
  - NDACC and PANDORA total column ozone 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 that NDACC stations often include a variety of instruments measuring total column ozone such as UV/visible spectroscopy, MAX-DOAS, Brewer, Dobson, LIDAR, ozonesonde, FTIR).
    Impact: 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 the O_3 ECV.
    Remedy: Develop strategies for network extension, and long-term preservation of data and measurement capabilities. This involves an in-depth study of the capabilities of the existing sites as well as a literature study on what distribution patterns would be most desirable.
    Timescale and cost estimate: 1 yr

The gaps in coverage which have been identified though are not being addressed within GAIA-CLIM include:

<u>H_2O:</u>

- ***Water vapour measurements with the lidar and microwave radiometer are often provided in a sparse way and under an uncoordinated effort (G1.13)***
  - Water vapour and carbon dioxide (CO2) are the principle greenhouse gases (GHGs). CO2 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 for sure 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 also this synergy, but they are often not coordinated thus losing their powerful observing capability at a large scale. However, the construction of such integrated system will strongly depend on the creation of long-term sustainability of the research based 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.
Remedy: A federated approach is the way to follow to minimize the number of redundant initiatives and to maximize the impact. The ESFRI funding might in the near future support this type of federated approach over long term (10 years at least). ACTRIS is candidate to become an ESFRI research infrastructure starting from 2016. GAIA-CLIM will ideally contribute to this initiative setting the metrology for both this techniques and thus facilitating their routine use at every site.
Timescale: uncertain; Cost estimate: moderate but if under the ESFRI label, at least for the European countries, it is sustainable.

- ***Continuous water vapour profiles from Raman lidars limited during daytime (G2.09)***

  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 lidar 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 at night 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 vapor 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 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 profile 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.

  Remedy: The ACTRIS-2 and HD(CP)² projects are working on this aspect and before April 2017 both should provide results and the assessment of the real performances of this synergetic solution. Technological improvements of lidar techniques for measuring water vapour are also expected but over mid and long term.

  Timescale: more than 5 years at unknown costs

T, H_2O, O_3, *wind*:

- ***There is currently limited aircraft data, for example in Eastern Europe (G1.14)***
  - Missing aircraft information in many places. Very few aircraft currently provide water vapour over Europe, and even fewer O_3. Both of these parameters require additional sensors to be added to aircraft. There is EUMETNET funding available for a slow increase in the number of aircraft that carry humidity sensors, but nothing is currently planned for O_3.

    Remedy: If suitable airlines in Eastern Europe can be identified it may be possible to include them in the E-AMDAR program. The gap cannot be addressed within GAIA-CLIM though the scientific studies carried out in the frame of task 1.4 will contribute to assess (at least for aerosol and water vapor) the optimal spatial and temporal coverage required in the region to ensure the satellite cal/val and the efficient monitoring of regional climate and, therefore, will provide input for minimizing the effort in the aircraft monitoring. (= also governance gap).

    Timescale and cost estimate: airlines are hesitant to attach additional sensors to their aircraft and certification is expensive and can take several years per airline per aircraft type; timeline for improvement of this gap is uncertain at the current stage.

Aerosols:

- ***24/7 operation of lidar systems (G2.01)***

  Lidar profiling of atmospheric aerosol and cloud layers has become important for climate research during the last decades. More recently, the volcanic eruption hazards of Eyjafjallajökull and Grimsvötn (Pappalardo et al., 2014) for aircraft safety have increased the need for a height-resolved monitoring of the aerosol concentration on continental scales. Most of the lidar measurements are performed on a discontinuous basis and not continuously over 24 hours, 7 days a week. Thousands of ceilometers and simple backscatter lidars are operating on a continuous basis all around the work though their contribution to the characterization of aerosol impact on weather and climate as well as for the satellite validation is limited compared to more advance multi wavelength Raman lidar system or the HSRL because of the strong assumptions they need to provide an estimate of the aerosol optical and microphysical properties.

  However, 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 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 already provide continuous data (24 hours/7 days a week).

  Remedy: In the frame of ACTRIS-2 H2020 project (2015-2019), the expertise in the network will be used to facilitate developments of easy to implement and robust solutions for automated operation and remote control of lidar instruments at EARLINET stations. The optimization of instruments for long-lasting or continuous (unattended) operation will increase the number of systems working 24/7 to increase the time coverage of lidar data. The first and second reports of ACTRIS-2 (D2.5 and D2.7 of ACTRIS) on technical upgrades and QA activities at EARLINET and Cloudnet stations expected on April 2016 and April 2017 respectively will provide an update about the progress within in the number of operational systems and an estimate of the timescale and cost required to make an advanced aerosol lidar operational at any other station. GAIA-CLIM work carried out in the frame of WP23 to define the full traceable uncertainty for the lidar optical properties will be joined to ACTRIS towards the near real-time delivery of 24/7 days aerosol products.

  (= also governance gap).

  Remedy: efforts towards to automation, increase the number of systems working 24/7 to increase the coverage.

  Timescale and cost estimate: require further investigation (= also governance gap).
- ***Lidar incomplete altitude coverage (G2.02)***
  - Lidar systems are limited in the measurements of the first hundreds of meter of the atmosphere close to the surface.

    Remedy: use of multiple telescopes. Implementation dependent on instrumental design. E.g. is existing system easily expanded.

    Timescale: No single instrument design is generally applicable

    Cost estimate: If the expansion is limited to a single channel the costs are modest. The number of channels that need to be involved in the expansion can be treated as a multiplicative factor.

<u>O_3:</u>

- ***Tropospheric O_3 profile data is limited (G2.10)***
  - Lack of tropospheric O_3 profile data for model assimilation and satellite validation.

    Remedy: Network establishment. Current data source is from ozone sonde launches that lack temporal resolution. Lidar measurements of tropospheric ozone profiles can remedy. In the US a network of a number of tropospheric ozone lidars has been established (TONET). In Europe a latent network exists.

Timescale: >5 y; Cost estimate: very high.<u>*CO:*</u>

- ***Limited availability of quantitative profiles of carbon monoxide (G1.09)***
  - There are, to this date, only very few quantitative vertical profiles of carbon monoxide. Such data are needed to verify and characterize vertical information in satellite products. The added value of vertical information from ground-based or space-borne data is still not clearly well established. The modelling work to be performed in the frame of GAIA-CLIM aims precisely to provide a clear evaluation of this added value of vertical profile information for the purpose of constraining the global and regional CO sources and sinks.

    Remedy: (not addressed within GAIA-CLIM) is to collect FTIR vertical profiles at 5-10 well distributed stations over a period of several years. Within GAIA- CLIM, the existing data will be used to quantify the added value of existing vertical profiles and to determine the potential benefits of additional data. The deliverable D1.5 (Summary of initial model-based study results and plans for remainder of project) expected on July 2016 will report on the work progress while final results will be delivered at the end of the project (D1.10: Report on the scientific assessment of gaps based on forward, inverse, and data assimilation modelling frameworks). In the frame of WP2, GAIA-CLIM will also provide traceable uncertainty estimates for the FTIR technique.
    Timescale and cost estimate: the implementation of this FTIR network is likely a mid-term project whose funding is high and uncertain.
    Risk: if the gap will be not fully addressed, is to have insufficient constrained global and regional CO budget from observations. Remedy if issue not fully addressed: use existing vertical information from space-borne sensors, benefiting from a full assessment of quality and reliability based on FTIR data, and attempt satellite validation using the limited existing dataset in combination with CTMs.

3.3 Gaps in Vertical Resolution

(G1.09: 1 gap in total)

The gaps in vertical resolution specifically refer to user needs on better-resolved vertical profile observations for the ECVs. Gaps have been identified though these gaps are not being addressed within GAIA-CLIM:

<u>*CO:*</u>

- ***Limited availability of quantitative profiles of carbon monoxide (G1.09)***
  - Large uncertainty in top-down global and regional CO inventories; Insufficient verification of vertical information in satellite products.
    Remedy: uncertain.
    Timescale and cost estimate: uncertain.

