METROLOGY FOR CLIMATE ACTION

26–30 SEPTEMBER 2022

Bureau International des Poids et Mesures

WORLD METEOROLOGICAL ORGANIZATION

Rapport BIPM-2023/03

IOM Report No. 142

This publication is available in pdf format, from

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BIPM-WMO Metrology for Climate Action Workshop, 26-30 September 2022

Introduction

This report together with the workshop website provide a summary of the inputs, discussions and recommendations from the Metrology for Climate Action Workshop hosted by the International Bureau of Weights and Measures (BIPM) and the World Meteorological Organization (WMO).

The workshop steering committee (who were also editors of the report) consisted of the following members:
Steering Committee Co-Chairs: Robert Wielgosz (BIPM) and Bruce Forgan (WMO)
Workshop Co-Chairs: Dolores del Campo Maldonado (CIPM/BIPM) and Anthony Rea (WMO)
Workshop Theme Co-Chairs: Emma Woolliams (NPL and EURAMET, United Kingdom of Great Britain and Northern Ireland), Janice Fulford (USGS and WMO, United States of America), Fabio Madonna (IMAA-CNR and GCOS, Italy), James R. Whetstone (NIST, USA), Phil DeCola (University of Maryland, USA) and Alex Vermeulen (Lund University and ICOS, Sweden)
Workshop Coordinators: Edgar Flores (BIPM) and Isabelle Ruedi (WMO)

Measurements provide a key resource in addressing climate change by: identifying and understanding the processes by which the Earth is changing; quantifying the long-term changes that are occurring; and mitigating for and adapting to the observed changes. The last of these requires society's decision makers to have an evidence-based foundation in how the Earth is changing and providing predictions of how it may change in the future under different emissions and land-use scenarios. Such evidence relies fundamentally on accurate, stable, and long-term observations of climate variables, their integration into modelling, and the use of observations in developing climate science. Measurement science can also support effective climate change mitigation through measurement-based monitoring to locate, quantify and thereby manage greenhouse gas emissions and removals, and with advanced analysis tools target effective mitigation opportunities and track the efficacy of emission reduction initiatives.

The workshop on Metrology for Climate Action was hosted by the BIPM and WMO as an on-line meeting during 26-30 September to:

(a) present progress and identify requirements for further development of advanced measurements, standards, reference data, comparisons and calibrations supporting the physical science basis for and adaptation to climate change, and

(b) Identify stakeholders' metrology needs, assess current metrological techniques, analyses, and modeling capabilities, and identify gaps in quantifying greenhouse gas emissions and uptake for effective actions on mitigating climate change and its impacts.

The workshop attracted 1078 registered participants, and 203 pre-recorded presentations and posters. Online questions for pre-recorded materials, interactive online poster sessions and specific topic discussion sessions resulted in 81 issues on key technical challenge areas for metrology and related areas being identified and 126 recommendations being made to address these, which are described within this report.

The workshop was organized along two major themes, covering multiple topics within each.

Theme 1 addressed 'Metrology in support of the physical science basis of climate change and climate observations'. The theme covered metrology in support of scientific understanding of the physical science basis of our planet's past, present and future climate. It included the metrology associated with measurements and monitoring of the climate system from both in situ and remote measurement techniques (including ground-based, airborne and satellite remote sensing) together with metrological techniques to propagate uncertainties from the measurements through to products derived through modelling and to reanalyses and other Earth system models. It encompassed activities that focus on understanding the climate system including multi-decadal observations to observe climate trends usually for global scale phenomena and with increasing interest in regional 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 the monitoring and mitigation of greenhouse gas 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 subnational 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 (e.g. sub-urban scales to national scales) and measurements required to monitor land-use, land-use change and forest (LULUCF) fluxes and urban fluxes. 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 greenhouse gas (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

Papers and posters that contributed to the workshop resulted from an open call, in which authors were required to address as many of the following elements as possible/appropriate:

(1) Introduction to progress or lack of progress (challenges) so far
(2) Indication of what is needed to improve the information content in environmental measurements or models
(3) Proposals of new or existing tools not currently in use, for improving information content
(4) Description of potential means to achieve that improvement
(5) Opportunities for collaboration between communities to achieve these improvements

The remainder of this report provides a summary of the issues and recommendations identified within each of the nine topic areas within the two Themes of the workshop. The workshop website at www.bipmwmo22.org also provides a long-term record of the workshop with many of the pre-recorded presentations and posters publicly available, and access to all materials for registered participants of the workshop.

The BIPM and WMO wish to acknowledge the support of EURAMET, the European Association of National Metrology Institutes, a partner in the organization of the workshop.

The workshop follows on from two previous events, one in 2010 on Measurement Challenges for Global Observation Systems for Climate Change Monitoring and the second in 2015 on Global to Urban Scale Carbon Measurements.

Follow up on the implementation and progression of the recommendations within this report will be coordinated by a Sector Task Group on Climate Change and Environment of the International Committee of Weights and Measures (CIPM)

1 Introduction to Theme 1: Metrology in support of the physical science basis of climate change and climate observations

1.1. Theme 1 Organizing Team

Theme chairs

- Janice Fulford (USGS and WMO, USA)
- Fabio Madonna (IMAA-CNR and GCOS, Italy)
- Emma Woolliams (NPL and EURAMET, UK)

Topic chairs and expert groups

Atmospheric Chemistry and Physics

- Betsy Weatherhead (University Colorado and Jupiter Intelligence, USA) **Chair**
- Sangil Lee (KRISS, Korea) **Rapporteur**
- Michael Kimlin (Queensland University, Australia)
- Louli Gordon (Harvard, USA)
- Joseph Hodges (NIST, USA)
- Gang Li (PTB, Germany)
- Fuu Ming Kai (NMC/A*STAR, Singapore)
- Irina Petropavlovkikh (NOAA, USA)
- Kehinde Ogunjobi (WASSC, Ghana)

Oceans and Hydrology

- Chris Merchant (Reading University, UK) **Co-chair**
- Paola Fisicaro (LNE, France) **Co-chair**
- Janice Fulford (USGS, USA) **Co-chair**
- Michael Winchester (NIST, USA) **Rapporteur**
- Christopher Waldmann (Marum, Germany)
- Rajesh Nair (IN-OGS, Italy)
- Bill Bell (ECMWF, UK)
- Christel Prudhomme (ECMWF, UK)
- Michael Ablain (Magellium, France)

Earth Energy Balance

- Greg Kopp (CU/LASP, USA) **Chair**
- Julian Gröbner (PMOD/WRC, Switzerland) **Rapporteur**
- Martin Wild (ETH, Switzerland)
- Nozomu Ohkawara (JMA, Japan)
- Nigel Fox (NPL, UK)
- Mohan Shankar (NASA, USA)
- Karine von Schuckmann (Mercator Ocean, France)

Biosphere Monitoring

- Nadine Gobron (JRC, Italy) **Chair**
- Bernardo Mota (NPL, UK) **Rapporteur**
- Isabel Trigo (IPMA, Portugal)
- Frederic Melin (JRC, Italy)

Cryosphere Monitoring

- Stefan Kern (University of Hamburg, Germany) **Chair**
- Carmen Garcia Izquierdo (CEM, Spain) **Rapporteur**
- Colleen Mortimer (ECC, Canada)
- Stefanie Arndt (AWI, Germany)
- Jinro Ukita (University of Niigata, Japan)
- Yves-Alain Roulet (MeteoSwiss, Switzerland)
- Louise Sandberg-Soerensen (DTU-Space, Denmark)
- Anne Munck Solgaard (GEUS, Denmark)
- Christian Hauk (Fribourg, Switzerland)
- Matthias Huss (ETH, Switzerland)

1.2. What Theme 1 covers

The scientific community faces three primary challenges in addressing climate change: 1) identifying and understanding the processes by which the Earth is changing; 2) quantifying the long-term changes that are occurring; and 3) mitigating for and adapting to the observed changes. The last of these requires society's decision makers to have an evidence-based foundation in how the Earth is changing and providing predictions of how it may change in the future under different emissions and land-use scenarios. Such evidence relies fundamentally on accurate, stable, and long-term observations[1] of climate variables, their integration into modelling, and the use of observations in developing climate science. Observational data can be combined with models to provide a reanalysis of present and historical climate, used to provide trends for several essential climate variables (according to the requirements set by the Global Climate Observing System, GCOS) or used to develop the scientific basis and test the performance of predictive climate models that provide future climate scenarios. Within the United Nations Framework Convention on Climate Change (UNFCCC), the Intergovernmental Panel on Climate Change (IPCC) Working Group 1 report summarises this understanding.

Historical successes in the fields of environmental sciences and climate change almost always trace back to well-understood observations. Some recent successes include: global understanding of both CO_2 and methane rise; global and regional increases in temperature; improved understanding and predictability of extreme events, including flooding, tropical cyclones, and fires; regular monitoring of harmful trace gases including ozone-depleting substances and pollutants; improved understanding of the water and carbon cycles and the energy balance; the inclusion of biological processes into climate models; and the understanding of the rapid changes in the polar and mountainous regions. In all these cases, well-characterized observations have led to greater scientific understanding of the Earth system and, when appropriate, policy implementation. The ability of observations to address relevant questions is, in part, hampered by the inability to measure with appropriate granularity, accuracy, and geographic coverage, along with the natural variability that exists in the complex Earth system.

In support of the investigation of the physical science basis of climate change and the implementation of high-quality climate observations, Theme 1 covers the interaction of metrological principles (providing metrological traceability, robust uncertainty analysis, and comparison methodologies) to such observations and to their integration into modelling and climate science.

Observational data is collated and processed through a multi-step value chain that includes:

1. Instrument manufacture and calibration / pre-deployment checks of reference, operational, and new sensor models
2. Instrument deployment, operation, and ongoing calibration processes and network design and operation, including the review and mitigation of current observation gaps, and establishing linked tiered networks
3. Data processing from raw instrument (signal) data to calibrated (or corrected) observational records of measured values (e.g., of physical or chemical quantities)
4. Observational record processing to essential climate variable records or other higher-level products (processing into bio/geo-physical quantities, often including spatial and temporal aggregation or gridding as well as conversion into the quantity), including the provision of ancillary information such as related spectroscopy aspects and comparability of products
5. Adjustment and use of historical records in modelling (reanalysis) and climate science, or to provide environmental information services
6. Use of models' scenarios, aggregate observational data, climate science and/or environmental information services to make societal decisions

[1] The word 'observation' is used in different ways. Here we follow WMO and metrology (VIM) conventions of using 'observation' and 'measurement' as the process of observing/measuring, and not the data output that results (which would be 'observation result' or 'measurement result'). The distinction between 'measurement' and 'observation' is defined differently for different communities, and we have not enforced a single usage on the different topic teams.

Theme 1 of this workshop focussed on points 1-4 of this value chain and was organised into five topics which were arranged around different Earth science disciplines:

- Atmospheric chemistry and physics
- Oceans and hydrology (including the water cycle)
- Earth energy balance
- Biosphere
- Cryosphere (polar regions and high mountain areas)

Since climate is a highly coupled system, there are natural overlaps between the topics. For example, soil moisture is relevant in hydrology and the biosphere, and ocean colour spans both oceans and the biosphere. The Earth energy balance topic had strong links to all the other topics, particularly through heat-uptake and -storage mechanisms. Cross-fertilization between teams helped in the formulation of recommendations.

1.3. Workshop participation

The workshop had strong participation from a broad range of observation disciplines, covering many of the GCOS essential climate variables, with participation from institutions and agencies in charge of calibrating and using observational instruments on ground-based, ocean-based, airborne and spaceborne platforms as well as those creating essential climate variable data records.

