GAIA-CLIM Report / Deliverable D4.3

Gap Analysis for Integrated Atmospheric ECV Climate Monitoring:

Update for GAIA-CLIM Gaps Assessment and Impacts Document from WP4

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Document history

Version	Author(s) / Reviewers	Date	Changes
0	Peter Thorne, Michiel van Weele	13/05/16	Document template provision to all WP leads
0.1	W. Bell	19/06/16	New entries for WP4.
1.0	W.Bell / H. Lawrence P.Thorne, C. Voces, R. Davy	30/06/16	Updated WP4 entries
1.1	W.Bell	01/07/16	Final edits following comments from PT, CV and RD.

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Executive Summary

This deliverable constitutes further input from WP4 (The assessment of reference data in global assimilation systems and characterisation of key satellite datasets) to the drafting of the living Gaps Assessment and Impacts Document (GAID) of Task 6.2 (WP6), led by KNMI. The purpose of the GAID is to collate and document gaps directly relevant to the aims of the GAIA-CLIM project. The GAIA-CLIM project is concerned with increasing the utility, use and value of non-satellite observations to characterise satellite observations. Further project details are available at www.gaia-clim.eu.

This deliverable refers to the second official release of the GAID (D6.4) and builds upon the gaps identified therein. In addition, it includes new gaps that have been identified in relation to the Work Package activities.

WP4 is concerned with demonstrating and developing the use of data assimilation systems (in particular, those which form part of numerical weather prediction (NWP) and reanalysis systems) for the validation of satellite observations. The specific focus of WP4 is the characterisation of data from several microwave sounding and imaging missions targeting atmospheric temperature and humidity. The WP also aims to show how reference data (from GRUAN) can be used to assess the uncertainties in NWP fields, both in geophysical space and in *top-of-atmosphere* (TOA) brightness temperatures computed from these fields using radiative transfer modelling. In the final phase of the project the applicability of this approach to the validation of new EO data – effectively using a global analysis as a *proxy for truth*, with reference data being used to establish the uncertainty of these fields – will be reviewed.

This deliverable further expands upon the gaps identified in the initial work package input, relevant gaps sourced externally, and new gaps that have been identified by participants. The gaps discussed herein are exclusively those related to the WP aims and remit (see prior paragraph). A key focus of the current iteration is to make the gaps and their remedies more SMART (Specific, Measurable, Actionable, Relevant and Time

bound) with realistic cost estimates and assessments of the risk / cost of leaving the gap un-remedied. In year 3 the GAID shall inform the development of a list of prioritised recommendations and this shift in emphasis is expected to help inform such an exercise.

This latest update includes some clear new directions for the work in GAIA-CLIM WP4 and subsequently, principally concerned with the need to develop error correlation models for GRUAN observations, and the need for an improved understanding of uncertainties in estimates of surface emission, for both ocean and land, and in the microwave and infrared parts of the spectrum.

1. Document rationale and broader context

The purpose of this document is to provide input to the Gaps Assessment and Impacts Document (GAID) of the GAIA-CLIM project arising from WP4. This WP is concerned with demonstrating and developing the use of data assimilation systems (in particular, those which form part of numerical weather prediction (NWP) and reanalysis systems) for the validation of satellite observations. The approach here has been demonstrated to be very effective in the characterisation and validation of several satellite sounding missions targeting atmospheric temperature. The aim in this project is to further develop this method and to extend the method to the more challenging problems associated with the assessment of microwave humidity sounders and microwave imagers. An important and overarching gap that this WP addresses is the need to establish uncertainties in NWP model fields themselves, and in the top-of-atmosphere radiances computed from these fields, using high quality reference measurements from the GRUAN network. Work completed during the first year of WP4 of GAIA-CLIM has identified several new specific gaps relating to the use of data assimilation systems for the validation of satellite sounding and imaging data. A key gap identified is the need for emissivity estimates, validated using experimental campaigns, and with uncertainty estimates. This has been shown to be important for microwave imagers over ocean but by extension it is also important over land, and for infra-red window channels.

The GAID has now gone through 2 iterations. The first iteration was based upon a combination of the user survey and individual inputs from this and the four remaining underlying Work Packages. The second iteration built upon this by incorporating feedback from the first user workshop and additional informal input delivered from this and other Work Packages. The third version shall build upon the second by considering input arising from this current set of deliverables. That version shall be discussed at the second user workshop to be held in Brussels in November 2016 and the input received shall lead to a further iteration, which shall form the initial basis for a set of prioritised recommendations arising from Task 6.3.