3.4 Gaps in Knowledge of the Uncertainty Budget and Calibration

(G1.10; G1.11; G1.12; G2.04; G2.05; G2.06; G2.07; G2.08; G2.11; G2.12; G2.13; G2.14; G2.15; G2.16; G2.17; G2.18; G2.19; G2.20; G2.21; G2.22; G2.23; G2.24; G2.25; G2.26; G2.27; G2.28;

G2.29; G2.30; G2.31; G2.32; G2.33; G2.34; G4.01; G4.02; G4.05: 35 gaps in total)

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 and that are being addressed within GAIA-CLIM include:

<u>All ECVs:</u>

- ***Insufficiently traceable uncertainty estimates (G1.10)***
  - Limited availability of traceable uncertainty estimates propagates to applications that use model or reanalysis fields. While a vast amount of data is 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 concerns has been raised also by the NMIs participating in atmospheric networks (e.g. METEOMET).
    Progress here is critical to have data record stable over time, insensitive to the method of measurement, uniform worldwide, based on references that can improve
    This will allow to establish the 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, better communication,
  - More informed use of data generated might allow large improvement in the accuracy of climate data record 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 little idea about the relative qualities of alternative datasets.
    Remedy: this gap requires improvements in the operational and research observing systems, addressed by GAIA-CLIM for several techniques (e.g. lidar, FTIR, microwave radiometer) in the frame of WP2, but also a better characterization of model-based & assimilation-based uncertainty, initiated by GAIA-CLIM in the frame of WP4.
    Timescale and cost estimate: a long term strategy, with a moderately low cost, is needed and likely more studies needs to performed over the next years to improve the model performance through the data assimilation.
    Risk: risks are related to the magnitude of the improvement of assimilation-based uncertainty due to the use of ground-based traceable column and profiling measurements. Previous studies show that the impact should not be neutral so the level of risk of not success is low, but the effective benefit will be assessed within the project duration.
    (= also governance gap).
- ***Traceable uncertainty estimates from baseline and comprehensive networks (G1.11)***
  - 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 baseline networks should be actively curated and retained. Datasets from baseline and comprehensive networks provide valuable spatio-temporal coverage, but often lack the characteristics needed to facilitate traceable uncertainty estimates. It is

therefore essential to identify 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.

GAIA-CLIM deliverable D1.3, released on November 2015, support the designation of non-satellite observational capabilities into a structured system of systems architecture consisting of reference quality, baseline and comprehensive networks

In particular, baseline network should:

1. periodically assess their measurements either against other instruments;
2. report representative uncertainties;
3. report metadata about changes in observing practices and instrumentation.

Comprehensive network should do the same work for at least the point 2 and 3.

Remedy: In view of the full data exploitation, at least baseline networks are asked to improve their current status to become closer to the reference networks in the provision of traceable uncertainty estimates. This will represent an essential contribution to make progress in the status of the global observing systems (also in relationship with G1.10). This gap cannot be solved within GAIA-CLIM, though the deliverable D1.3, defining the role of the different network, represents the instrument to assess the level of maturity of each network.

Timescale and cost estimate: for the improvement of the operation of baseline networks are strongly depending on the plans of international bodies and stakeholders.

Risk: the risk of not implementing this strategy, as it is described in the deliverable D1.3 of GAIA-CLIM, is that the potential impact of the observations provided by baseline (but also comprehensive) networks will be never fully exploited for the satellite Cal/Val and for the study of climate.

– ***Propagate uncertainty from well-characterized locations and parameters to other locations and parameters (G1.12, see also G4.05 below)***
    - Reanalysis is a systematic approach to produce data sets for climate monitoring and research. Key limitations to re-analysis are:

      1. observational constraints, and therefore reanalysis reliability, can considerably vary depending on the location, time period, and variable considered;
      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 observation, 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.
    - .

      Remedy: this is a relevant gap that requires modelling studies focused on the characterization of uncertainty propagation in models and assimilation systems. This gap can also provide essential contribution to make progress on G4.01. GAIA-CLIM will not specifically deal with this gap..

      Timescale and cost estimate: for the delivery of results from such kind of studies costs and timelines are both quite uncertain..

Risk: the lacking of appropriate techniques to propagate uncertainty from well-characterized locations and parameters to other locations and parameters is currently limiting the value of the re-analysis for the study of climate at the global scale and it is one of the challenge for the future improvement of this approach.

- ***Limited knowledge about how to propagate uncertainty from well-characterized locations and parameters to other locations and parameters (G4.05, see also G1.12 above)***
  - Essential contribution to make progress on G4.03 (Coverage/Parameter gap).
    Remedy: Modelling studies to characterize propagation of uncertainty in models and assimilation systems.

Temperature:

- ***Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances (G4.01)***
  - Lack of robust uncertainties associated with model fields and related TOA radiances preclude the use of these data for a complete validation of satellite EO data.
    Agencies and instrument teams sometimes slow to react to the findings of NWP based analyses of satellite data, due to lack of traceable uncertainties.
    Remedy: Assess uncertainties in NWP & reanalysis fields through systematic monitoring using GRUAN data.
    Timescale and cost estimate: GAIA-CLIM 48 manmonths.

H_2O:

- ***Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances (G4.02)***
  - Lack of robust uncertainties associated with model fields and related TOA radiances precludes the use of this data for a complete validation of satellite EO data. Agencies and instrument teams sometimes slow to react to the findings of NWP based analyses of satellite data, due to lack of traceable uncertainties.
    Remedy: Assess uncertainties in NWP & reanalysis fields through systematic monitoring using GRUAN data.
    Timescale and cost estimate: GAIA-CLIM; 48 manmonths.
- ***Reducing calibration uncertainties using a common reference standard (G2.08)***

  One of the paramount needs for developing a long-term dataset for monitoring atmospheric water vapour using lidar techniques is represented by the calibration of Raman lidar water vapour profile that varies randomly around some mean value (often addressed as calibration constant that depends only in 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 which is already typically measured in decades [Weatherhead et. al., 1998] [Boers and Meijgaard, 2009]. For this reason it is important to carefully examine any calibration technique developed for ensuring stable and long-term calibrations. Absolute and relative, but also hybrid calibration methods have been developed. More recently, reference calibration lamp, traceable tool according to NMIs, have proven to be robust for absolute calibration of water vapor Raman lidar to reduce systematic uncertainties and may represent a common reference on all the available systems. The cost of this lamp and of their operation use on a systematic basis is limited and affordable (less than 10 KEuros per year).

  Remedy: GAIA-CLIM WP2 deals with this technique in cooperation with ACTRIS-2 WP2. At a few station a comparison of different methods, absolute and relative will be investigated in order to provide recommendation about the solutions to implement in an systematic way and about the uncertainties they may imply in the monitoring of water vapor in whole troposphere and in the UT/LS.

Timescale: ~1 y; Cost estimate: GAIA-CLIM D2.4 and D2.5

- ***Uncertainties of ZTD, given by a 3rd party (IGS). Dominates GNSS-IPW uncertainty together with ground pressure uncertainty (G2.34)***
    - ZTD is one of the final products of GNSS-data processing, where the actual surface meteorological parameters are usually not necessary for quantifying the delay itself and its formal (1σ) error. It must be investigated if and what components of ZTD errors (obtainable from GNSS-data processing software and not already included in the formal error of ZTD) could be reasonable to add as components to the ZTD uncertainty budget. The investigations cannot be restricted to one data processing method (and software package) only. In recent work by T.Ning et al. (2015) compared to Ning (2012) and refereed in D2.1 the radial and tangential components of orbital errors have been added to ZTD uncertainty. Adding these error components would be similar for both PPP and DD methods as explained in Dousha, (2010). Currently a solution given in Ning et al. (2015) applies for PPP-method only and gets implemented by GFZ for GRUAN data analysis. Once getting GRUAN GNSS-IPW, it is known how its uncertainty is calculated, but it remains unclear what is and will be the situation with non-GRUAN data providers.