1.4. Theme 1 recommendations

Since the 2010 BIPM-WMO workshop there has been significant effort by the observation communities, through the WMO, GCOS and the space agencies, to develop the global climate observing system. Metrological approaches are embedded in the 2022 GCOS Implementation Plan [1], the CEOS quality assurance framework for Earth observation [2] and the WMO regulatory and guidance documents (e.g., [3,4]). The recommendations presented here are intended to encourage continued work in these areas with the desire to enhance the effort spent in the past on the different Earth science disciplines.

During the workshop, each topic team developed their own recommendations. These included both general recommendations and more detailed technical recommendations. Some technical areas built on collaboration that began before the 2010 WMO-BIPM workshop, while others were creating new collaborations.

There were several common subjects of recommendations for the different topic areas in Theme 1. Almost all topic teams developed recommendations about creating guidelines to improve the consistency of terminology for metrological concepts and to develop guidelines for applying metrological uncertainty analysis. The Guide to the expression of Uncertainty in Measurement (the GUM) has been written from the perspective of laboratory and industrial measurements and a common request was for this to be translated, through clear examples, to cover specific aspects of environmental observation (e.g., changing measurand, non-repeatability, spatial and temporal sampling, instruments that cannot be returned for recalibration, and large data sets). There are several recommendations for WMO to collaborate with the Joint Committee on Guides in Metrology for the development of examples and guides that demonstrate the GUM's application to different types of observations.

Common technical challenges included:

- Developing long-term time series from data despite step changes in observational technology and location, ensuring measurement stability and continuity and developing approaches for the harmonization and homogenization of data records
- Inter-comparing observational results taken in different ways, and potentially at different times or representative of different surface areas and/or different atmospheric air volumes
- Comparing observational results with model outputs
- Linking tiered networks, using the highest quality measurements from WMO "reference networks" or space agency "fiducial reference measurements" to a broader set of lower quality but higher spatial or temporal resolution data from formal and informal networks

- Developing methods to handle metrological traceability and uncertainty analysis when data is processed through complex processing chains, which increasingly include machine learning methods.

Metrology institutes can provide not only an important metrological viewpoint to such discussions, but also a means for connecting concepts and languages across observation and modelling fields. To achieve this, it is important that metrology institutes significantly increase their efforts in supporting climate observations and develop a framework for ongoing collaboration with observation and modelling experts. With this perspective, the following high-level recommendations from Theme 1 are made:

Number	Issue	Draft recommendation
T1-0.1	This workshop showed the value of existing collaborations created following the signing of the CIPM-MRA by WMO in 2010. In many topic areas covered by this workshop, scientific and practical collaborations between the metrology and observation communities have led to improved practices, a deeper understanding of uncertainties, and greater international consistency. What is needed now is greater coordination across the Earth science topic areas and between metrological disciplines (traditionally organized through the separate SI units) to create more strategic collaboration between metrology and observation.	**[Within next 12 months]:** The BIPM and WMO should establish a committee whose role is to oversee the implementation of the recommendations of this workshop, and establish links to other coordinating organizations, such as CEOS and IPCC, for improved coordination of metrological-climate activities across international organizations. Activities of the committee should cover both promotion and the implementation of the recommendations in this document.
T1-0.2	The technical challenges identified in this workshop require a broader metrological scientific approach to climate sciences than traditional and industrial laboratory metrology. Propagating uncertainties from instrument measurements to bio- or geophysical quantities derived from a combination of measurements and models, increasingly also involving machine learning, low-cost sensors, and other non-standard analysis techniques, or based on a tiered network of sensors, requires metrological research and a stronger collaboration between metrologists, data scientists, and observation and modelling experts.	**[Within next 2-3 years]:** The CIPM should encourage and support metrological institutes to perform the necessary metrological and data science research collaboratively with the appropriate communities and to share such thinking between national metrology institutes, e.g., through the group established in T1-0.1, to provide international coordination. Collaborative research to respond to environmental challenges is needed, and mechanisms such as EURAMET's funded research programmes are encouraged internationally where possible. BIPM should work with WMO to promote international research programmes with requirements for metrology.

References

[1] Chao, Qingchen; Han Dolman, Albertus Johannes; Herold, Martin; Krug, Thelma; Speich, Sabrina; Suda, Kazuto; Thorne, Peter; Yu, Weidong; Zemp, Michael. The 2022 GCOS Implementation Plan. GCOS-No. 244, Geneva: World Meteorological Organization https://library.wmo.int/doc_num.php?explnum_id=11317

[2] A best practice framework endorsed by The Group on Earth Observations (GEO) to establish The Global Earth Observation System of Systems — based on coordinated and harmonised processes and activities that enable interoperability. www.qa4eo.org

[3] Manual on WIGOS (WMO No. 1160)
https://library.wmo.int/index.php?lvl=notice_display&id=19223

[4] Guide to Instruments and Methods of Observation (WMO-No. 8)
https://library.wmo.int/index.php?lvl=notice_display&id=12407

2 Topic 1A: Atmosphere Physics and Chemistry

2.1. Introduction

The atmosphere moderates Earth's temperature through heat-trapping greenhouse gases. The physics and chemistry of the Earth's atmosphere is remarkably complex with additional complexity introduced by climate changes. Earth system observations are a key in understanding of climate changes. Overall, capabilities to observe the physical climate system have continued to improve and expand; for example, records from several satellite instruments of globally distributed, high-vertical-resolution profiles of temperature, humidity, and wind up to the lower stratosphere are now long enough and of sufficient quality to be relevant for climate assessments (IPCC). Recent progress in climate science offers valuable insights in forecasting climate trends, but further understanding is needed to improve our predictions of trends and climate extremes and the effectiveness of mitigation and adaptation strategies.

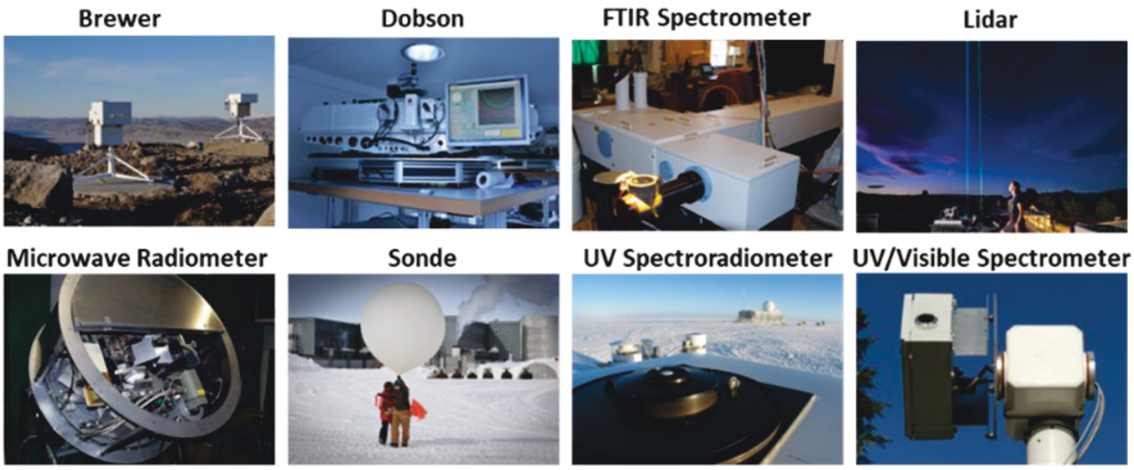

Figure 1: This figure shows a set of instruments used by the Network for the Detection of Atmospheric Composition Change (NDACC), a global network consisting of over 70 ground-based remote-sensing research stations with over 160 active instruments. NDACC plays a crucial role in the World Meteorological Organization's (WMO) Global Atmosphere Watch (GAW) Programme and is a significant component of the Integrated Global Atmospheric Chemistry Observation (IGACO) initiative.

The successful synergy between metrology and atmospheric chemistry/physics communities is poised to be expanded in a targeted manner to address some of the long-standing and emerging challenges of climate change. This focused effort includes expanding current understanding of processes; looking for both trends and changes in trends; observing new phenomena and chemicals and identifying fluxes at a regional level.

At the 2010 WMO BIPM workshop the atmospheric physics and chemistry topic was only partly addressed and most of the attention was devoted to satellite and greenhouse gases measurements and other trace gases species such as volatile organic compounds (VOCs). Main recommendations were related to quantify the level of trend detection achievable based on state-of-art measurements and the available standards. Reanalyses was also seen as an important tool to combine the information from models and observations to produce global estimates of climate parameters. Considerable attention was also paid to issues in spectroscopy.

The 2022 workshop was more comprehensive and inclusive of the large range of scientific disciplines important to this complex Earth System. The structure of the meeting was broader and covered different data types (e.g., surface-based, aircrafts, and satellite) and showed the existing blending of metrology and atmospheric science that improved knowledge of atmosphere and climate.

A closer relationship between the metrology and atmospheric science communities will allow identified, societally important challenges to be addressed more efficiently. Further collaboration between WMO and

BIPM was repeatedly recommended at the 2010 workshop, and in 2022, members of both groups continued to urge both structured and ad-hoc collaboration going forward. The basic recommendation that emerged from this latest meeting was that a standing relationship should be established between BIPM and WMO to coordinate work on metrology and climate observations to address common goals and responses and to improve clarity of communication. The 2022 workshop participants almost unanimously asked for specific guidelines on the application of metrology principles for field measurements.

2.2. Needs and recommendations in atmospheric chemistry and physics

Number	Issue	Recommendation
1A.1 **[a]**	**Continuity** Continuity of observations is a challenge for assessing long-term changes. Sensor changes over the time, for both satellite and ground-based measurements, contribute to erosion of the quality of collected data for both surface-based and satellite observations. Understanding drifts and traceability of individual instrument records is an important area for metrology. Merging of datasets into a harmonized record is critically important for understanding long-term changes; standard approaches for harmonization need development and testing.	**[Within next 2 years]:** Both WMO and BIPM should work with appropriate groups (e.g., ET-ACMQ) to identify issues and develop proper further actions important to long-term records. Efforts should focus on: • increased collaboration and communication between two communities (metrology vs meteorology) regarding uncertainty assessment; • more case studies or examples are needed to show the impact of using uncertainties in climate application • extended use of all available tools, to evaluate uncertainties in historical records, including statistical techniques, data assimilation approaches, instrument characterization, and impacts of temporal sampling, localized biases, vertical resolution, particularly where harmonization is required • bridging the QA/QC efforts in the different observation networks through standardization and harmonization of common QA/QC components, including establishing a common QA/QC Evaluation framework (using e.g. templates for protocols etc.). WMO should develop harmonized approaches for estimating and reporting uncertainties in all GAW data and identify additional metrology support.

Number	Issue	Recommendation
1A.2 **[b]**	**Tiered Networks and Low-Cost Sensors (LCS)** Tiered networks with extremely high-quality anchoring sites, routine monitoring and very low-cost monitoring are proving invaluable for scientific discovery, long-term monitoring, and appropriate information for policy decisions. All critical climate observations will benefit from strong tiered networks, including high-quality anchoring sites at a variety of locations through to moderate quality sites and as wide-spread network as possible for low-cost sensors. A full metrological evaluation of tiered networks is missing along with guidelines for instrument choices, calibration processes and quantification of uncertainties. Low-cost sensors have been already considered as an alternative method to fill spatial gaps of air quality monitoring. However, measurement issues that impact negatively on the utility of data from LCS must be addressed.	**[Within next 2 years]:** WMO and BIPM should examine the use of tiered networks and ensure an appropriate quantification of measurement uncertainty and precisions to existing tiered networks. Efforts should be made to assess the metrological characteristics of not just the highest tier of the network, but also the middle and lower tiers and determine if recommendations can be made to improve the entire global monitoring system through appropriate changes at any tier in the network. Potential networks for consideration could include the Climate Reference Network and the GCOS Reference Upper Air Network. **[Longer term]:** WMO and BIPM need to identify appropriate groups to address specific roles of LCS in the WMO community and to specify metrological issues and further actions. Efforts should begin within 12 months and be continued for the foreseeable future. • Jointly developed guidance for network planning, operation and interpretation will likely be both practical and effective for realistic observing networks. • Harmonized guidelines with traceable standards for sensor testing and calibration should be established and promoted. For example, LCS should be evaluated under expected operating environment conditions (e.g., concentration, temperature, humidity). • More portable calibration methods (e.g., traveling standards) for precise and reproducible measurements. • LCS could be further classified according to their measurement principles because different types of LCS have various strengths and limitations. • End users should be aware of the performance and limitations of the specific type of LCS. In the data being shared, the details of sensor type, calibration procedures, and other data QA/QC efforts should be included and transparent.

