1st Stakeholders' Meeting of the CIPM Sectorial Task Group for Climate Change and Environment

SUMMARY OUTPUTS

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1. Background

The 26th General Conference on Weights and Measures (CGPM), the plenary and policy-making body of the International Bureau of Weights and Measures (BIPM), in 2018 requested the International Committee of Weights and Measures (CIPM), the BIPM's non-plenary executive organ, with a policy-making function, to prepare a long-term strategic view to underpin the development of the BIPM and to identify the highest priorities for improved metrology.

Following this recommendation, the CIPM prepared an initial overview of some of the most important evolving needs in metrology with the intention of making recommendations on how to increase the international coordination role of the CIPM to address these needs; in particular to find mechanisms that reflect the multi-disciplinary nature of these "Grand Challenges", such as the changing climate and broader environment.

This overview was presented at the 27th meeting of the CGPM (2022) and the CGPM encouraged the CIPM to establish inter-disciplinary ("horizontal") groups to address the new challenges to complement the existing quantity-based ("vertical") structure of its Consultative Committees (CCs).

In September 2022, the joint BIPM-WMO workshop "Metrology for Climate Action" was held online. More than 1 000 scientists from around the world participated in the workshop and cooperated to provide a joint report summarizing a set of recommendations (https://www.bipmwmo22.org/). One of the main recommendations to the BIPM and World Meteorological Organization (WMO) was to continue to deepen the level of collaboration between both organizations, which would allow for more effective coordination on work on metrology and climate observations to address common goals and responses.

In response, the CIPM established the Sectorial Task Group on Climate Change and Environment (CIPM-STG-CENV) consisting of CIPM members and representatives of CCs that are already active in the field, representatives from the Regional Metrology Organizations (RMOs) active in climate change and environment together with representatives from the WMO and Global Climate Observing System (GCOS). The CIPM-STG-CENV aims to be an entry point for the stakeholders needs and as a facilitator of connections between the different active groups in the climate and metrology communities.

This objective is fulfilled by providing a global liaison point for metrology activities related to climate change and environment, advising the CIPM, liaising with Consultative Committees, RMOs and International Organizations with climate change and environmental programmes that are dependent on metrology. Other key activities of the group are to document and monitor internationally agreed metrology challenges, that is the objective of this report, and to encourage collaboration between the established working groups and the stakeholders to address these challenges.

2. Objective of the 1st CIPM-STG-CENV Stakeholders meeting

The main objectives of the 1st CIPM-STG-CENV stakeholders meeting have been the following:

- Compilation of an overview of activities that are being undertaken to address recommendations from the BIPM-WMO 2022 workshop
- Identification of the organizations, committees and groups that are coordinating activities to address recommendations from the BIPM-WMO 2022 workshop
- Identification of the recommendations from the BIPM-WMO 2022 workshop where no activity has been initiated and the reasons why it has not been done
- Compilation of an overview of new collaborative activities initiated between the observation and metrology communities
- Identification of new initiatives that could be progressed through collaborative actions between the observation and metrology communities, and the groups that could coordinate this work
- Identification of any new actions to be undertaken by the CIPM-STG-CENV, with a focus on those actions that cannot be addressed by existing structures, which would enable progress to be made in addressing the BIPM-WMO 2022 workshop recommendations and new initiatives.

In the next sections the main outputs of the meeting are summarized and organized along two major themes, in the same way as the 2022 workshops, covering multiple topics within each theme.

Theme 1 addressed 'Metrology in support of the physical science basis of climate change and climate observations'. The theme covered metrology in support of the scientific understanding of the physical science basis of our planet's past, present and future climate. It included the metrology associated with measurements used for monitoring the climate system and included both, *in situ* and remote measurement techniques (including ground-based, seawater, airborne, and satellite remote sensing) together with metrological techniques to propagate uncertainties from the measurements through to products derived by data integration, modelling, data assimilation and other Earth system models. It encompassed activities that focus on detecting variability and supporting the understanding of the climate system, including multi-decadal observations to detect climate trends. In many cases these are global-scale phenomena but there is an increasing interest in regional manifestations and thus a need for local/country level information. The specific topics covered within the theme were:

- Atmospheric chemistry and physics
- Ocean and water chemistry and physics (including hydrology)
- Earth energy balance
- Biosphere monitoring
- Cryosphere monitoring.

Theme 2 of the workshop addressed 'Metrology as an integral component of operational systems to estimate greenhouse gas emissions based on accurate measurements and analyses'. The theme covered metrology in support of monitoring and mitigation of greenhouse gas (GHG) emissions and natural sinks. It included the targeting, quantifying and tracking trends of emissions across local, regional, continental and global scales and the measurements that can

improve national and sub-national emission information and inventories. It encompassed activities that focus on measurement data and tools for mitigating anthropogenic forcing and attributing emissions across a range of geographic scales (for example, sub-urban scales to national scales) and measurements required to monitor land-use, land-use change, and forest (LULUCF) fluxes and urban fluxes. With the growing global effort to mitigate GHG emissions, new practices and technologies are being developed to reduce emissions and draw down legacy emissions and ultimately account for the carbon footprint of products. In each of these cases, there is a growing need for metrology to underpin the carbon emissions and/or removal. The topics covered within the theme were:

- Accuracy requirements for atmospheric composition measurements across economic sectors, and temporal and spatial scales
- State of play in integrated approaches for advanced GHG emission estimates and the way forward to operational services
- Novel GHG concentration and flux methods and sensors
- Strengthening the linkage of remote sensing GHG concentration measurements to emission fluxes
- Identifying emerging metrology needs associated with GHG emissions reductions and removal and associated impact of these activities.

