Strategic Research Agenda European Metrology Network for Climate and Ocean Observation

Version 1.0 (09/2022)

EURAMET

CLIMATE AND OCEAN OBSERVATION

Authorship and Imprint

This document was developed by the EURAMET e.V., European Metrology Network (EMN) for Climate and Ocean Observation.

Authored by the experts of EURAMET EMN for Climate and Ocean Observation coming from the following EMN Member institutes: SMD (Belgium), IMBiH (Bosnia and Herzegovina), DTI (Denmark), UT (Estonia), MIKES (Finland), MIKES-FMI (Finland), Aalto (Finland), MIKES-SYKE (Finland), LNE (France), PTB (Germany), EIM (Greece), INRiM (Italy), VSL (Netherlands), JV (Norway), GUM (Poland), INTiBS (Poland), IPQ (Portugal), IH-LQPM (Portugal), INM-RO (Romania), INTA (Spain), CEM (Spain), PMOD/WRC (Switzerland), METAS (Switzerland), UME (Turkey), NPL (United Kingdom).

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EURAMET e.V.
Bundesallee 100
D-38116 Braunschweig
Germany

E-Mail: secretariat@euramet.org
Phone: +49 531 592 1960

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About the European Metrology Network for Climate and Ocean Observation

The European Association for National Metrology Institutes (EURAMET) created European Metrology Networks (EMNs) in 2018 to support its vision to ensure Europe has world-leading metrological capability based on high-quality scientific research and an effective and inclusive infrastructure that meets the rapidly advancing needs of end users. The first six EMNs were established in early 2019 and have a remit to analyse the European and global metrology needs and to address those needs in a coordinated manner through the National Metrology Institutes (NMIs) and Designated Institutes (DIs) of Europe. EMN members will formulate common metrology strategies, including scientific research, infrastructure development, knowledge transfer and service offerings. The EMNs will provide a single point of contact for information, underpinning regulation and standardisation, and for promoting best metrological practice.

One of the first EMNs to be established was the EMN for Climate and Ocean Observation. The EMN has a scope that covers metrological support for in situ, ground-based and remote sensing observations of atmosphere, land and ocean Essential Climate Variables (ECVs) for climate observations and also to support the broader economic and ecological applications of Essential Ocean Variables (EOVs) observations. It is the European contribution to a global effort to further enhance metrological best practice into such observations through targeted research efforts.

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Contents

1 Introduction

1.1 Purpose and scope of document

This document forms the Strategic Research Agenda of the European Metrology Network for Climate and Ocean Observation (here, "the EMN"). It is a response to the "Stakeholder Needs Report" published in January 2021, which identified where metrology is needed to support the observations of essential climate variables[1] (ECVs) and the related essential ocean variables (EOVs).

After this general introduction, this Strategic Research Agenda comprises a set of tables, each describing a small number of related "metrology challenges" that were identified in the Stakeholder Needs Report. Those challenges are given word-for-word at the top of each table.

The Strategic Research Agenda is separate from the EMN Strategy, which focusses on the strategic operation of the EMN itself. The Strategic Research Agenda has a scientific focus and covers scientific developments, strategic technical partnerships and standardisation activity needed by the NMIs/DIs to support the identified stakeholder needs. Note that we have interpreted "research" here in a broad sense and include running comparisons, introducing quality assurance frameworks and training within that category.

This document is written for Europe's metrology community and for EURAMET and the European Metrology Partnership, to define priority areas for research and to see opportunities for collaboration with those engaged in observations, as well as with other EURAMET bodies, and particularly the other EMNs Mathmet and POLMO.

The EMN plans its activities according to the cycle given in Figure 1.1. This document summarises step 4 for the first time the EMN has worked through this cycle since its formation. We expect to repeat this process every two years.

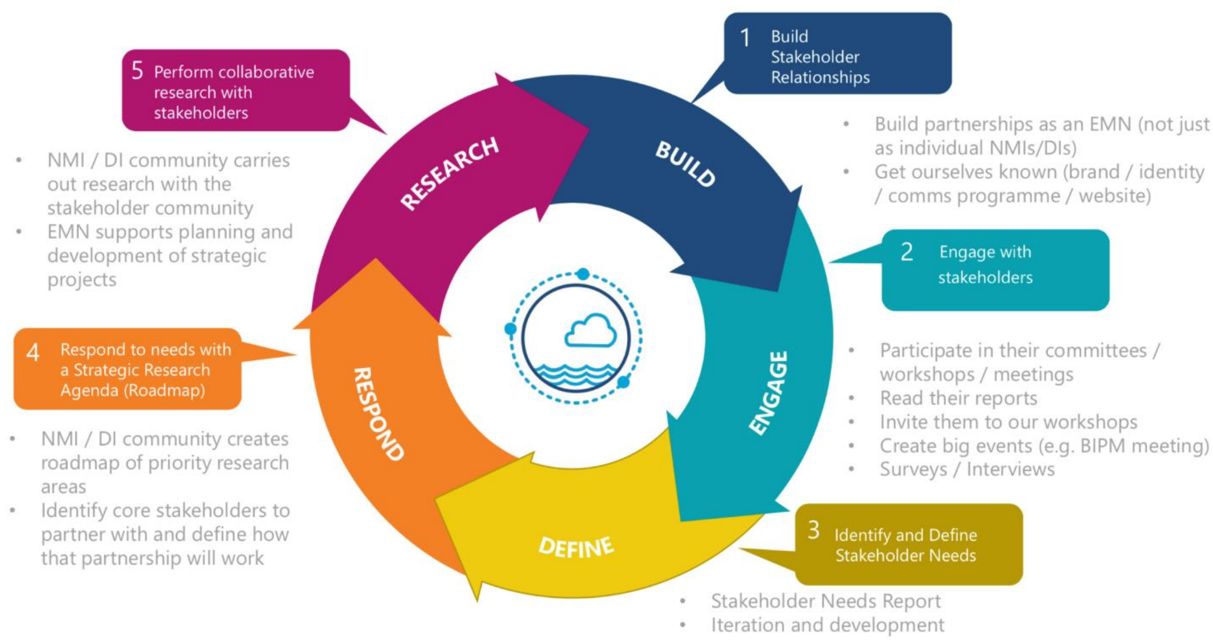

Figure 1.1 The stakeholder interaction cycle for the EMN for Climate and Ocean Observation

[1] ECVs are defined by the Global Climate Observing System (GCOS) and are categorised into Atmosphere, Ocean and Land ECVs. The Global Ocean Observing System (GOOS) has identified EOVs, which include all the Ocean ECVs and additional quantities that have non-climate ocean applications.

1.2 What we mean by "the metrology community"

We recognise the considerable existing expertise in metrological methods in the scientific, commercial and operational communities that make and use observations, and the ongoing and growing existing collaboration between those communities and metrology institutes. In this report we have, as short-hand, talked of "the metrology community" meaning the institutes that are formally recognised by the Metre Convention – the national metrology institutes (NMIs) and associated designated institutes (DIs). Climate and ocean observation is a multidisciplinary activity and metrology is one of those disciplines. This report, however, is designed to inform the formal NMIs and DIs, about opportunities for increased collaboration and participation.

1.3 Methodology for defining the strategic research agenda

The strategic research agenda is a response to the needs identified in the Stakeholder Needs Report and is therefore structured around those identified needs. We invited NMIs and DIs in Europe, through both this EMN's mailing list and the mailing list for the EMN Mathmet, to provide information about their existing and planned work in response to those needs and held workshops about each set of needs.

1.4 Organisation of the document

The main outputs of this document are the roadmaps that set the direction of research needed by the European metrology institutes to meet the stakeholder needs. Each roadmap consists of two tables. The first has the structure described in Table 1.1.

Table 1.1 Structure for the first roadmap table

Challenges:	A word-for-word quote of a small number of related challenges, written as in the Stakeholder Needs Report
NMIs / DIs active:	A list of NMIs and DIs who currently have activities relating to any elements in the roadmap
Key-stakeholders:	A list of some core stakeholder organisations related to our efforts in these challenges.
Overview	A description to put the challenges into context and to describe their scope
Outlook beyond 2033	A discussion of potential activities, and known gaps, that where activity will likely be needed after the end of the main roadmap.

