Fidelity and Uncertainty in Climate data records from Earth Observations

Needs and opportunities beyond the H2020 project FIDUCEO

Prof. Christopher J. Merchant
Principal Investigator, FIDUCEO

Earth Observation and Space Research Division Leader
University of Reading, UK

21 April 2017
updated 2 October 2017

FIDUCEO has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement n. 638822.

Executive Summary

Trusted observations of climate and environment from space assets are needed for science and society.

To create the required trust in such datasets and in the information derived from them:

- the uncertainty in the data/information needs to be quantified and communicated
- the user needs to have confidence that the provided uncertainty information is rigorous, transparent and traceable

Rigour, transparency and traceability can be provided by using metrological approaches propagate quantified uncertainty from lower-level satellite datasets to higher-level products and information. Therefore, normal good practice for satellite observations should evolve towards the situation summarised in Table 1. The FIDUCEO project addresses examples of the elements of this table presented in italic font.

Good practice	Applies to	Needs to be actioned by
Develop and provide traceable radiance uncertainty estimates per datum in satellite level 1 datasets.	*Key heritage fundamental climate/environmental data records.* Products from future/planned missions, such as Copernicus.	Heritage: collaborations of space agencies, research and metrological institutions. Future: space agencies, with industry, research and metrological institutions.
Harmonise radiances (level 1 data) across multi-mission series of compatible sensors (to ensure stability of derived products).	*Key heritage fundamental climate/environmental data records.* Products from future/planned missions, such as Copernicus.	Heritage: collaborations of space agencies, research and metrological institutions. Future: space agencies, with industry, research and metrological institutions.
Exploit radiance uncertainty estimates to quantify uncertainty in derived (level 2+) geophysical products.	Climate data records (*key heritage* and future records). Long-term environmental data records.	Operational and research organisations generating and distribution climate/environmental datasets (CDRs/EDRs).
Use and propagate uncertainty in CDRs/EDRs to quantify uncertainty information to higher-levels.	Producers of climate/environmental information derived (in part) from CDRs/EDRs.	Operational and research organisations providing climate/environmental data services.
Decision makers and non-expert users access and use uncertainty in climate information.	Information provided within climate/environmental data services.	Visualisation functions in climate/environmental data service providers.

Table 1. Good practice for satellite-based data records and climate information, from a metrological perspective.

Needs, gaps and opportunities beyond the FIDUCEO project have been identified that will move us towards this good practice (Table 2). For more detail, see corresponding sections 4.1 to 4.9 of this white paper.

Need / gap identified	Expected benefits	Possible mechanisms
4.1 Evolve space agency practice for future missions, including Copernicus space programme evolutions, such that provision of traceable, per-datum uncertainty estimates is standard for level 1 (radiance) satellite observations.	Uncertainty can be traceably quantified for derived climate and environmental data records. Capitalises on the investment in understanding instrument uncertainties during Phase B to D to benefit of downstream users.	Augment instrument compliance procedures with metrological focus on uncertainty characterisation. This significant evolution of mission-development practice can be built on FIDUCEO principles and tools as a baseline. Trials/research involving space agencies.
4.2 Transfer FIDUCEO methods for harmonising radiances between satellite missions to operational context.	Improved calibration of operational sensors, optimising their assimilation for weather and environmental forecasting and assimilation. Improved near-real-time data for monitoring of environment.	Trial of FIDUCEO-based harmonisation techniques within the Global Space-based Inter-Calibration System, possibly within context of a research action.
4.3 Combine emerging FIDUCEO and GAIA CLIM capabilities to prove worth of metrological validation of satellite radiance and uncertainty.	Level-1 uncertainty information is validated, adding to perceived trustworthiness. A degree of SI-traceability of satellite radiances in fundamental CDRs (FCDRs) may be established.	Research action building on FIDUCEO and GAIA-CLIM capabilities.
4.4 Need to learn how to exploit FCDR (radiance) uncertainty information to improve data assimilation outcomes.	Improved atmospheric forecasting and environmental re-analysis products.	Research action adopting FIDUCEO principles, involving weather agencies and re-analysis partners in Copernicus services.
4.5 Develop and apply Earth Observation metrology for active sensors.	Broader set of CDRs/EDRs provided with traceable uncertainty information.	Research action adopting FIDUCEO principles.
4.6 Apply Earth Observation metrology to other key historic satellite series.	Broader set of FCDRs/CDRs/EDRs provided with traceable uncertainty information.	Research action adopting FIDUCEO principles.
4.7 Traceable uncertainty model for atmospheric radiative transfer.	Improved uncertainty estimation in CDRs and re-analyses.	Research action extending GAIA-CLIM work on microwave radiative transfer uncertainty.
4.8 Develop comprehensive set of approximate theory and tools for uncertainty propagation to higher-level information and indices	Uncertainty information available for all applications and users irrespective of the space-time scale of the application.	Research action extending FIDUCEO principles to higher-level data, and propagating capability into Copernicus services.
4.9 Meaningful uncertainty visualisation for climate/environmental information/indices	Uncertainty information in higher-level products and indices is appropriately contextualised for interpretation and decision making.	Research action, and propagating capability into Copernicus services.