3. Theme 1: Metrology in support of the physical science basis of climate change and climate observations

3.1. Cross-cutting recommendations

This session was chaired by Dolores del Campo (CEM).

Progress since 2022

Some progress was reported in response to the common challenges detected in 2022, in particular:

- Importance of Calibration and Validation (Cal/Val): The Committee on Earth Observation Satellites (CEOS) Working Group on Calibration & Validation (WGCV) described activities in response to the multiple needs identified in the 2022 workshop report. It emphasizes the critical need for harmonized Cal/Val approaches to ensure the accuracy and quality of Earth Observation data and its efforts to establish such approaches. Harmonized Cal/Val is crucial for enhancing the interoperability of data from various satellite missions.
- Fiducial Reference Measurements (FRM): The concept of FRM were developed in recent years to provide reliable measurements that are suitable for use as references for calibrating and validating Earth observation satellites. These measurements are designed to be highly accurate, traceable to international standards and tailored to specific measurement validations for a class of satellite missions. FRMs help ensure that satellite data can be compared and used interoperably across different platforms, which is vital for long-term climate observations and other environmental applications. Detailed guidelines on how to establish 'CEOS-FRM' have been published in collaboration with metrology institutes. Efforts have begun to connect CEOS-FRM with the WMO reference networks, the latter classified according to the GCOS requirements

for a tiered system of networks that are suitable as references for climate studies. Initiatives such as FIDUCEO have worked well on the scale analysis for the uncertainties in support of different climate studies and applications.

- Challenges in Interdisciplinary Communication: the challenges posed by inconsistent terminology across different disciplines within Earth sciences were highlighted. Miscommunications arising from varied use of terms can hinder interdisciplinary collaboration. The CEOS task group on terminology has made clear recommendations for establishing a cross-disciplinary vocabulary and is working on developing a common vocabulary to improve communication and interoperability in Earth sciences. Requests were made to connect these efforts with efforts relating to the International Vocabulary of Metrology (VIM). However, there is still a need to work on a more accurate translation of the VIM metrological concepts to the climate science community.
- Metrology's Role in Climate Action: Metrology, the science of measurement, plays a vital role in supporting climate actions. The PTB's "Innovation Cluster Environment and Climate" is an example of how a metrology institute can coordinate its efforts to increase its impact. Metrology ensures that data used for climate indicators and assessment of climate models is reliable and traceable to recognized standards. This allows the models to become relevant for policymaking.
- Global Collaboration and Standards: The importance of global collaboration in establishing and maintaining quality standards for Earth Observation was stressed. The work of organizations like CEOS and their promotion of frameworks like QA4EO (Quality Assurance Framework for Earth Observation) is fundamental to achieving consistency in data quality across different countries and missions, enabling more effective global climate monitoring and response strategies.

Collaborative efforts

CEOS is developing activities regarding CAL/VAL harmonization and vocabulary, including ensuring measurement stability and continuity of long-term timeseries and developing approaches for the harmonization of data records. CEOS has also made efforts in developing guidelines on applying metrological uncertainty assessments (GUM) to Earth observation, as well as defining standards for CEOS-FRM that encourage metrological approaches.

GCOS is responsible for the reference networks (GCOS Reference Upper-Air Network (GRUAN) and GCOS Surface Reference Network (GSRN)).

New collaborative activities

Some collaborative activities were presented:

- CEOS and their promotion of frameworks like QA4EO (Quality Assurance Framework for Earth Observation) is working to achieve consistency in data.
- CEOS WGCV is instrumental in promoting metrology principles to improve the quality of measurements from both space- and ground-based calibration and validation (Cal/Val) activities.
- Terminology Development: The CEOS task group on terminology has worked to address issues related to inconsistent use of terms across Earth sciences. This effort aims to improve communication and interoperability by developing a coordinated approach to terminology.

New issues

Some emphasis was made on the need to develop joint approaches between the CEOS FRM concept and the GCOS reference networks to homogenize implementation criteria and develop guidelines.

It was reported that there is a need to develop not only a common vocabulary but also common data models to allow for different user profiles. The common vocabulary should be accompanied by a comprehensive data model to ensure both the proper structure and preservation of datasets over time. This approach would support data interoperability and consistency across different platforms and users, ensuring long-term sustainability and usability of the data.

An example of such a common data model already exists within the **Copernicus Climate Data Store (CDS)**. This dataset adopts a standardized data model to facilitate easy access and use of climate data by different user profiles, ensuring the data is structured in a way that supports both the immediate needs of users and the long-term preservation of the dataset.

3.2. Topic 1A: Atmosphere Physics and Chemistry

This session was chaired by Betsy Weatherhead (U. Colorado) and Fabio Madonna (U. Salerno, GCOS).

Progress since 2022:

Of the twelve issues identified in 2022, eleven have been addressed through presentations and posters in this meeting and five new potential issues have been identified.

Unaddressed Issues from 2022:

One recommendation, on the value of metrology incorporation into the full value chain of climate observations (1A.3), from the 2022 workshop remains unaddressed, emphasizing the need for a coordinated effort to establish measurement requirements across all stages of climate data collection. EURAMET, CEOS and WMO/GCOS may cooperate under a coordinated effort to setup a framework to propagate uncertainties from the raw measurements of any product level. This requires dedicated funding support, which is currently not available.

Collaborative Efforts:

This field is making rapid progress in a community that is ever more diverse and harnessing talent as never before:

- From the metrology community: CCMW-AQ, CCQM, CAAQMS, CCT-WGENV and National Metrology Institutes singly or as part of coordinated efforts such as European Metrology Partnership projects (for example, "22IEM03 PriSpecTemp").
- From the research infrastructure, international institutions/committees, and the private sector: ACTRIS, CEOS, other projects and efforts from private companies.
- From the atmospheric chemistry and physics sectors: WMO, ESA, Copernicus, NOAA, NASA, JAXA, USDOE, JPL, Satellite and meteorological agencies globally, including the private sector and observations of opportunity.

