Gaps Assessment and Impacts Document

(Version 1.0)

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Gap Analysis for Integrated
Atmospheric ECV Climate Monitoring
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Royal Netherlands Meteorological Institute
Ministry of Infrastructure and the Environment

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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 sub-orbital measurements henceforth) to characterise space-borne measurement systems.

Work under GAIA-CLIM will address:

1. Defining and mapping existing sub-orbital measurement capabilities

2. Improving metrological characterisation of reference data

3. Better accounting for co-location mismatches between reference and satellite data

4. The role of data assimilation

5. Creation of a '*Virtual Observatory*' bringing together all comparison data and providing public access to the information they contain

6. Identifying and prioritizing gaps in knowledge and capabilities

The objective of this Gaps Assessment and Impacts Document (GAID) is to identify and assess – through careful analysis against both existing and envisaged user requirements – yet unfulfilled user needs ('gaps') in the observation capability of ECVs within the sphere of the GAIA-CLIM project.

The impact assessment has focus on the availability of, and ability to utilize, truly reference quality traceable measurements in support of the long-term sustained space-borne 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.

Gaps 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 suggesting additional gaps or updating our knowledge of the identified gaps' status. Clear distinction is made between the gaps that are being addressed in GAIA-CLIM and other identified gaps, which are out-of-scope for the project.

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 gap identification and assessment and subsequent impact discussions will be continued during the project. The GAID is therefore a living document and several versions of this document will be produced throughout its lifetime during the project. Both the list of gaps and the impact assessment are expected to evolve.

GAID version history

Version	Principal updates	Owner	Date
0	Framework document	KNMI	9/4/15
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 early September 2015	KNMI	10/9/15

1 Introduction

1.1 The Key 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 geostationary (*Meteosat*, since 1977) and low-earth orbit (*MetOp*, since 2006) operational monitoring capacity in space, supporting the operational meteorological and climate services, and is currently being extended with *Sentinels* 1-5, forming the Copernicus Space Segment (CSS). Per 2015, the first Sentinels (S-1A, S-2A) are in orbit and the subsequent Sentinels are to be launched within the coming 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.

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, such as studies on climate variability and trends. This requires long-term sustained datasets from ground-based, in-situ and other so-called '*sub-orbital*' (i.e., not space-borne) sources 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. This constitutes a key strand of a multi-faceted approach to satellite data quality assurance, which may also include satellite-to-satellite comparisons and, if launched, space-borne reference measurements such as TRUTHS or CLARREO. However, few, if any, of the sub-orbital *'comparator measures'* provide fully traceable robust uncertainty estimates. Without full traceability in the comparator measures and with, e.g., non-robust results between the comparator measures, there is ambiguity in any sub-orbital data segment comparison that limits its scientific value and utility.

The key challenge regarding the gap assessment being performed herein in the GAIA-CLIM project is:

- (i) to identify important limitations of the sub-orbital monitoring segment for the climate monitoring focusing on selected atmospheric ECVs, the so-called '*sub-orbital gaps*',
- (ii) to assess these gaps and to estimate their impact, and
- (iii) to prioritize the needs and to create a set of recommendations on (further) actions to remedy the identified gaps.

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

- Quantified ***uncertainty estimation*** for the reference quality sub-orbital measurements
- Understanding of the uncertainties in the sub-orbital measurements including apparent discrepancies between data sets through ***mismatches in spatiotemporal sampling, collocation mismatches, and through the use of different measurement techniques***
- ***User tools***, will primarily be served within GAIA-CLIM through the Virtual Observatory

The Virtual Observatory shall bring together the work in the work packages on measurement traceability, co-location uncertainty, measurement capabilities mapping, and use of reference quality in data assimilation. The Virtual Observatory shall serve the data, uncertainties and a range of outputs as deemed appropriate. At time of writing of the current version of the GAID, the precise outputs of the Virtual Observatory remain unclear pending greater maturity of the underlying work, which shall enable a more precise scoping. It is likely to include results from statistical, metrological and data assimilation techniques in an appropriate and useable combination and to serve data in digital and graphical forms.