Table 2. Summary of identified post-FIDUCEO gaps and opportunities.

1. Background

FIDUCEO (Fidelity and Uncertainty in Climate data records from Earth Observations) is a 4-year programme ending February 2019 whose overall objectives are:

- to establish the framework and techniques for rigorous metrology[1] (measurement science) of historic Earth Observations (EO)
- apply EO metrology to key Fundamental Climate Data Records[2] (FCDRs), that underpin widespread understanding of Earth's changing environment of the past decades
- demonstrate the derivation of Climate Data Records from these FCDRs, illustrating the added scientific value of the innovative metrological information on uncertainty and stability

For more on the FIDUCEO project, refer to www.fiduceo.eu.

A General Assembly was held jointly with the H2020 project GAIA-CLIM (www.gaia-clim.eu) hosted by the European Centre for Medium-range Weather Forecasting (ECMWF) in Reading, UK, in March 2017.

At this meeting, European Commission technical office, Monika Kacik, requested that the FIDUCEO project prepare a discussion paper on the expected landscape of progress and remaining gaps that will prevail at the end of the FIDUCEO programme.

This document is written in response to that request. It expresses only the personal opinions of the author[3].

[1] Metrology is science of measurement and includes all theoretical and practical aspects of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology. The international vocabulary of metrology (VIM) is maintained by the Joint Committee for Guides in Metrology (JCGM), a group made up of eight international organisations – BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, and ILAC. Nations maintain metrological institutes affiliated with this international network, the UK institution being the National Physical Laboratory, Teddington. NPL is a critical partner within FIDUCEO to ensure the frameworks and tools developed both take advantage of and extend as needed rigorous metrological practice.

[2] A Fundamental Climate Data Record in the EO (satellite remote sensing) context is generally a timeseries of calibrated, geo-located measured radiances ("Level 1" satellite data). The value of the FCDR is that those radiances are sensitive to the geophysical states of Earth's environment. This means quantitative knowledge about those environments can be inferred (by mathematical inversion) and Climate Data Records and suchlike products produced.

[3] In this update of 2/20/17, generous comments on the April version from Heather Lawrence, Stephen English, Niels Bormann and Joerg Schulz have been taken into account to strengthen several points, particularly in sections 4.3, 4.4, 4.6 and 4.7.

2. Metrology of Earth Observation: Contribution to Science and Society

It is taken for granted here that complex modern societies need and exploit high-quality environmental information to understand and manage the significant challenges and opportunities of large-scale change. This requirement is well-established, and underlies major public investments in the Earth Explorer missions of the European Space Agency (ESA), the EU Copernicus space programme (which will sustain and expand many Earth Explorer mission capabilities over future decades), the established and emerging Copernicus services, major programmes to preserve historical Earth Observations and (re-)exploit them for climate applications, not to mention sustained investments in meteorological satellites and services.

