Stakeholder Needs Review Report European Metrology Network for Climate and Ocean Observation

EURAMET

Executive Summary

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CLIMATE AND OCEAN OBSERVATION

Authorship and Imprint

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Further information

This is the Executive Summary of the first version of the summary report on stakeholder needs including the three ECV themes (Atmosphere, Ocean and Land), and also covering Earth Observation and other measurement techniques and synergies between themes.

For further information about this document, please contact your national contact person of the EURAMET European Metrology Network for Climate and Ocean Observation.
See: https://www.euramet.org/climate-and-ocean-observation

Executive Summary

This Executive Summary is a synthesis of the Stakeholder Needs Report of the European Metrology Network for Climate and Ocean Observation (here "the EMN"). During 2020, the EMN carried out a review to identify and prioritise the ways in which metrology can support climate and ocean observation. The review report highlights the areas that we found that require urgent further collaborative metrological research between metrology institutes and experts in those observation systems and their applications.

This report uses the terms "climate and ocean observation" and "metrology community" in specific ways:

- The EMN has two related, but separate, themes – the "climate" theme relates to metrology for supporting the making and use of observations of essential climate variables (ECVs) in all three domains (atmosphere, ocean and land). The "ocean" theme relates to metrology for supporting observations of essential ocean variables (EOVs). These EOVs include all the ECVs in the ocean theme along with additional variables to cover a broader range of applications, including those needed to understand ocean biodiversity and to support the sustainable use of the ocean for cultural, social and economic benefit and as a food supply. Thus "climate and ocean observation" is used to describe both themes of the EMN and not to suggest any particular emphasis on the ocean within the "climate" theme.

- We recognise that there is a multidisciplinary community making and using climate and ocean observations and that people within those communities rightly also consider themselves "metrologists". Likewise, many people working in formal metrological institutes are already active in committees, consortia and networks involved in climate and ocean observation. Here, however, we use "the metrology community" and "metrologists" to only describe those working in institutes that are formally recognised by the Metre Convention as national metrology institutes (NMIs) and designated institutes (DIs). Within Europe, such institutes are members of the European Association for National Metrology Institutes (EURAMET) and eligible to be formal members of the EMN.

Metrology in Climate and Ocean Observation

To mitigate and adapt to climate change, decision makers in governments, industry and non-governmental organisations need access to high quality information about the historical, current and future state of the climate system and on the current anthropogenic greenhouse gas (GHG) emissions, water use and land use changes. Such information relies on direct observations of the state of the environment. Near-real time observations are used in climate and ocean data services and in numerical weather prediction (NWP) forecasts for a wide variety of societal applications. Longer-duration historical climate data records of essential climate variables (ECVs) are assimilated into climate reanalyses (which provide detailed information on the state of the historical climate). These long-term observationally-derived datasets are also key to validating and improving climate models and therefore help to improve our understanding of the physics, chemistry and biology of the Earth system. The ECVs are defined by the Global Climate Observing System (GCOS).

Figure 1 shows how climate observations fit into the climate decision making process. The outer loop (blue arrows) shows how individual observations (which come from both in situ and remote sensing methods) of the climate system are processed into climate data records (CDRs) of

ECVs, which in turn are used to tune and validate climate models. The climate models inform, and are informed by, integrated assessment models, models used by economists and social scientists to understand and predict changes in anthropogenic GHG emissions and land use. These integrated assessment models inform policy, which leads to changes in emissions and land use, which affect the climate (on decadal timescales) and the changed climate can be monitored by observations. The fast feedback loop (gold) provides near real-time (timescale 2-3 years) observations of GHG sources (emissions) and sinks (e.g. forests). These observations can support national inventories and thus the ‘Global Stocktake’ reports for the Paris Agreement. The changes in anthropogenic GHG emissions and land use can be observed directly, providing feedback to policy on timescales of a few years.