Feedback from the science advisory panel, the first General Assembly, and the review pointed collectively to the need to evolve the GAID to go beyond characterising the gap to considering in more detail implications, potential SMART remedies, costs, and the benefits of resolving them. This then shall help allow external and internal users to more fully explore and appreciate the gaps identified prior to work by Task 6.3 to collate a set of prioritised recommendations.

2. Summary of gaps from GAID v2 relevant to the current WP

The gaps identified in GAID that shall be considered in further detail in Section 4 are summarised below. This is a direct subset of relevant entries from Table 2.2 of the version 2 release of the GAID. These gaps arose from either the initial Deliverable from this WP (D4.1) or from subsequent internal or external input. All gaps are assigned an owner within GAIA-CLIM, even if they arose from an external source.

Gap Identifier	Gap Type	ECV(s)	Gap Short Description	Trace
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
G4.01	Uncertainty	T	Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances/brightness temperatures.	Bell et al., 2008 Bormann 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

A number of gaps identified in version 2 of the GAID have been retired in this version (v3) of the GAID. These gaps were previously numbered G4.03 – G4.06, and retain these numbers, although no longer considered part of this contribution to the GAID. The reasons for retiring these gaps are outlined below, for each of the gaps

G4.03 (Type: coverage/parameter, ECV: temperature/humidity). Description: 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.

Reason(s) for retirement of gap: redundant with updated and more appropriate specification of this gap (see new G4.11); difficulty in making this gap SMART; superseded by gap G4.11

G4.04 (Type: governance, ECV: temperature/humidity). Description: Datasets from baseline and comprehensive networks provide valuable spatiotemporal coverage, but often lack the characteristics needed to facilitate traceable uncertainty estimates.

Reason(s) for retirement of gap: overlap with retired G4.03 above, and redundant with (and superseded by) new G4.11.

G4.05 (Type: uncertainty, ECV: temperature/humidity). Description: Limited knowledge about how to propagate uncertainty from well-characterized locations and parameters to other locations and parameters.

Reason(s) for retirement of gap: overlap with retired G4.03 and G4.04 above, and redundant with (and superseded by) new G4.11.

G4.06 (Type: comparator uncertainty, ECV: temperature/humidity). Description: Difficulty to assess the importance of natural variability in the total model-observation error budget.

Reason(s) for retirement of gap: difficulty in making this gap SMART.

3. New gaps identified by WP participants to date

Subsequent to the first official input to the GAID (D4.1), substantial work has been undertaken in the Work Package in the following respects:

- Characterisation of the *on-orbit* performance of the GCOM-W AMSR-2 microwave imager, through comparisons with respect to Met Office and ECMWF global NWP models. The findings are detailed in the report delivered in fulfilment of D4.2 (part 1, delivered Month 12);

- Initial characterisation of the microwave sounder (MWHS-2) on-board China's FY-3C satellite, as work towards D4.2 (part 2, due Month 24);

- Initial characterisation of the F-19 SSMIS microwave imager/sounder, prior to the failure of the instrument in February 2016, as work towards D4.2 (part 3, due Month 34);

- Initial development and testing of the 'GRUAN processor' - a system developed to monitor differences between NWP model fields and GRUAN reference measurements, both in terms of geophysical variables (temperature and humidity) and in terms of top-of-atmosphere brightness temperatures computed from both GRUAN and NWP fields;

- Initial planning and preparations for integration of the GRUAN processor into the GAIA-CLIM 'Virtual Observatory'

These activities, in addition to advancing the aims of the GAIA-CLIM project, have given cause to reflect further on potential gaps in our collective knowledge and capabilities. This has led to additional gaps being identified.

The new gaps that the work package activities have identified are as follows:

G4.07. Error correlations for reference sonde measurements.

Gap Type: Uncertainty

ECV(s): Temperature, humidity

Gap Short Description: Full characterisation of error correlations for GRUAN measurements. In the context of WP4, GRUAN reference sonde measurements are being used to estimate the uncertainties in NWP model fields through routine comparisons between the two. Additionally, both GRUAN measurements and NWP model fields are being projected to TOA brightness temperatures. This projection requires an estimate of the error correlations in the GRUAN measurements (ideally represented by a full error covariance matrix). This is an active area of research within GAIA-CLIM and within the GRUAN community, but no estimates of the error correlations are available to date.

G4.08. Ocean surface emissivity estimates in the microwave

Gap Type: Uncertainty

ECV(s): Temperature, humidity, cloud liquid water, (ocean surface) wind speed, ocean surface temperature.

