GAIA-CLIM Report

Gap Analysis for Integrated Atmospheric ECV CLImate Monitoring:

Final review of and update to the GAID from the perspective of WP4

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Introduction

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

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

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

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

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

This document provides a snapshot of the gaps status as per December 2017 in relation to work package 4. It provides a third, and final, formal delivery of WP4 input to the process. The on-line 'Catalogue of Gaps' provides the latest version of the full content of the gaps and their proposed remedies. The catalogue is available from: http://www.gaia-clim.eu/page/gap-reference-list.

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

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

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

1. Summary of existing gaps for WP4

Table 1.1. Overview of the gaps identified under work package 3 under GAID V4 and their identified remedies

Gap reference/ ownership	Gap title	Remedies
G4.01	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity	• (R1) Development of tools to propagate geophysical profile data and attendant uncertainties to TOA radiances and uncertainties • (R2) Evaluate quality of NWP and reanalysis fields through comparisons with reference data as a means of establishing direct traceability
G4.08	Estimates of uncertainties in ocean surface microwave radiative transfer	• (R1) Intercomparison of existing surface emissivity models • (R2) The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the l region 1 – 200 GHz • (R3) Establish an ocean emissivity reference model in the spectral region 1 – 200 GHz • (R4) Reference-quality dielectric constant measurements of pure and saline water for the frequency range 1 – 200 GHz
G4.09	Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer	• (R1) The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based) • (R2) Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables
G4.10	Incomplete estimates of uncertainties in land surface infrared emissivity atlases	• (R1) Provision of validated land surface infrared emissivity atlases
G4.12	Lack of reference quality data for temperature in the upper stratosphere and mesosphere	• (R1) Use of GNSS-RO temperature profiles as a reference dataset for satellite Cal/Val

2. Detailed update on traces for the gaps arising from WP4

A small number of changes to gap traces have been made in this final review of the GAID. This reflects the maturity of gaps and remedies in the GAID document v4. The changes concern:

- Revised gap descriptions in light of WP4 progress, which has clarified the nature of the gaps;
- Refinements to overlaps between gaps and the interlinked nature of the gaps/remedies;
- Updates which reflect tangible achievements in WP4, which have made progress towards closing the gaps;
- In one case, the addition of two further remedies, where the existing remedies were considered insufficient to close the gap and recent work within WP4 has identified specific potential solutions.

Respective edits to the gap traces are summarised as follows:

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

G4.12 (lack of reference-quality data for temperature in the upper stratosphere and mesosphere) has been added as a related gap, which should be addressed before G4.01 can be closed. The detailed description and gap status now reflect the progress made in WP4 in developing the 'GRUAN processor' as a software deliverable. Previously, the gap referred to NWP validation of JPSS-1 ATMS, which was ultimately not possible within the timeframe of GAIA-CLIM (launch occurred 18 November 2017), this was replaced by a validation study of Meteor-M N2 MTVZA-GY.

G4.08 "Estimates of uncertainties in ocean surface microwave radiative transfer"

The gap detailed description now explicitly notes the need for a reference model for ocean microwave emissivity where the component parts of the model have traceable uncertainties, which can be propagated through to the model outputs. This has resulted in the addition of two extra remedies ("Remedy 3 – Establish an ocean emissivity reference model in the region 1 – 200 GHz"; "Remedy 4 – Reference-quality dielectric constant measurements of pure and saline water for the frequency range 1 – 200 GHz"). Remedy 4 is an essential component of Remedy 3. The new remedies propose to undertake the necessary experimental and modelling efforts to establish a reference model, considering in turn the fundamental underlying processes on which the emissivity calculation relies. Two recent references related to WP4 activities are cited.

G4.09 "Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer"

The gap abstract has been slightly reworded to note the relevance of this gap to WP4 activities within the NWP framework. The reference list has been corrected where necessary.

G4.10 "Incomplete estimates of uncertainties in land surface infrared emissivity atlases"

Only very minor changes to the wording of the detailed description have been made.

G4.12 "Lack of reference-quality data for temperature in the upper stratosphere and mesosphere"

The text of the detailed description has been revised for clarity.

3. Conclusions

This deliverable and the gap traces contained in the annexes constitute the third and final official input to the GAID process arising from WP4.

4. Annex I Updated GAIA-CLIM Catalogue of gaps for WP4

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

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

Gap abstract:

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

Part I: Gap description

Primary gap type:

Uncertainty in relation to comparator

Secondary gap type:

Knowledge of uncertainty budget and calibration

ECVs impacted:

- Temperature
- Water vapour

User category/Application area impacted:

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

Non-satellite instrument techniques involved:

Radiosonde

Related gaps:

- G4.08 Estimates of uncertainties in ocean surface microwave radiative transfer

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

G4.08 and G4.09 are concerned with uncertainties in microwave surface radiative transfer for respectively the ocean and land surfaces. This gap (G4.01), being concerned with modelled TOA radiances, is partially dependent on a knowledge of uncertainties in the surface microwave radiative transfer. G4.08 should be addressed with the current gap and G4.09 can be addressed independently
G4.10 is concerned with uncertainties in infrared land surface emissivity atlases. This gap (G4.01), being concerned with modelled TOA radiances, is partially dependent on a knowledge of surface emissivity uncertainties. G4.10 can be addressed independently of the current gap.
G4.12 is concerned with the lack of reference measurements for the higher atmosphere (pressures less than 40 hPa). This gap (G4.01) cannot be closed for this part of the atmosphere without first addressing G4.12.

Detailed description:

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

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

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

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

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

Operational space missions or space instruments impacted:

- Meteosat Third Generation (MTG)
- MetOp
- MetOp-SG
- Polar orbiters
- Microwave nadir
- Infrared nadir
- Passive sensors
- US Joint Polar Satellite System (JPSS): ATMS, CrIS instruments
- Chinese Fengyun (FY) weather satellites: MWTS, MWHS, MWRI instruments

Validation aspects addressed:

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

Gap status after GAIA-CLIM:

GAIA-CLIM partly closed this gap:

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

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

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

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Through lower cost, effective and timely validation of new microwave missions, of which there are	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation	High	More timely integration of new, validated satellite data sets into reanalyses.

>10 planned over the next 2 decades.	development, etc.) International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)		
Broader C3S user base	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High	Improved confidence in, and established quantitative uncertainties for, ERA temperature and humidity analyses. Improved confidence in projected impacts.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Sub-optimal validation of EO data	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Continued uncertainty on the value of NWP for the validation of (primarily temperature sounder and humidity sounder and imager) satellite data. Motivates more costly Cal/Val campaigns based on airborne measurements (a large and recurring cost for each new mission). Data users have less confidence in findings based on observational data of uncertain quality. Slower evolution of the community's understanding of the quality of EO data sets, particularly for new missions. Failure to recognise defects in instruments and/or processing chains may result in sub-optimal satellite data being used in downstream applications (e.g. reanalyses or climate studies).
Unknown uncertainties associated with NWP temperature and humidity fields	Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	While model biases and uncertainties remain unquantified, NWP centres cannot respond by targeting model performance

			improvements. Users of NWP and reanalysis data want reliable uncertainty estimates rather than taking the data on trust. While uncertainties are lacking, this limits the confidence in, and societal impact of, NWP forecasts and reanalyses.