A second table lists activities related to responses to the challenge that are either ongoing (happening now or planned to start before 2025) or needed in the medium-term (2026-2032). Items in the "ongoing" column are being done by at least one NMI or DI in Europe. Items in the "medium term" column may be planned by NMIs or DIs or may not be currently planned by any NMI or DI. If there is no NMI/DI in Europe active in preparing for that activity, then this is highlighted as a gap.

2 Roadmaps for Atmospheric Stakeholder Needs

2.1 Standards and calibration procedures for gases and particulate matter

Challenges:	**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 NO2). **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 N2O) 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. **Metrological support for field calibrations** and measurements, including guidelines for using measuring devices on site including environmental influences and their uncertainty contribution.
NMIs / DIs active:	VSL, METAS, LNE, NPL, INRIM, TUBITAK, VTT, MIKES-FMI
Key-stakeholders:	WMO-GAW, AGAGE, ICOS, ACTRIS
Overview	Four metrological challenges were combined here (listed above) since the response to them implies similar developments and concepts or common key-stakeholders and end-users. In this way NMIs/DIs can better identify existing gaps and take coordinated actions. The topics cover technical or organisational activities for chemical atmospheric parameters, measured in-situ, in particular relevant gas compounds and particulate matter. Some aerosol properties/parameters are also measured by remote sensing technics. These topics are covered in the section 5. Note that in some cases these needs and activities overlap with those relevant to the EMN on Pollution Monitoring (EMN POLMO). In those cases (e.g. aerosol property calibration, nitrogen oxide) we expect EMN POLMO to concentrate on applications related to air quality as well as focussing on stakeholder needs in this context, while this EMN considers the broader climate context.
Outlook beyond 2033	For aerosol calibration, the field calibrations represent a further challenge because of the complexity of the laboratory infrastructure that needs to be developed. Therefore, it is unlikely to be an active capability within the timescales of the roadmap below. In particular, a technical challenge will be for aerosol measuring devices including bioaerosol monitors for particle sizes up to 100 µm, because of their very low particle number and very large particle sizes.

Standards and calibration procedures for gases and particulate matter		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Coordinated engagement with key-stakeholders	• Participation in relevant working groups (e.g. WMO-GAW-VOC expert group). Active Involvement of key-stakeholders in the EMNs. (e.g ACTRIS, ICOS…) • Participation in TOARII (Tropospheric Ozone Assessment Report, sponsored by IGAC) together with ACTRIS members. • Build complementary engagement with aerosol communities, establishing collaborative metrology framework, taking advantage of DIs active in both communities • Coordinate with POLMO to create joint links with relevant stakeholders • Central Calibration laboratory designation (WMO-GAW) for relevant VOC and halogenated compounds.	Inclusion of radon calibration method in networks like ICOS and link to other data sources (EU JRC geological maps and online radiological measurements). Access to information on natural and anthropogenic GHG emissions and fluxes. Central Calibration laboratory designation (WMO-GAW) for other compounds lacking references
Development of CRM and fit-for-purpose working standard for gas components	• Development of working standards for VOC and NO_2 at atmospheric levels fulfilling quality objectives defined by measuring networks • Effort in the CCQM-GAWG to create a link between SI-traceability and the scale principle used in WMO (first with CO_2). • CRM for halogenated compounds (lacking accurate standards) and isotope composition (e.g. N_2O, CH_4) and very challenging/emerging compounds (e.g. oxy-VOC and formaldehyde).	Effort in the CCQM-GAWG to create a link between SI-traceability and the scale principle used in WMO (with other needed compounds according to stakeholders needs). Further CRM for halogenated compounds (lacking accurate standards) and emerging compounds.
Development of reference aerosols generators	Generation of source-specific reference aerosols (e.g. soot from diesel vehicles)	Generation of source-specific reference aerosols (e.g. related to aviation and shipping, and to simulate biomass and biofuel burning)
Development of reference methods for aerosols calibration	Development of methods for calibrating - black carbon monitoring instruments (light absorption) - optical and aerodynamic particle sizers (particle size up to 10 µm)	Further development of methods for calibrating: - black carbon monitoring instruments (light absorption and BC mass concentration)

	- PM monitors (PM2.5 and PM10 mass concentration)	- optical and aerodynamic particle sizers (particle size up to 50 µm)
Support for field calibration and real-air measurement	User-friendly tool for uncertainty assessment for real air measurement for VOC, including for instance sampling artefacts. (See also Table 6.2 on training) Development of procedures for field-calibration for reactive components	Development of metrological tools for the integration and comparison of real-air measurement techniques, including in-situ and remote sensing. Establish traceability chain for atmospheric low-level radon activity concentrations and develop transfer standard to provide calibration on-site.
European and international Partnership Projects	Participation in non-EURAMET calls.	Relevant participation in non-EURAMET calls (e.g. ACTRIS) Participation in non-EURAMET call scope definition or other "high-level committee"

2.2 Reference methods and instrumentation for humidity in the upper troposphere / lower stratosphere

Challenges:	**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 low air temperature).
NMIs / DIs active:	METAS, LNE, VTT, IPQ, PTB, NPL, INRIM, CNAM
Key-stakeholders:	GRUAN, GCOS, HMEI, radiosonde and water vapour sensor manufacturers
Overview	Water vapour represents a key greenhouse gas in the atmosphere; it is responsible for the global water and energy cycles on Earth. Accurate measurements of ground-based and airborne humidity, and of its profile in the atmosphere, are essential to support weather and climate change investigation and validate global observations from satellites. Radiosondes need SI-traceable calibration in conditions similar to those encountered in the upper atmosphere during sounding operations in terms of temperature, pressure and water vapour mole fraction to provide accurate humidity measurements, thereby minimising measurement bias or systematic error. Comparability is needed between the large number of different measurement methods which are used for measuring atmospheric water vapour including in-situ (e.g. radiosonde hygrometers, lyman-alpha sensors, frost-point hygrometers) and remote sensing methods (e.g. raman lidar, microwave radiometers). Comparability of results needs to take into account and correct

	for the correlation equations used to convert among the different quantities which can be used to express the upper air humidity.
Outlook beyond 2033	Realization of an Integrated European metrological infrastructure for the calibration of upper-air water vapour sensors in field conditions.

Reference methods and instrumentation for humidity in the upper troposphere / lower stratosphere		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Humidity references for UTLS conditions **($15 \cdot 10^{-9}$ mol/mol < x_w < 10^{-3} mol/mol)**	Reference gas mixtures for H_2O < 2 µmol/mol at UTLS pressure for lab calibration Standard humidity generator (-99 °C < T_{fp} < -20 °C; 200 hPa < p < 1100 hPa)	Metrology infrastructure for in situ calibration of upper-air water vapour sensors.
Aircraft observations	**Traceable and rapid atmospheric humidity measurements** Metrologically validated open-pass TDLAS H2O spectrometer (1st generation) onboard of atmospheric research aircraft (HALO). 2nd generation being developed.	
Comparability between water vapour methods	Involvement in WMO Radiosonde intercomparison campaign (2022/23)	Tools to establish the formal comparability and common traceability between atmospheric water vapour measurement methods.
European and international Partnership Projects	Participation in non-EURAMET calls.	Relevant participation in non-EURAMET calls (e.g. WMO-GCOS-CH) Participation in non-EURAMET call scope definition and other high-level committees to influence research direction.

2.3 GCOS surface reference network

Challenges:	Support the establishment of the surface reference network by the GCOS 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.
NMIs / DIs active:	INRIM, CEM
Key-stakeholders:	GCOS
Overview	Metrologists are nominated expert members and chairs of groups of the GCOS Task Team on GCOS Surface Reference Network. The network has been recently approved by the WMO EC and the implementation phase is progressing. Key topics: measurement requirements, uncertainty evaluation, support to sites certification processes, implementation of a dedicated metrology research infrastructure (including field sites and laboratories).
Outlook beyond 2033	Take part in the GSRN as permanent research infrastructure and experts in the Task Team during and beyond the implementation phase.