Gap Short Description: Lack of uncertainty estimates associated with ocean surface emissivity models. Ocean surface emissivity models are used to estimate ocean surface emissivity based on ocean surface wind fields, temperature and salinity. Several have been developed over the last two decades to support the assimilation of microwave imager data at operational NWP centres and to support applications based on retrievals of the ECV's listed above from satellite-based microwave imager observations. These models lack traceable estimates of the uncertainties associated with the computed emissivities in the 10-250 GHz range. Improved uncertainties associated with emissivity estimates could be developed through targeted campaigns using, for example, airborne radiometers.

G4.09. Land Surface emissivity estimates in the microwave

Gap Type: Uncertainty

ECV(s): Temperature, humidity, cloud liquid water, land surface temperature

Gap Short Description: Lack of uncertainties associated with land surface emissivity estimates. Land surface emissivity atlases in the microwave region (10-250 GHz) have been developed in recent years and these are widely used as starting points for dynamic retrievals of land surface emissivity within retrieval and assimilation schemes, which exhibits significant spatial and temporal variability in snow and ice covered regions. The validation of microwave imaging instruments over land requires independent, well characterised, dynamic atlases of land surface emissivity, with traceable uncertainty estimates based on validation campaigns using, for example, well calibrated airborne radiometers.

G4.10. Land surface emissivity estimates in the infrared

Gap Type: Uncertainty

ECV(s): Temperature, humidity, land surface temperature

Gap Short Description: Land surface emissivity atlases in the infrared region (2-16 µm) are required for the validation of infrared satellite sounding measurements over land. Work is underway to develop dynamic atlases of spectral emissivity in this part of the spectrum, based on measurements from polar-orbiting hyper-spectral infrared observations, however these new dynamic atlases need to be validated to ensure the estimates have robust uncertainties associated with them.

G4.11 Limited Geographical coverage of reference temperature and humidity radiosondes

Gap type: Coverage,

Gap Short Description: A comparison between NWP and reanalysis model fields and satellite observations reveals biases that vary geographically, particularly for the temperature and humidity sounders. Some or all of this geographical variation could be due to errors in the NWP or reanalysis model background and reference in-situ temperature and humidity radiosondes are needed to establish this. However, the available reference radiosondes that could provide estimates of uncertainties in NWP and reanalysis model fields are limited to a small number of locations. Work is on-going in work package 1 to better understand the geographical limitations of the reference in-situ data.

4. Detailed update on traces for the gaps arising from this Work Package for inclusion in the GAID

Within this section gaps that were detailed in Sections 2 and 3 are expanded to give a full trace of our current understanding of the gap, its impacts and its potential remedies. For those gaps identified in Section 2 we take as the starting point the corresponding text arising from the

GAID (v2, Section 3) text and / or the initial deliverable text as deemed most appropriate. This is then expanded upon here in an attempt to better delineate the gap, its impacts, its potential remedies (including indicative costs and timelines) and the scientific impact of (non-)resolution. Gaps are ordered numerically and each given a specific subsection.

G1.12 Propagate uncertainty from well-characterized locations and parameters to other locations and parameters

Gap detailed description

Reanalysis is a systematic approach to produce data sets for climate monitoring and research. Key limitations to re-analysis are:

1. Observational constraints, and therefore reanalysis reliability, can considerably vary depending on the location, time period, and variable considered;
2. The changing mix of observations, and biases in observations and models, can introduce spurious variability and trends into reanalysis output.

It is clear that to fully exploit the value of ground-based remote sensing observations, they must provide traceable uncertainty estimates. On the other hand, the spatial coverage of ground-based measurements at the current state of the global observing system is often not sufficient for the satellite Cal/Val and climate monitoring and geographical gaps does not allow to have a sufficient representativeness in the observation available, to assess the NWP and reanalysis fields and the equivalent TOA radiances. In addition, there is a limited knowledge about how to propagate uncertainty from well-characterized locations and parameters to other locations and parameters.

Activities within GAIA-CLIM related to this gap

GAIA-CLIM work carried out by ECMWF in the frame of task 1.5

Gap remedy(s)

Remedy

<u>Specific remedy proposed</u>

This is a relevant gap that requires several modelling studies focused on the characterization of uncertainty propagation in models and assimilation systems.
In the frame of GAIA-CLIM task 1.5, ECMWF will study the airmass-dependent biases for key satellite instruments (AMSU-A and MHS microwave temperature and humidity sounding instruments, Chinese FY-3C microwave temperature and humidity sounding instruments, MWTS-2 and MWHS-2) using reference in-situ radiosonde measurements for temperature and humidity with calculated uncertainty values, such as the GRUAN network. The objective is to assess whether the GRUAN network is 'geographically capable' of diagnosing such biases. This study will allow to learn more about how propagate uncertainty from well-characterized

measurement sites of Reference networks, such as GRUAN sites, to other measurement sites of Baseline networks, such GUAN sites, for both temperature and humidity profiles.