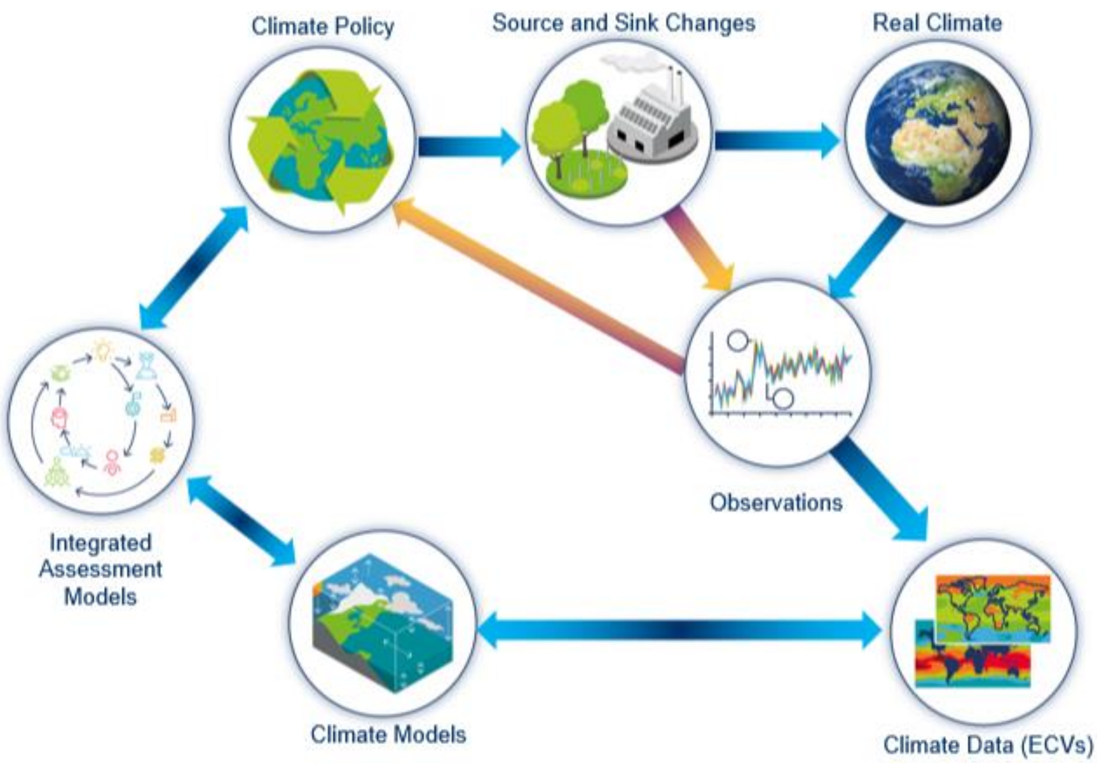

Figure 1 The role of climate observations within the decision cycle – using greenhouse gas emissions as an example where society can have a direct impact.

Some of the biggest decisions that humanity must make are based on climate models and the integrated assessment models they inform. Climate policy in many countries (and indeed many commercial enterprises) is now to achieve ‘net zero’ emissions by the middle of the century, or earlier. This is highly ambitious and requires fresh thinking and reliable data to support the required policy changes. It is therefore essential to have quality assurance (QA) of the entire value chain shown in Figure 1. Such QA requires reliable observations that are stable long term, linked to a common reference (ideally the international system of units, SI) and have robustly-determined uncertainties associated with them. It also requires that the models used in the data analysis are themselves quality assured and have associated uncertainties. Note that models are used to interpret raw observations, and to process such observations into ECVs, as well as in climate prediction and reanalysis.

Metrology, the science of measurement, can contribute to both the QA of observations and, through data scientists working in metrology institutes, to the QA of data processing and modelling. Metrology has ensured that the SI units have been stable for nearly 150 years, are consistent worldwide and are coherent, through the key principles:

1. Metrological traceability: Linking measurement results to a commonly-agreed primary reference (the SI);
2. Comparison between independent measurement approaches: both exploratory scientific comparisons and formal comparisons that support the formal "Mutual Recognition Arrangement" (MRA) between metrology institutes, and
3. Uncertainty analysis following the principles of the Guide to the Expression of Uncertainty in Measurement (GUM).

These key principles of metrology can, should and are being applied to the observations of our environment and our climate, albeit with necessary interpretation and adjustment, to provide QA to the observations that society relies on.