Part III: Gap remedies

Gap remedies:

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

Primary gap remedy type:

- Technical
- Technology Readiness Level (TRL) 6

Proposed remedy description:

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

Relevance:

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

Measurable outcome of success:

- Statistics available on the comparison, for all GRUAN sites, with respect to ECMWF and Met Office NWP fields.
- A web page displaying these statistics.
- An open-source GRUAN processor available to the wider community.
- Integration of the GRUAN processor into the GAIA-CLIM Virtual Observatory.

Expected viability for the outcome of success:

High

Scale of work:

- Single institution
- Consortium

Time bound to remedy:

Less than 3 years

Indicative cost estimate (investment):

Low cost (< 1 million)

Indicative cost estimate (exploitation):

Minor costs associated with hosting, upkeep and periodic reviews for updates

Potential actors:

- EU H2020 funding
- National Meteorological Services

Remedy 2: Evaluate quality of NWP and reanalysis fields through comparisons with reference data as a means of establishing direct traceability.

Primary gap remedy type:

- Technical
- TRL 6

Proposed remedy description:

The GRUAN processor developed for GAIA-CLIM offers the means of traceable evaluation of the quality of NWP fields at the GRUAN-site locations. Due to the scarcity of reference measurements for comprehensive evaluation of NWP data, it will be necessary to determine additional 'near-reference' measurements for which defensible uncertainty estimates can be provided. It is proposed to extend the assessment of NWP fields using other data of demonstrated quality, such as selected GUAN radiosondes and GNSS radio occultations, in order to sample a larger subspace of NWP regimes. Additionally, NWP and reanalysis systems now make use of ensembles (multiple forecasts to represent error growth from uncertain initial conditions and stochastic physics perturbations). Uncertainties as estimated from ensembles should be evaluated using available NWP minus reference-data differences. It is also desirable to extend the assessment to include atmospheric composition, for which reference composition measurements and their uncertainties are required.

Relevance:

NWP and reanalysis fields and products are very widely used for the validation and characterisation of EO data, although associated robust uncertainties are lacking. Traceable uncertainties will engender more confidence from users.

Measurable outcome of success:

Published uncertainties should be available for widely used NWP and reanalysis model fields such that the uncertainties and associated correlation structures are traceable to underlying reference data.

Expected viability for the outcome of success:

High

Scale of work:

- Single institution
- Consortium

Time bound to remedy:

Less than 5 years

Indicative cost estimate (investment):

Low cost (< 1 million)

Indicative cost estimate (exploitation):

Non-applicable

Potential actors:

- EU H2020 funding
- National Meteorological Services

References:

- Bell, W., English, S. J., Candy, B., Hilton, F., Atkinson, N., Swadley, S., Baker, N., Bormann, N. and Kazumori, M. (2008). The assimilation of SSMIS radiances in numerical weather prediction models. IEEE Trans. Geosci. Remote Sensing 46: 884–900.

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- Noh, Y.-C., Sohn, B.-J., Kim, Y., Joo, S., and Bell, W. (2016). Evaluation of Temperature and Humidity Profiles of Unified Model and ECMWF Analyses Using GRUAN Radiosonde Observations. Atmosphere, 7, 94; doi:10.3390/atmos7070094

G4.08 Estimates of uncertainties in ocean surface microwave radiative transfer

Feedback

Gap abstract:

Several passive microwave missions (operating in the 1-200 GHz range) make measurements in spectral regions where the atmosphere is sufficiently transmissive so that the surface contributes significantly to measured radiances. The calibration/validation of microwave satellite data to reference standards is hampered, for some instruments and channels, by a lack of traceable estimates of the uncertainties in the modelled ocean surface contribution. This is particularly important for microwave imagers, sensitive to total column water vapour, which are routinely assessed within numerical weather prediction (NWP) frameworks. It also affects the lowest peaking channels of microwave-temperature sounders such as channel 5 of AMSU-A. The accuracy of retrievals of atmospheric temperature and humidity over the ocean is also dependent on the accuracy of ocean surface microwave radiative transfer. The dominant source of uncertainty for ocean surface microwave radiative transfer is expected to be ocean emissivity estimates.

Part I: Gap description

Primary gap type:

Knowledge of uncertainty budget and calibration

Secondary gap type:

Parameter (missing auxiliary data etc.)

User category/Application area impacted:

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

Non-satellite instrument techniques involved:

Radiosonde (through use of the GRUAN processor)

Related gaps:

- G4.01 Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity
- G4.09 Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer

- G4.10 Incomplete estimates of uncertainties in land surface infrared emissivity atlases

Gap 4.01 is concerned with the use of NWP fields for the validation of observations relating to temperature and humidity. This gap (G4.08) identifies one component of the challenge described in G4.01, and affects temperature sounding measurements in the boundary layer and lower troposphere. It also covers humidity sounding (and imaging) in the boundary layer and lower troposphere
G4.08 is related to, but can be addressed independently of, G4.09 and G4.10

Detailed description:

Passive microwave observations from satellite radiometers are widely used to make remote-sensing measurements of the Earth's atmosphere and surface characteristics. Current missions operate in the spectral range of 1 – 200 GHz but this will be extended in the future to 229 GHz for the EPS-SG MWS instrument and to frequencies over 600 GHz for the ICI mission. Total column water vapour, cloud liquid water path, ocean surface wind speed and direction, sea-surface temperature and salinity, and profiles of humidity and temperature, are all derived from microwave observations. The top-of-atmosphere (TOA) spectral signals in this spectral range can, depending on the state of the atmosphere, comprise a significant component due to emission and reflection from the ocean surface. This is particularly true of microwave imagers (where data quality assessment and operational use at NWP centres rely on radiative transfer modelling including surface terms) and the surface-sensitive channels of microwave temperature and humidity sounders (e.g. AMSU-A channel 5 and window channels). It is therefore critical that uncertainties in the ocean surface microwave radiative transfer are accurately calculated. This requirement spans applications ranging from the assimilation of Level-1 products (for example) in reanalysis efforts, to the generation of Level-2 (and higher) products at all levels of maturity, ranging from near-real-time operational products to climate data records.

Several emissivity models have been developed over the last two decades to support the assimilation of microwave-imager data at operational NWP centres and to support applications based on retrievals of the ECVs listed above from satellite-based microwave imager observations. These models account for several processes influencing the emissivity of the ocean surface, including: polarised reflection of the ocean's (dielectric) surface derived from the Fresnel equations, large scale roughness due to wind-driven waves, small scale roughness due to capillary waves, and the radiative effect of foam at progressively higher wind speeds. An ocean surface emissivity model, which is widely used in the remote sensing and operational NWP community, is the Fast Ocean Emissivity Model (FASTEM), which forms part of the RTTOV fast radiative transfer model. Following the initial formulation by English and Hewison (1998), FASTEM has been developed over the last 20 years, with many recent developments guided and informed by an analysis of biases observed between satellite observations and simulations based on NWP models (Bormann et al (2011); Bormann et al (2012); Meunier at al (2014); and Kazumori et al (2015)). The current version of FASTEM (version 6) includes the dielectric constant model and wind speed terms developed by Liu et al (2011), the foam parameterisations of Stogryn (1972) and O'Monahan and Muircheartaigh (1986), and the wind-direction dependence terms developed by Kazumori et al (2015).