GCOS surface network		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Coordinated engagement with key-stakeholders	Participation in relevant working groups: TT-GSRN TT-GSRN SG1 (Lead Center) TT-GSRN SG2 (Governance) TT-GSRN SG3 (Requirements) TT-GSRN SG4 (Pilot stations and initial composition) TT-GSRN SG5 (Climate Reference stations) Collaboration with the launch of the Global Basic Observing Network (GBON). In the GCOS-WMO tiered approach principle, the GSRN is the top tier serving GBON and lower tiers as reference.	Continued participation in the TT-GSRN Support the implementation phase of the GSRN on matters concerning metrology and the certification of sites
Implement and make available a research	Identify appropriate site (compliant with WMO siting classification class 1), study instrumental setup	Make the research infrastructure a part of GSRN structure and promote studies on uncertainties,

infrastructure for the GSRN	and representativeness of the measurements	instrument change, improved measurement methods and the influence of siting conditions variations for climatological reference data.
Prescribe standards for measurements of climate reference data	Contribute to studies on defining standard reference instrumentation, for measurement methods, including evaluation of uncertainties. (TT-GSRN SG3) Take part in the preparation of GSRN regulatory material.	Support the evaluation of the use of standards in terms of their fitness for the purpose, during the implementation phase of the GSRN
Prescribe standards for the certification of the GSRN sites	--	Support the development of fit-for-purpose standards to be used in the certification of GSRN sites

2.4 Extreme environments and comparisons

Challenges:	**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**; 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.
NMIs / DIs active:	INRiM, CEM, JV, DTI, SMD
Key-stakeholders:	WMO GCW, WMO SC-MINT, SIOS, BIPM
Overview	Work in direct cooperation with the relevant expert teams and working groups of the identified stakeholders, to provide guidance and experimental support for improving data quality, traceability and comparability for physical measurements in extreme environments and key climate regions (e.g. High mountains, polar areas, and urban environments). This work relates predominantly to the measurement of the atmospheric ECVs, namely near surface temperature, pressure, water vapour (humidity), precipitation and surface wind speed. There is related work in the measurement of permafrost (see the Land section, Section 4.1). Satellite

	measurements of the polar regions and mountains are covered in the different roadmaps in section 5.
Outlook beyond 2033	Progress in supporting the revision, improvement and implementation of best practices, instrumentations and infrastructures for data quality in extreme environments. Extend the capabilities of existing calibration laboratories in Polar areas and plan new ones where the need is identified with the stakeholders. Continue to organize joint events as a common discussion/planning opportunity.

Field calibrations, comparisons, and extreme environments		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Coordinated engagement with key-stakeholders	BIPM WG Environment TG Air Temperature WMO SC-MINT WMO GCW SIOS (Svalbard Integrated Observing System)	BIPM WG Environment and TG Air Temperature WMO SC-MINT WMO GCW SIOS
Air temperature	Support the work of BIPM TG Air Temperature in a. Establishing a practical definition of the measurand for air temperature b. Identifying uncertainty components for air temperature measurements in all environments Drafting guidelines for the laboratory calibration of thermometers in air for these applications	Publish guidelines, definitions and best practices for air temperature measurements Guidelines for on-site calibration of thermometers
Precipitation	Calibration methods and references (rain generator) for non-catching rain gauges	Develop on-site and in-lab calibration facilities for non-catching rain gauges. Contribute to the CEN guidance document on non-catching rain gauges calibration.
High mountains	Implement research infrastructure/s for testing instrumentation and evaluating measurement uncertainties for mountain stations taking part in reference networks (Cryonet, GSRN, others). Progress in the use and improvement of on-site calibration	Improve research sites with metrologically characterised instrumentation (soil [See Table 4.1] and meteorological ECV).

	facilities and procedures for high mountains. Evaluate heat transfer phenomena in high mountain and periglacial areas, causing instabilities and rockfalls.	
Polar environment	Conclude the WMO intercomparison of thermometers and solar shield in the Arctic station. Progress the implementation and use of the Arctic Metrology laboratory.	Expand the implementation and use of the Arctic Metrology laboratory
Extreme climates	--	Supporting the definition, planning and conducting of comparisons of thermometers and shields in other extreme climates (different from the polar climate) and in areas with frequent extreme meteorological events.
Urban climates	--	Support the study of the main factors of influence of air temperature in urban climate. Conducting research activities for the definition of procedures for their evaluation

2.5 Improved metrological characterisation of spectral parameters

Challenges:	**Improved metrological characterisation of spectral parameters for chemical compounds** (e.g. absorption cross-section, spectral line).
NMIs / DIs active:	PTB, VTT, DFM, VSL, NPL
Key-stakeholders:	WMO, ESA, NASA, GRUAN, TCCON, NCEO, HITRAN, GEISA
Overview	The worldwide effort to track carbon sources using remote sensing technology has increased dramatically in the past years. Accurate spectroscopic parameters of the ECVs are vital to the success of remote sensing products and there is a need to improve performance to reach uncertainty levels from the sub-percent to sub-permil range. **1. Accurate spectral intensity requires accurate determination of many other parameters, such as effective path length, pressure, temperature.** Given the scope of this challenge, coordination of efforts between various research groups will be critical to success. Note that this is a longer-term challenge.

	2. Sophisticated line shape modelling is required for sub-percentage accuracy in retrieved amount fraction, for both line parameter retrievals and remote sensing retrievals WMO has stringent targets on atmospheric greenhouse gases compositions. There are several pressure- and temperature-dependent complications such as line mixing, collisional induced absorption. In the tropics, water vapour sometimes constitutes 4 % -5 % of the atmosphere. Collisional broadening of spectral lines by water vapour is much larger than that by air. Water vapour induced line shape parameters are needed to accurately characterize and model spectra of the tropical atmosphere. In summary, a fundamental understanding of the many mechanisms affecting line shape of the recorded spectra will require a variety of complementary high-sensitivity measurements and the development and validation of advanced spectroscopic models. **3. The widely used absorption cross section datasets from PNNL have only been validated for some selective molecules and bands.** Also, the PNNL datasets only cover **limited pressure and temperature combinations** thus fail to represent the entire range of atmospheric conditions. For polyatomic molecules, whose spectra are condensed, and not resolvable, cross section spectra are the only option for remote sensing retrievals. The work described here is of value for both in situ observations and remote sensing methods. See also roadmap 5.3.
Outlook beyond 2033	The longer-term vision is for uncertainty-quantified databases and the provision of SI-traceability within the scientific research groups working in this area – overcoming calibration barriers those scientific research groups currently experience.

Spectral characterisation		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Coordinated engagement with key-stakeholders	• Participation in CCQM-Task Group on Advanced Spectroscopy • Data entry to the GEISA 2020 database of six different molecules and their isotopologues • Pilot study on spectral parameters of selective molecules for laboratories aiming at sub-percentage to sub-permille accuracies • Case study with NCEO and NASA focusing on improving	Establishment of a scientific committee to organise regular meetings with remote sensing stakeholders

	the spectral parameters of the CO_2 thermal infrared bands	
Atmospheric Composition: Reference spectral line-by-line data of the primary greenhouse gases and air pollutants:	• Implementation of the reference spectroscopic infrastructures including FTIR, CRDS, TDLAS and comb spectrometers. • Measurements of reference spectra of the leading GHGs: CO_2, CH_4, N_2O; air pollutants: NO_2, NO, CO; as well as agricultural species, eg. NH_3 in the MIR and NIR regions. • Measurement of accurate band intensity ratios of different spectral bands of CO_2, CH_4 and N_2O to ensure data compatibility and comparability across different satellite observations. • Data entry to the GEISA and HITRAN databases for wider dissemination.	Other wavelength regions (as satellite measurements are also done in both the UV and VIS) Set up examples of high accuracy spectral data hosted at HITRAN or GEISA databases.
Atmospheric Composition: Reference absorption cross-section data of Halogenated-VOCs	• Engage stakeholders in workshop on uncertainty for remote sensing • Adoption of metrological absorption cross-sections of halogenated-VOCs to satellite retrievals e.g. limb-sounding ACE-FTS satellite sensors • Evaluating measurement uncertainties following GUM	Reference absorption cross-section data of other important polyatomic atmospheric species
Atmospheric Composition: Isotopically resolved spectral parameters of CO_2, CH_4, H_2O, N_2O	Metrological characterisation of optical isotope ratio spectrometer and application to the CCQM P204 CO_2 isotope ratio comparison. Stakeholder engagement in the Implementation of field deployable optical isotope ratio spectrometer (OIRS).	To establish an artefact-free primary standard on isotope ratio measurements for primary greenhouse gases
Modelling	**Classical molecular dynamic simulation of collisional induced effects** Spontaneous partnership with stakeholders including NASA(JPL), NCEO, CNRS(LMD)	Help to establish a rigorous uncertainty budget in HITRAN or GEISA databases or in its high accuracy derivatives. Rigorous and SI-traceable uncertainty budget in remote

	to study following minor but accuracy limiting effects: Sophisticated Line-mixing effects in the thermal-infrared bands of CO_2, Quantitative study of the critical intensity redistribution effects of CO, HCl, CO_2 and CH_4. **Harmonisation of spectral retrieval algorithms** Strategic partnership with stakeholder on spectral fitting between PTB and NASA/NECO/CNRS, to ensure comparability and compatibility of the underlying mathematics for spectral modelling and retrievals.	sensing retrievals using Monte Carlo simulation.
Air temperature	**Primary spectroscopic temperature measurement of gases** Develop primary spectrometric gas thermometry cross-validated against SPRTs, RIGT, DBT and noise thermometry aiming at <25 mK uncertainty	Practical spectroscopic thermometer for ambient air temperature measurements