      Remedy: In practice, there is much more GNSS-IPW data available from trusted networks and processed by trusted Analysis Centers (AC) – for example from E-GVAP http://egvap.dmi.dk/ or Suominet http://www.suominet.ucar.edu/data.html . These could be good sources of ground reference data if made available for the Virtual Observatory. The question is how to use the uncertainties given. Usually the GNSS tropospheric product consists of both ZTD, 1σ error of ZTD and IPW, but not always the metadata needed for GRUAN-like GNSS-IPW uncertainty estimation. If not restricting the project to GRUAN-GNSS product, then GAIA-CLIM (in VO) should offer a possibility to use GNSS-IPW from "whatever sites" by applying/implementing GRUAN-like uncertainty estimation following Ning et al. (2015) algorithm in VO. This needs not only the tropospheric product itself, but additionally all relevant metadata not coming with RINEX files. While using non-GRUAN GNSS-product "as is" then the VO-user needs to be aware, that the uncertainties are (or can be) calculated/estimated differently. Additionally the software settings and metadata used in GNSS-data analysis should be known. Otherwise it is impossible to compare ZTD and GNSS-PW values and uncertainties from different sites in a consistent way. For experimental work: processing a certain set of data (fixed size network, ca 1 month time window) with different data processing strategies (varying error models, data weighting algorithms). Experiments with DD are planned with Bernese and GAMIT and the results compared with PPP (GIPSY or Bernese in PPP mode or EPOS). The sites will be chosen from IGS-network and E-GVAP, including some from GRUAN. Further work outside this project's timeframe would be giving the recommendations for implementation of GRUAN-like uncertainty analysis in non-GRUAN Analysis Centers (for both PPP and DD method).
      In short, analysis of definition and handling of formal errors in different software and methods contributing to ZTD uncertainty budget. Numerical experiments. Timescale and cost estimate: GAIA-CLIM Task 2.1.6

Temperature, H_2O

- ***Lack of a comprehensive review of the uncertainty of the MW absorption spectrum used in MWR retrievals (G2.14)***
    - Most common MWR retrieval methods are based on the theory of radiative transfer through the atmospheric medium. Thus, uncertainties in modeling 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 dataset 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.

Impacts: Most operational MWR operate in the 20-60 GHz range, where relevant absorption comes from water vapor, oxygen, and liquid water. For water vapor, the absorption model uncertainties dominate the measurement error budget especially for high-humidity conditions. For oxygen, different absorption models agree very well at opaque channels (56-60 GHz), but show larger differences between them and with respect to MWR observations at more transparent channels (50-56 GHz). Uncertainties in the 50-56 GHz range may bias temperature retrievals in the upper atmosphere. For liquid water, the major uncertainties are related to supercooled water, which impact both the water vapor and the total column liquid water retrievals in presence of supercooled water.

Remedy: Modifications of absorption models are continuously proposed on the open literature based on laboratory data and MWR field observations. In addition there have been some recent advances in this area, specially related to liquid water absorption, which are yet to be published. To fill this gap, a review of the state-of-the-art and the associated uncertainty of MW absorption models is needed. The absorption model uncertainties need to be propagated through radiative transfer and inverse operator to estimate the total uncertainties affecting the retrieval methods. This goal is planned to be addressed within the GAIA-CLIM duration and will be reported in D2.2-D2.9.

Timescale: 2 years. Activities shall start at KO+11 and end at KO+33. A timeline diagram for G14 (as well as G13, G15-G17) is shown below; Cost estimate: 19 person/months at 50%.

<u>O_3:</u>

- ***Lack of rigorous O_3 lidar error budget availability (G2.11)***
  - Full exploitation of vertical profiles of tropospheric O_3 profiles hindered.
    Remedy: compile error budgets.
    Timescale and cost estimate: 1 yr, GAIA-CLIM WP2
- ***Lack of rigorous temperature lidar error budget availability (G2.12)***
  - Full exploitation of vertical profiles of tropospheric O_3 profiles hindered.
    Remedy: compile error budgets.
    Timescale and cost estimate: 1 yr, GAIA-CLIM WP2
- ***Uncertainty of the absorption cross sections used in the spectral fit & systematic errors on AMF air mass factor calculation (G2.26)***
  - Dominates systematic error in total column O_3 measured by UV-vis spectroscopy.
    Remedy: Standardize measurement protocols and retrieval methods to minimize sources of systematic biases.
    Timescale and cost estimate: unclear at this time and require further investigation.
- ***Random uncertainty in total column O_3 retrieved by UV-vis spectroscopy dominated by instrumental imperfections impacting on the spectral fit (G2.27)***
  - Uncertainties in the ozone slant columns retrieved with the data analysis fitting procedure are uncertainties caused by instrumental imperfections such as detector noise, resolution change, etaloning and other non-linearities of the detector, stray-light, and polarisation effects, as well as uncertainties in the Ring effect, unknown absorbers, and the wavelengths dependency of the AMF. Such uncertainties are mostly random in nature and therefore can be estimated statistically from the least-

squares fit procedure. However, fitting uncertainties derived from the least-squares analysis typically result in unrealistically small uncertainties and often underestimate the measurement uncertainty by a factor of two. Results from intercomparison exercises (e.g. Van Roozendael et al., 1998, Vandaele et al., 2005, Roscoe et al., 2010) show that state-of-the-art instruments hardly agree to better than a few percent, even when standardised analysis procedures are used. This indicates that the actual accuracy in the ozone slant columns is at least to some degree limited by uncontrolled instrumental and/or analysis factors.
Impact: Detector noise and instrumental imperfections impact on the quality of the spectral fit during the data analysis and hence on the resulting O_3 slant columns; this carries through to the final product, the O_3 total column.
Remedy: Improve our understanding of the discrepancy between the calculated fitting uncertainty and the more realistically estimated total random error, firstly, by evaluating all literature studies and other documentation available on this topic and secondly by using upcoming intercomparison campaigns to provide more state-of-the-art data for further investigations specifically tailored to this issue.
Timescale and cost estimate: unclear at this time & requires further investigation.

- ***Uncertainty in a priori profile shape for AMF calculations for zenith sky ozone retrievals (G2.28)***
  - ***O_3 and pressure/temperature a priori profiles are key input parameters for the AMF calculation. There is a lack of adequate data base of tropospheric O_3 in particular.*** 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 data base 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 the 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 in the network.
    Impact: AMF calculations are essential for the conversion of slant columns into vertical columns, and have the biggest impact on the uncertainty in total column O_3. Hence it is important to reduce the uncertainty introduced by the AMF calculations as much as possible.
    Remedy: Firstly, improve climatological data bases of a priori O_3 profiles, with particular emphasis on tropospheric O_3. Secondly, standardize AMF calculation methods and data bases of a-priori information used in AMF calculation.
    Timescale and cost estimate: unclear at this time & requires further investigation.
- ***The information content for tropospheric O_3 retrieval from UV-visible spectroscopy has not been fully characterized (G2.31)***
  - This gap limits the assessment of the usability of the technique for tropospheric O_3 monitoring.
    Remedy: Investigate the information content of tropospheric O_3 measurements from UV-visible MAX-DOAS measurements in a broad range of observation conditions.
    Timescale and cost estimate: unclear at this time & requires further investigation.
- ***More work is necessary to optimize and fully characterize methods of tropospheric O_3 retrieval from MAX-DOAS measurements (G2.32)***
  - This gap limits the assessment of the usability of the technique for tropospheric O_3 monitoring.
    Remedy: Study optimal approaches for tropospheric O_3 retrieval from MAXDOAS.
    Timescale and cost estimate: unclear at this time & require further investigation.
- ***A comprehensive error budget and validation of tropospheric O_3 retrieval from MAX-DOAS and PANDORA measurements is currently lacking (G2.33)***

- The lack of uncertainty characterization and information content analysis limits the potential for network capabilities assessment.
  Remedy: Perform error budget and sensitivity analysis of tropospheric O_3 retrieval, and conduct validation exercises.
  Timescale and cost estimate: unclear at this time & require further investigation.