FIDUCEO's ambition is to develop a widely application metrology of Earth Observation (EO), since we see the metrological approach as the most fruitful means to establish traceable, uncertainty-quantified evidence for climate and environmental change from space assets. Metrology brings hard-won rigour and clarity to EO, which is intrinsically a measurement science.

The core contribution is therefore in establishing the trustworthiness of climate and environmental information from space assets, so that scientists and decision makers can draw conclusions understanding the strengths and limitations of that information.

Technically, trustworthiness implies that the degree of uncertainty inherent in all data/information is quantified (on the scales of space and time relevant to a particular application). All data and associated uncertainty estimates need to be traceable, which means that, when necessary, the values are justified, reproducible and defensible.

Different users need information on a range of levels of processing, with decision makers typically interested in high-level information and indices, while technical and scientific applications may engage with lower-level data (e.g., 'level 2'[4] data).

The idealised chain of information flow from raw satellite measurements to climate information, is illustrated Figure 2-1.

[4] Level 2 ("L2") products are directly obtained by inference from FCDRs (which are L1). In L3 products, data are aggregated onto grids for convenience. L4 products address the needs of some users for data that are complete in space and time, by infilling gaps in L3 data with interpolated estimates for unobserved places and times. Higher-level data typically further process lower-level data, perhaps combining with other information sources, deriving indices etc. While this sequential account is conceptually valid, in practice, there are many variants—e.g., an L4 analysis may derive from L2 inputs bypassing L3.

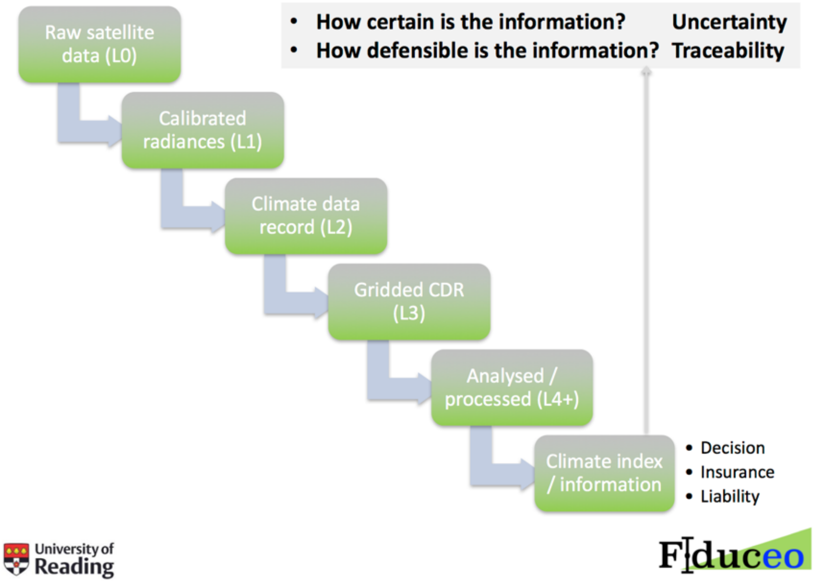

Figure 2-1. Idealised flow of information from raw satellite data to high-level climate information informing real-world applications. At lower levels, questions about data are often scientific. At higher levels, questions about data more often have implications for decisions, risk assessments and liability. Two pertinent questions are "How certain is this information?" (which is addressed by the metrological concept of uncertainty—i.e., the quantitative degree of doubt to attribute to any number) and "How defensible is the information?" (to which the metrological concept of traceability is relevant).

In each transformation of data to higher levels, the uncertainty present at the lower level causes uncertainty in the higher-level results (propagation) and assumptions, auxiliary data and computations used in the transformation contribute new sources of uncertainty[5].

[5] Note that some transformations, including averaging of data to larger scales, also reduce the magnitude of some components of uncertainty, so despite the accumulation of sources of uncertainty all through the chain, it is not inevitable that in the higher level information the uncertainty is large. Note also that some sources of uncertainty that are negligible in lower levels can dominate uncertainty in higher levels, understanding of which involves the nature of correlated errors.

