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Trustworthy Data to Enable Evidence-based Climate Action

NPL has helped embed metrological best practice into the activities of the global satellite-based Earth Observation community by providing training, SI-traceable ground and satellite-based measurement capability, and high-quality data and derived information

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The Challenge

Timely, robust, and proportionate action to mitigate the impacts of climate change relies on confidence in the predictive reliability of models underpinned by trustworthy data. These models are highly complex, combining many ‘process-level’ models that integrate both empirical and physical understanding of how the planet works. They require vast amounts of supercomputing resources and time to simulate how the state of the planet may evolve in response to changes, such as increased greenhouse gas (GHG) emissions. Most current models indicate a warming of the planet due to GHG emissions; however, there remains significant variance and uncertainty in their predictions (see **Figure 1**). Attempts to predict societal consequences are dependent on the outputs of these models.

Earth system cycles – water, carbon, and radiation – are complex and interdependent. Hence, changes in atmospheric composition can trap energy, leading to an imbalance in the planet’s radiation budget; the wider consequences are far-reaching (see **Figure 2**). These include rising sea levels, melting snow and ice, extreme weather events, and impacts on the biosphere, to name just a few. These secondary consequences can also create non-linear feedback that further alters the climate response. For example, reduced snow cover means less sunlight is reflected and more is absorbed by the planet, further raising temperatures.

The Global Climate Observing System (GCOS) of the World Meteorological Organization (WMO) has identified 56 Essential Climate Variables (ECVs) (**Figure 3**) that need to be monitored, with varying degrees of accuracy and precision, to improve our understanding of how the planet works and the consequences of our actions.¹ Many of the uncertainty requirements for these often bio-geophysical variables are comparable with the best capabilities of National Metrology Institute (NMI) laboratories under ideal laboratory conditions.

¹ World Meteorological Organization (WMO). Global Climate Observing System (GCOS). Essential Climate Variables. <https://gcos.wmo.int/site/global-climate-observing-system-gcos/essential-climate-variables>

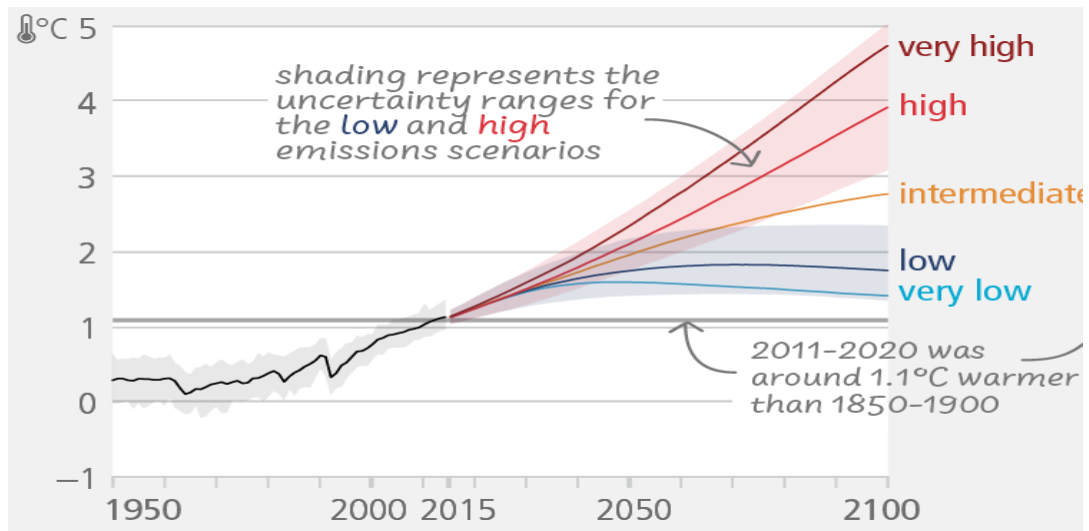


Figure 1. Plot showing the variance of climate models in predicting the future state of the planet (shading) in response to specific GHG forcing levels. From the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC AR6) (2022).



Figure 2. If energy into the Earth (E_{in}) - reflected, compared to that emitted by the Earth (E_{out}) - that absorbed by the atmosphere, remains equal, then the temperature remains stable. If not, then the Earth's temperature changes.