New Collaborative Activities:

The community is experiencing a “renaissance” in Earth observations, driven by advances in satellite constellations, unmanned aircraft and citizen science. Innovations such as GNSS Radio Occultation and lidar from space were highlighted as key tools for future climate monitoring.

New partnerships have emerged between the metrology and observation communities. This includes the development of fundamental principles for sensor network metrology and the establishment of an innovation cluster for environmental and climate monitoring.

New issues:

Starting from the presented papers and discussion had during the meeting, several new issues were detected and proposed for future collaboration on:

- Enhancing temperature measurements
- Quantum technologies for SWaP-C cost-effective sensors
- Low cost-sensor calibration and use of machine learning
- Using uncertainties in climate studies, for example, estimate of trends
- Web tools for carbon neutrality
- SI-traceable global reference for atmospheric climate monitoring
- Measurements and Source Attribution of other atmospheric constituents (for example, n-Alkanes, Radon).

Size, Weight, Power and Cost (SWaP-C) is a cost-effective means of designing systems that achieve an optimal balance between size, weight, power consumption and cost, where the cost is minimized while meeting functional requirements and performance standards.

Several important aspects warrant emphasis in relation to the challenges outlined above. These include the role of Research Infrastructures, which are particularly well-suited for targeted measurement campaigns that support standardized operational practices, and the need for a comprehensive characterization of low-cost sensors. Additionally, it is imperative to establish direct communication with manufacturers of cost-effective sensors to ensure that the nominal uncertainty ranges for each product are explicitly specified. Such transparency is critical for ensuring the appropriate application of each sensor, particularly in terms of its fitness for purpose.

In the context of calibrating low-cost sensors, it is advisable to develop a strategy in which specific nodes within the network function as reference points. This approach would enable cost-effective calibration by obviating the necessity of individually calibrating each sensor, thereby reducing operational costs while maintaining accuracy.

Moreover, the importance of maintaining continuous communication with end users cannot be overstated. Understanding the evolving needs of users is crucial for securing funding for projects that are aligned with these requirements. This approach should be inclusive, ensuring global representation and participation from all countries.

3.3. Topic 1B: Oceans and Hydrology

This session was chaired by George Petihakis (HCMR) and Johannes Karstensen (GEOMAR).

Progress since 2022:

Of the eleven issues identified in 2022, eight have been addressed through presentations and posters in this meeting and four new potential issues have been identified.

It is worth mentioning that substantial progress has been achieved in developing reference materials for seawater carbonate system variables and improving pH/pH_T measurement accuracy, which is critical for supporting the WMO's Global Greenhouse Gas Watch (G3W).

Unaddressed issues from 2022:

Several recommendations remain unaddressed:

- 1B.4: Oceanographers need to measure salinity with a standard uncertainty better than 0.002 g/kg to track climate-related processes. Together with temperature and pressure, salinity is the standard observation for physical oceanography; myriads of data are collected every year and working on 1B.4 must remain a high priority. The refining of the recommendation under 1B.4 by naming practitioner groups to approach (for example, GCOS/GOOS and observational networks such as GO-SHIP) is desirable.
- 1B.6: The ability to measure routinely seawater density with a standard uncertainty of 0.0015 kg/m^3 and improved (thermodynamic) models for relating density to salinity, temperature and pressure are required. This is essential for understanding ocean circulation and climate variability: density is a key variable for all physical oceanography. The refining of the recommendation under 1B.4 by naming practitioner groups to approach (for example, GCOS/GOOS and observational networks such as GO-SHIP) is desirable.
- 1B.7: Climate change warning systems for biological response to stressors, such as coral bleaching alerts, require better understanding of components of uncertainties. Marine ecosystems are a key issue for sustainable development goals. An example is the new United Nations agreement on biodiversity beyond national jurisdiction, also known as the BBNJ Agreement or High Seas Treaty. This offers the global community an opportunity to protect some of the abundant marine life and ecosystems in the two-thirds of the ocean that lie beyond any country's jurisdiction.
  Some initiatives such as the EU Horizon 2020 project BioEcoOcean or the Ecosystem ECVs could be approached.
- 1B.11: As the estimation of long-term trends are significant, there is a need for metrologically traceable techniques to quantify and verify observational stability, but assessing stability is an issue that still needs to be addressed according to the information provided during the meeting.

Collaborative efforts:

There are several groups that are active in this topic, including some CIPM Consultative Committee Working Groups such as the CCQM Working Group on Inorganic Analysis (CCQM-IAWG) and CCQM Working Group on Electrochemical Analysis (CCQM-EAWG) but also GOOS, GCOS and other programmes under the WMO or IOC-UNESCO umbrellas.

New collaborative activities:

The ECO ECOP West Africa Hub aims to fill a crucial gap in the Ocean Decade by focusing on nature and ocean-based solutions for climate remediation in West Africa, with a specific emphasis on Ghana. This initiative seeks to identify and collaborate with relevant stakeholders from diverse backgrounds, including scientists, corporate executives, government agencies, civil society groups, NGOs, academia and community organizations actively involved in nature-based solution activities in Africa.

The TRUSTED buoys project is an example of application of recommendation 1B.8 for sea surface temperature measurements. Thanks to the cooperation between Earth Observation scientists and metrologists, progress towards establishing Fiducial Reference Measurements by surface drifting buoys has been made.