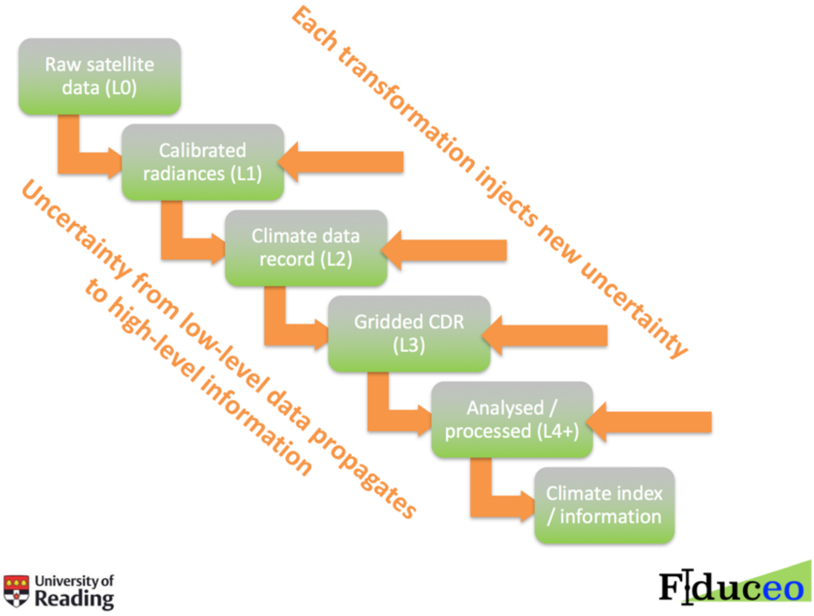

Figure 2-2. Accumulation of sources of uncertainty and propagation of uncertainty from lower-level to higher-level data.

This context is sufficient to explain the role of FIDUCEO and of Earth Observation metrology within a larger aspiration: in order to deliver trustworthiness of climate (and other environmental) information from space assets, the accumulation of sources of uncertainty and propagation of uncertainty from lower-level to higher-level data needs to be understood and the outcomes usefully (simply) communicated to users.

Normal good practice should evolve towards:

- space agencies developing rigorous, validated FCDR-level uncertainty information as a routine part of mission development and dissemination of their satellite observations—historic, current and future
- scientists (in space agencies and elsewhere) exploiting FCDR information metrologically to provide uncertainty estimates in climate (CDR) and environmental products at higher levels and across all spatio-temporal scales relevant to applications
- users of CDRs etc. trusting and exploiting the incorporated uncertainty information when testing models, creating climate indices, etc.
- decision makers and non-expert users being informed about the uncertainty in climate information in understandable ways, and having high levels of trust in their data and its uncertainty based on traceability

Success across the ever-increasing number of missions will require a continuous interaction of scientific and operational institutions to achieve these goals. Already, FIDUCEO partners are exemplifying this interaction in projects for the Copernicus Climate Change Service. Adopting and extending the language and analytical approach of metrology brings conceptual clarity, rigour and practical techniques to this enterprise, and also leads to improved quality data records and climate information.

3. Overview of what FIDUCEO will deliver

FIDUCEO will deliver:

- practical methodology and conceptual principles for providing per-datum uncertainty information in FCDRs (L1)
- practical tools and conceptual principles for harmonising satellite data across multi-decadal sequences of satellite missions, enabling long time-series to be rigorously created
- practical tools and conceptual principles for propagating FCDR uncertainty and attributing credible, traceable uncertainty estimates in CDRs (L2, L3)
- data sets demonstrating the above tools and principles for a range of satellite systems and types of climate data, targeting key historic mission series
- training and cookbooks to disseminate the FIDUCEO understanding to FCDR and CDR producers

FIDUCEO thus addresses the lower-level datasets from which EO-based climate information is derived, as illustrated by the targets in Figure 3-1.