Review of Stakeholder Needs

The stakeholders of the EMN are those who make or use climate and ocean observations. These include those who manufacture and calibrate sensors deployed in in situ networks and satellite sensors, those who operate observational networks and satellite systems, those who process raw data from current and historical networks and systems to give "fundamental data records" of raw data or derived "climate/thematic data records" of ECVs and EOVs, and those who use such observational records in climate or oceanographic models or to provide societal benefit or commercial services derived from these records. Most of these stakeholder communities are organised through international organisations and their committee structures and the EMN has sought to interface directly with those existing organisations.

During 2020, the EMN collated needs from stakeholder communities using an online survey, four webinar workshops and by participating in stakeholder committees. The EMN also reviewed summaries of historical workshops, scientific literature, and stakeholder community strategies and implementation plans to identify and prioritise the areas where metrology can most meaningfully contribute.

The stakeholder needs report describes the outcome of this review. After an introduction, it has five main sections, describing the metrological needs for:

- Atmosphere observation from ground-based instruments (the GCOS Atmosphere ECVs which are measured with in situ methods)
- Ocean observation from in situ instruments (the GCOS Ocean ECVs and additional Global Ocean Observation System (GOOS) EOVs)
- Land observation from in situ instruments (the GCOS Land ECVs which are measured with in situ methods)
- Remote sensing of ECVs and EOVs (by satellite-based, aircraft-based and ground-based remote sensing methods)
- General observations (a section that considers common needs across multiple themes)

In each section of the report there is a discussion of the identified needs, including quotes from our survey and references to the reports in which the need was identified. Each section ends with a table of priority requirements for that theme. Those tables are replicated in Appendix A of the Stakeholder Needs Report and in Section 5 of the stand-alone version of the Executive Summary.

Metrology Challenges for Climate and Ocean Observation

The traditional role of metrology in providing SI-traceability to observational systems, through reference standards, materials, instrumentation and associated calibration, remains important.

For some ECVs, SI traceability is already routinely provided through NMIs or DIs and there are ongoing requirements for operational services of this nature, iterative improvements and improved access to standards for field measurements. This is particularly the case for the provision of traceability to remote locations and/or for the low concentration levels of a given substance in the atmosphere / ocean. For other ECVs, the community has existing community standards that, while not SI-traceable, are considered at present to be fit for purpose, although many of these communities need support to assess the uncertainty and traceability to these standards. However, for several ECVs and observational methods, significantly improved and even new reference and working standards, materials and instrumentation are required – spanning measurements made in NMI laboratories, calibration laboratories, in the field and in space.

In a few cases, particularly for water vapour concentration in the atmosphere (humidity) and ocean pH, the definition of the measurand itself is ambiguous, with multiple possible definitions that depend on the method for taking the observation. Here, metrologists can work with the observational communities to support a standardisation of the definition and to provide comparisons and conversion factors between different methods.

Metrology institutes are already involved in the establishment of primary reference networks, including, for example, the GCOS Reference Upper Air Network, GRUAN, the planned establishment of a surface reference network, and the establishment of fiducial reference measurement (FRM) sites for satellite post-launch calibration and validation. Such reference networks are needed because many observations were not originally taken for climate purposes, and these provide the long-term stability and absolute accuracy required for a CDR. It is essential that metrology institutes continue to support the development of reference networks including in the provision of traceability and in establishing uncertainty analyses for the observed quantity in the environmental conditions.

There are several identified needs relating to running comparisons for observation communities. Such comparisons are needed at all the different levels: interlaboratory calibrations of calibration facilities, in field comparisons of observational instruments, comparisons of satellite data products over reference sites and comparisons of derived ECV products, including the algorithms used to process data (e.g. atmospheric correction of satellite data) and to generate ECVs.

More generally, there is a role for metrologists in supporting standardisation through definitions (as described above), through good practice guides – in some cases formal international standards – and through developing quality assurance and quality control (QA/QC) frameworks for observational practices and data provision. QA/QC frameworks can support requirements for traceability to the SI or a community-agreed reference and support the need for rigorous uncertainty assessment. Such frameworks are needed both for current observational networks and satellite sensors and for “data rescue” of historical data. Related to this there is a need to support the correct use of metrological vocabulary (e.g. uncertainty/error, traceability) in both vocabularies (written for scientists) and ontologists (written for computer databases) and to provide training in metrological techniques (uncertainty analysis and practical techniques).