Future initiatives:

Several new issues have been identified:

- The use of artificial Intelligence for uncertainty estimation
- There is general need for traceable uncertainties of biological and ecosystem ocean observations.

It is recommended to start a collaboration with the Observations Coordination Group (OCG) of GOOS that also will establish a link to GCOS.

3.4. Topic 1C: Earth Energy Balance

This session was chaired by Thorsten Fehr (ESA) and Laurent Vuilleumier (MeteoSwiss).

Progress since 2022:

On the eleven issues and fifteen recommendations, progress has been made for issues 1C.1 to 1C.7. Key progress includes:

- IR Scales Comparison: Efforts towards comparing the infrared (IR) scales underpinning the Libera and FORUM missions
- Global Stocktake from Space: The Earth Climate Observatory (ECO) has been established to monitor the Earth Energy Imbalance (EEI) with high accuracy
- Vacuum FIR Calibration System: A novel vacuum far-infrared (FIR) calibration system has been realized at PTB to support ESA's 9th Earth Explorer Mission FORUM
- Uncertainty Characterization: Improved methods for characterizing and validating uncertainties in BSRN *in situ* shortwave radiation fluxes
- TRUTHS Mission: The Traceable Radiometry Underpinning Terrestrial and Helio-Studies (TRUTHS) mission aims to provide a 'gold standard' imaging spectrometer in space for radiation imbalance studies and as a metrological reference for other missions. It is due to launch ~2030 and is under development
- SI-Traceable Radiometry: Development of SI-traceable shortwave absolute radiometry for the Libera instrument.

Unaddressed issues from 2022:

In this workshop, no presentations were made relating to recommendations from the BIPM-WMO 2022 workshop on the Earth-Heat Inventory. That is, the efforts that were

presented at the workshop were on the direct observation of the Earth radiation imbalance, and not on the storage and flux of heat energy that are obtained from ground observations of oceans, land, permafrost and the cryosphere. This suggests that the communities engaged in those efforts have not linked to the metrology community.

While space agencies are responsible for the continuity and stability of satellite instruments rather than the metrology community, metrology contributes to the goal by promoting their interoperability. Collaboration between metrology institutes (NIST, NPL, PTB, PMOD/WRC) and satellite calibration facilities is a key factor supporting interoperability, particularly when leading to the development of SI-traceable satellites.

Collaborative efforts

The CIPM Consultative Committee for Photometry and Radiometry (CCPR) has established a discussion forum on metrology for satellite observations to provide a consistent and coordinated response from the NMI radiometry community to the needs of the satellite-observation communities, particularly those related to climate change. This CCPR activity is linked to CEOS informally through several members who are part of both.

The CEOS working group on calibration and validation and the task group on terminology are also coordinating different initiatives.

New collaborative activities:

New collaborative activities have been initiated between the Observation and Metrology communities:

- Earth Climate Observatory (ECO): A global initiative to monitor the Earth Energy Imbalance from space.

New issues:

The description of energy transfer and distribution is based largely on models but there is little knowledge on uncertainty requirements for ground-based observations. Progress has been made on determining the uncertainty for ground-based solar radiation calibration and measurements, but thermal infrared calibration uncertainty is significant for ground-based measurements and requires a thorough analysis.

3.5. Topic 1D: Biosphere monitoring

This session was chaired by Julia Marrs (NIST) and Ruben Urraca (EC JCR).

Progress since 2022:

Of the ten issues and fourteen recommendations made in 2022, activities were reported in five issues and five recommendations. Some achievements include:

- Instrumentation and Metrological Methods: Progress has been made in the European Biosphere project, particularly in developing instrumentation for monitoring the dependence of secondary cosmic rays on atmospheric conditions. This work supports improved understanding of radiation effects on the ozone layer and biosphere.
- Uncertainty in Earth Observation Products: the efforts to improve uncertainty quantification for satellite-derived Earth Observation (EO) products were highlighted,

particularly those from the Copernicus Sentinel optical missions (L1 and L2). This progress is driven by successful implementation of the Quality Assurance Framework for Earth Observations (QA4EO) guidelines. These advancements are crucial for enhancing confidence in climate data used for land cover and environmental monitoring.

- Soil Moisture Metrology: There have been successful collaborations in developing traceable soil moisture measurements across Europe such as the Fiducial Reference Measurements for Soil Moisture (FRM4SM) or the European Partnership project SoMMet.

Unaddressed issues from 2022:

Despite these advancements, several critical issues identified in the 2022 workshop remain unresolved, specifically five issues: uncertainty propagation to high-level products, representativeness uncertainty, uncertainty usability, tipping points and radiative transfer models. In particular:

- Uncertainty Propagation (Issue 1D.4): There has been limited progress in addressing the full propagation of uncertainties to high-level Earth Observation products. This includes the evaluation of the representativeness and usability of these uncertainties for decision-making.
- Tipping Points and Biological Responses (Issue 1D.8): Recommendations to improve understanding of biological responses to environmental stressors, such as those related to tipping points in ecosystems, have not yet been fully addressed.
- Radiative Transfer Models (Issue 1D.9): While there has been progress in developing models, challenges remain in refining radiative transfer models for accurate biosphere monitoring, particularly for remote sensing applications.
- Uncertainty characterization for classification (1D.2). Categorical products are widely used to characterize the biosphere. Despite the progress in uncertainty characterization for classification (ESA CCI and NPL projects on land cover), an operational uncertainty framework for categorical variables is still missing. The main challenge is the lack of a formal definition of uncertainty for categorical variables, which are explicitly out-of-scope of the current VIM and GUM, although there is some effort to introduce them into the 4th edition of the GUM, and the lack of international guidelines. An additional challenge is the uncertainty propagation in machine learning models used for classification.
- Progress toward quantifying representativeness uncertainty (1D.5) may benefit from collaboration with researchers working on Emerging Metrology Issues (Topic 2E), such as carbon dioxide removal (CDR) efforts toward quantifying ecosystem carbon stocks and fluxes. Since global biogenic carbon fluxes are still associated with high uncertainties (on the order of 30 %), improved knowledge of the absolute magnitude and heterogeneity in these fluxes will be necessary to create ground truths used to assess remote sensing products' representativeness across landscapes.