Number	Issue	Recommendation
1A.3 **[c]**	**Beginning to End Measurement Requirements** Metrological approaches are useful for supporting climate science from instrument design, through to fundamental observations and final use of the data either to support analyses, ensure comparability of multiple products offered by climate services, develop policy or improve reanalysis and models. Unfortunately, current incorporation of metrological expertise is often limited to one stage of that full process. The value of metrology can only be fully understood with better incorporation of cross-disciplinary approaches into the full value chain of climate observations.	**[Within next 2 years]:** WMO and BIPM should initiate an effort with appropriate climate groups as recommended by WMO to apply metrological analyses to the full approach for environmental measurements. The effort should focus on which steps of measurement through to scientific results contribute significantly to the scientific results and identify areas where improvements could be made to reduce the uncertainty. This analysis should include issues often not included in classical metrological approaches such as spatial representativeness of observations and impacts of undesired effects. Datasets of temperature and both total column and surface ozone networks may offer the maturity to support this analysis. The final endpoint should be a clear benefit, to the health of the Earth System or as a direct benefit to human life. The effort would be aided by WMO, together with appropriate climate communities and BIPM representatives, convening meetings within the next 12 months to identify both the process and results for identifying measurement requirements. These results should make careful use of defined language when specifying attributes such as precision, stability, uncertainty, and accuracy. Results of these discussions and requests for improvements should be circulated broadly in the metrological community. Focus should not be limited to current measurement capabilities, to encourage future developments.

1A.4 **[d]**	**Aerosols and trace gases** Aerosols, methane, CO_2, water vapor, ozone and VOC's (including formaldehyde) each require specific attention to supply "fit for use" observations in the coming years. The successful development and application of metrological standards to these components depends on sustained international commitments for station operations, use of common reference standards, intercomparison of observational results and methods, and maintaining the archiving facilities. For aerosols, absorption coefficient measurements traceable to the SI supply the foundational measurement; improved reference materials will help establish common traceable techniques, will help improve cooperation between national metrology institutes, networks, and other stakeholders. Because of the policy relevance of black carbon, special effort is needed to develop calibration techniques for large aerosols. For CO_2 and methane, improvement in GHG emission source and sink estimates and attribution is critically important as the planet transitions energy usage and addresses a variety of mitigation efforts. Carbon isotope measurements are needed with a high spatial and temporal sampling, with a need for more ubiquitous ^{14}C measuring technologies that overcome limited availability of accelerator mass spectrometry measurements. Pursue alternative approaches for observations including high-sensitivity laser spectroscopic approaches with the potential for in situ measurements. For water vapor, ozone and VOC's, individual approaches are needed to assure each of these observational approaches are sufficient to meet scientific and societal need.	**[Within next 2 years]:** BIPM and WMO should contact leading networks and measurement programmes such as GAW, ACTRIS and NDACC to review their application of metrological principles and identify additional measures to implement these more firmly into climate monitoring. Each of the critical list of atmospheric components: aerosols, methane, CO_2, water vapor, ozone and VOCs is sufficiently unique that separate working groups will be needed to identify relevant issues and provide expert guidance. Because each observable has its unique challenges and metrological needs, individual groups should be established to address aerosols, methane, CO_2, and VOCs separately. Enhanced work should begin within the next 12 months and continue in a semi-permanent manner for the outgoing years. Specific issues identified in our meeting related to these observables include: **Aerosols:** multiple parameters for aerosols, including light absorption, size distribution, mass and chemical composition require standardization or improvement of standards for traceability and calibration. **CO_2/CH_4:** flux estimations for both CO_2 and CH_4 are the overarching goals with a strong need for metrological input to achieve these goals. New spectroscopy-based approaches for ^{14}C requires examination to estimate its accuracy and explore its usefulness. **Water:** inconsistency of results from different measurement techniques continues to be the significant challenge in measure both water vapor and liquid/solid water. New approaches require examination to determine if they can both provide low-impact observations and higher accuracy for observations. **Ozone:** inconsistency of results from different measurement techniques including observations of local concentrations as well as observations of vertically resolved ozone amounts are critical to both scientific understanding and policy information. **VOCs including formaldehyde:** traceable standards are required for all VOCs particularly for concentrations near ambient levels.

Number	Issue	Recommendation
1A.5 **[e]**	**Spectroscopic measurements** Accurate and consistent spectroscopic parameters for trace gases — including greenhouse gases — are vital to the success of remote sensing products. Improvement in the accuracy of these parameters will help to reduce foundational uncertainties from the sub-percent to sub-permille range. Additional efforts to improve interpretation and use of spectral intensity measurements are needed; this includes accurate determination of effective optical pathlength, temperature and pressure, spectral line intensity, and sophisticated line shape modelling is required for requirements with sub-percent uncertainty in retrieved amount fraction. Improved validation is needed of cross-section data sets under a range of temperature and pressure levels.	**[Within 2 years]:** WMO and BIPM to work with the spectroscopic communities such as HITRAN and GEISA to initiate identification of specific metrological issues within spectroscopic data requiring further action. The actions should build upon on-going activities in the CCQM-GAWG Task Group for Ozone Cross-Section and the CCQM-Task Group on advanced spectroscopy that focus on validated high accuracy intensities of the main greenhouse gases.

References

[a] T1-A23, T1-A25, GCOS Status Report; ACTRIS (2022), NDACC, GAW, AERONET, EARLINET.

[b] T1-A17, WMO GAW report (https://community.wmo.int/activity-areas/wigos/gbon), two presentations in the plenary session (By Dr. Wenjian Zhang and Dr. Valérie Masson-Delmotte)

[c] BIPM-WMO Workshop presentations/posters T1-A2, T1-A5, T1-A7, T1-A10, T1-A26, T1-A33, T1-A35, also T1-D9

[d] Aerosol (T1-A11, T1-A40, T1-A43) $^{14}CO_2$ (commented by Dr. Xin Lan, A1-A12), water vapor (T1-A19, T1-A23), VOCs (T1-A13, T1-A18, T1-A21)

[e] Spectroscopic measurements (T1-A4, T1-A36, T1-A38), QA/QC (T1-A7)

3 Topic 1B: Oceans and Hydrology

3.1 Introduction

Water, in the ocean and in the terrestrial water systems that hydrology focuses on, plays a critical role in the Earth's climate. The world's oceans cover approximately 70 % of the Earth's surface and contain more than 95 % of the Earth's water. These large percentages, coupled with the ability of water to absorb atmospheric gases such as carbon dioxide, explain the importance of the oceans to climate science and climate change mitigation and adaptation. In fact, the oceans have absorbed more than one quarter of the anthropogenic carbon in the industrial age, along with 90 % of the excess heat. Terrestrial water systems overwhelmingly account for the world's water not contained in the oceans. These water systems also bear an importance, because of the effects of climate change on ecosystems, the ability of hydrological factors to mediate some effects of climate change, the inherent connection between freshwater systems and the oceans, and the importance of freshwater to food production and human life. Understanding the oceans and hydrology, through high-quality observational data records supporting oceanographic and climate modelling, is therefore essential for understanding the three Earth climate cycles: the Earth energy budget (see Topic 1C, Section 4), the water cycle and the carbon cycle.

Understanding oceans and hydrology is also important for climate change mitigation and adaptation. The ocean's ability to absorb carbon dioxide can in theory be enhanced by the management of seaweed, sargassum, seagrass meadows, and enhancing phytoplankton growth. And climatic impacts on sea ecosystems, particularly around sensitive coral reefs need active management as part of humanity's adaptation strategy. Coastal and terrestrial water management can also reduce the impact of sea level rise, acidification, warming and changing precipitation patterns. Managing these mitigation and adaptation strategies requires reliable observations.

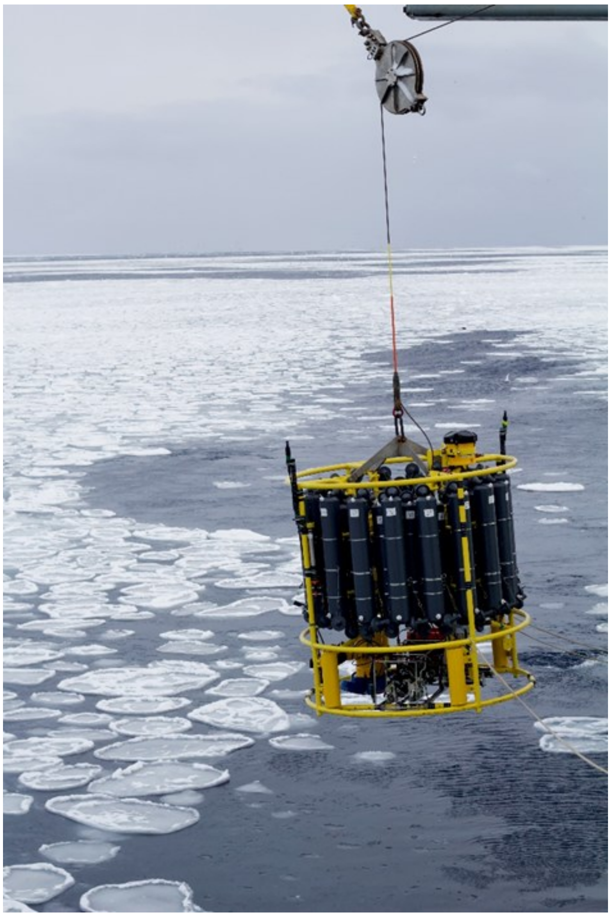

Figure 2: This figure shows the use of a rosette sampler, a device for water sampling in deep water used by oceanographers, to measure Conductivity, Temperature and Depth (CTD) in oceans and hydrology studies. This image shows a rosette being deployed in the South Indian Ocean during the U.S. GO-SHIP I06S 2019 research cruise. The photograph, taken by Isa Rosso, captures the rosette being lowered into the ocean to collect water samples at different depths. The data collected from CTD measurements are critical for understanding ocean circulation patterns, water mass characteristics, and the distribution of chemical and biological properties in the ocean.

Many physical properties of the ocean – the temperature, sea state, salinity, currents, wind stress, and dynamic topography – are measured at the surface by satellite observations, supplemented by reference and operational in situ measurements used for their validation. The state at depth is profiled using in situ instruments. Ocean biogeochemistry is predominantly observed with in situ sensors, although the satellite-derived quantity 'ocean colour' is used to determine chlorophyll concentration. Hydrological measurements are predominantly made in situ, although quantities such as river and lake heights and temperatures, and soil moisture, can also be ascertained using satellite observations.