3 Roadmaps for Ocean Stakeholder Needs

3.1 Establishing metrological traceability

Challenges:	**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
NMIs / DIs active:	LNE, PTB, INRIM, SYKE, NPL, CEM, SMD, IPQ, TUBITAK UME
Key-stakeholders:	IOC-UNESCO, GOOS, GOA-ON, MINKE Starting community

Overview	Metrological traceability is a key issue to ensure long-term comparability of measurement results. The oceanographic community deals with a wide variety of different quantities and uses very different techniques to measure the EOVs. Oceanographic research institutions are well organised in European and international organizations usually covering most EOVs. However, an institutional infrastructure to cover the metrological needs is not usually established within those structures. It is therefore essential that the different communities such as NMIs/DIs and oceanographic scientists put together their efforts to establish a metrological infrastructure to address the metrological requirements for EOVs. The table summarises the actions needed to ensure the long term comparability of ocean observation data and the metrological references necessary to cover the GCOS/GOOS quality requirements for the EOVs.
Outlook beyond 2033	Networking activities: • Creation of an EU Research Infrastructure consortium for metrology of oceanographic observations Research activities: Metrology in support of monitoring important EOVs of marine species abundance, marine biodiversity maps, mapping and classification of habitats such as wetlands, seagrass, kelp, coral, deep sea **(current gap in European NMIs/DIs capability, but request from our stakeholder needs survey)**

Establishing metrological traceability		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Coordinated engagement with key-stakeholders	Participation in relevant working groups and collaborative projects and involvement of stakeholder representatives in the EMN ocean section	Pave the way for the creation of a European Research Infrastructure to structure the community of the different actors actively involved in metrology for oceanographic observations, such as NMIs/DIs, oceanographic institutes, sensor developers and manufacturers, ...
Primary traceability	• Traceability of optical pHT measurements: definition of the measurand, definition of the traceability chain • SI traceability for Practical Salinity and standard seawater, including at high pressures • Development of gaseous primary and working standards for stable carbon isotopes	• Traceability for high-pressure pH measurements • Primary standards for TA by titrimetric methods • Realisation of gaseous primary standards for pCO2 by primary methods • Evaluation of the applicability of gaseous primary and working standards for the determination

	• Realisation of low frequency primary standards for ocean sound and calibration services for ocean acoustic instruments • Primary traceability of the thermometers used for sea water temperature measurements (SBE 35) for use at all depths in water. Currently, extremely low uncertainties are reported by manufacturers and end-users, which need underpinning metrology to validate. Building connections with communities and manufacturers to start conversations and understand issues.	of the stable carbon isotopes in seawater • Provision of traceability for acoustic standards for ocean conditions (ocean depth and temperature) • Primary method for DIC and suitable CRMs • Primary standards for DIC by coulometric method • Support the comparison and harmonisation of different sea surface temperature observation methods (in situ and satellite) at different depths. • Support primary traceability of the high-quality thermometers used as standards for sea water temperature measurements at surface and depth (SBE 35). Definition of procedures for the evaluation of influence parameters in the calibration of SBE35 and advanced analysis about the establishment of the most optimal calibration curve with associated uncertainties. Characterisation of the pressure dependence of the calibrations. Development of reference standards based on phase-change cells for calibration onboard ships during campaigns.
Development of CRM and fit-for-purpose working standard	• CRM TRIS/TRIS-HCl characterised for pH_T • CRM for total alkalinity • Calibration methods for dissolved oxygen using Winkler method	• Fit-for-purpose artefacts representatives of the marine sediment plumes (Particulate matter) • Development of calibration methods and facilities for optical and acoustical instruments for particulate matter.

3.2 QA/QC frameworks

Challenges:	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. Moving beyond **best practice guidance documents and standard measurement procedures** to international documentary standards, which can provide longer stability of measurement procedures over time.
NMIs / DIs active:	LNE, PTB, INRIM, SYKE, NPL
Key-stakeholders:	IOC-UNESCO, GOOS, IOC Ocean Best Practice System, EMODnet, MINKE Starting community
Overview	Oceanographic institutions have established QA/QC requirements to improve the quality of measurement data. The respective implementations, however, only rarely consider metrological principles to ensure long-term metrological comparability. Tools are needed to establish metrologically robust data to ensure reliable long-time observation (multi-decadal) of trends with associated uncertainties. There are needs to promote sharing of data, to improve data quality assurance and to practise good data management to help future-proof and secure valuable marine data. Agreed terminology and an agreed set of common standards for metadata, data format and content should be developed, maintained and supported through implementation by partners to facilitate international data exchange and ensure harmonisation of understanding. See as an example (in the UK) The Marine Environmental Data and Information Network (MEDIN). The table shows the actions needed to improve the quality of EOVs monitoring through harmonisation of protocols and definition of common guidelines for research methods and data acquisition.
Outlook beyond 2033	Adaption of the respective metrological QA/QC tools to next generation EOV-sensors and to digitized data collection and processing.

QA/QC frameworks		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Best practice guidance and standardisation activities	• Best practice guidance for QA/QC protocols for in-situ pH measurements • Protocols and guidance provided for joint projects on ocean noise monitoring • Validation of fluorescence sensors measuring in situ phytoplankton pigments (chlorophyll A and phycocyanin)	• Good practices and harmonized deployment protocols as well as quality control procedures for nutrient measurements • Feed into future ISO standards for ocean noise
Proficiency testing schemes	• Coordination of practical salinity comparison measurements within the framework of ISO 17025 accreditation • Provision of reference solutions and reference values for ILC as well as support to evaluate laboratory performances during ILCs • Proficiency test for both laboratory and field sensor measurements for Oxygen and Nutrients • Coordination of comparisons on the conductance ratio of (standard) seawater & practical salinity measurements with CTDs • Comparisons for performance of radiometers in field	• Development of a practical accreditation scheme, adapted to the diversity of the oceanographic community, to ensure the equivalence of in-situ CTD measurements.
Interoperability of databases	• Mapping the existing marine research databases (in conjunction with the MINKE community)	• Definition of common ontologies for marine data and guidelines for data collection and management • Establish connection with the European Open Science Cloud
Training	See section 6.2.	

3.3 In situ calibration and measurement uncertainties

Challenges:	**Development of a fit-for-purpose framework to calculate measurement uncertainties for in situ measurements of EOVs**. GOOS requirements set stringent target uncertainties for many of the EOVs which are close to the level of primary standards. In contrast to this demand, the oceanographic community is rarely aware of the metrological concept of measurement uncertainties and, consequently, the assignment of quantified uncertainties to measurement results is not well established. **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.
NMIs / DIs active:	INRIM, SMD, PTB, CEM, SYKE
Key-stakeholders:	OBPS, GOOS, EuroGOOS
Overview	The understanding of measurement uncertainty in the oceanographic community is rather heterogeneous. For a few EOVs and oceanographic institutions, it is similar to that in metrology. However, there is very often little awareness of uncertainty in the metrological sense. Uncertainty is considered rather as a matter instrument specification and qualitative QA/QC consistency checks of data. Moreover, metrological uncertainty calculation cannot simply be applied to in-situ ocean measurements for several reasons: Stable, repeatable, laboratory conditions cannot be realized in natural environments. Oceanography mostly deals with huge data sets. Field sensors may drift and often they cannot be recovered for re-calibration, if they are calibrated at all. Finally, in practice, oceanographers do not have the resources to spend many efforts on sophisticated uncertainty calculation, since they focus on their actual scientific and oceanographic tasks. Thus, metrology must develop easy-to-use methods for quantification of uncertainty in oceanography and establish quantified measurement uncertainty as the key quality indicator of EOVs, though considering oceanographic practice in particular.
Outlook beyond 2033	The oceanographic community is huge and rather diverse. The process of establishing quantified measurement uncertainties in oceanography for more than 30, rather different, EOVs will proceed beyond 2033. However, software tools should be developed for uncertainty quantification, based on self-consistency checks of huge data sets. This roadmap aims to take into aacount the parameters affecting the results of the measurements realised in-situ.