Measurable outcome of success

Outcome of success is strongly related to the outcome of the proposed modelling studies.

Achievable outcomes

Technological / organizational viability: medium

Indicative cost estimate: low (<1 million)

Relevance

The proposed modelling studies may effectively allow to resolve this gap. Remedies to this gap can also provide essential contribution to make progress on the gap G4.01.

Timebound

Timeline for the delivery of results for such studies is uncertain.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Lacking of appropriate techniques to propagate uncertainty from well-characterized locations limits the value of the re-analysis for the study of climate at the global scale.	Medium	Impact depends upon the outcome of the proposed modelling studies for specific ECVs.

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

Gap detailed description

Numerical Weather Prediction (NWP) models are already routinely used in the validation and characterisation of EO data, but a lack of robust uncertainties associated with NWP model fields and related TOA radiances prevent the use of these data for a complete and comprehensive validation of satellite EO data, including an assessment of absolute radiometric errors in new satellite instruments. Agencies and instrument teams, as well as key climate users, are sometimes slow (or reluctant) to react to the findings of NWP-based analyses of satellite data, due to the current lack of traceable uncertainties. The aim is to assess uncertainties in NWP fields through systematic monitoring, using GRUAN data, as part of WP4.

Activities within GAIA-CLIM related to this gap

GAIA-CLIM WP4 aims to advance current state-of-the-art (in using NWP models to validate satellite data) in two respects: firstly by further demonstrating the value of NWP in the validation of microwave temperature sounding instruments (including F-19 SSMIS and JPSS-1 ATMS), then evaluating and developing the method for the validation of microwave humidity sounders (*e.g.* FY-3C MWHS-2) and microwave imagers (GCOM-W AMSR-2); and secondly by estimating the uncertainties in NWP model fields through comparison with reference radiosonde data from the GRUAN network. These latter comparisons will be conducted both in geophysical variables (temperature, and humidity) and in top-of-atmosphere brightness temperatures.

It is estimated that significant progress can be made on both elements of this plan during the GAIA-CLIM project. (Timescale and cost estimate: GAIA-CLIM 2015-2018: 48 man/months of effort).

Gap remedy

Remedy #1

Developing a ‘GRUAN processor’ as a software deliverable from GAIA-CLIM WP4.

<u>Specific remedy proposed</u>

The software will be open-source and will enable users (albeit fairly expert users) to compare NWP fields from both ECMWF and Met Office (in the first instance) models with GRUAN data. This will include a comparison of temperature and humidity, as well as TOA brightness temperatures for all sensors supported by the (publically available) RTTOV radiative transfer model.

<u>Measurable outcome of success</u>

- 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.

<u>Achievable outcomes</u>

Technological / organizational viability: High

Indicative cost estimate: low (<1 million Euros)

Relevance

The solution proposed here is fully aligned with the requirement (to establish traceable uncertainties for NWP fields and radiances calculated from them).

Timebound

The remedy proposed here is a key focus, and deliverable, of GAIA-CLIM WP4, due for delivery (D4.4) in Month 24.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
NWP-based validation results /conclusions not taken into account by space agencies developing new instruments – as a result of a lack of uncertainties.	Medium-High ('Medium' for established agencies with some experience of this type of validation, 'High' for newer agencies developing new capability in this area.)	Failure to rectify sub-optimalities in instrument design and/or processing chains, resulting in sub-optimal data being used in downstream applications (climate studies & operational NWP, for example).

G4.02 Lack of traceable uncertainty estimates for NWP and reanalysis fields & equivalent TOA radiances - relating to humidity

Gap detailed description

The gap is closely related to that described above relating to temperature. The text above is therefore repeated here, for completeness.

Numerical Weather Prediction (NWP) models are already routinely used in the validation and characterisation of EO data, but a lack of robust uncertainties associated with NWP model fields and related TOA radiances prevent the use of these data for a complete and comprehensive validation of satellite EO data, including an assessment of absolute radiometric errors in new satellite instruments. Agencies and instrument teams, as well as key climate users, are sometimes slow (or reluctant) to react to the findings of NWP-based analyses of satellite data, due to the current lack of traceable uncertainties. The aim is to assess uncertainties in NWP fields through systematic monitoring, using GRUAN data, as part of WP4.

Activities within GAIA-CLIM related to this gap

GAIA-CLIM WP4 aims to advance current state-of-the-art (in using NWP models to validate satellite data) in two respects: firstly by further demonstrating the value of NWP in the validation of microwave temperature sounding instruments (including F-19 SSMIS and JPSS-1 ATMS), then evaluating and developing the method for the validation of microwave humidity sounders (*e.g.* FY-3C MWHS-2) and microwave imagers (GCOM-W AMSR-2); and secondly by estimating the uncertainties in NWP model fields through comparison with reference radiosonde data from the GRUAN network. These latter comparisons will be conducted both in geophysical variables (temperature, and humidity) and in top-of-atmosphere brightness temperatures.