A number of studies have been carried out to estimate the uncertainties of ocean emissivity models (e.g. Guillou et al 1996; Guillou et al; 1998, Greenwald et al; 1999). However, most studies which estimated uncertainties were carried out before the latest versions of FASTEM, which include considerable updates made by Liu et al (2011) and Kazumori et al (2015), and also tended to focus on one aspect of the model or one frequency. Therefore, despite a number of studies being carried out to validate the FASTEM model, it still lacks traceable estimates of the uncertainties associated with the computed emissivities in the 1-200 GHz range. This gap has been identified as an important deficiency in using NWP-based simulations for the validation of new satellite missions.

FASTEM is an approximate (fast) parameterisation of an underlying reference model (English et al., 2017). Such a reference model has three main components: (i) the dielectric model predicting the polarised reflection and refraction for a flat water surface (Lawrence et al. 2017); (ii) the roughness model which represents the ocean roughness due to large scale swell and wind-induced waves; and (iii) the foam model which commonly parameterises the ocean foam coverage as a function of wind speed and assigns a representative emissivity to the foam fraction. For a true reference model, each of these components should be associated with traceable uncertainties.

Operational space missions or space instruments impacted:

- Copernicus Sentinel 3
- MetOp
- MetOp-SG
- Copernicus Sentinel 3: Microwave Radiometer (MWR) instruments. MetOp (2006-2025): Advanced Microwave Sounding Unit (AMSU); Microwave Humidity Sounder (MHS). MetOp-SG: Microwave Imager (MWI); Microwave Sounder (MWS); Ice Cloud Imager (ICI)

Other:

- S-NPP / JPSS (2012-2030): Advanced Technology Microwave Sounder (ATMS)
- Feng-Yun 3 (2008-2030): Microwave Radiation Imager (MWRI); Microwave Temperature Sounder (-1 and -2); Microwave Humidity Sounder (-1 and -2).
- Global Change Observation Mission (GCOM-W1, 2012-2020): Advanced Microwave Scanning Radiometer-2 (AMSR-2)
- Special Sensor Microwave Imager / Sounder (SSMI/S, F-16 - F-19: 2003-2020)
- Meteor-M (2009-2030): MTVZA
- GPM (2014-): Microwave Imager (GMI)
- Megha-Tropiques (2011-): Microwave humidity sounder (SAPHIR)
- Coriolis (2003-): microwave radiometer Windsat
- Jason (2001-2021): microwave radiometers JMR and AMR

Validation aspects addressed:

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Gap status after GAIA-CLIM:

After GAIA-CLIM this gap remains unaddressed

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

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts

Lower cost, effective and timely validation of new microwave missions, of which there are >10 planned over the next 2 decades.	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	High	More timely integration of new, validated, satellite datasets into reanalyses.
Broader C3S user base	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High	Improved ERA humidity analyses, improved consistency in-time and geographically and in different phases of the satellite era, through improved homogenisation of datasets. Improved regionally resolved analyses and improved confidence in projected impacts
Identified risk	**User Category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Sub-optimal validation of new EO data	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Continued uncertainty on the value of NWP for the validation of imager data drives a requirement for more costly Cal/Val campaigns for each new system based on airborne measurements or equivalent. This will be a large and recurring cost for each new mission Less confidence in findings based on observational data of unknown quality. Sub-optimal (slower) evolution of the community's understanding of the quality of key measured datasets
High uncertainties associated with surface emissivity modelling	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV	Medium	The error component associated with surface emission modeling remains large and dominates the error budget for these observations, thereby limiting the weight given to these observations in climate reanalyses. Consequently limiting the accuracy of NWP and reanalysis

	Climate Data Records)		based analyses of lower tropospheric humidity over ocean. This will have knock-on effects on attempts to predict regionally resolved impacts of climate change.

Part III: Gap remedies

Gap remedies:

Remedy 1 – Intercomparison of existing surface emissivity models

Primary gap remedy type:

- Technical
- TRL 4

Proposed remedy description:

Undertake an in-depth intercomparison of available microwave ocean surface emissivity model outputs, for a carefully defined set of inputs (ocean state, atmospheric state). An intercomparison of emissivity models, in itself, will not achieve a validation of emissivity models, but the differences identified and quantified can shed light on the sources of bias in any given emissivity model. Such an intercomparison exercise is, therefore, a useful step towards a full validation of emissivity models. In many cases, however, such an intercomparison yields valuable insights into the mechanisms, processes, and parameterisations that give rise to biases. This approach thus constitutes a useful first step in the validation of (in this case) ocean surface emissivity estimates. The measurable output of success therefore, for this activity, will be a documented quantitative comparison of FASTEM (various versions) with another, independent, emissivity model, for a realistic sample of global ocean surface conditions. The probability of a successful outcome is high if the exercise can be coordinated through the appropriate international working groups (e.g. International TOVS Working Group, International Precipitation Working Group, GSICS, X-Cal), and is supported by national and/or international agencies.

Relevance:

An intercomparison exercise is a useful step towards a full validation of emissivity models. In many cases, such an intercomparison yields valuable insights into the mechanisms, processes and parameterisations that give rise to biases.

Measurable outcome of success:

Documented quantitative model inter-comparison: intercomparisons of non-traceable estimates, in this case outputs from independent ocean surface emissivity models, in themselves will not constitute a validation of any individual estimate. For example, independent estimates can be biased in the same sense. This motivates the need for the additional remedies associated with this gap.

Expected viability for the outcome of success:

High

Scale of work:

- Single institution
- Consortium

Time bound to remedy:

Less than 5 years

Indicative cost estimate (investment):

Low cost (< 1 million)

Indicative cost estimate (exploitation):

Non-applicable

Potential actors:

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

Remedy 2 – The use of traceably calibrated radiometers in experimental campaigns to validate ocean emissivity models in the region 1 – 200 GHz

Primary gap remedy type:

Deployment

Proposed remedy description:

Typically, validation of ocean emissivity models has been carried out using airborne campaigns. However, to date these campaigns have not used traceably calibrated radiometers, since there have been no primary reference standards available. However, primary reference standards are beginning to be developed and there are now some capabilities in China, Russia, and the USA. We propose using these traceably calibrated radiometers for field campaigns as well as airborne campaigns. It would be useful to exploid this type of radiometers in laboratory experiments using wave tanks and field campaigns with radiometers mounted on oil rigs. A combination of different techniques should lead to more robust estimates of the uncertainties in the emissivity models. Note that the determination of emissivity will be reliant on sufficiently accurate co-located estimates (from models) or in-situ measurements, of ocean surface skin temperature, salinity, and ocean surface wind speed.

Relevance:

A combination of different techniques should lead to more robust estimates of the uncertainties in the emissivity models.

Measurable outcome of success:

Documented, quantitative, evaluation of ocean surface emissivity models with respect to measurements of ocean surface emissivity obtained during experimental campaigns with traceably calibrated radiometers, for a globally representative range of ocean surface wind speeds, temperatures, and salinity.