The main objective of this Gaps Assessment and Impacts Document (GAID) is to identify – through careful analysis with internal and external stakeholders against existing, and potentially evolving, user and data requirements – yet unfulfilled user needs (‘gaps’). In the GAID context, the user requirements might relate to different user categories and might relate to the users of ECV data records and reference observations, users of in-situ baseline network data for climate studies, users of outcomes of validation studies and other comparison activities. Even though within GAIA-CLIM the term ‘user requirements’ sometimes will be used specifically to the user needs for the planned Virtual Observatory, many of the gaps that are listed in the GAID are broader in scope.

This document provides the evidence basis of the availability of, and ability to utilize, truly reference quality traceable measurements in support of the long-term sustained space-borne monitoring of a set of key atmospheric ECVs defined by the Global Climate Observing System (GCOS). The GAIA-CLIM primary ECVs are temperature, water vapour (H_2O), ozone (O_3), carbon dioxide (CO_2), methane (CH_4) and aerosols. The O_3 and aerosol precursors are being studied in the EU partner project QA4ECV and therefore discussion of user needs with respect to these ECVs is given somewhat lower priority in GAIA-CLIM. Not covered so far are user needs related to observations of oceanic, terrestrial and cryosphere parameters, which are currently outside the scope of GAIA-CLIM but would in principle be needed to assessed as well.

1.2 Approach to the GAIA-CLIM Gaps and Impact Assessment

In this document, an assessment is made of the existing identified ECV user needs (‘gaps’), which are being catalogued during the project. The 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).

Task 6.1 is providing input to the GAID on user needs, which partially have been identified external to GAIA-CLIM. A user survey has been undertaken and reported (GAIA-CLIM ‘Report on results of user survey’, Deliverable D6.1) and a first user workshop will be held on 6 October 2015 in Rome, Italy. A second workshop is planned for month 21 and a final workshop is foreseen for month 33. These user workshops are intended to provide important additional information on user needs, potential gaps and anticipated impacts for users, which will feed into the GAID. Inputs are further derived from, for example, 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 will be invited throughout the project, through the user workshops and the GAIA-CLIM website. To support external feedback on the GAID, a designated e-mail address (gaid@gaia-clim.eu) and a specific template for gap reporting are provided.

Inevitably, the materials that are brought together in the GAID still might 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

A complete overview of the sections of the GAID will be included here in a later version of this document.

2 Integrated Climate Monitoring of Atmospheric ECVs

2.1 Sub-Orbital Segment

An overview is being made of the contributions per ECV of the networks that define the sub-orbital segment for climate monitoring. Table 2.1 provides per primary GAIA-CLIM ECV an overview of contributing surface networks and airborne observations split by altitude domain and network, including the Network for the Detection of Atmospheric Composition Change (NDACC), GCOS (Reference) Upper-Air Network (G(R)UAN), Total Carbon Column Observing Network (TCCON), EUMETNET Aircraft Meteorological Data Relay Operational Service (E-AMDAR), In-Service Aircraft for a Global Observing System (IAGOS), Aerosol Robotic Network (AERONET), ACTRIS/EARLINET (Aerosols, Clouds, and Trace gases Research InfraStructure Network/European Aerosol Research Lidar Network), NOAA Global Greenhouse Gas Reference Network (GGGRN), as well as Air Quality (AQ) national networks.

Per network, the specific instrument techniques used are indicated: Surface in-situ, lidar, FTS, sondes, aircraft in-situ, balloon, 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 will build further on the work in Task 1 and will be modified and improved accordingly.