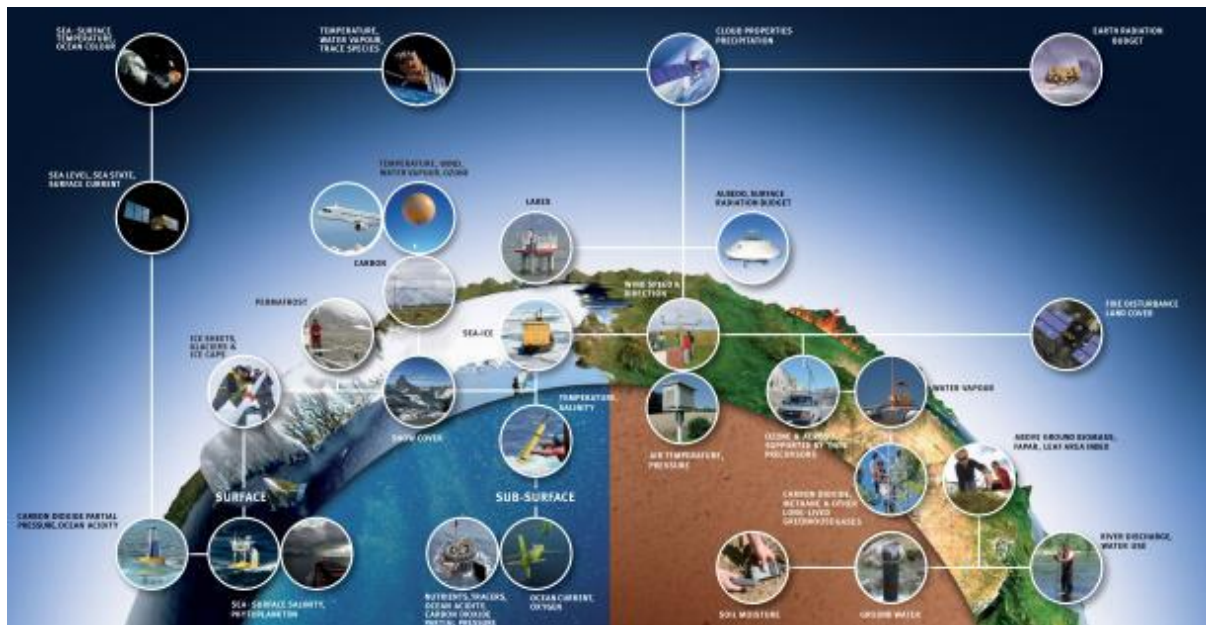


Figure 3. Schematic illustrating the Essential Climate Variables (ECVs) of the Global Climate Observing System (GCOS).

Two-thirds of these ECVs require observations from space-borne instruments to achieve adequate representativeness, and half require optical measurements. Although significant effort is devoted to pre-flight instrument calibration and characterization, the violence of launch and the harsh space environment result in degraded performance upon reaching orbit, with continual degradation thereafter. The unpredictable nature of this change complicates the assignment of reliable estimates of uncertainty to the measurements. This is particularly true for optical instruments, which are highly susceptible to contamination and misalignment due to movement during launch into space.

This not only makes data from individual satellite instruments harder to interpret but also makes it difficult to reliably combine signals from different satellites into the long time series needed to detect climate trends. Because the signals of measurements used to detect climate change are often so small, it can take decades for changes to become large enough to be detectable from background environmental and residual instrumental noise. Robust, low-uncertainty traceability to SI units, has long been recognized as essential to ensure that information derived from satellites is ‘fit for purpose’. However, achieving that goal is highly challenging and requires changes in the typical working practices of national metrology institutes (NMIs), i.e., to expand capabilities outside of the laboratory, such as for measurement of biogeophysical quantities that are often transformed by a model, as well as a more direct partnership between space agencies and the climate research community.

The Solution

Efforts to recover knowledge of the post-launch performance of satellite instruments have been pursued through on-board calibration infrastructure and observations of dedicated ‘ground truth’ targets and test sites, since the early days of Earth observation (EO) more than 40 years ago. These are characterized independently by using other measurement approaches, such as airborne instruments and ground-based optical instrumentation. These post-launch methods also need to be SI-traceable, which brings further challenges and has become more of a focus in the last two decades. On-board calibration systems of satellites degrade, as do ground-level field instruments. It is also difficult to assess how representative an *in situ* point measurement of, for example, surface reflectance or temperature, is of a satellite pixel spanning hundreds of metres.