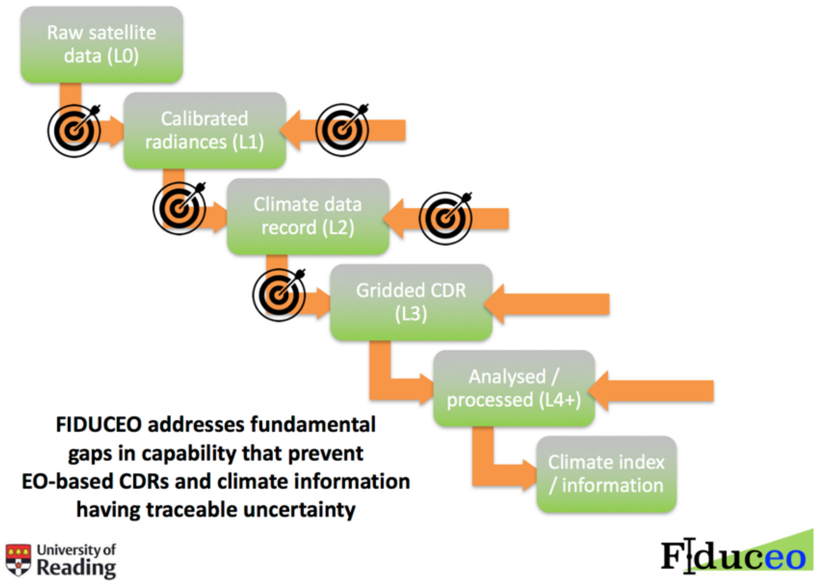

Figure 3-1. Stages of transformation targeted by FIDUCEO.

The specific datasets from FIDUCEO are presented in the tables below.

DATASET	NATURE	POSSIBLE USES
AVHRR FCDR	Harmonised infra-red radiances and best available reflectance radiances, 1982 - 2016	**SST, LSWT**, **aerosol**, LST, phenology, cloud properties, surface reflectance …
HIRS FCDR	Harmonised infra-red radiances, 1982 - 2016	**Atmospheric humidity**, NWP re-analysis, stratospheric aerosol …
MW Sounder FCDR	Harmonised microwave BTs for AMSU-B and equivalent channels, 1992 – 2016	**Atmospheric humidity**, NWP re-analysis …
Meteosat VIS FCDR	Improved visible spectral response functions and radiance 1982 to 2016	**Albedo, aerosol**, NWP re-analysis, cloud, wind motion vectors,…

DATASET	NATURE	USE
Surface Temperature CDRs	Ensemble SST and lake surface water temperature	Most of climate science … model evaluation, re-analysis, derived/synthesis products ..
UTH CDR	From HIRS and MW, 1992 - 2016	Sensitive climate change metric, re-analysis …
Albedo and aerosol CDRs	From M5 – 7 (1995 – 2006)	Climate forcing and change, health …
Aerosol CDR	2002-2012 aerosol for Europe and Africa from AVHRR	Climate forcing and change, health …

4. Post-FIDUCEO opportunities and gaps

4.1. Earth Observation Metrology for Future Missions, including Copernicus

Provision of trustworthy uncertainty information at level 1 (radiance products) needs to become standard satellite mission practice. The uncertainty information needs to be adequate for deriving the uncertainty properties of geophysical records, including CDRs, derived from the radiances. Technically, this implies quantification and dissemination of components of uncertainty associated with distinct error-correlation structures as well as required error-covariance information, to be used in propagating through retrieval processes.

This step-change development in the content of future satellite observations can be achieved for future missions by building FIDUCEO techniques and principles with regards to uncertainty budgets into Phase B to Phase D satellite mission development.

This will be a radical change, but *will unlock the full value of the engineering efforts already made to understand and control sources of error during mission developments*. Presently, that understanding is direct towards demonstrating compliance with requirements that are generally specified at the level of aggregated uncertainty and typically take no account of error correlation structure. Moreover, the detailed error understanding gained is not made available to the users of the satellite data, since that understanding is not embedded and disseminated as uncertainty information in the data products.