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 1.0.*

ECV per altitude domain	**Surface/PBL (< 1-2 km)**	**Total column**	**LT (< 6km)**	**UT (> 6km)**	**LS (< 25 km)**	**US+M (> 25 km)**
T	*G(R)UAN* Surface in-situ, sondes, MWR	*Not applicable*	*G(R)UAN* Lidar, sondes *E-AMDAR, IAGOS* Aircraft in-situ	*G(R)UAN* Lidar, sondes, CFH *E-AMDAR, IAGOS* Aircraft in-situ	*G(R)UAN* Lidar, sondes, CFH	*Not available*
H_2O	*G(R)UAN* Surface in-situ, sondes	*G(R)UAN* MW, ground GNSS	*G(R)UAN* Lidar, sondes *NDACC* Lidar, sondes *E-AMDAR, IAGOS* Aircraft in-situ	*G(R)UAN* Lidar, sondes *NDACC* Lidar, sondes *E-AMDAR, IAGOS* Aircraft in-situ	*G(R)UAN* Lidar, sondes *NDACC* Lidar, sondes *E-AMDAR, IAGOS* Aircraft in-situ	*Not available*
O_3	*NDACC* Surface in-situ, sondes, max-doas	*NDACC* MWR, Brewer-Dobson, max-doas	*NDACC* Sondes, lidar, MWR	*NDACC* Sondes, lidar, MWR *IAGOS* In-situ	*NDACC* Sondes, lidar, MWR	*NDACC* Lidar, MWR
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	*Actris/Earlinet* Lidar *NDACC* Lidar	*Not available*
CO_2	*NOAA-GGGRN* Surface in-situ / flask	*TCCON* FTIR	*Not available*	*Not available*	*Not available*	*Not available*
CH_4	*NOAA-GGGRN* Surface in-situ / flask	*TCCON* FTIR	*NDACC* FTIR	*NDACC* FTIR	*NDACC* FTIR	*Not available*

Table 2.2 provides an overview of the full 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.

In Section 3 of this report, the discussions on the gaps, the potential impacts on users and the potential remedies are presented. These discussions are structured per generic gap type and additionally by ECV, if appropriate. So far Table 2 is based on the input materials, which have been collected through deliverables D1.1, D1.2, D1.3, D1.4, D1.5. The collected inputs have been reviewed by the Management Team in early September 2015.

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 1.0.*

Gap Identifier	Gap Type	ECV(s)	Gap Short Description	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	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	D1.3
G1.03	Coverage Governance	H_2O, O_3, T, CO_2, CH_4, aerosols	Missing evaluation criteria for assessing existing observing capabilities	D1.1
G1.04	Coverage Governance	H_2O, O_3, T, CO_2, CH_4, aerosols	Lack of a comprehensive review of current sub-orbital observing capabilities for all the study of ECVs in atmospheric, ocean and land domains	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	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	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	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	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	D1.2
G1.10	Uncertainty	H_2O, O_3, T, CO_2, CH_4, aerosols	Insufficiently traceable uncertainty estimates	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	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.	n/a
G.1.13	Coverage Governance	H_2O	Water vapor measurements with the lidar and microwave radiometer are often provided in a sparse way and under an uncoordinated effort	D1.1, D2.1
G1.14	Coverage Governance	H_2O, O_3, T, *wind*	There is currently limited aircraft data, for example in Eastern Europe.	n/a
G1.15	Coverage Governance	O_3 (total column)	Northern Hemisphere bias in NDACC and PANDORA network sites distribution	D1.1, D2.1
G2.01	Coverage Governance	Aerosols	24/7 operation of lidar systems	n/a
G2.02	Coverage	Aerosols	Lidar incomplete altitude coverage	D2.2, D2.4
G2.03	Comparator unc. Governance	Aerosols	Incomplete collocation of sun and moon photometers with day and night time aerosol lidars	n/a
G2.04	Uncertainty Governance	Aerosols	Missing continued intercomparison with reference systems	D2.2 Wandinger et al., 2015
G2.05	Uncertainty	Aerosols	Lack of rigorous aerosol lidar error budget availability	D?.?; Earlinet
G2.06	Uncertainty	Aerosols	Need of Raman lidars or better multi-wavelength systems	D2.2 Veselovskii et al., 2012
G2.07	Uncertainty	Aerosols	Need for assimilation experiments of lidar measurements	D2.2 EU project website ACTRIS2: www.actris.eu
G2.08	Uncertainty	Aerosols	Reducing calibration uncertainties using a common reference standard	D2.2 Leblanc et al., 2008 ?ISSI report? Is it also for aerosol?
G2.09	Coverage	H_2O	Continuous operation of water vapor Raman lidars limited during daytime	n/a
G2.10	Coverage Vert. resolution	O_3	Tropospheric O_3 profile data is limited	n/a
G2.11	Uncertainty	O_3	Lack of rigorous tropospheric O_3 lidar error budget availability	Leblanc et al., 2008 ?ISSI report?
G2.12	Uncertainty	T	Lack of rigorous temperature lidar error budget availability	Leblanc et al., 2008 ?ISSI report?