At the 2010 WMO BIPM workshop there was limited focus on *in situ* ocean measurements, none on hydrologic measurements, with only traceability issues for salinity dealt with in detail. Progress in the 2022 workshop includes a much broader participation of the oceanographic community, leading to recommendations in respect of density, acidity, and carbonate chemistry. The 2022 workshop included the hydrology community for the first time. The 2010 WMO BIPM workshop included discussions about sea surface temperature and ocean colour from satellites and encouraged work to implement the then new quality assurance framework for Earth observation (QA4EO) and to develop collaborations for improved uncertainty analysis in satellite observations. In response to that several significant projects on developing satellite-relevant instances of metrological principles, have advanced practice in some ocean and hydrological observations, a situation that is mirrored on the *in situ* side by development of dedicated reference networks for ocean variables.

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3.2 Needs and recommendations in oceans and hydrology

Note that more information about these recommendations is provided in the notes after the table.

Number	Issue	Recommendation
1B.1 **[a]**	Joint efforts between observational scientists and metrologists are more effective when pursued within standing working groups, so that communications and collaborations can be effective over long periods. Areas that need collaborative attention include (1) developing common comprehension of metrological principles, traceability, and uncertainty; (2) practical guidance on measurement uncertainty estimation to assist in generating estimates that are complete, meaningful, and GUM compliant (important because the GUM is intended for laboratory measurements and is not easily applied to climate observations); (3) development of standard measurement methods with metrological principles embedded (networks to approach this problem exist, but without commonality in approach and level of detail regarding required data and metadata).	**[Within next 2 years]:** BIPM and WMO should, working with other existing groups (e.g., OBPS, GCOS, etc.) set up appropriate committees and working groups, or identify existing committees and working groups, where climate scientists and metrologists can effectively work together. (1) Metrological experts, working through OBPS, JCGM WG1, or other appropriate entities, should develop training on metrological principles, traceability, and uncertainty. (2) Metrologists should assist climate scientists in developing practical guides with examples, similar to the CITAC guide for analytical chemists. JCGM WG2, CCT, CCPR, CCQM, and RMOs are suitable venues, working individually or in cooperation. (3) Metrologists should work with OBPS (or other appropriate entities) to support the establishment of standardized methods with metrological principles embedded. Standardized methods should include requirements for reporting data and metadata.
1B.2 **[b]**	Earth Observation (EO) scientists need practical elaboration of GUM-compliant approaches to measurement uncertainty estimation to assist them in generating estimates that are meaningful and comparable. The GUM is not straightforwardly applicable for EO, hence there is a need for community-specific reference documents.	**[2+ years for scoping, 8 years for development of guidance]** BIPM and WMO should identify a suitable community where scoping could be undertaken to decide the details to be included in such practical guidance, after which development of guidance can be accomplished. A full international approach is needed, possibly undertaken in conjunction with space agencies like CEOS/CGMS JWGC or EO communities of practice like ESA CCI/Climate-Space.

Number	Issue	Recommendation
1B.3 **[c]**	Chemical oceanographers need multiple sources of reference materials for TA, DIC, stable and radiocarbon isotopes in DIC, pH, and standardized HCl (for TA titrations) that are comparable, metrologically traceable to the SI or other appropriate higher-order reference, and robust in the face of global crisis or supply chain disruptions.	**[5+ years to first NMI/DI programme, longer for other programmes to develop]** BIPM and WMO should identify opportunities for NMIs and/or DIs, working collaboratively with other expert organizations, to develop programmes in their respective regions to provide such reference materials, with global comparability assured through participation in CCQM key comparisons and other suitable intercomparisons.
1B.4 **[d]**	Oceanographers and climate modelers need to be able to measure Absolute Salinity S_A (mass of dissolved salts divided by mass of seawater) with a standard uncertainty of better than 0.002 g kg^{-1} to be able to follow the variability of many of the processes associated with climate change.	**[10+ years]** BIPM and WMO should help bring together metrologists and oceanographers to build the metrological framework for the measurement of S_A in seawater to the required specification, including reference materials, the establishment of SI traceability, and reference calibration methodology for instrumentation both in the laboratory and in the field. Technical barriers require research, and participation of multiple entities, including reference materials producers, researchers, instrument vendors, and practitioners.
1B.5 **[e]**	Oceanographers measure acidity using 'total' pH, an operational scale that has been calibrated for limited ranges of salinities, temperatures, and pressures. It is known that the effects of assumptions in the calibration of the scale become larger when moving away from ideal and laboratory conditions. Recent work using chemical thermodynamic models has clarified the relationship between total pH and the equivalent conventional thermodynamic total of hydrogen ions and demonstrated the likelihood that the total pH scale can be linked to the SI by directly calculating the influence of the assumptions noted above. It is not known how high pressure affects pH measurements for instruments calibrated at atmospheric pressures.	**[8+ years]** BIPM and WMO should support oceanographers, academics, and metrologists to establish research projects to complete chemical thermodynamic models (with ability to calculate, with quantified uncertainties, thermodynamic activity and speciation in the buffer solutions used to calibrate total pH) and to test the sensitivity of pH measurements to depth.

Number	Issue	Recommendation
1B.6 **[f]**	The ability to measure routinely seawater density, ρ, with a standard uncertainty of 0.0015 kg m^{-3} (1.5 ppm) and a more precise understanding of density as a function of Absolute Salinity, temperature, and pressure are needed to enable oceanographers to follow variations in ocean circulation, sea level, and absolute salinity caused by climate change.	**[10+ years]** BIPM and WMO should identify suitable working groups for metrologists to work with oceanographers to make progress in developing new measurement methods to enable ρ measurements at the required uncertainty both in the laboratory and in the field. Also, models and databases to relate ρ to S_A, T, and p need to be developed further. Metrological principles should be embedded in all these efforts.
1B.7 **[g]**	For climate change warning systems (e.g., coral bleaching alert systems), components of uncertainty for the measurements on which decisions are made are already considered. However, components of uncertainty associated with biological response to stressors (e.g., robustness of coral) are not generally considered. Such warning systems need to be improved by including these additional components of uncertainty, so that better societal decisions can be made.	**[3+ years for beginning work, 10+ years for good uncertainty estimations]** BIPM and WMO should identify suitable working groups for observation scientists and metrologists to work together to develop ways of incorporating the additional uncertainty components into decision thresholds. In many cases, fundamental research is still needed to understand how to quantify the biological response components of uncertainty.
1B.8 **[h]**	EO scientists depend on FRMs to help establish metrological traceability for measurands such as soil moisture, inland water level, sea surface temperature and sea level. Many gaps in FRMs remain for ECVs and EOVs, and theoretical/practical problems persist around representation uncertainty.	**[2 years for gap analysis, 8+ years for new metrological solutions]**: BIPM and WMO should identify appropriate groups where EO scientists can work with metrologists to identify gaps and plan solutions. NMIs and space agencies should lead the effort in cooperation with existing networks.
1B.9 **[i]**	Measurement uncertainties required for climate action are always decreasing. EO scientists can improve the uncertainties of their measurements, such as those of GMSL, by focusing efforts on the most important uncertainty components. Identification of the important components of uncertainty can be achieved through rigorous examinations of the relative contributions of the individual components of uncertainty.	**[2 years to much longer, depending on method to be examined]:** BIPM and CEOS to identify how EO scientists can work with metrologists to generate rigorous and complete analyses of measurement uncertainty, building on existing good practices, which will permit identification of the most important components of uncertainty and opportunities for uncertainty improvement.

Number	Issue	Recommendation
1B.10 **[j]**	Errors in satellite-derived climate data records are particularly complex, but progress has been made in applying FIDUCEO principles for E2E budget analysis in some cases. Use of E2E understanding to drive satellite mission requirements/analysis has even fewer exemplars (ASELSU seems to be pioneering here). Overall effectiveness of satellite observations will be enhanced by adopting these principles.	**[10+ years]**: BIPM and CEOS should identify how metrology, observation/climate and satellite technology experts can work together to trial and embed new approaches for E2E considerations of observational and mission requirements, to drive future developments. Space agencies should take the lead.
1B.11 **[k]**	EO scientists need practical, metrologically traceable techniques to quantify and verify observational stability requirements (e.g., from GCOS) for ECVs to enable accurate evaluations of climate change over multidecadal time scales.	**[1 years for scoping and prioritization, 5+ years for full implementation]:** BIPM and CEOS should identify how metrologists, in collaboration with climate scientists and Earth observers, should develop useful definitions of stability and rigorous theoretical and practical techniques for assessing and verifying stability of multidecadal/multi-mission EO-based climate data records. This work should be led by an NMI in close cooperation with GCOS and EO communities of practice (e.g., CCI/Climate-Space).

Notes

[a] Ocean acidification (OA) monitoring provides a good example of an activity that would benefit from collaborations set up within a standing committee or working group. The current paradigm governing the observation strategy for addressing the global phenomenon of OA distinguishes between the following two finalities:

i) "Weather", defined as measuring to identify relative spatial patterns and short-term variation. The "weather" objective requires the carbonate ion concentration (used to calculate saturation state) to have a relative standard uncertainty of 10 %. This implies an uncertainty of approximately 0.02 in pH, of 10 μmol kg^{-1} in measurements of TA and DIC, and a relative uncertainty of about 2.5 % in pCO_2.

ii) "Climate", defined as measuring to assess long-term trends with a defined level of confidence. The "climate" objective requires the change in carbonate ion concentration to be estimated with a relative standard uncertainty of 1 % (which is smaller than the uncertainty in the carbonate ion concentration itself). This implies an uncertainty of approximately 0.003 in pH; of 2 μmol kg^{-1} in measurements of TA and DIC, and a relative uncertainty of about 0.5 % in pCO2.

Currently, the "weather" objective measurement specifications for the indicated measurands are deemed achievable in competent laboratories and, with care, by some of the better autonomous sensors available on the market for monitoring them. On the other hand, the "climate" objective measurement specifications for the same measurands are achievable only by a very limited number of laboratories at present and are not typically achievable for all parameters by even the best autonomous sensors.

Currently, most of the effort relating to the assurance of measurement compatibility with established monitoring goals for OA measurands is being carried out by the oceanographic community, often within the framework of climate-related projects or programs or under the aegis of scientific associations or organizations of one kind or another. The efforts suffer from a dearth of professional metrological input and a disconnection from the SI.

Another example is the measurement of suspended particulate matter using multibeam echo sounders (MBES). GeoHab currently has a working group (the Backscatter Working Group), but inclusion of metrologists into this group is recommended.

Posters T1-B1 and T1-B10

[b] While the fundamental principles of the GUM address uncertainty in measurement in general, remotely sensed/Earth observations are characterized by inverse methods and spatio-temporal error correlation structures (e.g., in imagery) that could benefit from domain-focused equivalent guidance. Colloquially, such a guidance document might be referred to as a GUM4EO. It could be built on FIDUCEO outcomes and later progress made in projects that have adopted and extended FIDUCEO applications.

Issues that could be addressed in such a GUM4EO include: guidance for agencies/industry on developing Level 1(L1) uncertainty information during mission development; guidance for characterizing and efficiently disseminating uncertainty/error covariance information in L1 data; guidance on using L1 uncertainty/error covariance information to inform uncertainty in derived L2, L3, L4, and aggregated information; guidance on presenting uncertainty information at L2+; guidance on L2+ comparison to FRMs and other in situ measurement results; guidance on quality flags and metrological traceability; and guidance on verifying long-term observational stability (see also specific recommendation 19 on this, on a shorter timescale). Levels (L) refer to the extent of processing that has been undertaken on the data from satellites.

[c] For more than 30 y, the world's supply of reference materials for chemical oceanography have been provided by a single supplier, the Scripps Institution of Oceanography. For the past several years, the oceanographic community has realized that depending on only a single source is not optimum. The recent global pandemic showed that there must be multiple sources that provide comparable reference materials, so that disruption from one source does not necessarily mean a total lack of availability.