Expected viability for the outcome of success:

Medium

Scale of work:

Consortium

Time bound to remedy:

Less than 5 years

Indicative cost estimate (investment):

Medium cost (< 5 million)

Indicative cost estimate (exploitation):

Non-applicable

Potential actors:

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

Remedy 3 – Establish an ocean emissivity reference model in the spectral region 1 – 200 GHz

Primary gap remedy type:

- Technical
- TRL 4

Proposed remedy description:

Undertake the necessary research and modelling to establish a reference emissivity model where the constituent parts have associated robust traceable uncertainties. This should include a re-calibration of the dielectric constant model to new reference laboratory measurements of the dielectric constant of seawater (see Remedy 4). A roughness model which, incorporates information from a wave model (large scale ocean swell) and surface wind speed (influencing small scale ripples and waves) is also needed to predict scattering characteristics. Similarly, the contribution of foam can be derived in principle from a wave model and full radiative transfer (rather than assuming a nominal emissivity value for the foam fraction). These activities will require coordination. Traceable uncertainty estimation must be assured at each step, the documented code should be freely available, and the final reference model should be maintained and supported.

Relevance:

Current fast emissivity models lack traceable uncertainty estimates which is a key source of uncertainty in the radiative transfer modelling of surface-sensitive microwave satellite observations over ocean in the 1-200 GHz range.

Measurable outcome of success:

Documented and freely available software for the prediction of microwave ocean emissivity. The reference model constituent parts should have rigorous uncertainty estimates attached. The underlying basis of the model should be peer reviewed. The expertise for undertaking the necessary laboratory and modelling activities exists, but in disparate institutions that will require coordination. Establishing a fully characterised reference model would close this gap.

Expected viability for the outcome of success:

Medium

Scale of work:

Consortium

Time bound to remedy:

Less than 5 years

Indicative cost estimate (investment):

Medium cost (< 5 million)

Indicative cost estimate (exploitation):

Non-applicability

Potential actors:

- National funding agencies
- National Meteorological Services
- Academia, individual research institutes

Remedy 4 – Reference-quality dielectric constant measurements of pure and saline water for the frequency range 1 – 200 GHz

Primary gap remedy type:

Research

Proposed remedy description:

Ocean emissivity models rely on accurate measurements of the dielectric constant of water and seawater for a range of temperatures and frequencies. However, there are inconsistencies between measurements available in the literature (Lawrence et al 2017) and none have SI-traceable uncertainties. Measurements should be taken that are reference quality, i.e. SI-traceable and with validated uncertainty estimates. The uncertainties should include a calculation of the correlation between measurements of the real and imaginary components of the dielectric constant, so that the uncertainties can be properly transformed into radiance space. As well as ocean emissivity, this would also support dielectric constant models for cloud radiative transfer (e.g. the dielectric constant of super-cooled liquid water).

Relevance:

This will support a reference ocean emissivity model, allowing for cal/val of microwave imagers and surface sensitive channels of microwave sounders to reference standards.

Measurable outcome of success:

Documented and freely available measurements of the dielectric constant of seawater and pure water for a range of frequencies (1 – 200 GHz) and temperatures (-5 to +35 °C) with traceable uncertainty estimates.

Expected viability for the outcome of success:

Medium

Scale of work:

PhD or post-doctoral student

Time bound to remedy:

Less than 5 years

Indicative cost estimate (investment):

Medium cost (< 5 million)

Indicative cost estimate (exploitation):

Non-applicable

Potential actors:

- National funding agencies
- Academia, individual research institutes

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G4.09 Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer

Gap abstract:

There is a lack of traceable uncertainties associated with the contribution of land surface microwave radiative transfer to Top of the Atmosphere (TOA) brightness temperatures for microwave imaging and sounding instruments. The land surface emission exhibits significant spatial and temporal variability, particularly in snow- and ice-covered regions. There are a number of sources of uncertainty in the approaches currently used to estimate the land-surface contribution, including the emissivity and skin temperature prior, ineffective cloud and precipitation screening and errors introduced by the simplification of the radiative-transfer equation for practical computations. The accuracy of simulated radiances using Numerical Weather Prediction (NWP) models is limited, for some applications, by the uncertainty in modelled surface emission. Solving this gap will require a combination of different approaches, including the use of experimental campaigns which are useful to validate the overall contribution of the land surface.

Part I: Gap description

Primary gap type:

Knowledge of uncertainty budget and calibration

Secondary gap type:

Parameter (missing auxiliary data etc.)

ECVs impacted:

- Temperature
- Water vapour

User category/Application area impacted:

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

Non-satellite instrument techniques involved:

Independent of instrument technique

Related gaps:

- G4.01 Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity
- G4.08 Estimates of uncertainties in ocean surface microwave radiative transfer
- G4.10 Incomplete estimates of uncertainties in land surface infrared emissivity atlases

G4.01 should be addressed with G4.09
Argument: Gap 4.01 is concerned with the use of NWP fields for the validation of observations relating to temperature and humidity. This gap (G4.09) identifies one component of the challenge described in G4.01, and affects temperature sounding measurements as well as humidity sounding (and imaging) measurement in the boundary layer and lower troposphere over land.
G4.08 and G4.10 can be addressed independently.

Detailed description:

Passive microwave observations from satellite radiometers operating in the spectral range from 1-200 GHz are widely used to make remote-sensing measurements of the Earth's atmosphere and surface characteristics. Observations in this frequency range are sensitive to atmospheric humidity and temperature, as well as to emission and reflection from the surface. Microwave instruments, which are primarily used to estimate atmospheric temperature and humidity profiles (e.g. AMSU-A, MHS, AMSR-2), can also have a significant contribution from the surface, depending on atmospheric conditions. Currently the calibration/validation (cal/val) of these instruments tends to be carried out only over ocean due to more trustworthy estimates of the surface contribution, but in the future, this should be extended to the land so that cal/val can be performed over the full dynamic range of the instruments. To do this, it is necessary to validate the estimated land-surface contribution to the TOA radiances, and to calculate the associated uncertainties in radiance space.

The calculation of the land-surface contribution to the TOA radiances relies on simplified radiative-transfer equations, and estimates of the surface 'skin' temperature and emissivity. It is assumed that the land surface represents a homogeneous body with an emission equal to the skin temperature multiplied by an emissivity. An additional contribution to the TOA brightness temperature is calculated as the atmospheric emission reflected off the surface, which can be assumed to be either a specular or Lambertian reflection (Lambertian for snow-covered surfaces, specular for many other surfaces). In reality, the surface emission is more complex, due to multi-layers with heterogeneous dielectric properties (varying both vertically and horizontally), particularly for snow cover, and the reflection is likely to be not entirely specular or Lambertian. Furthermore, microwave emissions come from layers deeper than the surface (depending on frequency and dielectric properties) and so the use of a skin temperature estimate may not be appropriate for some conditions, particularly over deserts where the penetration depth is higher (see e.g. Norouzi et al; 2012).