The contrast between present practice and a FIDUCEO-inspired approach with a metrological focus is illustrated in this Table 3.

A metrological approach in no way contradicts current efforts focused on compliance, but harnesses and expands those efforts to create added value information directly in satellite products, and in public documentation. Issues may arise connected to commercial confidential material, but solutions can be found to have the necessary principles and results in the public domain in a form that ensures traceability of the uncertainty information.

Aspect	Compliance focus	Metrological focus
Estimating the magnitude of pixel-level uncertainty (e.g., in radiance) per datum	Worst-case combination of uncertainty from error sources to compared against a (generally) aggregated total uncertainty requirement[6]. Deliberately pessimistic to ensure compliance and acceptance.	Individual models/calculations of uncertainty from error sources, traceably document per error source. Realistic combination to inform expected in-flight characteristics.
Characterising the error-correlation structure across pixels and channels	Only in response to specific relevant requirements (e.g. cross-talk limits). Not considered for many error sources.	Integral part of uncertainty characterisation for all error sources.
Traceably documenting uncertainty information	Documentation focused on acceptance milestones. Results perhaps mixed with commercially sensitive and confidential material, and thus usually not available in a form supporting later traceability.	Documentation freely available and organised such as to support systematic traceability[7].
Dissemination of understanding of instrumental error sources to users	Not comprehensively or systematically attempted -- generic information may be published. Not quantitatively integrated into satellite products.	Understanding is embedded in product processing chain in order to include quantitative uncertainty information directly in satellite products per datum.

Table 3. Contrast of approach to uncertainty characterising during satellite mission/sensor development with a compliance focus compared to metrology focus built on FIDUCEO approach.

[6] Or, if not a total uncertainty requirement, at best a simplistic "random' vs. "systematic" requirement, which does not reflect the true nature of errors in sensors in general

[7] Note that for traceable uncertainty documentation, the results and high-level principles of analyses are typically sufficient, potentially by-passing much commercially sensitive information about the technology sitting behind those results. Issues around privy information may nonetheless be a significant area to solve in moving to (or adding) a metrological focus in mission development.

4.2. Harmonisation in Global Space-based Inter-Calibration System (GSICS)

Harmonisation is a new technique developed within FIDUCEO to bring consistency to the FCDRs of families of sensors, which is a requirement in order to maximise the stability and integrity of long-term (multi-decadal) climate and environmental data records derived from these space assets.

Technically, harmonisation is recalibration of sensors (re-estimating calibration parameters of sensors used to quantify the radiance measured by the sensors).

The Global Space-based Inter-Calibration System (GSICS) is an international collaboration initiated by the World Meteorological Organisation and the Co-ordination Group for Meteorological Satellites. In operational, real-time arena, GSICS addresses the same need as the harmonisation efforts in FIDUCEO for historical sensor series: GSICS "aims at ensuring consistent accuracy among space-based observations worldwide for climate monitoring, weather forecasting, and environmental applications". However, GSICS does not use harmonisation. It addresses this need through bias corrections between sensors, which add to and/or scale the operational calibration results. So, while the aim is similar, this is not a harmonisation approach based on recalibration.

Harmonisation by recalibration using FIDUCEO tools in principle should deliver a better outcome. (Technically, the reason is that recalibration doesn't impose an *ad hoc*, external bias-correction structure to the solution. Additionally, the FIDUCEO harmonisation accounts for correlated errors and uses a fitting procedure that is unbiased, neither of which is true of the least squares approach seemingly used in GSCIS to estimate inter-satellite offsets.)

Therefore, there is an opportunity to trial the harmonisation tools that will be produced in FIDUCEO on matches within the GSCIS system, with a view to operational deployment to deliver benefits to the meteorological observation system and weather forecasting.

4.3. Validation of FCDR Uncertainty via Budget Closure to In Situ References

If uncertainty information is presented per datum in FCDRs, then that information should be validated.

An opportunity for developing metrological validation of satellite uncertainties is available by exploiting, along with FIDUCEO capabilities, the results of the H2020 project GAIA-CLIM. GAIA-CLIM was independently proposed, but is highly complementary to FIDUCEO. Good links between the projects have been established, and some best-efforts joint objectives set.