In situ calibration and measurement uncertainties		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Support for in-situ calibration and measurement	• In situ calibration of thermometers for surface and subsurface ocean temperatures • Establishing uncertainty associated with water temperature of oceans in in situ measurements • Standardisation of methods for sonar imaging calibration using standard targets	• Calibration methods and data processing techniques for sensor networks and gliders. • Deployment of next-generation ocean observation sensors and platforms • Development of a test bed for the calibration of Suspended Particulate matter measurement instruments • In-situ quantitative calibration of sonars to enable comparison between systems and enable quantitative imaging • Evaluation and validation of the factors of influence in in situ calibrations and verifications. Conducting studies and developing the corresponding procedures for the quantification of the influence of these quantities on the instrument under calibration
Uncertainty quantification	• Research in the quantification of uncertainty of in-situ temperature and salinity measurements using CTDs • Research in quantification of spectrophotometric pH_T measurements • Uncertainty assessment for in-situ sonar calibration and effect of ocean conditions (depth, temperature...) • Uncertainty of speed of sound measurements at high pressures in the context of TEOS-10	• Research in the quantification of uncertainty of absolute salinity measurements • Development of an uncertainty framework regarding progression of uncertainties into data products of ocean observation systems • Development of a methodology to quantify crosswise consistency checks of huge amount of measurement data in terms of measurement uncertainty
Representative sampling procedures	Extend water quality analysis to include sampling uncertainties	• Development of a methodology to address "representation uncertainty" of EOVs (whether for point measurements used to represent a volume of the ocean (e.g. for modelling), or

		sampling (removing samples) vs in situ measurement)
On site comparisons of instrumentation		• Definition and establishments of procedures for the comparison of instrumentation in in-situ ocean locations.

4 Roadmaps for in situ observations of land ECVs

4.1 Support for Land ECVs

Challenges:	**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.
NMIs / DIs active:	NPL, Aalto, INRIM, UT, TUBITAK UME, DTI, JV
Key-stakeholders:	ESA, Environment agencies, WMO, national meteorological organisations …
Overview	The land domain is host to most of humanity's activities and provides a significant fraction of the world's biodiversity. The land has a major role in the Earth's climate, particularly through the photosynthesis of plants, and the activities of humans. For many land ECVs, satellite observations provide the principal climate coverage and consequently the respective in-situ observations are included in Section 5: Remote sensing. For the other ECVs, the metrological challenges (see above) associated with them are relatively generic and not, in general, technologically demanding. At this stage we percieve the most critical ECVs as anthropogenic greenhouse gas fluxes to support inventory accounting, soil moisture and permafrost.
Outlook beyond 2033	Although we anticipate greater engagement with other ECVs as time progresses it is unlikely that the demands on the metrology community will require significant new or targeted research. More use of services, perhaps with some tailoring to specific sensor types and volumes needed for a specific community. Of course, the identified challenges will need to be addressed for these new ECVs requiring interaction and understanding of those measuring and utilising the information from relevant ECVs. .

Support for Land ECVs		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Establishing/evidencing traceability to SI	Some ongoing measurement work to attribute an emission factor to particular anthropogenic contributors, e.g. methane from animal farming, land use change etc is on-going and the consequential link to satellite-based classifications, as both emitters and sinks. International soil moisture network is undertaking work to create a fiducial reference measurement (FRM) capability (see table 5.2), and some research is carried out on new in-situ sensors and the means to calibrate others in a cost-efficient manner. NMIs providing guidance and establishing calibration capabilities for point-scale soil moisture sensors. Research into cosmic-ray neutron sensing methods and comparisons between approaches and with satellite observations. Similarly, for Permafrost, work to provide sensor calibrations in the field is also on-going	Whilst this work is likely to continue it will be incremental in nature as the development needs are reasonably well-understood at the uncertainty levels needed. New demands from other ECVs may emerge but it is not clear from where any significant research demand will come.

Documentary measurement procedures	For Permafrost, the publication of a "best practice chapter" within WMO guide 8 Build collaboration with the hydrology community to support linking them with WMO expert teams.	Support the evaluation of the use and implementation of the guide for permafrost measurements Hydrology - Work with hydrological community, through the WMO expert teams, in reviewing documentation on hydrological methods and measurement procedures to include metrological concepts on this documentation
Mathematical analysis to define representativeness of observation	In common with many networks or multi-point measurements there is a need to define appropriate mathematics and subsequently parameterise it for appropriate ECVs. The necessary maths is unlikely to be specific to land ECVs but the environmental effects that need to be accounted for will be. This kind of analysis is also being carried out for the same above examples	As above

5 Roadmaps for Remote Sensing

5.1 Pre-flight and on-board calibration

Challenges:	Pre-flight calibration standards and methods to enable SI-traceable uncertainties that are 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.

NMIs / DIs active:	NPL, PTB, VSL.
Key-stakeholders:	ESA, EUMETSAT, National Space Agencies (e.g. DLR, CNES, …) commercial satellite builders / operators, and industrial suppliers (e.g. Airbus, Telespazio, STFC-RALSpace, TNO and similar smaller organisations)
Overview	The pre-flight calibration and characterisation of satellite sensors is generally carried out at specialist facilities in industrial space organisations, although some NMIs have capability to calibrate components of such sensors. Therefore, what is usually needed is transportable reference standards and calibration facilities that can be taken to those specialist facilities. Such reference standards usually have more demanding requirements than other radiometric calibrations (e.g. large fields of view), while also needing state-of-the-art uncertainties. Only a small number of European NMIs are working in providing this type of calibration, which is appropriate for the specialised nature of these measurements. However, those NMIs have focussed on visible, SWIR and thermal infrared sensors and there is a significant gap for SI-traceable microwave radiometric sensor calibration and SI-traceable characterisation of active sensors. Here we consider both the pre-flight calibration of satellite sensors and the development of references to fly on the satellite for onboard calibration. Vicarious post-launch calibration is covered in Section 5.2. and the data storage, analysis and reporting of such calibrations are covered in Section 5.4. While we focus predominantly on the needs of the European Space Agency and its suppliers, we also consider calibration requirements for commercial and experimental satellites (small sats) developed by others.
Outlook beyond 2033	Satellites to be launched up to 2033 are generally already in development (at least for the ESA satellites) and therefore calibration needs are reasonably well understood. ESA is beginning the thinking for sensors to be launched in the 2030s. Radiometric sensors are likely to have a higher spatial resolution, requiring more accurate geometric calibration, as well as more spectral bands. Active sensors (SAR and altimetry) are limited mostly by the necessary atmospheric corrections, and this will increase the demand on on-board microwave radiometers, and therefore the need for microwave instrument calibration. It is also likely that there will be a greater dependency on constellations of small satellites and thus low cost, calibration methodologies.

Pre-flight and onboard calibration		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Pre-flight calibration radiometric sensors UV (<400 nm)	• Tuneable laser facilities for calibrations down to at least 260 nm are available although low in power but are needed to serve mainly atmospheric chemistry focussed missions; also, those observing the sun.	Further enhancement of laser powers and other Vis-SWIR calibration capability to UV wavelengths to meet demands of newer sensors.