Having multiple sources would also improve overall measurement quality because different practitioners would establish metrological traceability through different materials, rather than everyone achieving traceability through the same material. NIST in the United States is already developing a new program to act as one source of reference materials for chemical oceanography in cooperation with NOAA and other agencies in the United States. Other NMIs and DIs are encouraged to do the same for their regions. Consistency could be assured through CCQM key comparisons, the framework for which is already well established.

On a related issue, it will be helpful for new seawater reference materials to represent as much as possible actual *in situ* conditions in the ocean. This is a serious challenge to producers of reference materials, but the benefits of being successful would be significant.

Posters T1-B3, T1-B8, T1-B12

[d] The reformulation of the Equation of Seawater (TEOS-10, in force since 2010) uses Absolute Salinity S_A (mass fraction of salt in seawater) as opposed to Practical Salinity S_P (which is essentially a measure of the conductivity of seawater) to describe the salt content of seawater. S_A is an essential quantity necessary for deriving other thermodynamic properties of seawater (e.g., density, enthalpy, entropy, sound speed, etc.) that can impact on atmosphere-ocean interactions relating to climate change.

Poster T1-B17

[e] Poster T1-B7

[f] The density of seawater r is the most important thermodynamic property for modelling ocean circulation or water level anomalies. Its measurement is also a means of determining the absolute salinity S_A of seawater. The required standard uncertainty (0.0015 kg m^{-3}) for measurement of r is very close to the best measurements made in metrology laboratories at atmospheric pressure. The current uncertainties in the relationships between S_A, temperature T, and pressure p range from 0.007 % to 0.012 % at best and do not meet the needs of oceanographers. They are also an obstacle to the development and calibration of instruments for in situ measurements.

To meet the needs of oceanographers, much progress is therefore needed to improve the uncertainties in the fundamental relationships between the parameters, particularly when p is different from atmospheric pressure. Considering the required uncertainty level and the importance of density/salinity measurements in ocean physics and climate change, it is a key technical challenge for metrology over the next decade.

Poster T1-B17

[g] Poster T1-B16

[h] Posters T1-B2, T1-B4, T1-B14, T1-B15, T1-B18

[i] Poster T1-B6

[j] Poster T1-B6

[k] Requirements on EO ECVs from GCOS rightly include requirements on observational stability because stability is clearly crucial to quantification of change on multidecadal times scales of long satellite climate records. A common understanding of what “stability” means when errors correlate on a range of timescale is missing. Similarly, what the stability requirement implies in terms of step-changes/breakpoints is also unclear, and these do occur, e.g., at the change overs of satellite missions/sensors through the record. EO practitioners who have attempted to estimate and verify stability have needed to generate *ad hoc* methods. There is also the absence of an authoritative theory of how to verify an estimated stability given real-world historical comparison data on the *in situ* side. Simulation of the impact of changing geographical match distributions over time may be important to include in practical assessments. There seems to be a need to develop technical means for the practical assessment and verification of observational stability.

Poster T1-B6

4 Topic 1C: Earth Energy Balance

4.1 Introduction

The Earth climate's current state and rate of change are driven by the flow of energy between different components internal and external to the Earth system. The external factors determine the overall Earth energy balance (EEB) and the rate at which energy is absorbed or lost by the Earth's system. The difference between the incoming solar radiation and the outgoing radiation, a sum of the reflected solar radiation and emitted thermal radiation, determines the EEB. A positive EEB, having more incoming than outgoing radiation, leads to global warming. The EEB is thus the most fundamental, direct measure of climate change. Current estimates of the EEB range from 0.4 W m^{-2} to 0.8 W m^{-2}, accelerating from an average of 0.47 ± 0.1 W m^{-2} for the entire period 1970 to 2018 to 0.87 ± 0.12 W m^{-2} for 2010 to 2018 (e.g., von Schuckmann et al., 2020).

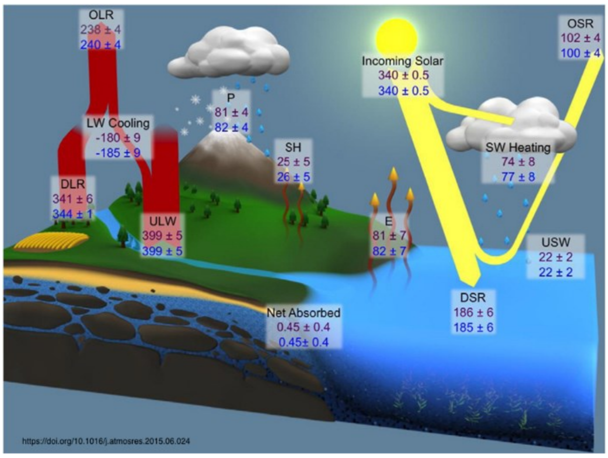

Figure 3: The figure shows a global and annual mean of the Earth's energy balance, which has been derived from various sources of optimized data. The optimization was carried out to account for all of the energy entering and leaving the Earth's atmosphere, and to balance these fluxes to obtain a net zero energy balance. The image includes two versions of the energy balance provided as an indicator of how the balance can change under different optimizations. All quantities are fluxes in units of Wm^{-2}. The numbers shown in magenta are the optimized fluxes after L'Ecuyer et al. (in press). The fluxes in blue are from a second optimization where the ToA fluxes are more tightly constrained to the CERES EBAF version 2.7 fluxes that in turn are constrained to independent OHC information. The surface fluxes in blue are also more tightly constrained to the GEWEX surface radiation flux product (note the DLR flux difference). Stephens et al. 2015.

There are two aspects to characterizing the EEB. The first is acquiring direct measurements of incoming and outgoing radiant energy, which must be done from space with extremely accurate radiometric instrumentation. The second is less direct, requiring knowledge of the energy uptake or loss by different components of the Earth system. This can include the already-committed warming due to greenhouse gases (GHGs) currently in the atmosphere even in the absence of further GHG emissions (although GHGs are not a long-term heat-storage medium). The four major such reservoirs are the oceans, land, permafrost, and cryosphere. These topics were discussed at the 2010 WMO-BIPM workshop, which included a session on 'Radiation and Earth Energy Balance.' The recommendations from that workshop led to ongoing collaborations between the metrology and observation communities, including several focused workshops over the intervening decade. These previous efforts provide a fundamental basis on which the 2022 workshop expands by defining specific technical recommendations. This recent workshop's EEB recommendations, compiled from the session's 22 accepted pre-recorded presentations and online posters as well as two interactive community-wide discussion sessions, centre around three subtopics: radiometric energy measurements, calibration sources, and the Earth heat inventory.

Direct Radiometric Measurements: The most fundamental EEB measurements are the Earth's net incoming and outgoing radiation. Both need to be measured with < 0.03 % uncertainties to discern energy imbalances directly. The former is given by the total solar irradiance (TSI), which is the spatially and spectrally integrated radiant energy from the Sun incident at the top of the Earth's atmosphere (ToA). This value, reported at 1 AU, is 1361 ± 0.5 W m^{-2} (Kopp and Lean, 2011; Prsa et al., 2016) but varies slightly with solar activity, as described by Kopp (2014). Globally averaged incident-energy values, as used in EEB studies, are one quarter of the TSI, or 340 ± 0.1 W m^{-2}, and achieve the measurement uncertainties needed to directly determine the incoming-energy portion of the EEB. Outgoing measurements, however, are more difficult since they must encapsulate the outgoing radiation from the entire Earth's surface, account for scatter and anisotropies, and span the solar-reflected plus thermal-infrared spectral ranges. These, therefore, have much higher uncertainties, with each of the outgoing short- and long-wave radiation having uncertainties of ~ 4 W m^{-2} (Stephens et al. 2015), making direct determination of the ~ 0.4 W m^{-2} EEB untenable. Lacking sufficient accuracies, the current outgoing-energy record relies on measurement continuity and stability to try to detect relative trends in the EEB. Improvements in accuracy are being pursued, with a new generation of spaceborne reference observatories, called "SI-Traceable Satellites" (SITSats), to be launched within this decade. These will not only acquire direct outgoing spatially and spectrally resolved radiance measurements for climate studies but also provide inter-calibrations for other on-orbit sensors to both improve measurement accuracies and broaden the global measurement scope spatially and temporally (Wielicki et al., 2013; Fox et al. 2020).

Calibration Sources: To make direct EEB observations with the necessary uncertainties and long-term stabilities requires SI-traceable, low-uncertainty, long-duration, radiometric reference standards. Some approaches rely on well-characterized and stable detectors, such as electrical-substitution radiometers and bolometers for use in both space and ground instrumentation (Kopp and Lawrence 2005; Fehlmann et al. 2012; Richard et al. 2020). Other approaches rely on accurate calibration sources, such as from thermal blackbodies for infrared spectral measurements (Taylor et al. 2020). Natural, on-orbit calibration sources include the Sun and the Moon, both of which are well characterized and can provide long-term stability monitoring and even accuracy calibrations for orbiting Earth-viewing sensors (Stone 2008; Kopp et al. 2017). Ground-based facilities to enable end-to-end calibrations are also needed to test and calibrate instruments under flight-like conditions (Kopp et al. 2007).

Earth-Heat Inventory: Heat-storage reservoirs can, for some length of time, cause an imbalance in the EEB by taking up or releasing energy, affecting climate change as well as climate adaptation and mitigation strategies. Understanding the heat uptake and release from reservoirs as well as their net inventory helps characterize the EEB. Many atmospheric properties determining energy availability at the ground as well as the storage mechanisms themselves are spectrally dependent, requiring knowledge of the incoming and outgoing spectral radiation. The primary four reservoirs detailed in the workshop include the oceans, land, permafrost, and cryosphere (sea ice and ice sheets). These overlap with other Theme 1 topics, particularly "Oceans and Hydrology" and "Cryosphere Monitoring," and further details on the Earth heat inventory can be found in those topics.

Below are the primary recommendations from the workshop's Earth Energy Balance topic, including suggested means and timelines to address them. These are grouped into the primary three subtopics described above.

4.2 Needs and recommendations in Earth energy balance

Number	Issue	Recommendation
1C.1 **[a]**	**Radiometric Energy Measurements: Uncertainties** Measurements of incoming and outgoing radiant energy lack the uncertainties needed to directly discern an imbalance in the Earth's energy budget, which determines climate change. Total solar irradiance (**TSI**) and globally averaged outgoing Earth radiation both need to be measured to **< 0.03 % standard uncertainties** to discern energy imbalances directly. These uncertainties are achievable for the incoming total solar irradiance but are much lower than those of the outgoing net radiation, which are more difficult due to spanning a broader spectral range, spatial inhomogeneities, and varying angular distributions. Achieving the needed uncertainties for the globally averaged outgoing measurements is difficult technically, requiring constellations of sensors, distant orbits, and improvements to angular-distribution models.	**[Ongoing work over next 10+ years]** **Lower Uncertainties from Ground-Based Calibration Facilities:** Research institutes and NMIs should create more stable spaceflight detectors and in-vacuum end-to-end ground-based irradiance- and radiance-calibration facilities capable of providing **radiometric uncertainties of < 0.01 % (*k* = 1)**. International spaceflight centers should utilize these facilities to calibrate higher-accuracy space-borne radiometric instruments and overlap on-orbit measurements to monitor long-term climate variability.
1C.2 **[b]**	**Radiometric Energy Measurements: SITSats** SI-traceable, low uncertainty, spatially and spectrally resolved radiance measurements in the visible to far-infrared can reduce times of trend detection of climate change in the presence of natural variability, enabling better attribution and more credible policy decisions. These require a **~ 10× reduction in on-orbit uncertainties**, nearly matching what is achievable in ground-based NMI laboratories.	**[Ongoing work with planned launches over next 10 years]** **SITSats**: NASA and ESA Earth-science divisions should create and fly SITSats (SI-Traceable Satellites), such as **CLARREO, TRUTHS, and FORUM**, to provide low-uncertainty measurements directly and to inter-calibrate other on-orbit sensors, extending the spatial, spectral, and temporal coverage of Earth-observing systems. The first SITSats should be launched within this decade and should have missions extended in time to overlap and validate each other.
1C.3 **[c]**	**Radiometric Energy Measurements: Stabilities** Measurements currently lack the uncertainties needed to directly determine the EEB via differences between incoming and outgoing radiation measured on an absolute scale (see T1.c1). Without such accuracies, discerning long-term trends relies on measurement stability	**[In next 2 years]** **Measurement Stability and Continuity:** On near-term timescales, prior to obtaining the desired on-orbit uncertainties (T1.c1), international space agencies should guarantee uninterrupted TSI and globally averaged outgoing Earth radiation measurements with