GAIA-CLIM adopts a similar metrology-inspired philosophy with respect to characterising uncertainty in measurements by in situ reference networks. GAIA_CLIM is also characterising mis-match uncertainty when comparing selected in situ reference measurements to satellite observations.

Comparison of matched satellite and in situ reference data is often undertaken, but typically the distribution of discrepancy between the two is not fully understood and exploited. Within GAIA-CLIM, numerical weather prediction (NWP) fields are a significant tool in, first, minimising, and second, characterising mis-match uncertainties.

Where satellite, in situ and mis-match uncertainty have been properly characterised, the discrepancy distribution is predicted in detail. Reversing this logic, comparison of predicted and observed discrepancy distributions is a powerful validation of the component uncertainty characterisations. Thus, bringing together the capabilities of FIDUCEO and GAIA-CLIM presents the basis for metrological validation of FCDR (e.g., radiance) uncertainty, and effort should be dedicated to realising this possibility.

To the degree that the in situ reference network is SI traceable (which is not the case for radiances measured in space) and adequately representative of global conditions, a level of SI-traceability for satellite radiances may be established by these comparisons.

One further point: since the diversity of satellite—in-situ-reference matches is limited typically by the in situ distribution, an additional role for NWP is to act as a point of comparison over a wider range of geophysical conditions. The logic is that having established a NWP-reference link, indirect satellite-reference comparisons can be mediated by NWP to other locations, giving opportunity for useful additional corroboration.

4.4. Use of FCDR Uncertainties in Data Assimilation

Data assimilation is a central technique in weather forecasting and environmental re-analysis, whereby observational and model-dynamic constraints are combined to provide a more optimal and complete estimate of the state of environmental systems (often the atmosphere). In combining these constraints, the uncertainty associated with each one needs to be estimated, so that each constraint exerts an appropriate influence on the solution: more uncertain observations should have less influence, for example.

Satellite radiances are very commonly assimilated. Presently, with no FCDR-level uncertainty information available in typical assimilated data streams, the error covariance allocated to radiances in assimilation is defined by indirect means, such as use of NWP departure statistics and assimilation diagnostics (Desroziers' method). FCDR uncertainty information discriminates the more and less certain satellite radiances and quantifies the correlations of errors between radiances of different wavelengths. FCDR-level uncertainty estimates (error covariances) can be combined with estimates of radiative transfer and representativity error covariances present in the data assimilation system. The result is a direct estimate of the radiance error covariance that can be compared with the indirect estimates mentioned above.

Such a comparison is informative about the limitations of the indirectly estimated error covariances, and can be used to revise and improve them, perhaps particularly in regards correlated errors.

A further use of FCDR uncertainty information relates to satellite radiance bias correction systems within data assimilation. The systematic components of uncertainty in the FCDR offer a constraint on the degree to which the bias correction system should adjust the FCDR radiances, which could, for example, reduce cases of over-adjustment of the radiances to compensate for biases that actually originate elsewhere in the system.

These are two valuable opportunities to develop and demonstrate the benefit of FCDR uncertainty information in the context of improved data assimilation. An example of an appropriate project would be to use FIDUCEO's harmonised, uncertainty-quantified HIRS FCDR in a trial of impact on atmospheric re-analysis.

4.5. Earth Observation Metrology for Active Sensors

FIDUCEO is demonstrating its applicability to a wide range of passive remote sensing technologies relevant to climate. Active remote sensing techniques include a range of radar and lidar technologies. From the climate viewpoint, radar altimetry for sea level would be the priority application of FIDUCEO in the domain of active remote sensing, since satellite sea level time series are subject to a range of harmonisation challenges across sensors and complex errors and error correlation structures.