Pre-flight calibration radiometric sensors Vis-SWIR (400 nm – 2500 nm)	• Development of tuneable-laser based transportable/in-house facilities for radiometric, spectral and geometric calibration of satellite sensors. Applications to MicroCarb, S3-OLCI, S3-SLSTR, TROPOMI. • Broadband in-vacuum reference sources for spectral radiance and narrowband reference sources with controlled wavefront curvature.	These methods will incrementally improve resulting in more automation and cost reductions. Of particular importance will be the SWIR where GHG sensors will become increasingly important.
Pre-flight calibration radiometric sensors TIR, THz and MW (> 3 µm)	• Ground based reference sources for spectral radiance up to 100 µm with uncertainties in terms of radiance temperature of less than 30 mK. • Emissivity measurements of cavity coatings, thermal design and optical ray tracing as well as characterisation and calibration of ground-based reference sources up to 100 µm to support FORUM. • Improved sensitivity to meet needs for higher spectral resolution sensors.	• Support organisation and analysis of TIR spectral emissivity measurements amongst all practitioners (not just NMI/DI) to facilitate harmonisation in both sensor and derived observations Develop ground-based SI-traceable reference sources and/or detectors for THz and Microwave sensors **(current gap in European capability).** The critical nuance is the evidenced SI-Traceability. • Develop ground-based emissivity measurements for such reference sources for the THz and microwave sensors **(current gap)**
Other pre-flight calibration and characterisation	• New sensors based on newer materials, few moving parts e.g. static FT require specialist calibration and characterisation capability	Development of techniques for new sensors as necessary for example active sensors, stray light etc.
On-board calibration references Vis-SWIR (400 nm – 2500 nm)	• Development of principles for onboard calibration capability of the TRUTHS SI-traceable satellite ($U < 0.3\%$) and developing capability for pre-flight calibration and characterisation of TRUTHS - Characterisation of diffusers. Replacement of tungsten lamps, lasers, LEDS	• Pre-flight calibration and characterisation of TRUTHS on-board calibration capability. Launch of TRUTHS. • Techniques to facilitate science quality 'low cost' cal of small satellites particularly those targeting net zero agenda
On-board calibration	• Development of on-board reference sources for spectral	• Flight of FORUM, IASI-NG incorporating new methods.

references TIR, THz and MW (> 3 µm)	radiance up to 100 µm with radiance temperature uncertainties less than 30 mK. Emissivity measurements for cavity coatings, thermal design and optical ray-tracing.	• TIR SITSAT (CLARREO (TIR) mission under consideration to fly requiring more robust on-board capabilities e.g. emissivity monitoring.
Other on-board calibration references	• Development of miniature phase-change cells for on-board traceability to the SI kelvin to calibrate adjacent temperature sensors	• Implementation in-flight of miniature phase-change cells and methods to evaluate emissivity changes in space
Satellites under development	• Development / design of: TRUTHS, FORUM, Libera (LASP) • Pre-flight calibration of: Microcarb, S3 OLCI and SLSTR, CO2M, S4/S5	• Development / design of: Sentinel (1,2,3,6) next generation instruments • Pre-flight calibration of: TRUTHS, FORUM, Libera (LASP) • GHG sensors

5.2 In situ measurement networks

Challenges:	**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 for all technology and application domains. **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.
NMIs / DIs active:	NPL, PMOD-WRC, PTB, Aalto, UT, MIKES-SYKE, MIKES-VTT, MIKES-FMI,
Key-stakeholders:	ESA, Copernicus, Academia, Gov/EU Environment agencies, WMO, Eumetsat…
Overview	Natural and artificial Earth reference targets are used for the in-situ validation and calibration of active and passive satellite sensors. The fiducial reference measurement (FRM) sites are sites that are SI-traceable and validated through comparison. The term "FRM" is used by ESA and the Copernicus Information Services. For active radar sensors, point-source emitters and corner-cube reflectors are used, along with artificial reflectance targets that test instrument parameters. For passive sensors in the solar-reflective spectral region, a broad range of natural and artificial sites are used for both geometric and radiometric cal/val. The natural sites include desert, ocean and vegetated sites, as well as use of the moon and atmospheric phenomena. NMIs and DIs support the operation, characterisation, comparison and uncertainty analysis for such sites, as well as the analysis of satellite-to-ground and satellite-to-satellite comparisons over such sites. For radiometric sites in the visible and SWIR spectral region, there is significant effort to

	reduce uncertainties associated with the ground and top-of-atmosphere of such sites from the typical 3% - 5% level to the 1% level needed for climate purposes. Such a transition requires the increased application of metrological approaches.
Outlook beyond 2033	Once TRUTHS is launched in ~2029-2030, it will make SI-traceable measurements of such sites from orbit with top-of-atmosphere uncertainties around 0.5%. This will be a game-changer (for the UV-SWIR spectral domain) in how such sites are used for the intercalibration of satellite sensors as they will act as transfer standards for the TRUTHS calibration. Increased emphasis will be placed on the creation of supersites capable of addressing multiple parameters, methods to autonomously maintain SI-traceable uncertainties for field measurements at these sites using minimal instrumentation will be critical. It is likely that increasing use will be made of hierarchies of in-situ sites with low cost networks providing spatial information anchored by 'good-quality' reference sensors.

In situ measurement networks		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
FRMs for Atmosphere viewing sensors	• Improvements underway for improved characterisation of sensors for e.g. aerosol optical depth, sky radiance, atmospheric composition particularly GHG emissions and ozone, UV-TIR largely evolutionary methods, Earth energy balance	Increased accuracy but also lower cost with a particular emphasis on GHG monitoring to support the stocktake
FRMs for Surface viewing sensors	• Incremental improvements in brightness temperature sensors reducing impact of localised environment on observations and creation of autonomous networks like RadCalNet of LST. • Increased autonomy and spectral content for surface reflectance, e.g. the HYPERNETS sensors and networks • Establishing a European reference for Ocean Colour validation	• High spectral content for hyperspectral sensors (CHIME, Flex etc). • Capabilities to meet needs of BioMASS mission and natural carbon sinks. • Land product/surface reflectance CEOS FRM network and LST established
FRMs for active sensors (radar)	• Establishment of FRM programmes with uncertainties for inland water, land ice and sea ice altimetry applications	• Lidar, broader SAR

Sampling representativeness in creating and using FRMs	• Formal networks of FRM quality sites with robust protocols, currently covering eight different parameters for satellite validation including vegetation, surface Temperature and GHGs • Use of Drones for sampling • Studies to consider optimal weighting strategies and representativeness e.g. view angle differences to satellites	• Increased number of FRM sites both for existing parameters and for increased range of parameters. • Autonomous drones (or similar) together with low-cost wide distribution of sensors • Ability of sites to provide sufficient accuracy to allow climate stability monitoring to be undertaken aligned with GCOS requirements.
Comparisons to evidence SI-traceability	Formal community comparisons for surface temperature, reflectance (water & land), land products, AOD, TSI with in-built SI-traceability (NMI/DI participation)	Increased number of parameters, and regularisation of comparisons with databases such as MRA
Data science methodologies for linking FRMs to satellite observations	See also (Section 5.3). Developing site models for FRM sites (covering BRDF, radiative transfer, retrieval) for solar-reflective satellite products	Site models for broader range of FRM sites, including for surface temperature sites and sites used for active sensors. Synergy of active and passive sensors.

5.3 Uncertainties in models and algorithms

Challenges:	**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.
NMIs / DIs active:	NPL, PTB, Aalto
Key-stakeholders:	ESA, Met Office, ECMWF, EU, Eumetsat, WMO, Environment agencies...
Overview	In climate and ocean observation, modelling is crucial. Models are used to interpret observations, to compare different types of observation, transform measurands to bio-geo-physical parameters, to bring observations into reanalyses and to test climate prediction models. Modelling approaches can be physically-based (I.e. the model is attempting to represent the underlying physics) or not. Non-physical approaches include techniques such as neural networks, regressions, etc. Understanding the flow of uncertainty through

	these models is often a tricky task, particularly when the model is not open source. This is because they can be highly multi-dimensional and the sensitivity coefficients between the inputs and outputs can be hard to determine. A second confounding factor is that models can predict physical quantities that cannot be measured in reality. For example, the direct path radiance at a specific height in the atmosphere can be modelled (and does exist) but measuring that same quantity is impossible without including some of the diffuse illumination. This makes validation of model outputs difficult/impossible in certain cases. A third factor is the consideration of uncertainty of influencing parameters that a model does not consider. Put another way, it is the uncertainty of the implict assumptions of the model.
Outlook beyond 2033	In this time horizon, computing power will allow much more sophisticated models with fuller paramaterisation and more complete physical representation. It is anticipated that many models will run in near real time and allow much more rigorous uncertainty analysis which the user community will be requesting, particularly in relation to the global stocktake and national inventories. This will also include climate and reanalysis models outputing anticipated observations rather than converting or assimilating ovservations into models