<u>H_2O, O_3, CH_4 (FTIR):</u>

- ***There is no clear agreement yet on what is the systematic part of the uncertainty and what is the random part of the uncertainty in FTIR measurements and how to evaluate each part (G2.18)***
  - 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 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 is important for determining accuracy and precision, e.g. when comparing to satellite data, and uncertainty of an average of data.
    Remedy: Recipe to evaluate systematic versus random uncertainty is being developed.
    Timescale and cost estimate: unclear at this time & requires further investigation.
- ***Line of sight and vertical averaging kernel are only approximations of the real 3D averaging kernel of a retrieval (G2.19)***
  - 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 measurement. 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.
    Remedy: Evaluate 3D averaging kernels.
    Timescale and cost estimate: unclear at this time & requires further investigation.

<u>H_2O, CH_4</u>

- ***The current spectroscopic databases contain too large uncertainties to model correctly the spectral windows used for H_2O and CH_4 retrievals (G2.20)***
  - This gap increases the uncertainty on the delivered H_2O and CH_4 products.
    Remedy: Perform and analyse spectroscopic experiments in the laboratory in the spectral bands used for ground-based and satellite retrievals.
    Timescale and cost estimate: unclear at this time and require further investigation. If new spectroscopic data become available, they will be evaluated in GAIA-CLIM.

<u>CH_4</u>

- ***Possible SZA dependence in the retrieval during polar vortex overpasses (G2.23)***
  - May influence CH_4 retrieval under polar vortex conditions.
    Remedy: Use AirCore measurements, currently limited availability.
    Timescale and cost estimate: unclear at this time & requires further investigation.

<u>CO_2, CH_4:</u>

- ***In-situ calibration can be verified by involving new data (G2.24)***
  - impact on the traceability to standards.
    Remedy: Involve new AirCore measurements.

Timescale and cost estimate require further investigation.

Aerosols:

- ***Lack of rigorous aerosol lidar error budget availability (G2.05)***
  - Full exploitation of vertical profiles of aerosol optical properties hindered.
    Remedy: compile error budgets.
    Timescale: 1 yr; Cost estimate: Part of GAIA-CLIM

The gaps in knowledge of the uncertainty budget and calibration which have been identified though are not being addressed within GAIA-CLIM include:

Temperature, H_2O:

- ***Missing microwave standards maintained by National/International Measurement Institutes (G2.13)***
  - The traceability of the MWR estimates and their uncertainty requires the traceability of MWR calibration to SI standards. This implies the use of certified black-body targets and temperature sensors (measuring the target physical temperature). Commercial black-body targets have reached a mature state, but their characterization is usually limited. Despite many realizations of microwave brightness temperature standards exist in the form of heated or cooled calibration targets, none are currently maintained as a standard by a national/international measurement institute (Walker, 2011).
    Impacts: Despite the efforts for fully characterizing the MWR absolute calibration, the traceability of MWR observations to national/international standards is currently not feasible.
    Remedy: Metrology applicable to microwave remote sensing radiometry is currently under development at some national/international measurement institute (e.g. National Institute for Standards and Technology, USA). These efforts include the development of a standard radiometer and standard high-emissivity black body targets. It is expected that SI-traceable calibration for black-body targets and transfer standards in the form of calibrated black-body targets will be available at the Microwave System Laboratory of NIST in the next few years. The aim here is to follow the activities at NIST and report updates to the GAIA-CLIM project (D2.2-D2.9), the COST Action TOPROF, as well as to microwave radiometer users and manufacturers.
    Timescale: 2-5 years; Cost estimate: still under investigation.
- ***Lack of unified tools for automated MWR data quality control (G2.15)***
  - Quality control (QC) procedures are fundamental for providing the users with tools for judging and eventually screening MWR data and products. Most of operational MWR 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 finally 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 procedure.
    Impacts: The availability and application of QC procedures is currently not fully harmonized and automated. This impacts the quantity and quality of the delivered data, as poor QC may result in either delivering faulty data or screening out good

data. As we stand, it is recommended to perform eye inspection routinely to detect suspicious data and faulty calibration, resulting in additional personnel costs.
Remedy: MWR QC procedures shall be harmonized and automated to the maximum extent possible. In the framework of the EU COST Action TOPROF, the Working Group on Microwave Radiometers (WG3) is actively addressing this issue by interacting with manufacturers and proposing ways for QC automation. The leader of GAIA-CLIM Task 2.1.2 is co-chairing TOPROF WG3. The results of these activities will be followed and reported within the GAIA-CLIM project (D2.2-D2.9) as suggestions to users and manufacturers.
Timescale: 2 years (TOPROF goes until Oct 2017); Cost estimate: still under investigation.

- ***Missing agreement on calibration best practices and MWR instrument error characterization (G2.16)***
    - o Common procedures are applied by the operators to perform MWR calibration and instrument error characterization. Currently, these procedures are provided by the manufacturers for the most and thus they are often instrument specific.
    - o Lack of standardization of calibration procedures and error characterization. Impact on network-wide product harmonization.
      Impact: Therefore, there is currently a lack of standardization in calibration procedures and error characterization. This in turn impacts negatively the harmonization of products provided by an heterogeneous MWR network.
      Remedy: The currently available practices for MWR calibration and error characterization shall be reviewed. From these, the best practices should be defined and reported, and the documentation shall be made available to operators and users. This task is currently tackled within the EU COST Action TOPROF by the Working Group on Microwave Radiometers (WG3). The leader of GAIA-CLIM Task 2.1.2 is co-chairing TOPROF WG3. The report documentation is expected within the next 1 year. The results of these activities will be followed and reported within the GAIA-CLIM project (D2.2-D2.9) as suggestions to users and manufacturers.
      Timescale: 1 year; Cost estimate: still under investigation.
- ***Lack of a common effort in homogenization of MWR retrieval methods (G2.17)***
    - o Different retrieval methods are applied by different manufacturers, operators, and users. Common retrieval methods include, but are not limited to, multivariate regression, neural networks, optimal estimation. This situation holds true for heterogeneous networks such as MWRnet. The uncertainty of MWR retrievals depends partially on the used retrieval methods, and the documentation and versioning of different methods are usually not easily accessible.
    - o Lack of harmonization of retrieval methods. Impact on network-wide product harmonization.
      Impact: There is currently a lack of homogenization in the quality and uncertainty of MWR products provided by an heterogeneous MWR network. Often, information of retrieval uncertainty are completely missing. The traceability of software documentation and versioning is also not guaranteed.
      Remedy: The different types and flavors of the retrieval methods currently exploited shall be reviewed and reported. The report shall be made available to users through metadata. A common retrieval method based on optimal estimation shall be developed for the MWR belonging to a network such as MWRnet. This task is currently tackled within the EU COST Action TOPROF by the Working Group on Microwave Radiometers (WG3). The leader of GAIA-CLIM Task 2.1.2 is co-chairing TOPROF WG3. A software package for a common retrieval method is expected within the next 2 years. The results of these activities will be followed and reported within the GAIA-CLIM project (D2.2-D2.9) as suggestions to users.

Timescale: 2 years; Cost estimate: still under investigation.

H_2O, O_3, CH_4:

- ***NDACC FTIR: Currently, no calibration with respect to standards (G2.25)***
  - Impact on the traceability to standards.
    Remedy: New techniques for calibration should be developed and implemented.
    Timescale and cost estimate require further investigation.