It is estimated that significant progress can be made on both elements of this plan during the GAIA-CLIM project. (Timescale and cost estimate: GAIA-CLIM 2015-2018: 48 man/months of effort).

Gap remedy

Remedy #1

Developing a 'GRUAN processor' as a software deliverable from GAIA-CLIM WP4.

<u>Specific remedy proposed</u>

The software will be open-source and will enable users (albeit fairly expert users) to compare NWP fields from both ECMWF and Met Office (in the first instance) models with GRUAN data. This will include a comparison of temperature and humidity, as well as TOA brightness temperatures for all sensors supported by the (publically available) RTTOV radiative transfer model.

<u>Measurable outcome of success</u>

- Statistics available on the comparison, for all GRUAN sites, wrt 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.

<u>Achievable outcomes</u>

Technological / organizational viability: High

Indicative cost estimate: low (<1 million Euros)

Relevance

The solution proposed here is fully aligned with the requirement (to establish traceable uncertainties for NWP fields and radiances calculated from them).

Timebound

The remedy proposed here is a key focus, and deliverable, of GAIA-CLIM WP4, due for delivery (D4.4) in Month 24.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
NWP-based validation results /conclusions not taken into account by space agencies developing new instruments – as a result of a lack of uncertainties.	Medium-High ('Medium' for established agencies with some experience of this type of validation, 'High' for newer agencies developing new capability in this area.)	Failure to rectify sub-optimalities in instrument design and/or processing chains, resulting in sub-optimal data being used in downstream applications (climate studies & operational NWP, for example).

[Gaps G4.03 to G4.06, from Version 2 of the GAID, retired at this version]

G4.07 Error correlations for reference sonde (GRUAN) measurements.

Gap detailed description

Many applications of reference radiosonde measurements require an estimate of error correlations. For example, as part of the comparison of reference sonde measurements and NWP fields, in terms of TOA brightness temperatures, it is necessary to have realistic estimates of the error correlation structure (*i.e.* between vertical levels) in the sonde measurements. Such estimates are a subject of current research, and as such, constitute a current gap.

Activities within GAIA-CLIM related to this gap

Some estimate of the error correlations are required to carry out significance testing for the GRUAN processor as part of WP4. As a first approximation, error covariance matrices will be developed, in consultation with experts from the GRUAN community, to include an exponential dependence between vertical levels, based on physical constraints. Longer term, and beyond the immediate scope of work within the GAIA-CLIM project, correlation estimates could be obtained from measurements. Such uncertainties are envisaged to be reported in the v3 GRUAN product (correlated, partially correlated and random terms) being developed by the GRUAN Lead Centre, which it is hoped will be released within the GAIA-CLIM project lifetime. A visit to the GRUAN Lead Centre is foreseen in autumn 2016 to discuss the issue and explore potential for collaboration on the matter.

Gap remedy

Remedy #1

Development of parametrised estimates of the vertical error correlation structure.

Specific remedy proposed

Simple parametrised versions of the vertical error covariances will be developed and tested as part of the significance testing in the GRUAN processor.

Measurable outcome of success

- Parametrised error covariances, developed and tested in consultation with experts from the GRUAN community

Achievable outcomes

Technological / organizational viability: High

Indicative cost estimate: low (<1 million Euros)

Relevance

The solution proposed here is fully aligned with the requirement (to establish traceable uncertainties for NWP fields and radiances calculated from them).

Timebound

The remedy proposed here is a key focus, and deliverable, of GAIA-CLIM WP4, due for delivery (D4.4) in Month 24.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high

		quality services to science / industry / society
Undue confidence/inaccurate uncertainty estimated in GRUAN products (including TOA radiances) arising from failure to consider correlated nature of some of the estimated uncertainties	High	Incorrect conclusions reached in applications that require use of averaging of profile properties such as but not limited to a onsideration of radiance equivalent products

G4.08 Estimates of uncertainties in ocean surface emissivity models.

Gap detailed description

Ocean surface emissivity models are used to estimate ocean surface emissivity based on ocean surface wind fields, temperature and salinity. Several have been developed over the last two decades to support the assimilation of microwave imager data at operational NWP centres and to support applications based on retrievals of the ECV's listed above from satellite-based microwave imager observations. These models lack traceable estimates of the uncertainties associated with the computed emissivities in the 10-250 GHz range. Improved uncertainties associated with emissivity estimates could be developed through targeted campaigns using, for example, airborne radiometers.