Some unaddressed recommendations are either for further in the future (3 to 5 years or 6+ year timeline) and/or are recommendations for the BIPM itself, rather than for others in the scientific community. But all of them should be maintained and monitored by the BIPM and by the

operational services that develop and validate high-level products and communicate with users (for Europe, this includes Copernicus Services and EUMETSAT Satellite Application Facilities).

Collaborative efforts:

EURAMET through some projects funded by the European Metrology Partnership, such as BIOSPHERE (improved measurements of cosmic rays, UV radiation, and ozone layer thickness) or SoMMET (soil moisture) is coordinating some efforts. Besides, the European Space Agency (ESA) has progressed in developing uncertainty budgets for the essential climate variables of the Climate Change Initiative (CCI) and is funding the Fiducial Reference Measurements for Soil Moisture (FRM4SM) project.

Other institutions active in the field are MeteoSwiss in soil moisture, NPL in uncertainty propagation on classification, and CIEMAT on sediment core dating.

New Collaborative Activities:

In addition to the projects mentioned in the previous paragraph, the Optical Mission Performance Cluster (OPT-MPC) was created in 2021 to bring together the experience of Sentinel-2 and Sentinel-3 Mission Performance Clusters. OPT-MPC is a collaborative effort led by ACRI ST that brings together multiple private and public institutions with NMIs such as NPL. OPT-MPC has formed a working group on uncertainties that contributed to the significant progress on uncertainty characterization of Sentinel 2 and 3 products.

The Aerosol Robotic Network (AERONET-OC) is a pre-existing observational network (established 2006), but new uncertainty characterization activities for radiometric measurements of ocean colour may have started.

New issues:

Paleoclimate is a topic which was not covered in the 2022 workshop and there is growing interest in the use of radionuclide dating of sediment cores for paleoclimate reconstruction. This involves analysing trapped organic compounds in fluids as “time capsules” to study ancient environmental conditions. The need for synergies between metrologists and environmental scientists to establish reliable age-depth models in paleo-environmental studies was highlighted.

It was recommended to create a plan for finalizing the following issues. Because topics later in the list will rely on those listed earlier, it is important to note that these must happen in sequence:

- Uncertainty of L1/L2 products. In particular, more progress is needed in the uncertainty characterization of biosphere categorical products. A methodological framework to develop uncertainty budgets of categorical variables is missing. Uncertainty of high-level products
- Uncertainty usability and representativeness.

3.6. Topic 1E: Cryosphere monitoring

This session was chaired by Emma Woolliams (NPL) and Filomena Catapano (ESA).

Progress since 2022:

Since 2022, some progress has been made in addressing the recommendations from the BIPM-WMO 2022 workshop. Out of the nine issues identified, progress and efforts relating to seven have been addressed through presentations and posters at this workshop. Additionally, three new initiatives have been proposed, focusing on enhancing the understanding and monitoring of the cryosphere.

Unaddressed issues from 2022:

Despite the progress, some issues remain unaddressed. Limited direct actions have been taken on issues 1.E1, 1.E2, 1.E6, 1E.8, and 1.E9. The main challenges include the limited connections between the metrology and observation communities, which are generally project specific. The wide variety of measurement quantities and techniques, along with challenging conditions, also make it difficult to link these issues to the CIPM Consultative Committees. Challenges in obtaining reliable snow cover data were highlighted in a presentation.

Collaborative efforts:

Several organizations, committees, and groups have been coordinating activities to address the recommendations from the 2022 workshop. Notable collaborations include:

- EURAMET: Arctic air temperature comparison and European Metrology Network projects.
- CEA LIST: New initiatives.
- The NMIs CEM and INRIM have been collaborating with the WMO on ground-based cryosphere measurements.
- The NMIs NPL and RISE have been collaborating with ESA and others on satellite-based cryosphere measurements (from optical, radar and geodesy missions) and the ground-based measurements that support them. Presentations described work with ice sheets and sea ice measured from radar altimetry, and geodesy measurements of frozen water.
- SIOS: Offers a comprehensive Calibration/Validation (Cal/Val) site in Svalbard for collaboration.

New collaborative activities:

Three new collaborative activities have been initiated between the Observation and Metrology communities:

- Svalbard as a supersite for cryosphere-observing satellite Cal/Val activities: Proposed by SIOS. The unique characteristics of Svalbard, notably accessibility, location, research infrastructure and satellite overpass frequency make it a supersite for Cal/Val activities for the current constellation of EO satellites, and upcoming platforms such as CRISTAL, CIMR, ROSE-L, and Sentinel-1 next generation.
- Cosmic neutrons metrology for permafrost studies: CEA proposed leveraging cosmic neutrons as a non-invasive and scalable method for assessing ground-ice content (~10m wide on ~1m depth) in permafrost and landscapes.

There was a EURAMET proposal to organize a cryosphere metrology workshop bringing together the communities linked ground measurements, space measurements and metrologists. This could help to identify the groups that could tackle the unaddressed issues in the cryosphere domain.