Number	Issue	Recommendation
	combined with measurement continuity. Instruments must have better stability than the trends they are attempting to detect and space agencies must maintain overlap between successive instruments, avoiding data gaps in critical EEB measurements.	instruments having **stabilities < 0.01 % (*k* = 1) per decade** to detect long-term EEB trends. NASA continues to be supportive of continuity of solar-irradiance and outgoing broadband energy measurements, with the **TSIS-1/TIM and CERES** currently providing those measurements.
1C.4 **[d]**	**Calibration Sources: Sun and Moon.** Consistent, SI-traceable, low-uncertainty, long-duration, on-orbit spectral calibration sources are needed for calibrating, adjusting, and checking Earth-observing instruments operating in the visible and near-infrared spectral regions. The Sun and Moon can provide these on-orbit sources if sufficiently characterized. Being inherently very stable, they can also bridge non-overlapping instruments, mitigating measurement data gaps (T1.C3). Solar measurements and models currently achieve the needed accuracies to provide such an on-orbit calibration source for any instrument able to directly measure the spectral solar irradiance. Lunar irradiances used as on-orbit calibration references need improved uncertainties from the current modelled levels of about 5 % to 10 % to less than 1 %. This will involve: 1. Acquiring lunar observations through full libration cycles to account for changes in the Moon's apparent size and orientation, and 2. Reducing discrepancies between lunar models.	**[Present and Near Future]** Space agencies (NASA, ESA, CMA) should recommend Earth-observing instruments begin regularly acquiring **irradiance measurements of the Sun and/or the Moon**. Spectral solar irradiance (**SSI**) measurements should be continued. Solar models based on these measurements can extend the SSI records to historical times for retroactive calibrations of past solar-viewing instruments. Operators of the SITSat missions **CLARREO Pathfinder** and **TRUTHS** as well as smaller, more dedicated missions such as **ARCSTONE**, should provide improved lunar-irradiance measurements within the next few years, to provide better data on which to build or improve **lunar-irradiance models**. Those models can then be applied to estimate lunar irradiances at any era for intercomparisons with instruments' lunar observations. Metrologists should continue working with space agencies to make lunar observations through full libration cycles (> 3 years) and develop methods that combine the observational results to improve agreement between lunar models.
1C.5 **[e]**	**Calibration Sources: Space-Qualified UV Sources** Space-qualified SI-traceable calibration sources for tracking instrument performance in the UV spectral range are not readily available. Remote	**[Present and Near Future]** Research institutes and NMIs should investigate the stability of UV sensors and support the selection and development of suitable

Number	Issue	Recommendation
	sensors monitoring EEB have larger uncertainties at UV-blue wavelengths because spectral responses of sensors decrease at these wavelengths, and sources have low signal-to-noise.	radiation-hard sensors for the UV spectral range. NMIs should further develop stable UV sources. National space institutes and commercial instrument providers should space-qualify existing narrowband UV-blue sources, as currently used for terrestrial applications. On-orbit assets should inter-calibrate and compare with SITSats such as CLARREO Pathfinder.
1C.6 **[f]**	**Calibration Sources: Uncertainties in the Thermal Infrared** Reduced uncertainties for measurements of Earth-emitted thermal radiation (which span a broad spectral region and account for a significant fraction of the Earth's emitted radiant energy) are needed to determine the EEB directly. This would require improved characterizations of instrument spectral-response functions at far-IR wavelengths (>30 μm). FTIR spectrometers are typically used for making these types of measurements but are limited by low SNRs in the thermal-infrared EEB regions.	**[Present and Near Future]** Research laboratories and commercial instrument providers should investigate techniques to improve SNR of far-IR sensors using sources and optical configurations that are currently used in FTIR spectrometers utilized for instrument characterizations.
1C.7 **[g]**	**Calibration Sources: On-board Blackbody Calibration Sources** For the operational timeframe of upcoming missions like FORUM (scheduled for launch in 2026), on-board blackbody calibration sources will need to deliver 100 mK (k = 3) uncertainties in the MIR and FIR spectral range to determine climate trends via absolute accuracy.	**[In next 2 years]** Research laboratories, NMIs, and universities should continue to investigate the use of small fixed-point cells incorporated into blackbodies. Instrument operators should consider alternatives, such as the feasibility of verifying on-board reference blackbody calibrations in the MIR via fiducial reference measurements of the spectral radiance in atmospherically transparent windows, allowing vicarious measurements of ground scenes for intercomparisons.
1C.8 **[h]**	**Earth-Heat Inventory: Oceans** The ocean heat content observing system currently undersamples ocean measurements polewards of 60° latitude, in the deep ocean (> 2000 m depth), and in some shallow areas (< 300 m depth).	**[In next 5 years]** Researchers and data users should continue efforts to further advance calibration corrections, metrological uncertainty evaluations, data recovery, and processing of the historical datasets for the full

Number	Issue	Recommendation
	Argo is an international programme that collects information on temperature, salinity, pressure, and biogeochemical components such as oxygen, pH, nitrates, chlorophyll, etc. of the world's oceans. Data are collected using robotic instruments that drift with the ocean currents and move up and down between the ocean surface and a mid-water level. This 20-year-old ocean observation system is global and ongoing but needs technical input to provide improved knowledge of ocean heat content.	Argo record. Extension of the Argo project into sub-sampled areas with further technical developments and expanded coverage of shallow areas is recommended.
1C.9 **[i]**	**Earth-Heat Inventory: Land** There are no international data-acquisition and curating efforts to obtain currently lacking subsurface temperature profiles after the year 2000 and/or in the southern hemisphere.	**[In next 5 years]** An international organization such as GCOS is needed to motivate and coordinate increased sampling of subsurface temperature profiles and acquire and consolidate resulting and extant data. WMO and BIPM should find ways to support this activity.
1C.10 **[j]**	**Earth-Heat Inventory: Permafrost** Permafrost heat storage is the heat required to change the mass of ground ice at a certain location. Melting permafrost is an Earth tipping point for climate. Due to current limitations in observational data, a permafrost model, rather than observations, is required to estimate the heat uptake by thawing of ground ice.	**[In next 5 years]** Ground-based instruments are needed to monitor ground ice and water content, which are currently lacking for permafrost studies, and increased spatial sampling of soil temperature. More accurate values will help validate the models that can extend those data temporally and spatially. WMO and BIPM should find ways to support this activity. See also recommendation 1E.6.
1C.11 **[k]**	**Earth-Heat Inventory: Cryosphere** Ice-sheet melting is a key climate tipping point. Several components of cryosphere heat storage are limited by a lack of observations, scarce sampling (e.g., thickness for sea ice or ice melt below sea level, firn and ice temperatures for glaciers), or sustained observing-system elements (e.g., satellite altimeter missions with high-inclination polar-focused orbits). These are needed to complete the cryosphere component for the assessment of Earth's heat inventory.	**[In next 5 years]** Space agencies need to acquire sustained remote-sensing components from polar-focused orbits including reliable gravimetric, geodetic, and ice-velocity measurements, knowledge of ice thickness and extent, and snow/firn thickness and density to better understand ice sheets and glacier. Metrological support of research in all these topics is discussed under the cryosphere topic.

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5 Topic 1D: Biosphere Monitoring

5.1 Introduction

The biosphere is the sum of all the ecosystems on Earth. The climate impacts the state of living species and ecosystems, and the biosphere influences the Earth system through the energy, water and carbon cycles. Climate change therefore affects the organisms present in these ecosystems, and the organisms react to these changes by adapting or migrating; but can also disappear.

Figure 4: An example of an atmospheric station and validation site that assist in evaluating and enhancing the precision of land surface temperature (LST) measurements and model simulations. The validation of LST measurements is a complex process and the difficulty arises due to uncertainties when transitioning from point source measurements to satellite or model grids, especially for land essential climate variables (ECVs) due to surface heterogeneity, observation conditions and measurement conditions. Picture source https://www.imk-asf.kit.edu/english/skl_surfacetemperature.php

The importance of climate change impacts on the biosphere and its fundamental role in the carbon cycle has long been recognized. The IPCC has reported on terrestrial and oceanic ecosystems since their first assessment report in 1990. The UNFCCC has asked for reporting on emissions and removals of greenhouse gases including changes to terrestrial ecosystems, initially based on the 1996 revised IPCC Guidelines for National Greenhouse Gas Inventories, and refined in 2019, and on establishing dedicated good practice guides for the Land Use and Land Use Change and Forestry (LULUCF) sector in 2003 and a supplement for Wetlands.

The Global Climate Observing System (GCOS) community has developed the concept of essential climate variables (ECVs). ECV data records are intended to provide reliable, traceable, observation-based evidence for a range of applications, including monitoring, mitigating, adapting to, and attributing climate changes. This concept has been broadly adopted worldwide as the guiding basis for observing climate, including by the UNFCCC, WMO, and space agencies operating Earth observation satellites. Climate modellers also use ECVs to study drivers, interactions, and feedbacks due to climate change, as well as teleconnections (large scale linked events such as the El Niño-Southern Oscillation (ENSO), tipping points, and fluxes of energy, water, carbon, and to predict future change.

GCOS currently specifies 54 ECVs, of which 8 are associated with the biosphere and these have been addressed using satellite data. However, currently the challenge is to develop quality assured ECVs, namely in validating these products globally in a consistent and systematic way, identifying and reducing the uncertainties on the related observations and producing time-series of sufficient length. Cross-platform observations are also required to increase confidence in the understanding of the biosphere responses to climate change. As stated in the IPPC AR6 Chapter 2 section 2.3.4 Biosphere (Gulev et al., 2021) "In summary, there is high confidence that vegetation greenness (i.e., green leaf area and/or mass) has increased globally since the early 1980s. However, there is low confidence in the magnitude of this increase owing to the large range in available estimates."

Sustained observation of ECVs relies on a range of different platforms and sensors, based on feasibility, building on the long-term existence of *in situ* and satellite components. At the level of space Earth Observation (EO), new (pre-)operational products using past or new instruments (e.g., Copernicus Sentinels) are systematically delivered providing longer-term series and at higher spatial resolution, respectively. For *in situ*, several terrestrial monitoring networks exist for ground-based measurements, such as FLUXNET, long-term ecological research (LTER), terrestrial ecosystems research network (TERN), National Ecological Observatory Network (NEON) and the World Radiation Monitoring Center (WRMC) Baseline Surface Radiation Network (BSRN). In addition, field campaigns such as those performed by the FRM4VEG project, have been developing new measuring approaches to establish Fiducial Reference Datasets (FRM) standards for biosphere variables.

In the 2010 WMO-BIPM workshop, the biosphere contributions were limited to considerations on pre and post launch calibration, the need for traceability, and on a couple case studies focused on certain instruments. Most of the focus was on the impact of instrument measurement uncertainty. The 2022 workshop brought together a group of more than 100 authors and co-authors from 29 organizations (academia, research centres, space agencies and networks), grouped in 10 presentations and 4 posters focusing on a wider range of ECVs (Land Surface Temperature, FAPAR, Soil Moisture), and uncertainty sources. Topics vary from instrument calibration, comparison uncertainty, regridding covariance, spatial scale variability and representation, assimilation of observation results into models, radiative transfer model tools in support of metrology, and many others.