Activities within GAIA-CLIM related to this gap

WP4 involves the assessment of at least two microwave imager instruments (AMSR-2 and FY-3C MWRI). Work carried out during Year 1 of GAIA-CLIM has already highlighted an issue with inconsistencies in various ocean surface emissivity models, which significantly effects the values of simulated radiances computed from NWP fields. Absolute validation of the various models is currently lacking and hence it is likely that this will remain a significant contribution to the uncertainty in the NWP simulated brightness temperatures. Comparison of the FASTEM model (versions 3 and 6) with other emissivity models will be carried out during Years 2 and 3.

Gap remedy

Remedy #1

Inter-comparison of ocean surface emissivity models

Specific remedy proposed

Inter-comparison of available emissivity models.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. In many cases, however, such an intercomparison yields useful 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 measureable 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.

Achievable outcomes

Technological / organizational viability: Medium

Indicative cost estimate: low-medium (€1M). The work undertaken as part of WP4 will amount to 3-6 man. months of effort (€50K). This will be the start of a longer process of emissivity model intercomparison, development and ultimately validation. Longer term effort to be ~36-100 man-months (~ €360K – 1M).

Relevance

The solution proposed here is fully aligned with the requirement (to establish traceable uncertainties for NWP fields and radiances calculated from them).

Timebound

The remedy (#1) proposed here - an intercomparison of ocean surface emissivity models- will be started within the timeframe of GAIA-CLIM WP4, but is expected to take longer than the GAIA-CLIM timeframe.

Remedy #2

Airborne measurements, using traceably calibrated radiometers, combined with traceable in-situ measurements, or traceable estimates from models, of ocean temperature, surface wind-speed and salinity.

Specific remedy proposed

Airborne campaigns to validate emissivity models in the region (10-250 GHz) using traceable airborne radiometry at these frequencies. 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.

Measurable outcome of success

Documented, quantitative, evaluation of ocean surface emissivity models with respect to measurements of ocean surface emissivity obtained during airborne campaigns, for a globally representative range of ocean surface wind speeds, temperatures and salinity. Peer reviewed.

Achievable outcomes

Technological / organizational viability: Medium. Airborne radiometry capability exists in Europe and the US.

Indicative cost estimate: medium (>1 million Euros). Airborne campaigns cost ~€250K per 3-week campaign. Several would be required to sample the full range of ocean surface wind speed and ocean surface temperature conditions.

Relevance

The solution proposed here is fully aligned with the requirement (to establish traceable uncertainties for NWP fields and radiances calculated from them).

Timebound

Remedy #2 is a longer term aspiration, that could be completed in a 2-5-year timescale, resources permitting.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Lack of uncertainties in surface emissivity models mean that model-based validation is of limited value for microwave imager validation, requiring reliance on traditional satellite-satellite match-ups which fail to deliver a global picture of instrument and radiative transfer model biases.	High	Continued uncertainty over quality of microwave imager data, for use in climate applications and operational NWP.

G4.09 Estimates of uncertainties in land surface microwave emissivity atlases.

Gap detailed description

Microwave imagers are highly surface sensitive, particularly in dry atmospheric conditions, to emission from the surface and so the validation of microwave imaging instruments over land requires independent, well-characterised values of emissivity with traceable uncertainty estimates. Land surface emissivity atlases in the microwave region (10-250 GHz) have been developed in recent years and these are widely used as starting points for dynamic (*i.e.* those updated on a daily timescale or less) retrievals of land surface emissivity within retrieval and assimilation schemes. Such atlases can provide a good estimate of the emissivity in most surface conditions, particularly for un-changing environments such as rainforests and deserts. However, for some conditions, particularly snow and ice, the emissivity exhibits significant temporal and (in the case of snow and ice) spectral variability and atlas values based on climatological averages are then less accurate. For this reason, we suggest both the development of dynamic land emissivity atlases (e.g. daily-monthly maps of emissivity) in the short-term as well as the development of emissivity models in the long-term, particularly for snow and ice-covered surfaces. Both should be validated against experimental campaigns with traceable measurements, using, for example, well calibrated airborne radiometers, in order to obtain uncertainty estimates for these emissivity values.

Activities within GAIA-CLIM related to this gap

None

Gap remedies

Remedy #1

[Step 1: Development of dynamic land surface emissivity atlases in the MW, derived (for example) from dynamic estimates of spectral emissivity at window channel frequencies from NWP systems (see Remedy #2 below)]. Step 2: Airborne measurements, using traceably calibrated radiometers, combined with traceable *in-situ* measurements (or model-based estimates where the accuracy has been previously determined) of land surface temperature over a diverse range of land surface environments and over several seasons.