G2.13	Uncertainty	T, H_2O (+column), *liquid H_2O*	MWR Missing standards maintained by National/International Measurement Institutes	D2.1 Walker et al., 2011
G2.14	Uncertainty	T, H_2O (+column), *liquid H_2O*	Uncertainty of the MW absorption spectrum used in MWR retrievals	D2.1
G2.15	Uncertainty Governance	T, H_2O (+column), *liquid H_2O*	Automated MWR data quality control	D2.1 EU Cost action TOPROF
G2.16	Uncertainty Governance	T, H_2O (+column), *liquid H_2O*	Calibration best practices and instrument error characterization	D2.1 EU Cost action TOPROF
G2.17	Uncertainty	T, H_2O (+column), *liquid H_2O*	Homogenization of retrieval method	D2.1 EU Cost action TOPROF
G2.18	Uncertainty	H_2O, O_3, CH_4	Agreement on systematic vs. random part of the uncertainty and how to evaluate each part	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	NORS_D4.2_DUG.pdf
G2.20	Uncertainty	H_2O, O_3, CH_4	Spectroscopic uncertainties	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	Hase et al, 2012 Hase et al., 2013
G2.23	Uncertainty	CH_4	possible SZA dependence in the retrieval during polar vortex overpasses	n/a
G2.24	Uncertainty	CO_2, CH_4	In-situ calibration can be verified by involving new data	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	NORS_D4.3_UB.pdf NDACC_UVVIS-WG_O3settings_v2.pdf
G2.27	Uncertainty	O_3 (column)	Random uncertainty in spectral fit and AMF calculations	NORS_D4.3_UB.pdf NDACC_UVVIS-WG_O3settings_v2.pdf
G2.28	Uncertainty	O_3 (column)	Uncertainty in a priori profile shape for AMF calculation	Hendrick et al., 2011
G2.29	Uncertainty	O_3 (column)	Uncertainty in vertical averaging kernels	Eskes and Boersma, 2003
G2.30	Uncertainty	O_3 (column)	Uncertainty in PANDORA measurements	Herman et al., 2015
G2.31	Uncertainty	O_3 (tropospheric column)	Information content of MAX-DOAS tropospheric O_3 measurements	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	Same as for G2.31
G2.33	Uncertainty	O_3 (tropospheric column)	Random and systematic uncertainties of MAX-DOAS tropospheric O_3 measurements	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)	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.	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 co-location criteria.	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.	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.	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.	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.	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.	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	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. Comprehensiveness is lacking for extension to locations and parameters where reference datasets are not available	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	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 and parameters.	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.	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)	**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	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	CCI toolbox Giovanni GSICS

G5.04	Technical	H_2O, O_3, T, CO_2, CH_4, aerosols	Usability of reference database needs to be ascertained: subset definition	WP5
G5.05	Technical Governance	H_2O, O_3, T, CO_2, CH_4, aerosols	Usability of reference database needs to be ascertained: format	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.)	ICARE multibrowse and associated graphical modules? Felyx project NOAA NPROVS
G5.07	Technical Governance		Incomplete development and/or application and/or documentation of an unbroken traceability chain of Cal/Val data manipulations for atmospheric ECV validation systems.	D5.1 Keppens et al., 2015 (traceability chain) QA4ECV: http://www.qa4ecv.eu/ QA4EO: http://qa4eo.org/
G5.08	Comparator unc		Missing quantification of additional uncertainties introduced in the comparison results due to differences in (multi-dimensional) sampling and smoothing of atmospheric inhomogeneity	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)?