Uncertainties in Models and algorithms		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Utilising models for Validation and sensitivity analyses	• Use of observations to validate models and their use for satellite validation and product definitions – 3D Radiative transfer codes and parameterisation through digitised observations for land products. • Testing of RT code with physical measured artefacts. • Assess criticality of key parameters in complex models such as Global circulation Models for climate prediction – sensitivity of parameters can be used as an observation to test validity of model e.g Cloud radiative forcing	• Widespread adoption of 3D models at validation sites for assessing modelled differences. • Creation of representative models and propagation of uncertainties from application driver to observation as default.
Reporting of uncertainty from modelled datasets	Storing of uncertainty and covariance information in metadata through effects tables (e.g. Fiduceo style). Ensemble model predictions provided.	Harmonised methods for storing and reporting of error sources and uncertainty contributions in metadata that is tagged robustly to data sets.
Accounting for uncertainty in assumptions	Fiduceo (+0); Rigorous assessment and accounting for all sources of	Internationally agreed methods formalised

	uncertainty and where not available evidence for attributed values.	
Uncertainties through learning-based approaches (eg. continually learning NNs)	• Assess uncertainties through sensitivity analyses. • Initial collaboration with Mathmet EMN in this area.	International protocols on testing and reporting uncertainties in ML and NN etc. developed in Mathmet and applied to climate observations.
Reanalyses	• Establishing techniques for the consistent treatment of uncertainties in observations and those of the model predictions • Treatment of covariances, representation uncertainty	Agreed best practises and toolboxes to allow consistent treatment of uncertainties.
Development of models based on metrological principles	• Eradiate RT code developed on physical model and documented to provide full detail of uncertainty assessment • Atmospheric correction code under development for TRUTHS with full Si-traceability and uncertainty assessment	Best practices established on the development and test of models to meet metrological principles.
Retrieval algorithms	Support the development of and assessment/reporting of uncertainty of retrieval algorithms. • Work in progress related to satellite retrieval of GHGs (CO_2 and CH_4) including the necessary spectral signatures/cross-sections (see section 2.5). • Activities on atmospheric composition from airborne limb sounders. • Land products, surface reflectance and derived quantities such as land use classifications	Increased computing power will allow more rigorous algorithms and uncertainty propagation. Techniques will become more visible and start to be widely adopted as part of new QA reporting practices which will be recommended by space agencies etc

5.4 Metrologically-based QA framework

Challenges:	**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. **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).
NMIs / DIs active:	NPL, PTB, PMOD, UT
Key-stakeholders:	ESA, EU, Environment agencies, Eumetsat, climate service users (e.g. insurance sector)
Overview	Over the last decade there has been a significant increase in the demand for harmonised, internationally-consistent data and, with it, practical implementable QA frameworks. In 2010 CEOS created the QA4EO whose principles are now widely adopted. These principles are not radical and are based on sound metrological approaches, but their specific linkage to EO (in the broadest sense) data and their applications has meant QA4EO is widely adopted. Subsequent to the creation of QA4EO, there have been numerous projects to develop strategies that can optimally implement the principles especially from the EU e.g. QA4ECV, Gaia-Clim, Fiduceo and several variations and follow-ons with ESA and Eumetsat. WMO already operates a QA framework for its observational programes. The main challenges now lie in how to optimise the implementation and reporting of the key elements of a QA programme, so that it can be readily interpreted by a non-expert user and does not significantly overcomplicate or drive up costs where not necessary. The overall aim is to develop strategies and methods to allow uncertainties (assessment of confidence) to be determined and propagated from observation through to information derived from multi-decadal data from multiple observing platforms, ideally certified as trustworthy.
Outlook beyond 2033	Great strides towards achieving a fit for purpose QA framework have been achieved, so an integrated climate observing system composed of satellite and in-situ observations delivering information on demand to meet the needs of society is a reasonable ambition. Such an observing system would be expected to have appropriate analytical tools to facilitate intergration, interpretation and creation of services through AI and other digital manipulation which will monitor mitigation and adaptation strategies but also allow litigation.

Metrologically-based QA framework		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Development of bespoke community-specific QA reporting framework	QA4EO (ESA and CEOS frameworks), C3S, ESA EDAP and CEOS CARD4L, FIDUCEO like methodology are now being incorporated in many ESA and Eumetsat projects with NMI/DI involvement being recommended. Each project extends concepts to new technical areas, with application to vis-TIR radiometric sensors as well as development of methods for active sensors and microwave sensors. FRM programme (see Section 5.2) is following similar methods and also obliging NMI/DI involvement.	Operational QA framework becoming implemented within at least the European space sector. This will include operational funding for FRMs and climate data, e.g. through ESA's new climate space programme and Copernicus. These will have major impact particularly focussed on climate mitigation, adaptation and stocktake.
Participation of observational networks in formal QA processes of metrology and ISO/WMO structures	Development of ISO/WMO-certified standards for observational networks. Establishment of CMCs in the KCDB for climate-specific parameters	Ongoing development of standards and CMCs, participation and extension of network involvement.
Methods to remove impact of biases and gaps in data sets and time series allowing interoperability	• Tools and strategies to assess time series and combination of data sets are underdevelopment: WMO networks, TSI, CDRs and FDRs. • Methods to assess and remove biases from satellites are under-development using infrastructure such as PICS, RadCalNet, moon, and other Cal/Val infrastructure. Atmosphere TCON stations and others • GAIA-Clim, QA4ECV and FIDUCEO all developed case studies on creating CDRs.	Operational infrastructure to deliver harmonised EO data for at least optical domain established – utilising outputs of SITSAT missions together with other test-site infrastructure. Activity to expand to cover all technical domains at uncertainty levels needed for climate will likely be on-going. Effort to build long time base records from heritage as well as new sensors will continue to be a major focus.
Certification schema	ESA project starting to evaluate prototype schema for certifying the quality of commercial services.	Towards the end of the period an operational 'certification' system will be in place for not just commercial services but also EO/climate products as a whole. It is likely that any certification

		system will be international but likely to start in Europe, greater regulatory heritage, as a demonstrator. Products/services related to GHG emissions and AFOLU are likely to be the starting point.

6 Roadmaps for general metrology challenges for climate and ocean observations

6.1 Historical data and low-cost sensor networks

Challenges:	**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. **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.
NMIs / DIs active:	NPL, METAS, LNE, IPQ, PTB
Key-stakeholders:	WMO data rescue experts, ESA Long Term Data Preservation Programme, Climate and Clean Air Coalition, Meteorological organisations, organisations collecting "citizen science", e.g. Met Office Weather Observation Website
Overview	Both historical observation data and low cost sensor networks are examples of the use of observation data that has not been originally developed to meet the rigorous modern-day requirements of a climate study, but which potentially has valuable information for climate science. However, the two approaches are fundamentally different, and so are treated independently in the table below. Historical observation data are extremely valuable for climate reanalyses and for developing climate model studies and include 19th century meteorological observations and ship records, used originally to monitor the weather and for navigation, as well as satellite data from the 1960s-1990s, where satellites were also predominantly used for weather forecasting, but we now wish to get climate-quality information from them. The WMO-CCI is coordinating the reuse and preservation of historical data. In satellite Earth observations, the ESA Long Term Data Preservation programme is also a leading activity. Low cost sensors are defined here as sensors that are 10× or more cheaper than reference sensors and usually also smaller in size, mass and power consumption. In general they are used for near-real time applications and are often considered as integrated in characteristics by the network, rather

	than as individual sensors. We include low cost meteorological and air quality sensors and small often commercially funded satellites. Such sensors are generally not calibrated individually and need to be considered as a network.
Outlook beyond 2033	We expect to see a wider range of low-cost sensors deployed and more creative use of sensors initially deployed for other purposes.

Historical data and low-cost sensor networks		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Historical meteorological and navigation sensor analyses	• Collaborative work with data users and providers on how to assess uncertainties in 100-year near-surface air temperature records (individual station and averages) • Collaborative work on bias corrections in historical radiosonde measurements, including application of adjustment factors from the reference network and derivation of uncertainties in homogenised data sets.	
Historical satellite data analyses	Research projects to establish fundamental data records from satellites over 30+ years	
Paleoclimatology		Initial collaboration with paleoclimatology community **(current gap in European NMI capability)**
Low-cost sensor networks of physical atmospheric measurements	Establishment of experimental meteorological stations to compare sensors of different types. Running comparisons of sensor technologies. Preparing guides on characterisation and calibration.	