O_3:

- ***Cell measurements carried out to characterize FTIR instrument line shape(ILS) have their own uncertainties (G2.22)***
  - Inaccurate knowledge of the ILS leads to inaccurate vertical O_3 profiles.
    Remedy: Development of improved techniques for ILS characterization in the retrievals. This should also include an uncertainty estimate for the ILS characterisation, e.g. how sensitive is the cell measurement to the ILS (ILS kernels)
    Timescale and cost estimate require further investigation.
- ***Vertical averaging kernels (when provided) are only approximations of the real 3D averaging kernel of a retrieval using UV-Vis spectroscopy (G2.29)***
  - 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-air mass factor of this layer i and the total air-mass factor calculated from an ozone profile climatology. However, vertical averaging kernels (when provided) are only approximations of the real 3D averaging kernel of a retrieval.
  -
    Impact: Comparisons cannot account fully for the representativeness of the data.
    Remedy: Evaluate 3D averaging kernels for zenith-sky UV-visible twilight measurements using 3D chemistry-transport models.
    Timescale and cost estimate require further investigation.
- ***Systematic uncertainty on PANDORA direct-sun measurements are limited by temperature effects not corrected in current operational baselines (G2.30)***
  - The neglect of temperature effects (related to the O_3 spectroscopy in the Huggins bands) leads to seasonally dependent systematic biases of various amplitude depending on the latitude of the site.
    Remedy: Introduce a method to operationally account for temperature effects in the PANDORA total O_3 retrieval baseline.
    Timescale and cost estimate require further investigation.

CO_2, CH_4:

- ***Current spectroscopic databases contain uncertainties (G2.21)***
  - Spectroscopic uncertainties mainly increase the co-retrieved O_2, which is used as an internal standard, thus increasing the uncertainty of the CO_2 and CH_4 products.
    Remedy, timescale and cost estimate require further investigation.
- ***Cell measurements carried out to characterize FTIR instrument line shape(ILS) have their own uncertainties (G2.22)***
  - Inaccurate knowledge of the ILS leads to larger uncertainties on the retrieved concentrations (XCH_4, XCO_2).
    Remedy: Development of improved techniques for ILS characterization in the retrievals.
    Timescale and cost estimate require further investigation.

Aerosols:

- ***Missing continued lidar inter-comparison with reference systems (G2.04)***
  - Export the intercomparison program of EARLINET to all the other networks and to the ceilometers.
    Remedy: establish a coordinated effort in the frame of the WMO/GAW.
    Timescale and cost estimate require further investigation. Discussions are ongoing in the framework of WMO-CIMO (Expert team on new remote sensing techniques).
- ***Need of Raman lidars or better multi-wavelength systems (G2.06)***
  - Raman lidars or multi-wavelength Raman lidars are undoubtedly the backbone of a 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, Shipley et al., 1983) or Raman lidars (Ansmann et al., 1992). 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 to have a large number of this system available as anchor reference station for the study of the impact of aerosol on weather and climate and for the satellite validation. Moreover this anchor station could be the future backbone of a larger network incorporating also simpler lidar or ceilometers and 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 advance lidar systems and study if the coverage of the existing networks at the global scale is sufficient for the aerosol study.
    Remedy: Task 1.4 of GAIA-CLIM will partly deal with this problem and it will provide an estimation of the aerosol variability at the continental or at the global scale providing also recommendation for the optimal design of an aerosol lidar network (D1.9 expected on December 2017). This gap also crosses with the funding plans of agencies and Met Services who are encouraging the development of ceilometer/simple lidar networks but they are often neglecting the need for a few reference Raman lidar. The development of new robust solution available in the commercial market may also increase the number of Raman system deployed at the global scale over the next 5-10 years. Future work will be to assess this commercial solution using the WP2 work on the measurements traceability and the activities carried on within the ACTRIS-2 calibration center. (= also governance gap)
    Timescale and cost estimate require further investigation.
- ***Need for assimilation experiments using lidar measurements (G2.07)***
  - Lidar data can be effectively assimilated to largely improve model skills. At the current, it is possible to conduct data assimilation with the attenuated backscatter. Data assimilation is possible with horizontally sparse vertically dense data. Lack of data assimilation experiment of aerosol lidar measurements does not indicate if the current state of the technology fulfils the modellers needs.
    Remedy: ACTRIS-2 activities (ACTRIS-2 WP12) will develop a new solution for the lidar data assimilation. In particular, the available lidar NRT data will be used for the routine evaluation of operational models, while quality-checked (QC) and added-value (higher level data) products generated within ACTRIS networking activities will be used for the retrospective assessments of the model simulations (reanalysis/reforecasts). The potential of ground-based measurements of ACTRIS-2 aerosol parameters for improvements in the aerosol regional prediction will be also explored through pilot studies for extreme events of public relevance, like volcanic eruptions, mineral dust storms and biomass burning events. Building on the growing interest by the global NWP community in using high accuracy data from ground-

based networks to constrain satellite data biases, ACTRIS-2 will also test the use of ground-based lidar data to anchor the bias correction for satellite lidar data, using a variational bias correction scheme. The activity will try to overrun the current challenges like those related to the observation density, the observation biases, and to need of model to be able to capture realistic correlations in the vertical for global forecasts.
Timescale: Delivery of ACTRIS-2 results is expected on March 2017 with an Initial Report on bias correction activities and on assimilation activities while more consolidated results will be part of the final report on value of measurements in the reduction in global model, expected on April 2018 (D13.3, D13.4, D13.5 of ACTRIS-2). This activity should continue over the next years with an effort that should be quantified by the Met Services. Cost estimate: ?

3.5 Uncertainty Gaps in Relation to Comparator Measures

(G2.03; G3.01; G3.02; G3.03; G3.04; G3.05; G3.06; G4.06; G5.08: 9 gaps in total)

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 and that are being addressed within GAIA-CLIM include:

All ECVs

- ***Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the inter-comparisons (G3.01)***
  - 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 of an individual measurement. To quantify these additional uncertainties, 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 ECVs in model or satellite gridded data (e.g. Verhoelst et al., 2015, for total ozone), information on smaller scales is most often restricted to results from dedicated campaigns or specific case studies, e.g. Sparling et al. (2006) for ozone, Hewison (2013) for meteorological variables, and Pappalardo et al. (2010) for aerosols.
  - Due to the exploratory nature of these studies, neither global nor complete vertical coverage is achieved. For instance, information on small-scale variability in the ozone field is limited to altitudes and regions probed with dedicated aircraft campaigns. Consequently, separating comparator uncertainty from measurement uncertainty at these scales is problematic in many validation studies. Moreover, this gap precludes an optimal definition of co-location and coincidence criteria.
  - Potential remedies include not only more dedicated measurement campaigns, which require substantial investment, but also statistical analysis of available satellite and ground-based data sets. Within GAIA-CLIM, the latter type of work will be undertaken within task 1.4 (D1.9) for temperature, humidity and aerosol load using data from polar orbiting sensors like IASI and MODIS. Further progress can be expected with upcoming satellite missions offering an increase in both horizontal resolution (Sentinel-

5p) and temporal resolution (Sentinel-4).

- ***Limited quantification of the impact of different co-location criteria on comparison results (G3.02)***
  - Only few ground-based satellite validation studies explore the impact of the adopted co-location criteria on the comparison results (e.g. Wunch et al., 2011, and Dils et al., 2014, for CO2, Verhoelst et al., 2015, for O3, and Pappalardo et al., 2010, for aerosols). Still, atmospheric variability is often assumed to impact the comparisons (e.g. De Maziere et al. 2008) but without detailed testing of several co-location criteria, this impact cannot be quantified.
  - This gap can be remedied with specific studies addressing the impact of co-location criteria on comparison results, both using statistical approaches on co-located data sets, and from simulations on gridded (model) data. This work is part of GAIA-CLIM WP3 and will be reported in deliverable D3.4 (expected February 2017). Further work is also planned outside of GAIA-CLIM, e.g. in a new working group set up at the last GRUAN-GSICS-GNSSRO WIGOS Workshop on Upper-Air Observing System Integration and Application.
- ***Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties (G3.04)***
  - Besides the uncertainties in a comparison resulting from non-perfect co-location in the sense of nominal measurement coordinates (e.g. satellite pixel center versus station geo-location), a further source of uncertainty are the differences in smoothed perception of the inhomogeneous atmospheric field. Indeed, a measurement is sensitive to a 4-D airmass, within which atmospheric variability cannot always be neglected. The extent of this airmass is not limited to purely geometrical properties such as the satellite pixel footprint, but it also includes sensitivity along the entire line-of-sight between photon source and detector. For instance, for nadir measurements of scattered light, substantial sensitivity may be located in the line-of-sight between sun and surface. While some pioneering literature exists on the quantification of the smoothing properties of different (types) of instruments (e.g. von Clarmann, 2009, Lambert et al., 2011), this work is far from exhaustive and is still to be performed for some ECVs (e.g. aerosols) and for many current satellite and ground-based instruments.
  - Work in this direction is planned in WP3 for ECVs and instruments targeted by GAIA-CLIM, but on the long term, this gap will require continued efforts to fully characterize the spatiotemporal smoothing and sampling properties of both new ground-based instruments and upcoming satellite sensors.
- ***Missing comparison error budget decomposition including errors due to sampling and smoothing differences (G3.06)***
  - 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, 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. 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 was published by Cortesi et al. (2007) on uncertainty budget closure for MIPAS/ENVISAT ozone profile validation, by Ridolfi et al. (2007) for the case of MIPAS/ENVISAT temperature profiles validation, by Fasso et al. (2013) in the context of radiosonde intercomparisons, and by Verhoelst et al. (2015) for GOME-2/MetOp-A total ozone