Additionally, the UN Decade of Action for Cryospheric Sciences (2025-2034) presents an opportunity to conduct ambitious international projects aimed at understanding the mechanisms behind the collapse of the cryosphere and mapping out future scenarios.

New issues:

Future initiatives will be required that are focused on addressing the new issues identified through the collaborative actions previously mentioned. Key areas include:

- Geodesy and Altimetry for Mass Change Applications: Developing new methods for monitoring mass changes in the cryosphere combining and/or comparing geodesy and altimetry observations
- Cosmic Neutrons for Permafrost Monitoring: Further explore this new approach for comparison and validation of permafrost measurements.

4. Theme 2: Metrology as an integral component of operational systems to estimate greenhouse gas emissions based on accurate measurements and analyses

4.1. Topic 2A: Accuracy requirements for atmospheric composition measurements across economic sectors, and temporal and spatial scales

This session was chaired by Robert Wielgosz (BIPM) and Sergio Moreno (WMO).

Progress since 2022:

Substantial progress has been made in this topic area, notably due to the already established close relationships between institutes active in the WMO-GAW programme and the CCQM Gas Analysis Working Group. Of the 12 issues and 30 recommendations identified in the 2022 Workshop, 10 issues, and 22 recommendations were being addressed in the 6 presentations and 16 posters submitted to the 2024 stakeholder meeting.

Unaddressed Issues from 2022:

At the time of the stakeholder meeting limited actions had been undertaken for the following recommendations:

- 2A.6, where there is still a need for a uniform approach to purity measurements to assure reference materials are of sufficient quality to allow WMO/GAW DQOs to be met or exceeded, and an action that could be taken forward in a reformed CCQM-GAWG TG on Purity
- 2A.8, where the atmospheric greenhouse gas standards and monitoring community need access to affordable high quality air matrix gases and certified zero air. This would

require a collaborative approach between NMIs/DIs, WMO-CCLs, ISO TC 158, and Specialty Gas Industry and a group to take on leadership of the activity.

An issue where there had been some progress, but further actions would be beneficial was:

- 2A.4, where the stability carbon monoxide standards in air at ambient levels is limiting quality of field measurements, but with posters reporting activities on assessing the stability of carbon monoxide in aluminium cylinders and calibration needs for ambient monitoring, challenges in the accurate measurement of atmospheric composition including CO amount fractions, and Carbon Monoxide Proficiency Testing Schemes.

Collaborative Efforts:

A series of collaborative efforts are being coordinated by task groups within the CCQM Working Group on Gas Analysis (CCQM-GAWG), and bringing together NMIs and expert external laboratories including those providing standards to WMO and other networks, and notably:

- CCQM-GAWG Task Group on GHG Scale comparisons, addressing issues, 2A.7 and 2A.5, and developing infrastructure to increase accessibility first CO_2 and then other GHG scale standards for amount fraction measurements. The aim is for levels of internal consistency between sets of standards that are required by the atmospheric monitoring community (https://www.bipm.org/en/committees/cc/ccqm/wg/CCQM-GAWG-TG-GHG)
- CCQM-GAWG Task Group on CO_2 and CH_4 stable isotope ratio measurements, addressing issues, 2A.10, 2A.11, and 2A.12, and developing infrastructure to increase accessibility for CO_2 and CH_4 stable isotope ratio standards. The aim is for levels of internal consistency between sets of standards that are required by the atmospheric monitoring community (https://www.bipm.org/en/committees/cc/ccqm/wg/ccqm-gawg-irwg-tg-isotop)

New Collaborative Activities:

In 2023 a number of new collaborative efforts have been initiated, including:

- A major new programme in the WMO (WMO Global Greenhouse Gas Watch) to establish an integrated global greenhouse gas observing system (both surface- and space-based) with near-real time international exchange of all observations. Meetings in January and October 2023 organized by the WMO, included presentation of the increased standards accessibility activities being led within the CCQM TGs (https://community.wmo.int/en/meetings/observations-within-global-greenhouse-gas-watch).
- Collaborations between metrology institutes and newly formed national networks to determine GHG emissions at the national and local levels requiring increased provision of fit for purpose GHG scale standards, with an example being KRISS (Republic of Korea).
- NMIs developing standards and taking on the role of WMO-CCL for individual GHGs, with an example in June 2023, METAS (Switzerland) was designated as a WMO-GAW Central Calibration Laboratory (CCL) for ten halogenated VOCs.
- A new CCQM-GAWG Task group on passivation chemistry for gas standards, to address recommendations 2A.2 and 2A.3, is being formed.

New issues:

A number of new issues were presented at the meeting and notably:

- An initiative within ISO/TC 207/SC/WG17 to develop standards for Emission determination in Urban Environments based on Measurement, with requests for additional experts to join the drafting group including Groups establishing ground-based observation systems, and link to the measurement standards work being coordinated with the CCQM-GAWG TGs.
- Activities to determine more accurate spectral parameters for halogenated GHGs, which could be incorporated into the CCQM GAWG Task Group on Advanced Spectroscopy (https://www.bipm.org/en/committees/cc/ccqm/wg/ccqm-gawg-tg-adv-spec).
- Activities for high flow accurate GHG measurement in stationary sources which could be integrated into the activities of CCM Working Group on Fluid Flow (CCM-WGFF; https://www.bipm.org/en/committees/cc/ccm/wg/ccm-wgff).
- A need to better characterize the measurements of eddy covariance flux estimates which could be integrated into the activities of CCM Working Group on Fluid Flow (CCM-WGFF; https://www.bipm.org/en/committees/cc/ccm/wg/ccm-wgff).

4.2. Topic 2B: State of play in integrated approaches for advanced greenhouse gas (GHG) emission estimates and the way forward to operational services

This session was chaired by Leonard Rivier (ICOS) and Robert Wielgosz (BIPM).