During the workshop, EO space producers, *in situ* networks and modellers stated that the support from the metrology community has been crucial in characterizing and better understanding the source of uncertainty in the data and how this are propagated to the final products. Although great progress has been made since the last workshop, new challenges require that existent and new metrological approaches be tailored and developed to the biosphere theme. The BIPM and WMO should help to coordinate and promote within all forums activities that bring together the biosphere community, metrologists and space agencies.

5.2 Needs and recommendations in biosphere monitoring

Number	Issue	Recommendation
1D.1 **[a]**	**Uncertainty for biosphere products** There is a lack of understanding of a common metrological terminology and guidelines on uncertainty calculation for EO based, and downstream, biosphere products. Across product providers and modellers, there is often a different understanding of uncertainty, and its estimation is often retrieved by non-metrological processes such as ensemble models bias or by comparison with so-called reference independent data.	**[Within next 12 months]** BIPM, working with WMO and related groups, should initiate activities to enable the development of cross-community agreed guidelines and tools for metrological approaches with GUM-style guidelines for EO-based products (at all processing levels) and *in situ* measurements. A biosphere focus group should consider how these are applied to the biosphere ECVs. BIPM and WMO should implement a process to identify metrologists who can participate in the communities that are establishing standards for satellite and *in situ* measurements of biosphere ECVs. And, through such groups, metrologists should support the development of uncertainty guidelines tailored to the biosphere applications, perhaps with some guidelines for considering metrological practices when writing and reviewing papers. WMO and BIPM should encourage and enable the participation of metrologists in new programs that are like the historical FIDUCEO and QA4ECV projects and the ongoing QA4EO and FRM/FDR projects.
1D.2 **[b]**	**Uncertainty propagation for classification** There is therefore a strong need to 1) develop metrological methods and tools to propagate and estimate uncertainties for high-level products and 2) advise the communities concerned and communicate these approaches. There is a need for methods to propagate uncertainties through classification. This is also needed for either: 1) auxiliary information products (cloud masks, aerosol type) or 2) burned area or 3) land cover classification. There is also a gap on how to propagate uncertainties when using Artificial Intelligence (AI) and Machine Learning (ML) based approaches on biosphere ECV retrieval algorithms.	**[Within next 2-3 years]:** BIPM should encourage data scientists within metrology institutions to develop methods on how to propagate uncertainties through various classification process, in collaboration with those developing algorithms (academic and research organizations), and through the change of spatial scale at the level with the land model community. This aims to present research activities to CEOS LPV to work towards a standard approach. **[3-5 years]** BIPM should integrate the advice & protocols developed through that research into the suite of documents that form the JCGM GUM.

Number	Issue	Recommendation
	There is a need to assimilate uncertainties in the land model through these additional processes.	
1D.3 **[c]**	**Reanalysis and model uncertainties** Reanalysis data (atmospheric, land and oceanic climate variables) are used in the retrieval of ocean and land ECVs. Existing reanalysis data do not come with traceable uncertainties, which limits the ability to either propagate uncertainties to EO ECVs when used as inputs, e.g. for atmospheric corrections or to validate observational uncertainties. There is the need for quantifying uncertainties associated with output model data (reanalyses) to use as inputs in Earth Observation products processing chains.	**[Within next 2 years]:** BIPM with WMO and the biosphere community should establish collaborative links between data scientists working in metrology institutes, metrologists with familiarity with biosphere Earth observation products and scientists working on biosphere products. Workshops should be arranged to discuss the challenges and existing approaches in the community and in metrological institutes. These workshops should lead to collaborative research projects to develop methods to propagate uncertainties through to reanalysis and models. **[3-6 years]:** Collaborative research and ongoing workshops and dedicated meetings should develop concepts and guidelines to propagate uncertainties through data assimilation and into reanalysis. **[6+ years]:** BIPM should integrate the advice and protocols developed through that research into the suite of documents that form the JCGM GUM.
1D.4 **[d]**	**Uncertainty propagation to high-level products** When merging time series from different satellite missions for climate (long-term) studies, high level products, e.g. L3/L4 products from single satellite missions are often treated independently. There is the need to provide consistent multi-mission products with related uncertainties. Interoperability and stability among different sensing technologies or geophysical retrieval algorithms is not always guaranteed. Need for a variable-centric metrological treatment, superseding the usual EO mission-centric one.	**[Within next 2-3 years]** WMO and BIPM to identify appropriate groups to (CEOS-LPV) to organize workshops with the EO communities and to identify metrologists who can participate in the CEOS-WGCV-LPV workshops to define protocols on how to use sensor comparisons to perform bias corrections at Level 3. Product developers and climate scientists should engage the metrology community, to ensure that products' traceability (preferable to SI).
1D.5 **[e]**	**Representativeness uncertainty**	**[Within next 2 years]:** BIPM to encourage data scientists and metrologists to start work with appropriate biosphere community researchers to define appropriate techniques to account for the *in situ* data spatial and temporal

Number	Issue	Recommendation
	In both ‘validation’ or ‘*in situ* data’ assimilation in models, there is a difficulty in understanding and considering all the uncertainty effects that impact the process of moving from a point source measurement to a pixel size area (satellite) or model grid, especially for land ECVs, considering the surface heterogeneity, observation conditions and measurement conditions. Product inter-comparisons at different spatial resolutions or grid structures, should be made re-meshing products using a common target grid and ensure that uncertainties are reported properly (data interpolation method with covariance).	(surface heterogeneity and seasonality) representativeness with respect to satellite pixel or model grid. WMO-BIPM to encourage and enable metrologists to participate in discussions at CEOS-LPV which will lead to proposing R&D projects including *in situ* providers, EO validation community; climatologists; statisticians, and biosphere modelers and to address this issue during the validation meetings promoted by the space agencies and sponsored by CEOS LPV.
1D.6 **[f]**	**Uncertainty validation** There is a need to validate ECVs and their uncertainties and assess their conformity to well-defined requirements (such as those provided in the GCOS IP). Verification is desirable with reference *in situ* measurements, but a more general process is required to both these purposes (particularly when coverage of reference measurements is not sufficient).	**[Within next 3 years]:** BIPM and WMO to establish connections that will allow metrologists and data scientists in cooperation with data providers, to develop a standard metrology-based approach for uncertainty verification covering biosphere ECV products from observation and model outputs. CEOS LPV to work with National Measurement Institutes (NMI) in defining intercomparison exercises standards for uncertainty assessments.
1D.7 **[g]**	**Uncertainty usability** There is a general need for communicating the uncertainty values to users and decision makers in a comprehensive, yet simple, way. This is technically challenging as distributing complete descriptions of uncertainty (including information on error covariance, systematic vs random components, …) is computationally expensive. It is likely also to be difficult for most users to use. Methods for simplifying uncertainty presentation and distribution, without losing important rigour, are needed.	**[Within next 12 months]:** WMO, in collaboration with Copernicus though its next R&I programme can help to define some research activities and case studies for how the provision and distribution of uncertainty information could be improved. BIPM can identify metrological communities who may be able to help in such projects. Technical aspects should be discussed within the various biosphere communities to define how best to cater to the diverse needs of users in terms of uncertainty distribution.
1D.8 **[h]**	**Tipping points** Components of the biosphere can face tipping points, e.g., due to extreme climatic events.	**[Within 5+ years]:** BIPM and WMO should initiate a process to work with the the climate modelling community, Earth observation experts working in biosphere, and identify experts from the metrology community to collaborate on projects that

Number	Issue	Recommendation
	Assessing and representing the associated increased uncertainty is difficult but also very relevant for society and decision makers: even though low, the possibility of tipping points needs to be properly conveyed and integrated in management policies.	will research how to handle observational and modelling uncertainties and their impact on identifying tipping points and discontinuities. Enhanced integration of probabilistic approaches in metrology should be considered.
1D.9 **[i]**	**Radiative transfer models** Radiative transfer models (RTMs) are used for radiometric calibration and in processes such as correcting for the atmosphere, scaling between satellite and in situ measurements and as such, are an essential part of the EO value chain. However, RTMs are difficult to make metrologically robust, this is because: (1) Propagating uncertainties through Monte Carlo-based RTMs is challenging due to the large number of input variables and scene complexity. (2) Few (if any) SI-traceable input data are available, which makes it practically impossible to build SI-traceable synthetic reference data for calibration. (There is some work on this in the Eradiate code project) (3) The complexity of RT modelling makes validation against selected SI-traceable measurements highly desirable. However, at to date, no SI-traceable *in situ* or top-of-atmosphere radiometric records can be used as a reference. However, simulated radiance values must come with appropriate uncertainty. Therefore, work is needed to identify how to propagate of uncertainties through RTMs and how obtain SI-traceable simulated data.	**[Within 3 years]:** BIPM and WMO to identify the right communities to work together to create a discussion forum for uncertainty analysis and traceability through radiative transfer models. This forum to establish methods for uncertainty propagation for continuous and discrete variables and to establish research projects and to explore novel methods tailored to RT simulations (e.g. Lapeyre et al., 2022, Govaerts et al. 2022). **[3-5 years]:** The forum established above, to work with WMO, BIPM and CEOS WGCV on: • the definition of radiative property databases with built-in uncertainty information • supporting the production of SI-traceable radiative property databases which can be used as input for RT simulations. • the production of SI-traceable ToA and in situ measurements to validate radiative transfer models • benchmarking RTMs against each other using SI-traceable input associated with actual observation results, co-sponsored by the WMO • comparing RTMs against corresponding SI-traceable satellite observation results (as an option to be considered).
1D.11 **[j]**	An increase of the biologically active UV radiant exposure can significantly affect human health, plants, and marine ecosystems. The role of atmospheric ionization by cosmic rays in ozone	WMO and BIPM to investigate the need for and correct communities to support research into identifying and quantifying the relationship between

Number	Issue	Recommendation
	depletion and, in general, in atmospheric chemistry and climate remains debated and poorly understood. Cosmic rays alone also inflict genetic or epigenetic changes in living beings. Progress in our understanding will be achieved combining technological improvements to available instrumentation, data from modern satellite technologies, and application of new techniques to permit identification and accurate quantification of the correlations between cosmic rays, ozone depletion and anthropogenic emissions. To understand the role of cosmic ray-induced electrons in ozone depletion, interaction cross sections of these electrons with atmospheric species are also needed. The developments need to be embedded into an appropriate metrological framework.	cosmic radiation and ozone depletion and the impact this has on health and ecosystems.

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- [a] From topic discussion
- [b] From presentation T1-D7 and topic discussion
- [c] From topic discussion
- [d] From presentations T1-D3, T1-D9 and topic discussions
- [e] Topic discussion, From presentations T1-D3, T1-D8, T1-D1, T1-D6, Also Merchant et al. (2017), IOCCG (2019)
- [f] From topic discussion
- [g] From topic discussion
- [h] From topic discussion
- [i] From presentation T1-D2 and topic discussions. Also Govaerts et al., 2022, Lapeyre et al., 2022, Widlowski et al., 2013,2015.
- [j] From presentation T1-D11

6 Topic 1E: Cryosphere Monitoring

6.1 Introduction

The cryosphere has a key role in many interaction processes on Earth. The cryosphere is composed of the terrestrial snow cover, mountain glaciers, polar ice sheets and glaciers, permafrost and the (sea) ice floating on the polar oceans and lakes. All components of the cryosphere are vulnerable to the observed and predicted climate warming and these changes influence global conditions. Melting of mountain glaciers and polar ice sheets contribute to global sea-level rise, with a forecast acceleration. Mountain glaciers, and terrestrial snow cover are also a key component of the global hydrology cycle and hence of the water supply for billions of people both for drinking water and irrigation. Thawing permafrost poses a hazard for various parts of the human-made infrastructure, by de-stabilizing ground surfaces and/or rock slopes and enhances coastal erosion – especially in the Arctic Ocean. Apart from permafrost, all the cryosphere components also influence the fraction of solar radiation that is reflected by their (white) surfaces. The observed warming and related shrinkage of ice- and snow-covered areas triggers a positive feedback mechanism that can lead to more warming and consequently enhanced melting.