3 Impact Assessment per Gap Type per ECV for the Sub-orbital Climate Monitoring Segment

3.1 Introduction

In this section, the impacts of each of the gaps are being discussed from the (end-)user perspective, 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 current GAID Version 1.0 primarily includes 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. The list of gaps, as well as the discussion on impacts and potential remedies, is expected to mature during the GAIA-CLIM project and regular updates in this section are expected with each revision.

The results of the user survey ('Report on results of user survey', deliverable D6.1) implicated a clear need for user education and capacity building on how sub-orbital and/or satellite data can be used 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 on sub-orbital 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 sub-orbital 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.
      Remedy: enhanced coordination amongst global stakeholders.
      Timescale and cost estimate: uncertain.

- ***Lack of a comprehensive review of current sub-orbital observing capabilities for the study of ECVs in atmospheric, ocean and land domains (G1.04)***
    - Mapping of current observing capabilities has been carried out by each network under an uncoordinated effort across the community measuring ECVs.
      Remedy: enhanced coordination amongst global stakeholders like the WMO Commission on Basic Systems, GCOS, GEOSS, GAW, and the federated networks adhering to this programs.
      Timescale: uncertain; Cost estimate: requires further plans and investigation.
- ***Need for a scientific approach to the assessment of gaps in the existing networks measuring ECVs (G1.07)***
    - Assessment of gaps has commonly been performed without a scientific basis or using an ad hoc approach never applied in an extensive and systematic way. A comprehensive scientific approach assessing the gaps in the current observing capabilities of the system of systems does not exist.
      Remedy: 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.
      Timescale and cost estimate: uncertain.
- ***Evaluation of the effect of missing data or missing temporal coverage of full traceability data provided by ground-based networks (G1.08)***
    - There are only a few efforts at quantification of the effect of temporal sampling in the determination of atmospheric variability. Prevents full traceability of both the model/assimilation quantity and also the observational dataset.
      Remedy: use of geo-statistical approaches to assess this effect; Research to characterize model-observation differences with focus on enhancing representation of “observation operators”.
      Timescale and cost estimate: uncertain.

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

- ***Northern Hemisphere bias in NDACC and PANDORA network sites distribution (G1.15)***
    - The lack of coverage in space and time limits the potential of the network for e.g. latitudinal dependencies and global trend studies, satellite validation and long-term assessment of the O_3 ECV. Develop strategies for network extension, and long-term preservation of data and measurement capabilities.

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)***
    - 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.
      Remedy: A federated approach like those already partly established for the aerosol network most of which are also in charge for water vapour measurements using Raman lidar and microwave radiometer.
      Timescale: uncertain; Cost estimate: low-moderate.
- ***Continuous water vapour profiles from Raman lidars limited during daytime (G2.09)***
    - During daytime most of the available lidar systems measuring water vapour are

limited to 2-3 km above ground level, only DIAL system can do better, but worse in the UT/LS.
Remedy: Instrument development.
Timescale: 5 y; 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.
    Remedy: If suitable airlines in Eastern Europe can be identified it may be possible to include them in the E-AMDAR program (= also governance gap).

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 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.
    Timescale: still under investigation, cost estimate: depending on system but not too high.

O_3:

- ***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.
    Timescale: 5 y; Cost estimate: very high.
    (= also a gap on vertical resolution)

CO:

- ***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.

3.3 Gaps in vertical resolution

(G1.09; G2.10: 2 gaps 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:

O_3:

- ***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.

Timescale: 5 y; Cost estimate: very high.
(= also a coverage gap)

CO:

- ***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:

All ECVs:

- ***Insufficiently traceable uncertainty estimates (G1.10)***
  - 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; better characterization of model-based & assimilation-based uncertainty.
    Timescale and cost estimate: uncertain.
- ***Traceable uncertainty estimates from baseline and comprehensive networks (G1.11)***
  - Datasets from baseline and comprehensive networks provide valuable spatiotemporal coverage, but often lack the characteristics needed to facilitate traceable uncertainty estimates. Essential contribution to make progress on G1.10.
    Remedy: 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
    Timescale and cost estimate: uncertain.
- ***Propagate uncertainty from well-characterized locations and parameters to other locations and parameters (G1.12, see also G4.05 below)***
  - Limited knowledge about how to propagate uncertainty from well-characterized locations and parameters to other locations and parameters. Essential contribution to make progress on G4.01.
    Remedy: modelling studies to characterize propagation of uncertainty in models and assimilation systems.
    Timescale and cost estimate: uncertain.