As with the ocean surface, physically-based models have been developed to allow the estimation of land surface emissivity (e.g. Wang and Choudhury, 1981; Njoku and Li, 1999; Weng et al., 2001) for different surface types and different frequencies. Methods to estimate the surface type from satellite observations have also been developed (e.g. Grody, 1988). However, in order to accurately calculate the emissivity using physically-based models, a large number of input parameters are required that are difficult to estimate accurately over the spatial scales needed for satellite measurements. Progress in this area is still ongoing, but as a result, it has become necessary to rely on retrievals from satellite observations, following the methods developed by Karbou et al (2006; 2010). At the Met Office, for example, the microwave skin temperature and emissivity values are retrieved simultaneously in a 1D-Var system from the window channels of temperature and humidity sounders. At ECMWF and Meteo-France, the emissivity is also calculated from window channel observations, but with the skin temperature taken from the NWP model values.

Uncertainties in the land-surface contribution to the TOA radiances are a combination of uncertainties in: the emissivity values used, skin-temperature estimates, and the simplified radiative-transfer equations. The individual uncertainties of each of these contributions should be accurately estimated. As well as validating the individual components, the overall contribution can also be validated using experimental campaigns with ground-truth data, as well as comparisons to the TOA brightness temperatures from satellite instruments. It is likely that a combination of approaches will be needed to close the gap on uncertainty.

Estimates of uncertainties in retrieved land-surface emissivity have been calculated by Prigent et al (1997, 2000) and Karbou et al. (2005a), from the standard deviations of values retrieved from the satellite observations of different instruments. The authors provided gridded maps of uncertainties, which were shown to be around 2% on average. However, these uncertainties are indicative rather than robust, and are likely to be underestimates since they do not account for uncertainties due to: the calibration of the satellite instruments used in the retrievals, the temperature-humidity profiles used to calculate the channel transmittances, cloud screening, and surface temperature data. Ruston et al (2004) also carried out emissivity retrievals from SSM/I satellite observations over the USA and estimated the uncertainties in retrieved emissivity by randomly perturbing the input parameters. The authors concluded that errors were around 2% for frequencies less than 85 GHz. Their methods did not include possible errors in the atmospheric component due to the water-vapour continuum, however.

A number of experimental campaigns have been carried out to evaluate land surface emissivities over different surface types. For example, Harlow (2011) demonstrated how airborne microwave measurements can be used to validate the emissivity of snow-covered ice, relating to snow depth and snow pack characteristics, and quasi-Lambertian reflectance behaviour. Comparisons of different emissivity models have also been carried out. Ferraro et al. (2013) attempted an inter-comparison of several EO land emissivity data sets over the USA. The authors found differences of around 10 K in radiance space (emissivity x skin temperature) for frequencies up to 37 GHz and greater differences up to around 20 K for higher frequencies. These differences appeared to be generally systematic rather than random, with similar seasonal trends captured by the different datasets. Tian et al (2014) estimated uncertainties in retrieved emissivity values by comparing retrievals from different satellite sensors. They estimated similar uncertainties to Ferraro et al (2013), with systematic differences around 3 – 12 K over desert and 3 – 20 K over rainforest (with largest differences at the higher frequencies above 80 GHz). Random errors were estimated to be around 2 – 6 K.

As well as estimating uncertainties in the emissivity values retrieved, it is important to also consider uncertainties due to assumptions made in the simplified radiative transfer equations. For example, Karbou and Prigent (2005b) estimated the uncertainties in emissivity due to the specular assumption by performing emissivity retrievals from brightness temperatures simulated, using both the specular and Lambertian assumptions. They concluded that the errors in retrieved emissivities due to the specular assumption were less than 1% for most surfaces.

While to date there have been considerable efforts to validate the calculation of the surface contribution to TOA microwave radiances at frequencies between 1 – 200 GHz, none of the uncertainty estimates have been traceable or complete. This is in part due to the complexity of the problem and it is likely to take a combination of a number of approaches before the gap can be fully closed. However, in part 3 below we suggest two areas of development which could contribute to the estimation of uncertainties in the land surface radiative transfer to reference standards.

Operational space missions or space instruments impacted:

- MetOp
- MetOp-SG
- Polar orbiters
- Microwave nadir

- Passive sensors
- Other, please specify:
- MetOp (2006-2025): Advanced Microwave Sounding Unit (AMSU); Microwave Humidity Sounder (MHS)
- MetOp-SG: Microwave Imager (MWI); Microwave Sounder (MWS); Ice Cloud Imager (ICI)

Other:

- S-NPP / JPSS (2012-2030): Advanced Technology Microwave Sounder (ATMS)
- Feng-Yun 3 (2008-2030): Microwave Radiation Imager (MWRI); Microwave Temperature Sounder (-1 and -2); Microwave Humidity Sounder (-1 and -2).
- Global Change Observation Mission (GCOM-W1, 2012-2020): Advanced Microwave Scanning Radiometer-2 (AMSR-2)
- Special Sensor Microwave Imager / Sounder (SSMI/S, F-16 – F-19: 2003-2020)
- Meteor-M (2009-2030): MTVZA

Validation aspects addressed:

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Gap status after GAIA-CLIM:

After GAIA-CLIM this gap remains unaddressed

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

Identified benefit	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Resolution of this gap will enable greater use of surface-sensitive satellite observations over land in NWP data assimilation systems (either by permitting the use of extra channels, or giving greater weight to existing observations).	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	Medium	Potential improvements in ERA near-surface analyses; improved confidence in projected impacts. Greater confidence in ECV parameters derived from passive microwave sensors, such as soil moisture.

Identified risk	User category/Application area benefitted	Probability of benefit being realised	Impacts
Sub-optimal validation of new EO data	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Less confidence in findings based on observational data of unknown quality over land. Sub-optimal (slower) evolution of the community's understanding of the quality of key measured datasets
High uncertainties associated with surface emissivity modelling	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	Medium	The error component associated with surface emission modeling remains large and dominates the error budget for these observations, thereby limiting the weight given to these observations in climate reanalyses – consequently limiting the accuracy of NWP and reanalysis based analyses of lower tropospheric humidity over land. This will have knock-on effects on attempts to predict regionally resolved impacts of climate change.

Part III: Gap remedies

Gap remedies:

Remedy 1: The use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based).

Primary gap remedy type:

Deployment

Secondary gap remedy type:

Research

Proposed remedy description:

This remedy concerns the use of traceably calibrated radiometers in land surface measurement campaigns (both airborne and ground-based). Such campaigns can be used to validate both the (combined) emissivity and skin temperature estimates calculated from window-channels observations for temperature and humidity sounders, and emissivity models. Such campaigns would need to be undertaken across a sufficiently diverse set of land-surface types and meteorological seasons to provide representative results that enabled broad applicability. There is also a need for robust ground-truth activities in such campaigns to minimise the uncertainty.

Relevance:

It is proposed to use traceably calibrated radiometers in land surface measurements campaigns (both airborne and ground-based. Such campaigns can be used to validate both the (combined) emissivity and skin temperature estimates calculated from window-channels observations for temperature and humidity sounders, and emissivity models.

Measurable outcome of success:

Documented, quantitative evaluation of land surface radiative transfer contributions with respect to measurements obtained during airborne campaigns for a globally representative range of land surfaces.