Specific remedy proposed

Airborne campaigns to validate emissivity atlases, and models, in the region (10-250 GHz). These should sample a diverse range of surface types and characterize the seasonal cycle for those surface types which exhibit a strong seasonal dependence (or are suspected of doing so).

Measurable outcome of success

Documented, quantitative, evaluation of land surface emissivity atlases (and models) with respect to measurements of land surface emissivity obtained during airborne campaigns, for a globally representative range of land surfaces. Peer reviewed.

Achievable outcomes

Technological / organizational viability: Medium

Indicative cost estimate: medium (>1 million Euros)

Relevance

The solution proposed here is fully aligned with the requirement (to establish traceable uncertainties for NWP fields and radiances calculated from them).

Timebound

Remedy #1 is a longer term aspiration, that could be completed in a 2-5 year timescale, resources permitting.

Remedy #2

- Establishing dynamic atlases of land surface emissivity, building on existing 'climatological' atlases, but using operational data assimilation systems to derive optimal estimates of land surface emissivity from satellite observations.

- Conducting inter-comparisons of independent land surface emissivity atlases, both dynamic and climatological.

- Ground-based radiometer measurements (e.g. J.-C. Calvet et. al., 2011) over a range of surface types and measuring for a range of frequencies using traceably calibrated radiometers, and supported with traceable *in-situ* measurements.

Specific remedy proposed

- Establish dynamic land surface emissivity atlases.
- Inter-comparison of available emissivity models.
- Development of emissivity models over a wide range of frequencies (10 – 250 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

Measurable outcome of success

Documented, quantitative, evaluation of 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. Peer reviewed

Achievable outcomes

Technological / organizational viability: Medium

Indicative cost estimate: medium (>1 million Euros)

Relevance

The solution proposed here is fully aligned with the requirement (to establish traceable uncertainties for NWP fields and radiances calculated from them).

Timebound

These remedies are longer term aspirations, that could be completed in a 2-5 year timescale, resources permitting.

Gap risks to non-resolution

Identified future risk / impact	**Probability of occurrence if gap not remedied**	**Downstream impacts on ability to deliver high quality services to science / industry / society**
Lack of uncertainties in land surface emissivity models mean that model-based validation is of limited value for microwave imager validation over land.	High	Continued uncertainty over quality of microwave imager data, for use in climate applications and operational NWP.

G4.10 Estimates of uncertainties in land surface infrared emissivity atlases.

Gap detailed description

Land surface emissivity atlases in the infrared region (2-16 µm) are required for the validation of infrared satellite sounding measurements over land. Work is underway, 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.

Activities within GAIA-CLIM related to this gap

None

Gap remedy

Remedy #1

- Establishing *dynamic* atlases of land surface spectral emissivity in the mid-infrared, utilising observations from hyper-spectral infrared instruments (e.g. IASI) on polar orbiting satellites.

- Conducting intercomparisons of land surface emissivity atlases.

- Airborne measurements, using traceably calibrated radiometers, of land surface emissivity in the mid-infrared.

Specific remedy proposed

- Establish dynamic land surface infrared emissivity atlases.
- Inter-comparison of available emissivity models.
- Airborne campaigns to validate land emissivity models in the region (10-250 GHz)

Measurable outcome of success

Publicly available, open-source, dynamic (daily) spectral emissivity atlases in the infrared (2.5-16 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. Peer reviewed

Achievable outcomes

Technological / organizational viability: Medium. Spectral emissivity in the IR is now derived from hyper-spectral IR sounders continuously and in near-real time at the Met Office, as part of the operational NWP system. Work is underway to incorporate such estimates into a dynamically updated atlas using a Kalman filter and to make this publically available. This is expected to be achieved by the end of 2017. The facilities to carry out airborne campaigns exist in Europe (Met Office FAAM aircraft) and costs are typically €250K per three week campaign.

Indicative cost estimate: medium (>1 million Euros)

Relevance

The solution proposed here is fully aligned with the requirement (to establish traceable uncertainties for NWP fields and radiances calculated from them).

Timebound

These remedies are longer-term aspirations, that could be completed in a 2-5 year timescale, resources permitting.

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Lack of uncertainties in IR land surface emissivity models mean that model-based validation is of limited value for infrared sounder validation over land.	High	Continued uncertainty over quality of infrared data over land, especially for near surface channels, for use in climate applications and operational NWP.