- ***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)***
    - Standards for absolute calibration to reduce systematic uncertainties already exist and have proven to be robust, need to use a common reference on all the available systems.
      Remedy: compile error budgets.
      Timescale: 1 y; Cost estimate: still under investigation
- ***Uncertainties of ZTD, given by a 3rd party (IGS). Dominates GNSS-IPW uncertainty together with ground pressure uncertainty (G2.34)***
    - If not handled in a proper way, it may affect drastically the GNSS-IPW uncertainty estimate. Fixing it equal to 4mm is just a compromise, excluding outliers from longer time series.
      Remedy: 20-36 Months, Analysis of definition of formal errors in different software and methods. Numerical experiments.
      Timescale and cost estimate: GAIA-CLIM Task 2.1.6

Temperature, H_2O

- ***Uncertainty of the MW absorption spectrum used in MWR retrievals (G2.14)***
    - Currently the information on absorption model uncertainty is dispersed. Oxygen absorption uncertainties dominate error in mid-troposphere temperature retrieval. Water vapour and liquid water absorption uncertainties dominate errors in water vapour and total column liquid water retrievals.
      Remedy: Review current uncertainty of MW absorption models.
      Timescale: 1-2 years; Cost estimate: still under investigation.

O_3:

- ***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: GAIA-CLIM WP2: 1 y; Cost estimate: still under investigation.
- ***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: GAIA-CLIM WP2: 1 y; Cost estimate: still under investigation.
- ***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.
- ***Detector noise and instrumental imperfections impacting on the spectral fit; pseudo-random AMF uncertainties related to errors on a-priori profile shape, aerosol, cloud information (G2.27)***
  - Random uncertainties are dominated by instrumental performance and pseudo-random errors on AMF calculations. There is a lack of harmonization of the AMF calculation methods, which can introduce inconsistencies in the network.
    Remedy: Standardize AMF calculation methods and data bases of a-priori information used in AMF calculation.
    Timescale and cost estimate: unclear at this time & require further investigation.
- ***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 (G2.28)***
  - AMF uncertainties for zenith-sky twilight O_3 retrievals are dominated by errors on a priori profile shape effects. In regions where tropospheric or stratospheric O_3 contents deviate from the climatological values, errors of several percent can be introduced on total O_3 retrievals.
    Remedy: Improve climatological data bases of a priori O_3 profiles, with particular emphasis on tropospheric O_3.
    Timescale and cost estimate: unclear at this time & require 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 & require 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.

H_2O, O_3, CH_4 (FTIR):

- ***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)***
    - 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 & require further investigation.
- ***Line of sight and vertical averaging kernel are only approximations of the real 3D averaging kernel of a retrieval (G2.19)***
    - Comparisons cannot yet account fully for the representativeness of the data.
      Remedy: Evaluate 3D averaging kernels.
      Timescale and cost estimate: unclear at this time & require further investigation.

CH_4

- ***The current spectroscopic databases contain too large uncertainties to model correctly the spectral windows used for CH_4 retrievals (G2.20)***
    - This gap increases the uncertainty on the delivered 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.
- ***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 & require further investigation.

CO_2, CH_4:

- ***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 y; Cost estimate: still under investigation.

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:

- ***MWR missing standards maintained by National/International Measurement Institutes (G2.13)***
    - Currently no traceability to SI standards is feasible for MicroWave Radiometry (MWR).

Remedy: Develop primary standards at National/International Measurement Institutes; Develop transfer standards.
Timescale: 2-5 years; Cost estimate: still under investigation.