Expected viability for the outcome of success:

Medium

Scale of work:

Consortium

Time bound to remedy:

Less than 5 years

Indicative cost estimate (investment):

Medium cost (< 5 million)

Indicative cost estimate (exploitation):

Non-applicable

Potential actors:

- National funding agencies
- National Meteorological Services

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

Remedy 2: Use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables

Primary gap remedy type:

Research

Proposed remedy description:

While retrievals of emissivity and surface-skin temperature are currently used for microwave atmospheric sounding and imaging instruments over land, as a long-term goal, it would be beneficial to move towards the use of models which require physical inputs either from Land Surface Models (LSMs) or remotely-sensed variables. Uncertainties should also be estimated. We therefore suggest, as long-term goals:

- The development of emissivity models over a wide range of frequencies (1-200 GHz) that rely on remotely-sensed parameters and/or atlases of land-surface characteristics; and are validated with ground-based or airborne radiometer measurements for different surface types.
- Inter-comparisons of available emissivity models, in particular physically based (e.g. multilayer) and simplified models.

Relevance:

There is a need to establish traceable uncertainties for NWP fields and radiances calculated from them.

Measurable outcome of success:

Documented, quantitative, evaluation of land surface emissivity values estimated from models with respect to measurements of land-surface emissivity obtained during experimental campaigns, for a globally representative range of surfaces.

Expected viability for the outcome of success:

Medium

Scale of work:

- Single institution
- Consortium

Time bound to remedy:

Less than 5 years

Indicative cost estimate (investment):

Medium cost (< 5 million)

Indicative cost estimate (exploitation):

Non-applicable

Potential actors:

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

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G4.10 Incomplete estimates of uncertainties in land surface infrared emissivity atlases

Gap abstract:

Land surface emissivity atlases in the infrared region (3-17 μm) are required for the validation of infrared satellite sounding measurements over land. Work is underway, outside of the GAIA-CLIM project, to develop dynamic atlases of spectral emissivity in this part of the spectrum, based on measurements from polar-orbiting hyper-spectral infrared observations and using a rapidly updating Kalman Filter. However, these new dynamic atlases need to be validated to ensure the estimates have robust uncertainties associated with them.

Part I: Gap description

Primary gap type:

Knowledge of uncertainty budget and calibration

Secondary gap type:

Parameter (missing auxiliary data etc.)

ECVs impacted:

- Temperature
- Water vapour

User category/Application area impacted:

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

Non-satellite instrument techniques involved:

Independent of instrument technique

Related gaps:

- G4.01 Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances – relating to temperature and humidity
- G4.08 Estimates of uncertainties in ocean surface microwave radiative transfer

- G4.09 Imperfect knowledge of estimates of uncertainties in land surface microwave radiative transfer

G4.10 should be addressed with G4.01
Argument: Gap 4.01 is concerned with the use of NWP fields for the validation of observations relating to temperature and humidity, This gap (G4.10) identifies one component of the challenge described in G4.01, and affects temperature and humidity sounding measurements in the boundary layer and lower troposphere over land.
G4.08 and G4.09 can be addressed independently of G4.10

Detailed description:

Passive-infrared observations from satellite radiometers operating in the spectral range from 17-3.3 μm are widely used to make remote-sensing measurements of the Earth's atmosphere and surface characteristics. Vertical profiles of humidity and temperature and surface properties such as skin temperature are derived from measurements in this spectral region. The top-of-atmosphere (TOA) spectral signals in this range can, depending on the state of the atmosphere, comprise a significant component due to emission and reflection from the land or ocean surface. It is therefore critical that validated models of (ocean and land) surface emissivity are available for the analysis of these infrared observations. This requirement, for validated models of emissivity, spans applications ranging from the assimilation of Level-1 products (for example) in reanalysis efforts, to the generation of Level-2 (and higher) products at all levels of maturity ranging from near-real-time operational products to climate data records.

There are particular challenges to representing the emissivity of land surfaces. In contrast to the ocean, where the physical mechanisms governing the surface emission can be parameterised, the infrared land surface emission is highly dependent on properties such as land-surface coverage (vegetation, bare soil, snow and so on), roughness and moisture content. These properties may change slowly (seasonally) or rapidly (daily). As a result, it has become necessary to rely on infrared land surface emissivity atlases, which characterize in a gridded fashion the global variations in emissivity at different frequencies.

There are several notable examples of publicly available atlases. The ASTER Global Emissivity Dataset has been compiled using cloud free scenes from the Advanced Spaceborne Thermal Emission and Reflection Radiometer on the Terra satellite. Monthly emissivity maps at 5 km spatial resolution are available for the years 2000-2015 (Hulley et al., 2015). Validation with laboratory spectra from four desert sites resulted in an absolute error of approximately 1%.

Capelle et al. (2012) applied a multispectral method for the retrieval of emissivity and surface temperature from IASI clear sky fields of view. They obtained a high spectral resolution product over the tropics for the period 2007-2011. The product was validated against emissivity spectra retrieved with an airborne interferometer (Thelen et al., 2009) to within an absolute accuracy of 2%.

Borbas et al. (2007) developed the UWIREMIS global land surface emissivity atlas for the 3.7 to 14.3 μm range. The atlas was derived by regressing the MODIS operational land surface emissivity product against laboratory emissivity spectra. At the Met Office, the UWIREMIS atlas is used as a first guess in the 1-D variational retrieval of surface emissivity for IASI observations over land.

The use of infrared emissivity atlases in NWP models is evolving. At the Met Office, work is underway to incorporate emissivity estimates derived from sounders such as IASI into a dynamically updated atlas (Gray, 2016). By using a Kalman filter approach, it is intended that the atlas can be updated in near-real-time as new observations become available. Thus, it would be able to capture short term emissivity variations in a way that static atlases cannot. This methodology is promising; however, such atlases need to be validated to make sure the retrieved values have robust uncertainties associated with them.

Operational space missions or space instruments impacted:

- MetOp
- MetOp-SG
- Polar orbiters
- Geostationary satellites
- Infrared nadir
- Passive sensors
- AIRS on Aqua; CrIS on NOAA JPSS satellites; HIRAS, GIIRS on Chinese Feng-Yun series; IRS on future Meteosat Third Generation satellites

Validation aspects addressed:

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)
- Auxiliary parameters (clouds, lightpath, surface albedo, emissivity)

Expected gap status after GAIA-CLIM:

After GAIA-CLIM this gap remains unaddressed

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

Identified Benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Resolution of this gap will enable greater use of surface-sensitive satellite observations over land in NWP data assimilation systems (either by permitting the use of extra channels, or giving greater weight to existing observations).	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	Medium	Potential improvements in ERA near-surface analyses; improved confidence in projected impacts.
Broader usability of ECV parameters	Climate research (research groups working on development,	Medium	Greater confidence in ECV parameters derived from passive infrared sensors,

	validation and improvement of ECV Climate Data Records)		such as land surface radiation budget.
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Sub-optimal validation of new EO data	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.) Climate research (research groups working on development, validation and improvement of ECV Climate Data Records)	High	Less confidence in findings based on observational data of unknown quality over land. Sub-optimal (slower) evolution of the community's understanding of the quality of key measured datasets
High uncertainties associated with surface emissivity modelling	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	Medium	The error component associated with surface emission modeling remains large and dominates the error budget for these observations, thereby limiting the weight given to these observations in climate reanalyses – consequently limiting the accuracy of NWP and reanalysis based analyses of lower tropospheric humidity and temperature over land This will have knock-on effects on attempts to predict regionally resolved impacts of climate change.