column validation. However, no such studies have hitherto been performed for most other ECVs and/or instruments.

  - The remedy will be detailed studies, based on either explicit physical modelling of the observing systems, or on statistical approaches, in which an attempt is made to close the uncertainty budget of the comparisons made in validation exercises. For selected ECVs and instruments, this is a key ambition of WP3 in GAIA-CLIM. Future validation studies can then benefit from advances made within GAIA-CLIM, but it remains important that validation protocols and committed resources are extended accordingly.

- ***Difficulty to assess the importance of natural variability in the model-observation error budget (G4.06)***
  - Prevents full traceability of both the model/assimilation quantity and also the observational dataset.
    Remedy: Research to characterize model-observation differences with focus on enhancing representation of "observation operators".
- ***Missing quantification of additional uncertainties introduced in the comparison results due to differences in (multi-dimensional) sampling and smoothing of atmospheric inhomogeneity (G5.08)***
  - Dominates random uncertainty in comparisons of satellite and non-satellite observations for most ECVs. Significant contribution to systematic uncertainty in these comparisons. Obstructs the interpretation of comparison results.
    Remedy: Model-based and statistical studies will address these issues for key ECVs in GAIA-CLIM WP3. Awareness raised through the GAIA-CLIM Virtual Observatory.

The uncertainty gaps in relation to comparator measures, which have been identified though are not being addressed within GAIA-CLIM include:

- ***Incomplete collocation of sun and moon photometers with day and night time aerosol lidars (G2.03)***
  - To fully exploit the synergy between lidars and photometers, collocation between them at the various sites is recommend, also considering the new technologies like the moon photometer and the RRlidar.
    Remedy: Seek opportunities to co-locate the photometers with the lidars or vice versa.
    Timescale: Limiting factor in timescale in terms of the relocation of instruments may be related to obligations in ongoing programmes and discontinuation of (climatological) timeseries. Alternative is expansion of the number of deployed instruments. Sunphotometers have been a standard product for a large number of years. Moon photometers, however are a relatively new development and would require purchase of new instruments. Affordable options for RR lidar (rotational Raman) are becoming available as replacement options for VR channels. The developments are ongoing, and improvement is foreseen in the next five years.
    Cost estimate:relocation of instruments is virtually cost neutral. Expansion of the number of deployed instruments depends on the type and number of instruments needed. Since lidars are more complex and costly than the photometers, it is likely more cost effective to purchase additional photometers to co-locate with the lidar.
- ***Missing generic and specific standards for co-location criteria in validation work (G3.03)***
  - Different validation exercises on the same ECV/instrument combinations are often performed using different (sub-optimal) co-location criteria. This makes an intercomparison of the validation results difficult and it limits optimal use of the ground-based networks. 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.

  - Remedy: Publication of generic and detailed validation protocols, including both the metrology aspects of a data comparison and recommendations on optimal co-location criteria. While such a publication is not directly within the scope of GAIA-CLIM, the studies on co-location criteria performed in WP3 will provide essential information on which to base these standards. Resources required to further valorise this work in the shape of a published protocol is estimated to be only moderate.

- ***Representativeness uncertainty assessment missing for higher-level data based on averaging of individual measurements (G3.05)***
  - The creation of level-3 (and level-4) data by averaging non-uniformely distributed measurements inevitably leads to representativeness errors, see e.g. Coldewey-Egbers et al., (2015) for the case of a level-3 (gridded monthly means) total ozone data set. However, estimates of the related uncertainties are rarely included with the data product. Also the representativeness of the ground-based network should be taken into account when validating these data sets, i.e. the sparse spatial and temporal sampling of the ground network often impacts the derived monthly (zonal) means, and this is not often taken into account.
  - Remedy: Studies quantifying the representativeness of averages by either using physical or statistical modelling tools. This requires only a moderate additional investment for each data product and/or validation exercise, but perhaps a more substantial effort to raise awareness with data providers and end users. This work is not part of the scope of GAIA-CLIM, but tools developed within WP3 may be beneficial to future research in this direction.

3.6 Technical Gaps

(G1.02; G1.05; G1.06; G5.01; G5.02; G5.03; G5.04; G5.05; G5.06; G5.07: 10 gaps in total)

Technical gaps might include e.g. specific missing tools, data portal technicalities, etc. Specifically, gaps related to data policies, user training etc. are considered gaps in governance (see section 3.7) and not pure technical gaps.

The pure technical gaps which have been identified and that are being addressed within GAIA-CLIM include:

<u>All ECVs:</u>

- ***Need to assess suitability of measurement maturity assessment (G1.02)***
  - 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. But to date the assessment has not been carried out. This is foreseen for target GAIA-CLIM networks and ECVs in Task 1.2 but the assessment should be able to be applied more broadly to other ECVs and measurement domains if it is to have more broad 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.

    Remedy:

    GAIA-CLIM will undertake the D1.3 based assessment for a number of ECVs and networks and this may lead to subsequent revisions to the guidance. Opportunities should be sought to apply the same assessment to other domains. This may involve incorporation into future national or international level projects.

Review of effectiveness should occur prior to end of GAIA-CLIM and inform D6.7 discussion on this issue.
Timescale: Initial GAIA-CLIM assessment completed at end of Task 1.2 and shall inform an update to this gap assessment. Users outside GAIA-CLIM shall be encouraged to undertake the assessment and provide feedback (through WIGOS, see G1.03) and other national and international projects.
Cost estimate: Minimal. Some time will be required by task 1.1 members to collate and assess feedback but that was foreseen and remains available in consortium members time budgets against this task.

- ***Lack of unified tools showing all the existing observing capabilities for measuring ECVs with respect to satellite spatial coverage (G1.05)***
    - A unified tool able to visualize all the sub-orbital observing capabilities of measuring ECVs at the global scale with respect to spatial and temporal coverage of space-based sensors is indeed missing. Several tools are already available for several networks of the global observing system but all of them are designed on the basis of very specific needs, using different logics, tools, and typically including just one ECV and only one or a small subset of the networks at the global scale.
    One of the brightest examples is represented by the OSCAR (Observing Systems Capability Analysis and Review Tool) system of the WMO (http://www.wmo-sat.info/oscar/) and in particular for the surface based capabilities (https://oscar.meteoswiss.ch/OSCAR/index.html, still in form of a beta version under development. Anyhow this tool is, at the present state, focused on the WMO mission and does not include all the ECVs and all the existing networks. Moreover satellite tool, also available, is designed separately by the ground based tool,
    A unified tool able to show at once all the existing non-satellite capabilities along with the field of view of the satellite based instruments can strongly help end-users in the implementation of new validation strategies and in the full exploitation of both ground based and satellite data, can inform the users on the available measurements of different ECVs and within different Earth's domain (atmosphere, land, ocean) through a quick and smart analysis of the geographical distribution of the system of networks at the global scale.
    Remedy: GAIA-CLIM will provide such a software in the frame of task 1.3. The software will be also able to evaluate each network (taking advantage of the metadata collected in the frame of GAIA-CLIM task 1.2) using the maturity matrix approach elaborated within task 1.1. This software (delivered on February 2017) might be established as a permanent service to update over the next years. This work might be offered to the community also to encourage a joint effort amongst global stakeholders like GCOS, GEOSS, GAW to foster the design of tools that, on the way of those already implemented in similar past initiatives carried out in the frame of the same programs, will try to encompass all the components of system of observing systems.
    Timescale and cost estimate: ?
- ***Lack of a common effort in metadata harmonization (G1.06)***
    - Metadata is an increasingly central tool in the current web environment, enabling large-scale, distributed management of resources. Recent years has 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 utilized. Several effort have been spent to improve the

harmonization of metadata across the networks and International programs but this is still not sufficient. The latest example of harmonization effort is related to the WIGOS (https://www.wmo.int/wigos) standard, currently under elaboration at the WMO.