Low-cost sensor networks of atmospheric composition measurements	Development of fit-for-purpose setup and guidelines for the characterisation and calibration of LCS. Running comparisons of sensor technologies. Collaborating with sensors manufacturers and end-users. For city emissions applications, to collaborate closely with the EMN POLMO; drone-based measurements. Engage with standardisation committee for guidelines on low-cost sensors characterisation/validation	Further development of low-cost sensors and their calibration approaches in closer collaboration with community (manufacturers and users)
Low-cost sensor networks – data science	Data science techniques for processing low-cost sensor networks to support cross-comparisons and network calibrations, including traditional and artificial intelligence methods. To develop generic methods that allow for a metrological treatment of distributed sensor networks.	Application of techniques in specific networks Accuracy vs completeness (representativeness analysis). To develop machine-interpretable and metrology-aware descriptions for sensor networks using semantics and ontologies
Low-cost satellite sensors and satellite constellations	QA processes for low-cost satellite sensors – supporting space agencies on how to incorporate commercial satellite sensor data into their products Hypernets sensor and similar sensors for low cost in situ FRMs.	Development of techniques for the automatic calibration of satellite constellations using reference sensors and artificial intelligence
Re-use of data collected for other purposes	The low-frequency ocean acoustic data collected by the CTBTO in support of the test ban treaty may be used for climate-related oceanographic research such as ocean acoustic thermometry (data is available real-time and historically for up to 20 years)	Improved understanding needed of environmental influences on acoustic propagation over ocean basin scales.
Citizen Science		Metrological analysis to assess fitness-for-purpose of citizen science inputs cf higher accuracy, less distributed references, data science methods (similar to low-cost networks) to identify outliers

6.2 Training, vocabulary and frameworks

Challenges:	**Defining vocabularies and data-science ontologies** for key metrological concepts. Working within the communities to make metrological vocabulary more consistently used, 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. **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.
NMIs / DIs active:	NPL, LNE, PMOD, UT, INRIM, IPQ, SMD, TUBITAK UME, CEM
Key-stakeholders:	WMO, ESA, CEOS, GCOS
Overview	One of the most common requests from our stakeholder survey and commonly given in metrology and observation workshops is for training in both instrumental techniques and in uncertainty analysis. Most communities such this training to be tailored to their specific applications so developed in collaboration with each community. It is important that we connect the training that we develop for these applications to generic training developed for example through EMN Mathmet. As well as generic training there is a need to support the standardisation of a metrological vocabulary for observations. Terms such as “error” and “uncertainty” are often not used correctly. And concepts such as “interoperability”, “harmonisation”, “representation uncertainty” etc are not systematically defined. Metrological concepts are also not well defined in community ontologies and metadata standards. Such training and standardisation is not just one way – as a metrology community we have to learn how to adapt and interpret our metrological principles to apply to the challenging observation applications. This is particularly important for data sets that have been derived by combining observations with models. Some communities have established strong community guidelines that are treated as de facto standards for observational processes. Other communities are considering formal standardisation through organisations such as ISO, such as the CEOS Analysis Ready Data for Land community. Others are only beginning to make informal recommendations. Metrology institutes are supporting such efforts through active participation in those community discussions.

Outlook beyond 2033	It is likely that the need for training, formal definition of metrological concepts and particularly the application of principles to derived data products will only expand over time. Applications to data sets derived from machine learning methods will expand.

Training, vocabulary and frameworks		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Improving community awareness of metrology	Progress with the MINKE community in the creation of a research infrastructure for marine metrology, contributing to atmospheric monitoring networks with reference laboratory function when needed … promotion through EU projects, ESA and international community committees e.g. CEOS QA4EO, WMO etc as well as tradeshows and general articles for trade media.	Extend regular and active participation of NMI/Di's generally in non-EURAMET calls and in the communities that establish the Horizon Europe, Copernicus and ESA calls.
Training in instrumentation and calibration techniques	• Contribute to guidance material in tender specifications, to avoid misinterpretation of terms such as accuracy, precision, resolution etc. between manufacturers and real on-site use performance. • Support community comparisons • Provide training to communities (VOCs, solar irradiance, thermometer calibrations, ocean pH, humidity, satellite ocean colour, surface temperature, reflectance, land product …), regional bodies, (training is a required part of FRM projects) • Supporting institutes in getting accreditation	• Coordination of training activities to benefit from each other's experience • Extension of training to more communities • Increased on-site training • Collaborating with capacity building programmes by organisations like GOA-ON with supporting training materials especially for developing countries
Training in uncertainty analysis tailored for communities	• Establishing links to ongoing efforts by EMN Mathmet for generic uncertainty training courses • Establishing a metrology training programme on the CEOS CalVal Portal for Earth	• Other tailored uncertainty documents, examples and training? • Case studies for the GUM websites tailored to these applications

	Observation practitioners (cross links to EMN website) • Train NMI/DI community in standardised methods so that they can be used consistently	
Formal definitions of key vocabulary and ontologies	• Participation in the CEOS task Group on Terminology • Contribute to the preparation of the WMO Standard Vocabulary • Support use of VIM by WMO, CEOS, IOC and others. • Making EO data Findable, Accessible, Interoperable and Reusable (FAIR) both for machines and for people	• Bringing metrological concepts into the ontologies of the "Climate and Forecast Convention" standard names • Discussion on formal metrological concepts in the interface between observations and numerical weather prediction and reanalysis models
Supporting standardisation frameworks for ECV measurements	Ocean, see roadmap 3.2 Satellite Earth Observation, see roadmap 5.4	
Uncertainty assessment in models		Engage with climate modelling community to ensure regular climate model intercomparisons (CMIP 6) are metrologically robust

6.3 Societal risk: metrology to decisions

Challenges:	**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.
NMIs / DIs active:	NPL, SMD
Key-stakeholders:	Insurance industry, Governments, UN, Decision makers generally, WMO Commission for Service, Copernicus Climate Change Service
Overview	When observations (of both the climate system and of anthropogenic emissions and land use changes) are used to inform the policy of governments and of commercial companies, there is a translation from measurements and models to economic concepts such as "likelihood" and "risk". This translation has to be informed and traceable and also provided in a way that is meaningful to governments, economic markets and companies. Within such processes, it is important that metrological concepts such as "uncertainty" can also be translated into ways that decision makers can understand. The IPCC uses a defined vocabulary to describe both uncertainty and confidence, but there is considerable criticism of these terms. Work is needed to consider how concepts of measurement uncertainty, as

	well as the confidence in models and model averaging, inference and 'expert judgement'/'expert elicitation' can be expressed in ways that are readily understood by decision makers.
Outlook beyond 2033	As this is an area that is quite new for the NMI community to engage with, we do not yet have a clear vision of what might be needed long term. The ongoing and medium term activities will help define the long term opportunities

Societal risk: metrology to decisions		
Theme	**On-going (2022 - 2025)**	**Medium term (2025 - 2032)**
Development of case studies that show how observation links through to real world applications	Small numbers of case studies, mostly in Earth observation area, showing link between societal application and metrological challenge, e.g. in sea level rise looking at the trend requirement from climate science perspective and then the measurement and model uncertainties to identify what part of the process needs improving.	Considerable opportunity for metrology institutes to work with experts on such case studies, following similar frameworks. Topics not yet identified, and very little current European NMI activity.
Participation by metrologists into description of uncertainty for decision makers	Participation in IPCC committees working on uncertainty topics.	Current gap in European metrology capability
Participation by metrologists into discussions of societal definitions of uncertainty and risk	Early-stage participation in committees that are establishing key concepts and terminology.	Work with communities
Collaborative projects with insurance and similar organisations	Some work started to investigate how uncertainty impacts risk critical sectors, with insurance community most receptive and understanding of the value of quantification of risk and the criticality of data to populate and validate models	Current gap in European metrology capability
Metrology support for climate adaptation measures	Early studies and workshops to establish role of measurement and metrology in climate adaptation	Continue and extend efforts in this area

EURAMET e.V.
Bundesallee 100
38116 Braunschweig
Germany

Phone: +49 531 592 1960
Fax: +49 531 592 1969
E-mail: secretariat@euramet.org

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