The National Physical Laboratory (NPL) in the UK has risen to this challenge by undertaking climate change research supported by national funding, the European Union, and world and national space agencies to embed metrological best practice in the space sector. This included developing measurement capabilities (e.g., a tuneable laser-based calibration facility for satellite instruments, a radiometer to measure Infrared radiance from black bodies for surface temperature calibrations, large aperture black bodies for satellite infrared calibration, etc.) that are traceable to the SI, have rigorous uncertainty assessments, and have been demonstrated to be reliable via comparison-based evidence. NPL has also worked within existing international structures such as the Committee on Earth Observation Satellites (CEOS)² for nearly 30 years, promoting common terminology and a shared understanding of how uncertainties should be estimated and combined. This led, in 2010, to the creation of the Quality Assurance Framework for Earth Observation (QA4EO),³ which has been endorsed and implemented worldwide and is underpinned by a set of open-source software tools (Community Metrology; COMET Toolkit) for uncertainty assessment and propagation.⁴ In addition, dedicated in-person and online training courses have been created to support consistent understanding and interpretation.⁵

To reduce uncertainty in satellite data, NPL has coordinated comparisons between satellite instruments and, within the EO community, *in situ* calibration and validation (Cal/Val) methods for land and ocean reflectance and surface temperature measurements. This also includes additional indirect ECVs, such as leaf area index, sea level height, and ice thickness. Analysis of these comparisons has helped establish best practices in the community.

² Committee on Earth Observation Satellites (CEOS). <https://ceos.org/>

³ A Quality Assurance Framework for Earth Observation (QA4EO). <https://qa4eo.org/>

⁴ A Quality Assurance Framework for Earth Observation (QA4EO). <https://qa4eo.org/>

⁵ National Physical Lab. Uncertainty Analysis and Quality Assurance for Earth Observation Datasets. <https://training.npl.co.uk/product/uncertainty-analysis-and-quality-assurance-for-earth-observation-datasets/>

The importance of adopting this metrological best practice has been recognized by CEOS through the creation of the Fiducial Reference Measurement (FRM) label and the associated certification process.^{6,7} Space agencies are now requesting that post-launch Cal/Val activities become FRM-certified so that their uncertainty can be evidenced against SI units using metrological best practice.

In addition to uncertainty assessment, NPL has designed and built instrumentation and methods to reduce measurement uncertainty for a variety of Essential Climate Variables (ECVs), both in space and on the ground. These include networks of field instruments for measuring surface reflectance (RadCalNet,⁸ **Figure 4a**; Hypernets⁹) and vegetation parameters (**Figure 4b**), as well as transportable facilities for pre-flight calibration and characterization of satellite sensors using tuneable lasers in a new facility, the *Spectroscopically Tuneable Absolute Radiance calibration and characterisation Optical Ground Support Equipment* (STAR-cc-OGSE, or “STAR”).¹⁰ The STAR facility was used to calibrate the recently launched MicroCARB satellite (Carbon Dioxide Monitoring Mission) for GHG monitoring¹¹ (**Figure 5**).

The greatest impact is likely to be realized with the launch of a new class of satellite sensors, originally called SITSats (SI-Traceable Satellites) and now referred to as FRMsats. These FRMsats would provide uncertainties from orbit-based measurements at an unprecedented level and are anticipated to meet the most demanding climate requirements. These would serve as gold-standard reference measurements in space and be used to recalibrate other satellite instruments.¹² In effect, these satellite sensors would serve as in-flight metrology laboratories, such as that of the European Space Agency (ESA) TRUTHS mission.¹³ Although development of TRUTHS has stalled, it remains a highly desirable mission and is expected to be reinstated in some form in the future.¹⁴

⁶ Goryl, P.; Fox, N.; Donlon, C.; Castracane, P. Fiducial Reference Measurements (FRMs): What Are They? *Remote Sens.* 2023, 15, 5017. <https://doi.org/10.3390/rs15205017>

⁷ CEOS Cal/Val Portal. FRMs Assessment Framework. <https://calvalportal.ceos.org/web/guest/frms-assessment-framework>

⁸ CEOS Radiometric Calibration Network portal. <https://www.radcalnet.org/#/>

⁹ LANDHYPERNET data portal. HYPERNETS. <https://landhypernet.org.uk/>

¹⁰ EURAMET Case Study. Reducing cost and improving the accuracy of radiometric sensor calibrations: Terrestrial and space. <https://www.euramet.org/casestudies/casestudiesdetails/news/reducing-cost-and-improving-the-accuracy-of-radiometric-sensor-calibrations-terrestrial-and-space>