Progress since 2022:

The 2022 recommendations from this topic addressed needs for a unified approach to quality assurance of inverse atmospheric modelling approaches, the need for an easily implemented transparent framework to assess inversion modelling results, improvement in atmospheric transport model skills, and improvements in satellite data. They also addressed needs in relation to methane emission tracking, urban GHG emission estimates and business and standardization issues.

Unaddressed Issues from 2022:

The 12 issues raised in 2022, have led to broad recommendations at the organizational or multi-organizational level, which would require one or more entities to take on a leadership role and address these. As this is a field in which only a small number of Metrology Institutes have active programmes, and where these are relatively new activities, leadership of activities would be most readily driven by the applied measurement/modelling community.

Collaborative Efforts:

Reports were received on number of collaborative efforts:

- WMO IG3IS integrated global greenhouse gas information system
- Long open-path measurements of CH_4 and CO_2 in urban areas in the US
- GHG gas monitoring and modelling in the US
- GHG emissions evaluated by mobile experiments in the Russian Federation
- GHG inversion system development at the Urban Scale in China
- GHG emissions measurements and modelling in the UK
- The integrated GHG monitoring system in Germany

- Developing new methods for atmospheric inversion models in Europe
- WMO-GAW and GGMT-2024.

New issues:

Recent developments in Artificial Intelligence emulators were discussed and the potential of these in replacing both dynamic global vegetation models (DGVMs) and ocean models in the future, with their validation, remains an issue to be addressed.

The importance of independent transport model evaluation was reaffirmed. Controlled released experiments are one way to address this issue. Performance metrics are still insufficiently used.

4.3. Topic 2C: Novel GHG concentration and flux methods and sensors

This session was chaired by Hong Lin (NIM) and Kevin Cossel (NIST).

Progress since 2022:

This topic addressed new and/or novel methods for measurement emission fluxes and concentrations with a focus on new sensing approaches. Recommendations addressed needs for improved coordination with the atmospheric science and observing community and instrument vendors and the need to close the observational data gap via novel sensors and measurement capabilities. Of the six issues and eight recommendations made in 2022 only limited progress had been achieved in three issues and three recommendations, noting that individual efforts for topics such as calibration were ongoing, but linking to broader coordinated efforts remained a challenge to be addressed.

Unaddressed Issues from 2022:

Issues that were identified where there was a continued need for these to be addressed were:

- Better coordination between the atmospheric science community and instrument developers, with instrument developers needing guidance on what gases to target, what measurement sensitivities are needed, what spatial and temporal resolutions are needed, and what instrument requirements (stability, cost, etc.) are required in order to be able to design suitable systems.
- Calibration methods and comparability/traceability of GHG abundance measurements needs to be ensured.
- Calibration methods and comparability/traceability of different flux measurement methods needs to be ensured.
- Novel sensors and measurement techniques need to be deployed rapidly and widely to support better climate science.
- Existing guidance needs to develop into standards, especially for private sector involvement.

Collaborative Efforts:

A number of efforts on measurement calibration/validation are ongoing for example at GCOS, ICOS Cities, NIM (Point sources and fugitive emissions measurements) and NIST (Consensus standards of methane plume observations from satellites), but there is no single organization with an overarching coordination role for such activities.

New issues:

The following new issues were identified:

- Needs for effective calibration processes for mid-cost sensors
- Needs for multispecies measurements, including isotopes
- Needs for validation methods for flux measurements
- The need for coordinated instrument intercomparisons
- The need for flux measurement intercomparisons.

Currently, issues are being pursued in different projects and institutes, with collaboration being handled on a bilateral basis, potentially also due to the limited number of programmes that are ongoing in the field. With increasing activities and institute participation, the interest in more extended collaboration/coordination may grow.

4.4. Topic 2D: Strengthening the linkage of remote sensing GHG concentration measurements to emission fluxes

This session was chaired by Richard Barker (NPL) Annmarie Eldering (NIST).

Progress since 2022:

The recommendations from the 2022 workshop were broad and addressed communities with which there are some links to the metrology community through tailored NMI services in a very few specialized institutes, but without the NMI community being fully integrated into the EO and GHG atmospheric science community and stakeholders. Specific challenges for the NMI community to integrate into the community include:

- Complexity: While there is significant demonstrated success connecting remote sensing atmospheric concentration data to reference standards, emissions flux measurands involve considerable multi-parametric modelling and data processing to tackle many different atmospheric physics problems.
- Fragmented stakeholder community: Considerable differences in priorities of specific missions and the priorities of different space agencies and "new space" commercial stakeholders exist with respect to data quality and how it is addressed.
- Cost: The significant cost of satellite missions and the challenges in gaining funding make it harder to acknowledge and justify further investments to address data quality *en masse*.

Stakeholder groups that need to address metrology issues include:

- Space agencies launching satellites and offering "mapping" services:
    - ESA – Sentinel 5P Tropomi, Sentinel 5, CO2M
    - NASA – OCO 2,3
    - UKSA/CNES - Microcarb
    - JAXA – GoSat 1,2, GW
    - CSA (China) – TanSat.
- "New Space"/Commercial enterprises with satellites or satellite data for high flux events, for example, MethaneSat, Prisma, GHGSat, EnMap, Carbon Mapper, Airmo, EMIT.
- Agencies with data and other services, such as:

- ECMWF (Europe) with Copernicus being the programme (funded by European Commission) with specifically CAMS (Copernicus Atmosphere Monitoring Service) the specific part of the programme dealing with GHG
- NOAA (USA)
- Met Office (UK)
- CEOS (Global).