Part III: Gap remedies

Gap remedies:

Remedy 1: Provision of validated land surface infrared emissivity atlases

Primary gap remedy type:

- Technical
- TRL4

Secondary gap remedy type:

- Deployment
- Research

Specify remedy proposal:

There is a need to establish a comprehensive set of dynamic land surface infrared emissivity atlases. It is first required to perform an intercomparison of available emissivity models to ascertain their potential strengths and weaknesses and highlight where the greatest uncertainties exist. It is then necessary to coordinate airborne campaigns to validate land-emissivity models in the infrared-spectral region with a special focus on those domains where current models are most uncertain. The resulting improved infrared emissivity atlases should be made openly available in usable formats and broadly advertised. Peer-reviewed publications are likely to be required to build confidence in and raise awareness of these products.

Relevance:

There is a need to establish a comprehensive set of dynamic land surface infrared emissivity atlases. The resulting improved infrared emissivity atlases should be made openly available in usable formats and broadly advertised.

Measurable outcome of success:

Publicly available, open-source, dynamic (daily) spectral emissivity atlases in the infrared (3-17 μm). Documented, quantitative evaluation of infrared land surface emissivity atlases and models with respect to measurements of land-surface emissivity obtained during airborne campaigns, for a globally representative range of surfaces.

Expected viability for the outcome of success:

Medium

Scale of work:

Consortium

Time bound to remedy:

Less than 5 years

Indicative cost estimate (investment):

Medium cost (< 5 million)

Indicative cost estimate (exploitation):

No

Potential actors:

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

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G4.12 Lack of reference-quality data for temperature in the upper stratosphere and mesosphere

Gap abstract:

The GCOS Reference Upper Air Network (GRUAN) provides reference in-situ data for temperature and humidity with traceable estimates of uncertainty. This network can be used to validate NWP short-range forecasts for temperature and humidity to reference standards (see gap G4.01). The NWP temperature and humidity forecasts can then be used to perform satellite Cal/Val of new instruments, with improved knowledge of the associated uncertainties. However, there are very few GRUAN data above 40 hPa and none above 5hPa. We therefore identify a gap in reference-quality observations in the upper stratosphere and mesosphere, which particularly affects the calibration/validation of microwave and infrared temperature sounding channels at these heights, particularly AMSU-A channels 12 – 14, ATMS channels 13 – 15, CrIS channels at 667.500 cm^{-1}, 668.125 cm^{-1}, and 668.750 cm^{-1}, IASI channels at 648.500 - 669.750 cm^{-1} and AIRS channel numbers 54 - 83.

Part I: Gap description

Primary gap type:

Vertical domain and/or vertical resolution

Secondary gap type:

Knowledge of uncertainty budget and calibration

ECVs impacted:

Temperature

User category/application area impacted:

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

Non-satellite instrument techniques involved:

Radiosonde

Related gaps:

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

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

G4.01 should be addressed after G4.12.
Gap 4.01 concerns about the lack of validation of NWP fields to reference standards. Validating NWP fields at 20 – 0.01hPa cannot be done without reference-quality data at these heights.
G6.03 should be addressed with G4.12
The colocation of GNSS-RO with a GRUAN sonde is in principle forecastable at least two weeks into the future. Potential 'golden overpass' times, when the GRUAN site is coincident with a polar orbiter measure and a radio occultation measure, are therefore predictable.

Detailed description:

The direct assimilation of microwave and infrared temperature sounders into Numerical Weather Prediction (NWP) and reanalysis systems improves estimates of the atmospheric state, directly improving both the NWP weather forecasts, as well as the long-term monitoring of atmospheric temperature by reanalysis systems, such as Copernicus C3S reanalysis (ERA-5 and later). When data from new temperature sounders (e.g. ATMS, AMSU-A, IASI, AIRS, CrIS) become available, it is important to assess the quality of the observations before they can be assimilated. Short-range temperature forecasts from NWP systems provide a good reference for validating new temperature-sounding satellite instruments due to the high accuracy of these forecasts, particularly in the troposphere. For example, estimates of the uncertainties of tropospheric temperature forecasts for the ECMWF system indicate that they are around 0.1K in radiance space (Bormann et al, 2010). Using NWP forecasts as a reference also facilitates the inter-comparison of satellite data, since differences in time and space of the measurements can be accounted for with the use of a forecast model. This allows to estimate inter-satellite biases (e.g. Bormann et al 2013; Lu et al 2015).

While NWP temperature fields are very useful as a reference for satellite Cal/Val, this method does not currently lead to fully traceable estimates of uncertainty (see gap G4.01), since the uncertainties in the NWP background, the uncertainties in the radiative-transfer model, and the spatial-mismatch uncertainties are not known to fully traceable standards. This first point can be addressed by using reference in-situ data such as from GRUAN for assessing the uncertainties in the ECMWF and Met Office NWP short-range forecasts of temperature and humidity. To do this, a tool known as the 'GRUAN processor' has been developed based on the EUMETSAT NWP Satellite Application Facility (NWP SAF) Radiance Simulator (see https://www.nwpsaf.eu/GProc_test/ins.shtml). This tool can be used to calculate the differences between GRUAN-temperature measurements and NWP forecasts in both geophysical space (temperature and humidity as a function of height) and radiance space (radiances as a function of channel for different satellite instruments) and compare these differences to the GRUAN uncertainties.

GRUAN reference temperature measurements are available from the surface to an atmospheric height of up to 5 hPa. However, less radiosonde data are available in the stratosphere than the troposphere and none above 5 hPa. In the upper reaches balloon-burst propensity leads to potentially biased sampling of solely warmer tail conditions. The lack of reference data in the upper stratosphere and mesosphere affects the assessment of uncertainties in NWP temperature fields to reference standards, leading to a poorer assessment at heights around 40 – 5 hPa and no assessment being possible above 5 hPa. In turn, this affects the calibration/validation of new temperature sounding data, which are sensitive to this portion of the atmosphere. This is particularly true of AMSU-A channel 14, whose weighting function peaks around 2 – 3 hPa, but it also affects channels 12 – 13 (peaking at 10 and 5 hPa respectively). The equivalent channels on ATMS are also affected, and there are also a number of infra-red temperature sounding channels on hyperspectral infrared sounders which are affected, including CrIS channels at 667.500 cm^{-1}, 668.125 cm^{-1}, and 668.750 cm^{-1}, IASI channels at 648.500 – 669.750 cm^{-1} and AIRS channel numbers 54 – 83. Furthermore, the weighting functions for most satellite sounding channels have a stratospheric tail with some small sensitivity to the stratospheric temperature, so that this will contribute to the uncertainty of the Cal/Val for all channels, although with less of an impact for the channels peaking lower in the atmosphere.