G4.11 Geographical sampling of reference in-situ data

Gap detailed description

Comparisons between satellite observations and NWP model and reanalysis fields often reveal biases that have a geographical structure. This has been observed both in previous studies (e.g. Lu et al 2011, Lu and Bell 2014) and in the assessment of the FY-3C sounders (MWTS-2, MWHS-2) for work package 4. Similar biases are observed for a number of different satellite instruments measuring at the same frequency, and so are likely to be due either to errors in the radiative transfer forward model used to transform the background fields into radiance space or to errors in the background fields themselves. Comparing reference in-situ data for atmospheric temperature and humidity to the model background fields could give us estimates of the uncertainty in the background fields at different locations and help us determine whether the geographical biases observed in O – B statistics are due to the model background or to other sources. However, the reference in-situ data is limited to a small number of locations and so this is only possible if the areas sampled cover the whole range of geographically-dependent biases that have been observed for satellite data.

Activities within GAIA-CLIM related to this gap

An assessment of observation minus NWP background statistics, sub-sampled at the GRUAN reference sites, is envisaged in work package 1 (task 1.5). This should help to develop an understanding of whether the GRUAN reference data are 'geographically capable' of assessing the geographic variability of NWP background errors. See task 1.5 documents for more details.

In addition, an assessment of departure statistics for measurements from the GUAN will be used to help assess the extent to which the background errors are homogeneous, and hence the validity of the assumption that NWP fields can be sampled at a limited number of GRUAN sites, and the resulting derived uncertainties assumed to apply globally.

Gap remedies

Remedy #1

Background departure analysis at GRUAN (and GUAN) locations

Specific remedy proposed

Assess background departures at GRUAN (and GUAN) locations, to assess the capability of GRUAN reference data to characterise background errors.

Measurable outcome of success

Report on a quantitative assessment of background departures at GRUAN sites, as well as at GUAN sites. The background departures from the GRUAN sites will be computed and evaluated in both geophysical and radiance space.

Achievable outcomes

Technological / organizational viability: Medium. This work forms aprt of the work planned for WP4 of GAIA-CLIM.

Indicative cost estimate: low (< €0.5 million)

Relevance

The solution proposed here is fully aligned with the requirement (to establish traceable uncertainties for NWP fields and radiances calculated from them).

Timebound

Remedy#2 forms part of the workplan for GAIA-CLIM, and will be complete by 2017.

Assessment in task 1.5 (see above).

Gap risks to non-resolution

Identified future risk / impact	Probability of occurrence if gap not remedied	Downstream impacts on ability to deliver high quality services to science / industry / society
Lack of understanding of global representativeness of GRUAN based validation of model fields	medium	Continued uncertainty over validity of 'GRUAN-validated' model fields as a source of EO validation data.

5. Summary

The input to the Gap Analysis and Impacts Document to date from Work Package 4 comprises gaps identified at the outset of the project, as well as several new gaps identified as a consequence of the work carried out during Year 1 of GAIA-CLIM. Those identified at the outset are essentially high level gaps that defined the work plan for GAIA-CLIM WP4: the need to establish robust uncertainties (in atmospheric temperature and humidity) for NWP fields and the TOA radiances calculated from them, using reference quality measurements from the GRUAN network. The work planned in WP4 will deliver, by the end of GAIA-CLIM, robust estimates of the errors in temperature and humidity in NWP fields and in equivalent TOA radiances.

The new gaps identified in the first year of GAIA-CLIM, and recorded for the first time here in or input to v3 of the GAID, relate to detailed components of the radiative transfer modelling when using NWP fields as a validation source. Specifically, these new gaps identify the need for robust uncertainties in the ocean and land surface emissivity estimates that are required to derive an uncertainty budget for TOA radiances. The immediate requirement within the GAIA-CLIM project is for improved understanding of microwave surface emissivity estimates, but by extension, the same is required for the mid-infrared part of the spectrum.

References

J.-C. Calvet, J.-P. Wigneron, J. Walker, F. Karbou (2011): Sensitivity of Passive Microwave Observations to Soil Moisture and Vegetation Water Content: L-Band to W-Band. *IEEE Trans. Geosc. Rem. Sens.*, vol 49, no. 4.

Glossary

AMSR2	Advanced Microwave Scanning Radiometer 2
EO	Earth Observation
ECV	Essential Climate Variable
FASTEM	Fast Microwave Emissivity Model
F-19 SSMIS	F-19 Special Sensor Microwave Imager/Sounder
GRUAN	GCOS Reference Upper-Air Network
GCOM-W	Global Change Observation Mission –Water
IASI	Infrared Atmospheric Sounding Interferometer
JPSS- ATMS	Joint Polar Satellite System -Advanced Technology Microwave Sounder
MWHS-2	Micro-Wave Humidity Sounder -2
MWTS-2	Micro-Wave Humidity Sounder-2
TOA	Top of Atmosphere