There are also requirements for metrological data science. These requirements include the development of methods to propagate uncertainties and error covariance structures through data assimilation, reanalyses and models. They include developing metrological methods for assessing the uncertainties associated with complex processing chains, including neural networks and classification processes. They include considering the uncertainties inherent in models. Data science techniques are also needed to determine outliers in large networks of autonomous sensors, particularly for low-cost sensors, and to understand scaling and representativeness as individual observations on different scales are compared.

This section has provided an overview of the different areas where metrology can support climate and ocean observation. The tables below give our list of prioritised challenges and the full Stakeholder Needs Report describes these needs, and specific needs for particular ECVs or measurement methods in more detail.

Tables of prioritised challenges

Metrology Challenges for Observations of Atmosphere ECVs
Fit-for-purpose working standards at appropriate concentrations, ensuring an unbroken SI-traceable calibration chain. There is also a need to improve the sampling and analytical methods for ambient measurements and to assess relevant influence parameters (typically aerosol and ozone precursors such as VOCs or NO_2)**.**
Certified reference materials for newly emitted halogenated compounds lacking standards (e.g. greenhouse gases such as HCFCs). Reference materials and a traceability chain for new measurements of isotopic composition and atmospheric tracers (e.g. dissemination of N_2O) must also be established**.**
Development of calibration procedures for aerosol properties using filter-based absorption photometers to provide a metrological framework for aerosol metrics beyond PM2.5 and PM10, and to generate source-specific reference aerosols in the laboratory.
Improve reference methods and instrumentation, typically for humidity measurements in the upper troposphere/lower stratosphere (less than 10 µmol/mol) under adapted environmental conditions (e.g. low pressure and temperature).
Support the establishment of the surface reference network by the GCOS (similar to GRUAN) as the top level of the WMO Integrated Global Observing System prescribed tiered approach in conjunction with the launch of the Global Basic Observing Network.
Metrological support for comparisons, particularly for challenging measurements lacking well-defined SI-traceability, and to compare surface, upper-air and satellite measurements (i.e. where there are very different traceability chains), including on site comparisons with metrological rigour for extreme environments and challenging locations e.g. cryosphere and high mountains.
Metrology support for specific initiatives focussed on the cryosphere, high mountains and urban areas. There is a need for metrologists to participate in multidisciplinary partnerships focussed on observations and predictions in key climate areas (e.g. to participate in the establishment of an integrated high-mountain observation, prediction and services initiative).
Metrological support for field calibrations and measurements, including guidelines for using measuring devices on site including environmental influences and their uncertainty contribution.
Improved metrological characterisation of spectral parameters for chemical compounds (e.g. absorption cross-section, spectral line)**.**

Metrology Challenges for Observations of the Ocean
Definition of proper measurands and fit-for-purpose high order and working standards that ensure unbroken SI-traceable calibration chains. Currently, some of the ocean ECVs and EOVs are not defined in terms of SI units (e.g. pH, salinity). This makes it difficult to compare results obtained in different time and places, particularly when technology breaks occur.
Certified reference materials are essential tools to ensure the metrological traceability of results via the calibration of instruments, or to validate analytical measurement methods. Currently very few reference materials exist for some of the ocean ECVs and EOVs (e.g. inorganic carbon variables, pCO2, TA, pH) and most of them are not certified by NMIs/DIs.
Development of a metrologically based QA/QC framework and associated tools to facilitate field measurement reliability and consistent uncertainties. Currently, few oceanographic institutions are familiar with ISO 17025 accreditation. A scheme could be created on the example of QA4EO, establishing guidelines written in collaboration between the oceanography and metrology communities.
Organisation of interlaboratory comparisons for in situ measurements following metrological best practice to establish 'degrees of equivalence' and biases to enable international interoperability and harmonisation for long term comparability.
Fit-for-purpose uncertainties for in situ measurements, including training courses: GCOS requirements set stringent target uncertainties for many of the ECVs which are close to the level of primary standards. In contrast to this demand, assignment of uncertainties according to metrological concepts is not well established in oceanography.
Moving beyond best practice guidance documents and standard measurement procedures to international documentary standards, which can provide longer stability of measurement procedures over time.
On-board calibration for underwater instruments mounted on research vessels continuously measuring oceanographic parameters such as temperature, salinity, pressure, sound speed and bathymetry to ensure traceability and accuracy of measurements over instruments' lifetimes and to account for environmental conditions and for their operation in dynamic mode.