The gap identified here is twofold – a lack of reference observations at 40 – 5 hPa, and no reference observations above 5 hPa. The first part could be solved by supplementing the GRUAN-reference dataset with GNSS Radio Occultation (GNSS-RO) observations and products, including sets of bending angles and temperature retrievals. GNSS-RO bending angles have a high vertical resolution and uncertainties have been calculated both for these observations and for the derived temperature profiles with a high accuracy (Kursinski et al 1997). This makes GNSS-RO observations potentially very valuable as references for the calibration/validation of new satellite temperature-sounding data. We propose, therefore, including both the bending angles and derived temperature profiles, along with their estimated uncertainties, in the GRUAN processor in future work. This requires efforts to co-locate GRUAN profiles and GNSS-Radio Occultations. Such work will benefit where GRUAN sites in future make use of an EUMETSAT simulator that predicts up to two weeks in advance coincidence of polar orbiter overpasses and GNSS-RO occultations.

It should be noted that there are some known drawbacks to using GNSS-RO temperature profiles as a reference, however. Firstly, since the observations are directly sensitive to pressure/temperature rather than temperature, there is a so-called null space, in which the observations are blind to combined mean errors in temperature and pressure, which cancel each other out. Because of this, it is important to keep using reference radiosondes such as the GRUAN observations. Secondly, the temperature profiles at higher altitudes are less accurate since the observations rely on the bending by the atmosphere and in thin atmosphere the signal-to-noise ratio becomes very low. This makes it difficult to use GNSS-RO observations as a reference at altitudes above around 5 hPa (Healy and Eyre, 2000; Collard and Healy, 2003). The use of GNSS-RO measurements would therefore not help the lack of observations about 5hPa, but it would increase global coverage, improving the cal/val of new satellite temperature sounding data at heights of 40 – 5 hPa.

There is a clear need to develop instrumentation capable of measuring temperature routinely above 40 hPa (and in particular above 5hPa) in a traceable manner with metrologically well characterised uncertainties. The remedy defined here (using GNSS-RO temperature profiles as a reference dataset) only partially closes this gap and does not obviate the need for technological developments in upper atmosphere profiling.

Operational space missions or space instruments impacted:

- MetOp
- MetOp-SG
- Other, please specify:

All instruments with temperature sounding channels whose weighting functions include a significant contribution from 40 – 0.01 hPa. This includes:

- All AMSU-A instruments (NOAA, MetOp and Aqua satellites)
- Special Sensor Microwave Imager/Sounder instruments (F-16 to F-19)
- ATMS instruments (Suomi-NPP, JPSS-1 and later)
- MWTS-2 instruments (FY-3 satellite series)
- MWHS-2 instruments (118 GHz channel 2) on FY-3 satellite series
- MTVZA-GY instrument on Meteor-M
- IASI instruments (MetOp series)

- AIRS instruments (Aqua)
- CrIS instruments (Suomi-NPP and JPSS satellite series)
- HIRAS instruments (FY-3D and later satellites)
- GIRSS (FY-4E and later)
- MTG (Meteosat Third Generation) IRS

Validation aspects addressed:

- Radiance (Level 1 product)
- Geophysical product (Level 2 product)
- Gridded product (Level 3)

Gap status after GAIA-CLIM:

After GAIA-CLIM this gap remains unaddressed

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

Identified benefit	User category/Application area benefitted	Probability of benefit being realised	Impacts
Space Agencies	International (collaboration) frameworks (SDGs, space agency, EU institutions, WMO programmes/frameworks etc.)	High	Better calibration/validation of stratospheric and mesospheric temperature sounding data
Numerical Weather Prediction	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.)	High	Improved assimilation of AMSU-A and ATMS higher peaking channels (particularly channel 14 AMSU-A and channel 15 ATMS) Improved assimilation of the higher peaking channels on infra-red hyperspectral sounders (AIRS, IASI, CrIS) Quantitative assessment of the biases in short-range forecasts in the upper stratosphere and mesosphere
Copernicus C3S Reanalysis	Operational services and service development (meteorological services, environmental services, Copernicus services C3S & CAMS, operational data assimilation development, etc.) Climate research (research	High	Improved assimilation of temperature sounding channels sensitive to the upper stratosphere and mesosphere (see above)

	groups working on development, validation and improvement of ECV Climate Data Records)		
Identified risk	**User category/Application area benefitted**	**Probability of benefit being realised**	**Impacts**
Sub-optimal Cal/Val of atmospheric sounding data at heights of 40 – 5 hPa, due to very little available reference data.	All users and application areas will suffer from it.	High	Less confidence in the validation of NWP data to reference standard for these atmospheric heights, given the smaller number of available reference data.
No Cal/Val to reference standard possible for atmospheric sounding data strongly sensitive to heights above 5 hPa (e.g. AMSU-A channel 14).	All users and application areas will suffer from it.	High	The 'true biases' of upper stratospheric and mesospheric temperature sounding channels cannot be known due to a lack of reference data. Consequentl,y there is a larger uncertainty associated with the mean forecast and analysis values in the upper stratosphere and mesosphere This uncertainty is supported by jumps observed in the long-term time series of stratospheric/mesospheric temperature analyses from reanalysis, associated with the AMSU-A data available at the time.

Part III: Gap remedies

Gap remedies:

Remedy 1: Use of GNSS-RO temperature profiles as a reference dataset for satellite Cal/Val

Primary gap remedy type:

- Technical
- TRL 5 – technology development / demonstration

Secondary gap remedy type:

Research

Proposed remedy description:

As a first step, we propose the inclusion of GNSS-RO bending angles and derived temperature profiles and their uncertainty estimates in the GRUAN processor. It is important to keep the bending angles, as well as the temperature profiles, since the latter have additional sources of uncertainty due to the need for prior information in the retrievals. This first step would involve some technical work. It would also require work by GRUAN sites to improve scheduling to match with GNSS-RO profiles within reasonable colocation criteria. EUMETSAT has developed a tool that has been shown to be able to forecast occultation positions with >98% skill up to two weeks in advance. This can forecast optimal launch times to create a full profile from the surface to 5hPa that coincides with a polar orbiter overpass.

A second step would be to carry out a research study comparing the NWP forecasts with GNSS-RO bending angles and derived temperature profiles and evaluate whether the mean differences fall within the uncertainty estimates. This would lead to an indication of the uncertainties in NWP temperature fields, as indicated by comparison with GNSS-RO observations.

The final step would be to evaluate these uncertainties in radiance space for different satellite instruments. The proposal here follows the procedure that is currently being used for GRUAN data in the GAIA-CLIM project.

Relevance:

The solution proposed here addresses the lack of reference observations for temperature at atmospheric heights 40 – 5hPa. This is important for the calibration/validation of stratospheric temperature sounding channels. An additional benefit would be increased global coverage of reference temperature-sensitive observations.

Measurable outcome of success:

Firstly, development of the GRUAN processor to include GNSS-RO observations and uncertainties. Secondly, a documented study of the comparison between GNSS-RO temperature profiles and NWP temperature fields in both geophysical space (temperature-height) and radiance space (radiances by channel) for different satellite instruments.

Expected viability for the outcome of success:

High

Scale of work:

- Single institution
- Consortium

Time bound to remedy:

Less than 1 year

Indicative cost estimate (investment):

Low cost (< 1 million)

Indicative cost estimate (exploitation):

Non-applicable

Potential actors:

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

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