- ***Automated MWR data quality control (G2.15)***
    - Currently the MWR data quality control is not fully automated. Manual 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 MWR 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.
- ***Homogenization of MWR retrieval methods (G2.17)***
    - Lack of harmonization of retrieval methods. Impact on network-wide product harmonization.
      Remedy: Report differences in retrieval methods; develop a common retrieval method.
      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.
      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)***
    - Comparisons cannot account fully for the representativeness of the data.
      Remedy: Evaluate 3D averaging kernels for zenith-sky UV-visible twilight measurements.
      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.

<u>Aerosols:</u>

- ***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.
- ***Need of Raman lidars or better multi-wavelength systems (G2.06)***
    - Retrieval of aerosol microphysical properties and mass concentration requires at least a one-wavelength Raman lidar better if multi-wavelength systems.
      Remedy: limit the retrieval to these systems and study if this coverage is sufficient for the aerosol study.
      Timescale and cost estimate require further investigation.
- ***Need for assimilation experiments using lidar measurements (G2.07)***
    - 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 JRA3 will help assessing this issue.
      Timescale: 48 months; Cost estimate: still under investigation.

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 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:

<u>All ECVs</u>

- ***Incomplete knowledge of spatiotemporal atmospheric variability at the scale of the inter-comparisons (G3.01)***
    - Difficulty determining optimal co-location and coincidence criteria. Difficulty estimating sampling and smoothing difference errors. Statistical analysis on existing co-located data sets.
      Remedy: More dedicated field campaigns. Future missions with high spatial resolution will provide further insight (e.g. Sentinels).
- ***Limited quantification of the impact of co-location criteria (G3.02)***
    - Difficulty to assess the importance of natural variability in the total error budget.
      Remedy: Definition of a generic approach to what a good co-location can be,

followed by specific studies exploring different co-location criteria in a systematic way (addressed in WP3).

- ***Limited characterization of the multi-dimensional (spatiotemporal) smoothing and sampling properties of atmospheric remote sensing systems, and of the resulting uncertainties (G3.04)***
    - Unknown contribution to the comparison error budget. Limits interpretation in terms of data quality.
      Remedy: GAIA-CLIM WP3 will describe and quantify these uncertainties for selected ECVs and instruments.
- ***Missing comparison error budget decomposition including errors due to sampling and smoothing differences (G3.06)***
    - Limits interpretation of comparisons in terms of data quality and fitness-for-purpose.
      Remedy: Studies quantifying the errors due to smoothing and sampling differences in actual comparisons, either using physical or statistical modelling tools (addresseed for specific ECVs and instrument techniques in WP3).
- ***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 satellite-to-sub-orbital comparisons for most ECVs. Significant contribution to systematic uncertainty in satellite-to-sub-orbital data 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, timescale & cost estimate require further investigation.
- ***Missing generic and specific standards for co-location criteria in validation work (G3.03)***
    - Difficulty to compare different validation exercises. Limits optimal use of the ground-based networks.
      Remedy: Publication of generic and detailed validation protocols, including metrology aspects of a data comparison and recommendations on optimal co-location criteria.
- ***Representativeness uncertainty assessment missing for higher-level data based on averaging of individual measurements (G3.05)***
    - Unknown contribution to the total uncertainty of the measurement, impacting both scientific use and validation work.
      Remedy: Studies quantifying the representativeness of averages by either using physical or statistical modelling tools.

3.6 Technical gaps

(G1.02; G1.06; G5.01; G5.02; G5.03; G5.04; G5.05; G5.06; G5.07: 9 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 not 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:

All ECVs:

- ***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 networks and is beneficial to identify shortcomings in the practices applied by network operators.
      Remedy: Ensure viability of Task 1.2 activities to determine data tiers as set out in Task 1.1 activities. Testers from Task 1.2 to assess some test study cases.
      Timescale: months; Cost estimate: none.
- ***Lack of a common effort in metadata harmonization (G1.06)***
    - Different metadata formats are adopted among the different networks making the data harmonization effort at the global scale and n the different observation domain challenging.
      Remedy: WMO to push all the observing networks to conform to WIGOS standards; Also: enforce harmonised data for the Virtual Observatory.
      Timescale: starting from 2018 when WIGOS-OSCAR will be fully operational; Cost estimate: requires further plans and investigation.
- ***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 will be a problem for an interactive web tool. Store sample data locally.
      Remedy: agreement on WMO data policy; develop shared data policy. Develop user friendly access, e.g. using Earth System Grid as for CMIP5.
- ***Access to data in multiple data formats and structures (e.g. granularity of data). Lack of standardized metadata (G5.02)***
    - Loss of metadata due to reformatting of data by user.
      Remedy: Sample data at the highest possible level to minimize the time in data transfer. Employ meta data standard such as WIGOS.
- ***Efficient data management to collocate observations needs to be improved (G5.03)***
    - Enables collocations for long time series of satellite data. Can impact the visualization tools.
      Remedy: Develop further existing colocation tools (NPROVS, ICARE, STAMP). Metadata should be well documented to help the collocation.
- ***Usability of reference database needs to be ascertained: subset definition (G5.04)***
    - Analyses may be impaired if tools cannot run consistently across databases. Lack of pertinent reference subset database (spatial extent, time range, sampling, resolution, variables, etc.).
- ***Usability of reference database needs to be ascertained: format (G5.05)***
    - Analyses may be impaired if tools cannot run consistently across databases. Tool development may be impaired by format issues and lack of data consistency.
      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; G2.15; G2.16; G4.04; G5.01; G5.07: 14 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. 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 sub-orbital observing capabilities for the study of ECVs in atmospheric, ocean and land domains (G1.04)***
  - Mapping of current observing capabilities has been carried out by each network under an uncoordinated effort across the community measuring ECVs.
    Remedy: enhanced coordination amongst global stakeholders like GCOS, GEOSS, GAW, and the federated networks adhering to this programs.
    Timescale: uncertain; Cost estimate: requires further plans and investigation.
- ***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.

O_3:

- ***Northern Hemisphere bias in NDACC and PANDORA network sites distribution (G1.15)***
  - The lack of coverage in space and time limits the potential of the network for global studies such as latitudinal dependencies and global trend studies, satellite validation and long-term assessment of ECV. Develop strategies for network extension, and long-term preservation of data and measurement capabilities.

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

H_2O:

- ***Water vapor measurements with the lidar and microwave radiometer are often provided in a sparse way and under an uncoordinated effort (G1.13)***
  - Several stations are routinely performing water vapor measurements with the microwave radiometer and with the Raman lidar (column and profiles) often at the same site exploiting also this synergy, but they are often not coordinated losing their powerful observing capability at a large scale.
    Remedy: Agree on a federated approach like those already partly established for the aerosol network most of which are also in charge for water vapor measurements using Raman lidar and microwave radiometer.
    Timescale: uncertain; Cost estimate: low-moderate.
- ***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.
    Remedy: If suitable airlines in Eastern Europe can be identified it may be possible to include them in the E-AMDAR program (= also coverage gap).

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)***
    - To fully exploit the synergy between lidars and photometers, collocation between them at the various sites is recommended, also considering the new technologies like the moon photometer and the RRlidar.
      Remedy, timescale & cost estimate require further investigation. *(gap is being discussion)*
- ***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.

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 1 a compilation has been made of the gaps that have been formulated by the project team by the end of June 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. An internal review of this Version 1 was performed by the WP leads before submission in September 2015.

The results of the user survey (Task 6.1) implicated a clear need for user education and capacity building on how sub-orbital and/or satellite data can be used 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 sub-orbital observations.

In Table 2.1 a first overview has been attempted of the contributions of the networks and sub-orbital instrument techniques per ECV per altitude domain.

Table 2.2 lists the identified gaps and each gap is associated with one or more of the generic gap types.

In Section 3 the input is summarized as has been provided from the work packages D1.1, D1.2, D1.3, D1.4, and D1.5 on the gap impacts and potential remedies.

Future versions of the GAID will include comments and further suggestions from the team members, new input based on the upcoming work package deliverables, input obtained through the user workshops, input obtained via the website through a template and with a dedicated e-mail address to provide input (e-mail: gaid@gaia-clim.eu), and potential input from upcoming scientific publications as well as other external documents.

GAID Version 1.0 will be presented at the first user workshop on 6 October 2015 in Rome.

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