- Remedy:within this current process GAIA-CLIM, in the frame of task 1.2 and, in synergy with WIGOS representatives, will provide for all the networks reviewed at the global scale and measuring the ECVs of interest for the project a unified metadata format that will try to extend and integrate WIGOS format (or keeping the formats interoperable); WIGOS the team will be advised on the modification/integration of the WIGOS format required to accomplish the needs of metadata reporting for each instrument and ECV investigated within the project.
  This work will be finalized on September 2016 (D1.7) and afterward a dialogue with WIGOS will be likely keep alive until 2018 when WIGOS-OSCAR system will be fully operational. The GAIA-CLIM metadata will be used for all the reviewed networks but also for the all the data records that will be available on the GAIA-CLIM virtual observatory (WP5).
  Timescale: a long term strategy to avoid the existing fragmentation in the metadata collection goes through a coordinated effort among the networks and the international programs and bodies dealing with metadata of climate measurements. A possible strategy could be that, after the release of WIGOS format, WMO could undertake the lead of this task to push all the observing networks to conform to WIGOS standards and to improve it according to their specific needs. This will be provided as recommendations also in the GAIA-CLIM deliverables, but this initiative can just be promoted by GAIA-CLIM during the project duration.
  Costs are uncertain for this type of activity.
  Risk: different metadata formats are adopted among the different networks, international bodies and research programs (often not interoperable) making the data harmonization effort at the global scale and in the different observation domain challenging.

– ***Access to data in multiple locations with different data policies and accessibility (e.g. speed of retrieving and unpacking, password protected, etc) (G5.01)***
  - Lack of access or low speed access is an issue forinteractive web tools.Remedy: agreement on WMO data policy; develop shared data policy. Develop user friendly access such as provided by the Earth System Grid used for CMIP5.

– ***Access to data in multiple data formats and structures (e.g. granularity of data). Lack of standardized metadata (G5.02)***
  - User often reformat data because data are served using different structures. This often leads to the loss of metadata which may result in wrong analyses.
    Remedy: Employ meta data standard such as WIGOS for all data from reference networks. .Sample data at the highest possible level to minimize the time in data transfer.

– ***Efficient data management to collocate observations needs to be improved (G5.03)***
  - The lack of efficient data management (data and meta data format issues, lack of data consistency) is negatively impacting the potential for data analysis using collocation from multiple measurement systems.
    Remedy: Enable collocations for long time series of satellite data by further developing existing collocation tools such as NPROVS, ICARE, STAMP enhanced by appropriate visualisation tools. Metadata should be well documented to help the collocation.

– ***Usability of reference data needs to be improved: high functionality in subset selection (G5.04)***

- Analyses may be impaired because a multitude of tools for sub-setting data (spatial extent, time range, sampling, resolution, variables, etc.) exist but cannot be consistently applied to reference data.
- Remedy: Provide a demonstrator and later an operational system that is capable of dealing with standardised input data. The usage of standards needs to be fostered through international agreement, e.g. WIGOS.

- ***Usability of reference data needs to be improved: format (G5.05)***
  - See G5.04 though specifically on format issues.
    Remedy: Specify subset format using appropriate standards.
- ***Need for analysis tools to exploit reference database (G5.06)***
  - Tools to analyse data sets are very diverse: time-series / instantaneous, spatially localized / large extent, column integrated / profile. Reference data base is of little use if pertinent analysis tools are lacking. Overly complex tools may hinder analysis. Remedy: Develop further existing visualization and analysis tools (e.g. inter-comparison, statistics, etc.) to accommodate data set diversity.
- ***Incomplete development and/or application and/or documentation of an unbroken traceability chain of Cal/Val data manipulations for atmospheric ECV validation systems. (G5.07)***
  - General lack of documentation. Missing Quality Indicators in many validation studies. Quality Indicators not always fit for purpose. Incoherent and poorly traceable validation results. Potential impact of ground-based validation not maximized. Development for several ECVs ongoing in EU FP7 project QA4ECV. Further application in the Multi-TASTE Cal/Val system foreseen in GAIA-CLIM.

There are no pure technical gaps which have been identified though are not being addressed within GAIA-CLIM.

3.7 Governance Gaps

(G1.01; G1.03; G1.04; G1.13; G1.14; G1.15; G2.01; G2.03; G2.04; G2.06; G2.15; G2.16; G4.04; G5.01; G5.07: 15 gaps in total)

Governance gaps include e.g. coordination, funding, data policy (dissemination, free access), unclear methodologies, traceability, missing documentation, lack of user training, etc. Specifically excluded here are purely technical gaps (see section 3.6).

Governance gaps which have been identified and that are being addressed within GAIA-CLIM include:

<u>All ECVs:</u>

- ***Missing agreement for levels of data and associated names across domains (G1.01)***
  - 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. Different domains use distinct conventions and conflate labels. Suggestions is to see this as a subset of G1.03 given how things have developed in the interim so we should retire this gap and move forwards just with G1.03 which now includes the relevant aspects of this gap that are not yet addressed
    Remedy: Canvas stakeholders on suitability of adopting task 1.1 outcomes.
    Timescale: years; Cost estimate: low.
- ***Missing evaluation criteria for assessing existing observing capabilities (G1.03)***

- No effort has been made to define and broadly agree amongst global stakeholders the measurement and network characteristics underlying a posited system of systems approach to Earth Observation.
  Remedy: enhanced coordination amongst global stakeholders.
  Timescale: uncertain; Cost estimate: uncertain.

– ***Lacking of a comprehensive review of current non-satellite observing capabilities for the study of ECVs in atmospheric, ocean and land domains (G1.04)***
  - 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. These activities support an increasing range of services with high socio-economic benefits. User requirements have become more stringent and new requirements have appeared with respect to these applications. More observation systems serve needs for real-time, near-real-time and non-real-time availability.
    In order to allow EO providers and users to maximize the value of existing observations and implement user friendly mapping facility, a comprehensive review of the current observing capability at European and global scale for all the ECVs is needed. This will facilitate also an identification of the existing geographical gaps in the global observing system.
    While a comprehensive review of space-based mission and needs has been put together within official document of the international community (like the CEOS Handbook and in the "Satellite Supplement" to the updated GCOS Implementation Plan), the mapping of current observing capabilities has been carried out by each network under an uncoordinated effort across the community measuring ECVs.
  - Extensive review have been already provided by WMO, GEOSS, GCOS, but they are limited to a sub-set of network or to a subset of ECVs, often drive by the mission of each single program of international institution.
  -
    Remedy: GAIA-CLIM will spent a huge effort in putting together one of the more extensive review of the existing capabilities for the measurement of a multitude of ECVs according to those listed within the GAIA-CLIM project. Results will be delivered on September 2016 (deliverable D1.6).This task will be considered for being established over long term as a service activity regularly updated starting from the end of GAIA-CLIM, after March 2018.
    Timescale: ?
    Cost estimate: for this activity is low but the importance of keeping this service alive over long term is critical to avoid the fragmentation already experienced in the past. It is obvious that the review might be reinforced by a capillary exchange of information resulting from an enhanced coordination amongst global stakeholders like the WMO Commission on Basic Systems, GCOS, GEOSS, GAW, and the federated networks adhering to this programs. This final task has an uncertain scenario and requires further plans and a cost assessment.