Metrology Challenges for In Situ Observations of Land ECVs
Support to establish and assess traceability and associated uncertainty to community agreed (ideally SI) references for measuring systems under operational conditions.
Support to write documentary measurement procedures and best practice in a metrologically robust manner.
Mathematics to facilitate representativeness of observation from multiple samples/sites at both single locations and as part of a network.

Metrology Challenges for Remote Sensing
Pre-flight calibration standards and methods to enable SI-traceable uncertainties that commensurate with the needs of climate, available for cost/time efficient calibrations under operational conditions at industry/academic locations. These should cover the needs of all sensor domains e.g. passive optical through to active microwave, and address all necessary parameters and observational platforms e.g. space through to surface networks.
On-board calibration standards and methods to enable SI-traceable uncertainties that commensurate with the needs of climate to be achieved. This requires NMIs to support the transition of terrestrial techniques to orbit, assess degradation and uncertainty estimates for their use for all technology domains.
Establishing FRM quality test-sites/measurements for post-launch Cal/Val. This includes enabling SI-traceability in the field, uncertainty evaluation of in situ and its propagation/representativeness to the satellite all domains.
Development of a metrologically-based QA framework and associated methods/tools to facilitate evaluation and consistent reporting of end-to-end uncertainty of Level 1 and consequential higher-level data products. Including training support on uncertainty evaluation.
Metrological assessment of uncertainty of models & algorithms particularly those required to transform top-of-atmosphere measurands to bottom-of-atmosphere parameters, including support to developers, guidance on assessment, including the challenges of 'machine learning' methods. Means to establish uncertainty characterisation and representation for 'classification' systems e.g. land cover type, cloud masks etc. is also needed.
Comparisons and guidance for organisation of comparisons of community 'measuring systems'. Comparison of satellite-to-satellite and satellite-to-ground systems following metrological best practice to establish 'degrees of equivalence' to enable international interoperability and harmonisation for long-time base FDRs.
Methods to establish metrologically robust FDRs and CDRs. How to combine both similar (e.g. sat series) and differing (different sensor designs) sources of data to create long-time base (multi-decadal) series with associated uncertainties. Facilitating interoperability (bias removal).

General Metrology Challenges for Climate and Ocean Observations
Performing metrological analysis on historical data and supporting data rescue. Investigating historical data – from networks, individual measurement records and early satellites to improve the calibration, perform comparisons, understand measurement methods and establish improved traceability and uncertainty evaluations based on modern knowledge. In this, supporting the development of robust uncertainty and covariance analysis for all observations used in reanalyses.
Metrological framework for model uncertainties. Establishing methodologies to evaluate uncertainties in ECVs processed partially or fully from models, in reanalyses and in climate models, including development of community-focused good practice guides.
Calibration methods and data processing techniques for low-cost sensor networks. Providing fit-for-purpose low-cost calibration to low-cost sensors and evaluating uncertainties and outliers in deployed low-cost sensor data.
Defining vocabularies and data-science ontologies for key metrological concepts. Working within the communities to make metrological vocabulary consistent, and ensuring formal ontologies contain enough terms to describe uncertainty robustly.
Providing training in metrological techniques. Theoretical training in concepts (e.g. uncertainties, traceability, comparison) and in practical training in calibration methods.
Supporting the development of QA frameworks and formal standardisation for networks. Working with community committees to establish metrologically-robust frameworks for network operation and data handling.
Support discussions on how uncertainty should be translated to commercial and societal risk. Create links from the observations through the models to societal and commercial decisions. Engage in the ongoing dialogue about how uncertainty should be treated in each stage of the value chain.

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