Programmes such as: WMO G3W (Global), GEMMA (UK), GHGMMIS (USA), CAMS CO2MVS (Copernicus CO_2 Monitoring Verification and Support Capacity).

Collaborative Efforts and New issues:

Significant collaborative efforts are ongoing within the EO community and where metrology is playing a key role, with presented examples being:

- Development of fiducial references for greenhouse gases
- Linking space-based GHG missions to *in situ* standards through ground-based FTIR observations through TCCON and COCOON networks
- Proposals to enhance SI traceability the TCCON and COCCON observations.

The level of integration of NMI programmes within the area is likely to remain at the individual NMI engagement level through already established stakeholder programmes. If engagement of the metrology community broadens, then opportunities for additional coordinated activities could arise.

4.5. Topic 2E: Emerging Metrology Issues (Ocean, CCUS, CDR, Agricultural Emissions)

This session was chaired by Maribel I. Garcia-Ibañez (IEO-CSIC) and Pamela Chu (NIST).

The continued rise of the atmospheric CO_2 concentrations and resulting climate change, pose an existential threat to our planet, human health, food security and economic prosperity. Following the Paris Agreement and the IPCC recommendations, a global effort is underway to reduce emissions by transitioning to non-GHG emitting energy sources, changing manufacturing practices and developing approaches to draw down atmospheric CO_2 concentrations to pre-industrial levels. As a result, there is significant attention on the carbon emissions associated with products, especially the emissions associated with the hard-to-abate industries such as steel, cement and chemical products. In addition to low-carbon emission manufacturing approaches, new technologies such as carbon capture, use, and storage and CO_2 removal are being developed and deployed. There is a growing need for sound measurements and validated models to ensure appropriate and effective carbon emission reduction and removal strategies are pursued and that the carbon emissions associated with products are appropriately quantified.

New issues:

The session was introduced to broaden the scope of activities addressed in the previous workshop, with five presentations and five posters addressing measurement challenges in topics such as:

- Carbon Dioxide Removal (CDR): recommendations for monitoring, reporting, and verification (MRV) and standards for quantifying carbon credits in nature-based CDR settings like forestry and soil carbon
- Challenges associated with the implementation of basin-scale carbon storage
- Verification of the emissions from livestock buildings
- Metrology needs to accelerate development and commercialization of carbon mitigation technologies and products
- Data quality frameworks for “fitness-for-purpose" ocean observations
- RMs for Direct Air Capture of CO_2.

Areas where metrology issues were expected to arise were:

- Carbon removal, mitigation, storage, credits
- Monitoring, Reporting and Verification (MRV) of CDR
- Data management and knowledge systems
- Climate modelling and validation – baseline characterization
- Product carbon footprints.

Possible expectations of stakeholders from collaboration with the metrology community for:

- Development of the foundational measurement infrastructure to underpin carbon removal quantification
- Support for the creation of standardized protocols for MRV emissions and removals in various settings
- Advanced methods for data collection and management
- Enhanced methods for model validation.

Involvement of Metrology Institutes in these areas is mostly at an early stage and expected to be progressed through measurement focused events within stakeholder scientific meetings and fora, to define needs and expected outputs.

5. Further remarks

Following the 1st CIPM-STG-CENV meeting, which had over 400 registered participants, and the subsequent meeting of its core group, several additional recommendations have been drawn from the attendees and group members.

The participants found the meeting useful for understanding the wide range of collaborations in the field of climate observations. The format with short presentations and posters was welcomed, although it was suggested that the posters did not get sufficient visibility. It was unanimously agreed on the need for biennial meetings to monitor progress in various activities and identify new challenges. It should be emphasized that the objective of the meeting is not to engage in detailed technical discussions but rather to hold high-level discussions that help identify gaps requiring more effort and uncover new unmet needs. It was recognized that there were many activities ongoing where metrology could play a role, with some that would fall

within the scope of structures created by the CIPM, but with the majority coordinated by other bodies but for which there were opportunities for National Metrology Institutes to become involved.

It is important to highlight that the CIPM-STG-CENV is not a group aimed at developing technical activities *per se*. Instead, its purpose is to guide and facilitate contact between existing working groups within the metrology and climate communities that are working towards the same objectives. If necessary, the CIPM-STG-CENV can also foster the formation of specific task groups within the BIPM structure.

It would be useful for each biennial stakeholder meeting to provide an update on metrology activities that were ongoing at various levels and indicating where National Metrology Institutes were playing a role, and notably within:

- CIPM Consultative Committees and their WGs/TGs
- Regional Projects/Groups
- National Projects/Groups
- Groups/Projects organized by International Organizations.

In consequence, it was considered effective to keep a small coordinating core-group as the correct structure of the STG to achieve its goals. Additionally, it is recommended to update the structure of the core-group to include representatives from the metrology community covering Consultative Committees and Regional Metrology Organizations with active programmes in the area, International Organizations with measurement programmes within the scope of the STG, and experts with competencies in the fields covered by the group. Regarding International Organizations, besides continuing to include WMO and GCOS, it would be necessary to incorporate representatives from other international organizations/programmes responsible for observations. These include the oceanographic community, such as GOOS, being the guardian of the marine observations that contribute to the GCOS and can be reached for further discussion via the GOOS expert committees (OOPC, IOCCP, GOOS BioEco) and via the Observation Coordination Group (OCG), and the satellite community, including CEOS, and the GHG emissions community including the UNEP IMEO programme and the WMO G3W. The potential engagement of CIPM-STG-CENV (or another structure to be created by the CIPM) in UN Decade activities was discussed, specifically for an upcoming decade on the cryosphere but possibly also in the current UN Decade for ocean science for sustainable development.

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