– ***Datasets from baseline and comprehensive networks provide valuable spatiotemporal coverage, but often lack the characteristics needed to facilitate traceable uncertainty estimates (G4.04)***
  - Essential contribution to make progress on coverage/parameter gap G4.03. Identify 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.

<u>O_3</u>:

– ***Northern Hemisphere bias in NDACC and PANDORA network sites distribution (G1.15)***
  - NDACC and PANDORA total column ozone 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 that NDACC stations often include a variety of instruments measuring total column ozone such as UV/visible spectroscopy, MAX-DOAS, Brewer, Dobson, LIDAR, ozonesonde, FTIR)
Impact: 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 the O_3 ECV.
Remedy: Develop strategies for network extension, and long-term preservation of data and measurement capabilities. This involves an in-depth study of the capabilities of the existing sites as well as a literature study on what distribution patterns would be most desirable.
Timescale: 1 yr

Governance gaps which have been identified though are not being addressed within GAIA-CLIM include:

<u>H_2O:</u>

- ***Water vapour measurements with the lidar and microwave radiometer are often provided in a sparse way and under an uncoordinated effort (G1.13)***
  - Water vapour and carbon dioxide (CO2) are the principle greenhouse gases (GHGs). CO2 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 for sure 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 also this synergy, but they are often not coordinated thus losing their powerful observing capability at a large scale. However, the construction of such integrated system will strongly depend on the creation of long-term sustainability of the research based 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.
    Remedy: a federated approach is to way to follow to minimize the number of redundant initiatives and to maximize the impact. The ESFRI funding might in the near future support this type of federated approach over long term (10 years at least). ACTRIS is candidate to become an ESFRI research infrastructure starting from 2016. GAIA-CLIM will ideally contribute to this initiative setting the metrology for both this techniques and thus facilitating their routine use at every site.
    Timescale: ?
    Cost estimate: moderate but if under the ESFRI label, at least for the European countries, it is sustainable.
- ***Automated MWR data quality control (G2.15)***
  - Currently the MWR data quality control is not fully automated. Eye inspection is often performed to detect spurious data and faulty calibration.

Remedy: Develop fully automated QC procedures.
Timescale: 2 years; Cost estimate: still under investigation.

- ***Calibration best practices and instrument error characterization (G2.16)***
  - Lack of standardization of calibration procedures and error characterization. Impact on network-wide product harmonization.
    Remedy: Define protocols for best practices; make documentation available to users.
    Timescale: 1 year; Cost estimate: still under investigation.

T, H_2O, O_3, *wind*:

- ***There is currently limited aircraft data, for example in Eastern Europe (G1.14)***
  - Missing aircraft information in many places. Very few aircraft currently provide water vapour over Europe, and even fewer O_3. Both of these parameters require additional sensors to be added to aircraft. There is EUMETNET funding available for a slow increase in the number of aircraft that carry humidity sensors, but nothing is currently planned for O_3.

    (= also coverage gap)
    Remedy: If suitable airlines in Eastern Europe can be identified it may be possible to include them in the E-AMDAR program. The gap cannot be addressed within GAIA-CLIM though the scientific studies carried out in the frame of task 1.4 will contribute to assess (at least for aerosol and water vapor) the optimal spatial and temporal coverage required in the region to ensure the satellite cal/val and the efficient monitoring of regional climate and, therefore, will provide input for minimizing the effort in the aircraft monitoring.

Aerosols:

- ***24/7 operation of lidar systems (G2.01)***
  - Most of the lidar measurements are performed on a discontinuous basis and not continuously over 24 hours 7 days a week.
    Remedy: efforts towards to automation, increase the number of systems working 24/7 to increase the coverage.
    Timescale & cost estimate: require further investigation (= also coverage gap).
- ***Incomplete collocation of sun and moon photometers with day and night time aerosol lidars (G2.03)***
  - See the discussion of this gap in Section 3.5 on Uncertainties in Comparator Measures
)
    Remedy (governance aspect only): networks of lidar and photometers need to collaborate on joint strategies for collocation. In Europe, this is done in ACTRIS (e.g. EARLINET and Aeronet Europe). Investigations are needed on strategies for global networks
    Timescale and cost estimate require further investigation (gap is being a subject of discussions)
- ***Missing continued intercomparison with reference systems (G2.04)***
  - Export the intercomparison program of EARLINET to all the other networks and to the ceilometers.
    Remedy: establish a coordinated effort in the frame of the WMO/GAW.
    Timescale & cost estimate require further investigation.
- ***Need of Raman lidars or better multi-wavelength system (G2.06)***
  - See the gap description in the section on uncertainty gaps

3.8 Parameter Gaps

(G4.03: 1 gap)

Parameter gaps are a separate generic category. These gaps include user needs related to parameters 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.

One parameter gaps has been identified that will be addressed within GAIA-CLIM:

<u>All ECVs:</u>

- ***Traceable uncertainty estimates are often limited to a few locations and parameters where reference datasets are available. Comprehensiveness is lacking for extension to locations and parameters where reference datasets are not available (G4.03)***
    - Limited availability of traceable uncertainty estimates propagates to applications that use model or reanalysis fields. Progress here is critical for establishing the 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.
      Remedy: Mix of operational improvements in observing systems (G4.04; governance gap) and better characterization of model-based and assimilation-based uncertainty (G4.05; uncertainty gap).

There are no parameter gaps which have been identified though are not being addressed within GAIA-CLIM.

4 Summary

In summary, in this Gaps Assessment and Impacts Document (GAID) Version 2.0 a compilation has been made of the gaps that have been formulated by the project team by the end of December 2015. The gaps have been summarized and grouped into a set of generic gap types. So far only limited effort on harmonization has been made.

The results of the user survey (Task 6.1) implicated 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 need for functional match-up facilities was clear, while it might be difficult to define the functionality such that it will be taken up by users. Another important gap that was clearly revealed was related to user familiarity with, and use of, uncertainties on non-satellite (reference) observations. The first user workshop in Rome provided, a.o., input on specific gaps in relation to the validation of greenhouse gases, and specific operational user needs for CAMS validation. In Section 3 now a first discussion on the impact and potential remedies for each of the identified gaps has been detailed.

At the General Assembly in Helsinki (10-11 February 2016) the suggestion was made to reorder the GAID outline per GAIDv3. The next version of the GAID (GADIv3) will be modified to better be able to manage the comments and further suggestions from the team members, to allow new input based on the upcoming work package deliverables, and also to better detail the specific external input as obtained through the user workshops. Further input as obtained via the website, and potential input from new scientific publications as well as other external documents will be taken into account.

GAID Version 1.0 has been presented for feedback at the first user workshop on 6 October 2015 in Rome.

GAID Version 2.0 will be presented for feedback at the GCOS conference *Global Climate Observation: the Road to the Future* on 2-4 March 2016 in Amsterdam.

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List of Acronyms

AQ	Air Quality
C3S	Copernicus Climate Change Service
CAMS	Copernicus Atmospheric Monitoring Service
CFH	Cryogenic Frost point Hygrometer
E-AMDAR	Eumetnet Aircraft Meteorological Data Relay
ECV	Essential Climate Variable
ESFRI	European Stratgy Forum on Research Infrastructures
FTIR	Fourier Transform InfraRed spectroscopy
GCOS	Global Climate Observing System
GHG	Green House Gas
GRUAN	GCOS Reference Upper-Air Network
GUAN	GCOS Upper Air-Network
IAGOS	In-service Aircraft for a Global Observing System
LS	Lower Stratosphere
LT	Lower Troposphere
MW	Microwave
MWR	Microwave Radiometer/try
NDACC	Network for the Detection of Atmospheric Composition Change
PBL	Planetary Boundary Layer
US+M	Upper Stratosphere and Mesosphere
UT	Upper Troposphere