4.6. Further Historical FCDRs and CDRs of Value

The following sensor series are of high value for climate and environmental data records (in addition to those addressed within FIDUCEO) and amenable to FIDUCEO harmonisation and uncertainty analysis in order to unlock the maximum scientific and societal value from the data, as listed in

In addition, the FIDUCEO project develops an exemplar of a single CDR per FCDR, whereas the following additional CDRs (at least) can be developed with traceable uncertainties from the FIDUCEO FCDRs: land surface temperature, plant phenology, cloud properties, surface albedo, atmospheric humidity, stratospheric aerosol and wind motion vectors.

SENSOR SERIES	NATURE	APPLICATION
SSMR, SSM/I, SSMIS	Surface-sensitive passive microwave conical-scanning radiometers, channels from ~19 GHz to ~86 GHz, from 1978	Sea-ice concentration, ocean wind speed, columnar water vapour and cloud liquid water over the ocean, precipitation.
ATSRs	Dual-view visible and infra-red scanning radiometers with two-point calibration, from 1991 to 2012	Sea, lake, land and ice surface temperature with reference-level stability (once harmonised). Atmospheric cloud and aerosol. Phenology.
Radar altimeters	Ranging from orbit to surface using time delay	Global and regional sea level variability and change, sea-ice freeboard and lake and river levels.
Nimbus satellites	Variety of visible and infra-red sensors	New insights into weather, climate and environment of 1970s and early 1980s, covering important, inadequately understood climate regime shifts and events.
Geostationary Imagers (e.g. GOES, HIMAWARI)	Fixed viewing area with high time resolution	Diurnal variability in various observables, including: sea, lake and land surface temperature, cloud, aerosol.
AMSU-A/MSU	Passive microwave, sounding of atmospheric temperature, from 1998 onwards.	Atmospheric temperature re-analysis and (by reducing biases) improved NWP forecasting.

Table 4. Contemporary and historical sensors series form which additional scientific and societal benefit is considered to be available from applying FIDUCEO FCDR methods.

4.7. Traceable Uncertainties in Atmospheric Radiative Transfer

Remote sensing uses a process of inference to derive geophysical products of interest from the values of radiance measured by a satellite sensors. This "retrieval" process is often dependent at least in part on the ability to simulate satellite observations given assumptions about the geophysical (including atmospheric) state. This ability is embedded in radiative transfer (RT) models. Within GAIA-CLIM, there is innovative work on developing traceable uncertainties in atmospheric RT for some of the microwave domain. It is recognised as an area of considerable importance, requiring further development and wider application.

Attempting the equivalent for the thermal (infrared) and visible (reflectance) parts of the light spectrum is significantly more challenging, but achieving this would enable uncertainties on simulated radiances that could:

- inform retrieval methods, allowing this uncertainty component in retrieved geophysical parameters to be accounted for properly for the first time
- constrain the expected distribution of observation-simulation errors in numerical weather prediction and re-analysis systems
- assist the validation of level 1 radiances and uncertainties at in-situ/reference sites (uncertainty budget closure experiments)

4.8. Theory and Tools for Estimating Uncertainty in Higher-level Products

Higher-level data products (such as gridded versions of climate data records and indices) are required by users on a wide range of space-time scales (instantaneous to decades, local to global), dependent on the application. This is achieved by data averaging in some form. The propagation of uncertainty from full resolution datasets to such averaged scales is fully understood in principle (error propagation theory) but is not computationally tractable in practice. Approximate methods based on a general theory need to be devised and embedded in tools available for producers of higher-level climate/environmental information.

Higher-level products also may combine diverse data sources in new and complex ways. The FIDUCEO principles applied to the L1 to L3 transformations apply to higher-level transformations, although requiring development and trial of extended methods and tools.

4.9. Contextualising Uncertainty in High-Level Climate Indices and Information

Assuming the traceable chain of uncertainty propagation to high-level datasets and climate/environmental indices is achieved, the meaningful presentation of such information to decisions makers and other users is required. The aim is to provide the context for the degree of certainty one can have in the information on which interpretations and decisions are based. This is not an obvious or trivial gap, since it is established that the mode of presentation of any given uncertainty information can materially affect the perceived importance and implications of that uncertainty in the mind of the user.