¹¹ EURAMET Case Study. Reducing cost and improving the accuracy of radiometric sensor calibrations: Terrestrial and space. <https://www.euramet.org/casestudies/casestudiesdetails/news/reducing-cost-and-improving-the-accuracy-of-radiometric-sensor-calibrations-terrestrial-and-space>

¹² Boesch, H; Brindley, H; Carminati, F; Fox, N; Helder, D; Hewison, T; Houtz, D; Hunt, S; Kopp, G; Mlynczak, M; Pagano, T S; Revercomb, H; Richard, E; Rosenkranz, P; Shea, Y; Simis, S; Smith, D; Stone, T C; Sun, W; Xiong, J; Wielicki, B; Yang, H; Ye, X (2022) SI-traceable space-based climate observation system: a CEOS and GSICS workshop, National Physical Laboratory, London, UK, 9-11 Sept 2019. <https://doi.org/10.47120/npl.9319>

¹³ Fox, Nigel. The European Space Agency. Truths: the gold standard reference for climate measurements. https://www.esa.int/Applications/Observing_the_Earth/TRUTHS

¹⁴ World Meteorological Organization (WMO). GCOS Report-244. The 2022 GCOS Implementation Plan (GCOS-244). <https://library.wmo.int/records/item/58104-the-2022-gcos-implementation-plan-gcos-244>



Figure 4. Left side (a) NPL managed RadCalNet tower hosting a radiometer measuring the reflectance of the Earth in the Namib desert as a reference for satellites. Right side (b) tower hosting NPL instruments monitoring vegetation at Wytham woods in Oxfordshire, UK.



Figure 5. The NPL STAR facility shown here deployed at the Airbus cleanroom in Toulouse, France. The facility was used to calibrate the French/UK MicroCARB mission for GHG monitoring.

A Quantifiable Impact

The principles of the QA4EO framework have been adopted by the world's space agencies, with organizations such as the European Space Agency (ESA) and the EU Copernicus programme explicitly requiring compliance in their work programmes. Over the last 3 years, the in-person training courses on uncertainty evaluation have been attended by more than 250 researchers, and online participation has increased several-fold. The RadCalNet network, for which NPL ensures consistency and metrological traceability across member sites while also maintaining the Gobabeb site for ESA, has more than 7 000 registered users, of whom around half are active.

At the request of the commercial sector, NPL has also developed online tools¹⁵ to help organizations demonstrate their performance capabilities to a broad set of stakeholders (e.g. buyers and users of their data) in a transparent and fair manner. This includes a demonstration of their measurement capability, including uncertainty, and how they establish metrological traceability to the SI. This helps maximize the utility of their data and commercial return on investment by enabling more science-quality applications through robust quality assurance.

The international metrology community, led by the Bureau International des Poids et Mesures (BIPM), has organized several workshops in conjunction with the WMO to identify research priorities and promote joint work. In Europe, a network of NMIs to coordinate climate-focused research has operated for nearly a decade under the auspices of EURAMET,¹⁶ and a variety of similar initiatives have been established within the working groups of the CIPM Consultative Committees.

Although much of the climate metrology work of most NMIs currently centres on the calibration of instrumentation, there are increasing examples – particularly at NPL – of activities extending into fieldwork, modeling, and uncertainty propagation through to the derived information ultimately needed by policymakers. This work has recently prompted, and will continue to prompt, new questions for the climate research and measurement community, such as how our measured emissions compare with those estimated using ground-up methods, or how much carbon is stored in our forests.

It is clear from the actions of space agencies, climate researchers, and other users that the role of metrology in climate science is now better understood, and metrology institutes are sought out as partners to help provide the confident results policymakers need to act robustly and in a timely manner. Furthermore, the importance of metrology to the EO and climate community is now widely recognized by both users (space agencies and climate researchers) and the NMI community at large. It is now commonplace for the specifications of climate

¹⁵ RadVAL. Radiometric Validation Analytics Tool. <https://ceos-pvp.org/>

¹⁶ EURAMET. European Metrology Network (EMN) for Climate and Ocean Observation. <https://www.euramet.org/climate-and-ocean-observation/>

measurement projects to require the involvement of an NMI, or at least for the organization to follow prescribed metrological best practices, as part of the delivery.

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