Figure 5: This image shows one of the Copernicus Sentinel-3 satellites, which were launched in 2016 and 2018. Copernicus Sentinel-3 satellites are one of the latest innovations in Cryosphere Monitoring and employ synthetic aperture radar altimeter instruments. These instruments provide detailed information on various aspects of the oceans, such as the thickness and extent of sea ice, to support environmental monitoring and climate science applications. However, to ensure the accuracy and reliability of this information, it must be validated using independent observations. The St3TART project aims to supply fiducial reference measurements (FRMs) to support the European Space Agency's Sentinel-3 Mission Cal/Val activities. The project's roadmap and preliminary proof of concept focus on terrestrial surfaces of interest, including inland water bodies such as lakes, reservoirs, and rivers, estuarine areas, sea ice, and land ice areas such as ice sheets and mountain glaciers.

For further information see https://spaceflight101.com/copernicus/sentinel-3-spacecraft/ and http://hydrology.irpi.cnr.it/projects/st3tart/

Picture source: https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-3/Rise_and_shine_for_Sentinel-3A

The components of the cryosphere vary on a wide range of timescales, ranging from days (snow, sea- and lake ice) to millennia (ice sheets, permafrost). In addition, changes in ice sheets, permafrost and mountain glaciers can be considered being irreversible in human timescales. There is growing evidence that some elements of the cryosphere have so-called tipping points – i.e., thresholds in, e.g., geographic coverage or mass, that once surpassed can trigger ever more accelerated retreat or mass loss – for instance via marine ice sheet instability or marine ice cliff instability.

Due to the harsh weather conditions that are associated with the cryosphere regions and the logistical challenges to install and use equipment for *in situ* measurements, the satellite remote sensing observations take a very relevant role in the cryosphere monitoring. The continued advances in satellite observation technologies have created a wealth of information on a wide range of cryosphere parameters and as the only cryosphere quantity permafrost cannot be adequately monitored remotely and relies on a network of diverse sensors (e.g., to observe borehole temperature or ice content of the soil). Satellite observations, however, need the support of ground-based and air-borne measurements, and in the case of sea ice, measurements from sea-based and sub-sea-based platforms for both algorithm development and validation and for product evaluation. Satellite records are also limited in their timescales.

Efforts in data rescue and the enhanced digitization of archived analogue data and hand-written notes, provides long term records about quantities such as sea ice coverage and motion or snow coverage on land. In some locations, we have century-long information about glacier extent and glacier mass changes in mountain areas.

In situ observations in the cryosphere are difficult to make, and satellite observations can be difficult to interpret in a region of ever-changing snow and ice. For these reasons, every measurement matters, and it can be difficult to standardise techniques between different research groups operating in different parts of the world and in some cases, it is difficult to create a clear definition of the measurand. However, i) it is of utmost importance to keep improving the cryosphere observations in terms of traceability, accuracy, comparability, sustainability, and transparency of the methodologies applied, ii) we need to ensure sustainability of the observation systems to guarantee uninterrupted, comparable, and homogeneous time series, and iii) we need a better understanding of the uncertainty sources.

In short, across the different Cryosphere Monitoring domains defined in [1], there are high-level and common needs for establishing well-defined criteria on the quality of measurements and for better documentation of measurements and communication among different research and user communities. In some technical areas, existing collaborative work between domain experts and metrologists has already led to improved methodologies, which can be used as examples for other areas with a lower involvement of metrology. We recommend traceability and uncertainty as key concepts for the increased levels of quality and comparability of measurements. We also recommend an enhanced level of communication between the different communities about how measurements are made and analysed. Emphasis is needed in the context of representativeness, fiducial reference measurements, communication between ground- and space-borne communities as well as enhanced involvement of the metrology community in the planning and conduction of field campaigns.

6.2 Needs and recommendations in cryosphere monitoring

Number	Issue	Recommendation
1E.1 **[a]**	Document [1] defines the different cryosphere domains (Snow, Glaciers, Ice sheets, Ice shelves, Icebergs, Sea ice, Lake ice, River ice, Permafrost, Seasonal frozen ground and Surface meteorology (at CryoNet stations)), each of which is characterized by several variables. The GCOS Essential Climate Variables (ECVs) [2] also define four cryosphere domains (Glaciers; Ice sheets and ice shelves; Permafrost; Snow). Discussions at this workshop have shown the value of greater collaboration between the observation communities (across all those cryosphere domains and including both *in situ* and remote methods) and metrologists. Such collaboration has begun in some specific application areas; but is not yet common. The workshop has identified several areas where collaborative research is needed (see below) and the metrology community needs to identify people who can build these collaborations, and who can develop a deeper knowledge of cryosphere variables and physical and chemical measurement processes and sensors, as well as the processing of observations into essential climate variables. Such collaboration will also need, and will lead to, greater consistency in the use of metrological terminology – a need identified in several different domains. From a metrological perspective, many of these observations are interdisciplinary, involving methods from different CIPM Consultative Committees, and some are not easy to map onto the CIPM/CC structure (e.g., sea ice extent or satellite altimeter measurements of ice thickness). Many of the observations are also indirect, involving complex data processing and analysis to convert the measurand into the desired observational variable.	**[Within the next year]:** BIPM with WMO should establish a cross-disciplinary group to analyse the measurement challenges across the different cryosphere domains and the related variables as described in [1,2], and identify those that can be addressed with the CIPM/CCs or in WMO/ INFCOM/ Global Cryosphere Watch (GCW). **[Within 2-5 years]:** BIPM and WMO to enable participation of the experts from their respective networks within the CIPM/CCs or in WMO/ INFCOM/ Global Cryosphere Watch (GCW) to address the challenges that have been identified in the cross-disciplinary group, as well as enabling metrology expert participation in activities of other bodies such as Space Agencies and coordinating bodies such as CEOS, the International Association of Cryosphere Sciences (IACS) or the Standing Committee for Antarctic Research (SCAR), and international project consortia such as, e.g. Ice sheet Mass Balance Inter-comparison Exercise (IMBIE), to address identified challenges. **[Within 4-7 years]:** WMO/ INFCOM/ GCW should encourage the traceability and the uncertainty evaluation of the Cryosphere variables measurements and initiate the process for including these objectives in its terms of reference. **[Within 3-10 years]:** BIPM and WMO should consolidate the work of the cross disciplinary group in identify and progressing measurement challenges in the cryosphere through workshops as needed.

Number	Issue	Recommendation
1E.2 **[b]**	During the workshop we identified that the degree of implementation metrology in each of the cryosphere domains is very different. Each cryosphere domain includes several variables [1] and some of these have poorly defined, or not agreed definitions (including the measurement units). Greater consistency in how measurements are taken by different research groups, and how data and uncertainties are analysed are needed. There is a need in non-satellite (*in situ*) observations for: • Increased metrology consistency in terms of vocabulary • Deeper understanding about the cryosphere variables included in each of the domains in terms of the physical/chemical processes involved in each measurement. • Deeper analysis about the implied instrumentation in each cryosphere variables measurements • Calibration procedures for the instrumentation used for in situ measurement of cryosphere variables • Measurement procedures for field conditions, which identify the main factors of influence that affect the observation, • Consistent approaches for metrological traceability and uncertainty analysis.	**[Within 2-4 years]:** The different technical groups of the WMO/ INFCOM/ GCW, with the involvement of metrology experts, CIPM/CCs (recommendation 1E.1) should review the state of the art of definitions of the cryosphere variables in each of the cryosphere domains [1] [2] and analyse the corresponding different measurement techniques, including the measurement units, for their fitness-for-purpose. The analysis will involve the calibration procedures for instrumentation and the performance of measurement procedures. Special attention should be paid to the inclusion of metrological approaches in these procedures. **[Within 4-7 years]:** As a function of the conclusions of this review, the different technical groups of the WMO/ INFCOM/ GCW (with the inclusion of metrology experts, CIPM/CCs) (recommendation 1E.1) should determine and draft the **specific metrological needs** and activities to be performed in each of the different cryosphere variables. Addressing of these metrological needs will core to updated versions of the calibration and measurement procedures for the different cryosphere variables. These procedures can be amended by the technical groups of the WMO/INFCOM/GCW and/or by funded research projects, as a function of the needed metrology implementation in the calibration procedures and measurement procedures. **[Within 4-7 years]:** In addition, the different technical groups of the WMO/ INFCOM/ GCW, in collaboration with CIPM/CCs (Recommendation 1E.1) will analyse the metrological needs in terms of field comparisons of instrumentation, comparisons of measurement methods and/or of analysis techniques.
1E.3 **[c]**	Some research work has begun on how to establish robust uncertainty analysis and metrological traceability to climate records of cryosphere ECVs derived from satellite observations. This includes work on both active and passive satellites, and the development of climate data	**[Within 2-5 years]:** CIPM/CCs and WMO should encourage and enable data scientists working in NMIs to work on the improved quantification of uncertainties from satellite FDRs through complex retrieval algorithms to the final product. This could be achieved by building on / transferring knowledge gained from pioneering projects such as FDR4ALT to other domains of the cryosphere monitoring community,

Number	Issue	Recommendation
	records of ECVs from those. However, this work is in the early stages, mostly in Europe, and does not cover all sensors and applications. Cryosphere ECVs must be processed from satellite FDRs (i.e., from the physical quantities) to ECVs such as snow thickness and Snow Water Equivalent (SWE) on land, sea ice concentration and thickness, snow thickness on sea ice, melt/freeze-onset on snow / sea ice / ice sheets, sea-ice motion and sea-ice age, and potentially even more variables. Such processing involves combining observation results and model outputs, and therefore uncertainty analysis for retrievals are needed. Increasingly, scientists are developing algorithms involving machine learning (ML), and uncertainty analysis for machine learning is not well known.	e.g., via workshops co-organized by the respective communities and BIPM/WMO and the establishment of working groups. This work should include both traditional and ML-based retrieval approaches. The cross-disciplinary group (recommendation 1E.1) should encourage NMIs/DIs to identify suitable organizations to support improved pre-flight calibration of microwave radiometers. It should also identify metrologists to support uncertainty analysis of existing microwave radiometer, and active satellite sensor data, and to enhance re-processing cycles of such existing data to better incorporate mission life-time induced sensor drift and ageing.
1E.4 **[d]**	Ground-based observation sites (and airborne/waterborne observations) are widely used for both climate monitoring and for satellite calibration and validation. For some variables/methods good practice has been established (e.g. through the technical working groups of WMO/INFCOM/GCW) but the involvement of metrology in other variables is still at a very early stage. For satellite calibration and validation, the satellite community has begun investigating how to apply “fiducial reference measurement” (FRM) techniques to the non-satellite (ground/*in situ*) measurements that support satellite observation. But there is still significant work to be addressed, such as to enhanced coordination and planning of network design, stronger implementation of good practices, and community-agreed approaches where rigorous methodologies cannot be applied because of the unique challenges of cryosphere measurements. Ideally these efforts would be combined, with joint approaches by WMO/INFCOM/GCW sites and FRM sites, also involving the modelling	**[Within 12 months]:** The cross-disciplinary group (recommendation 1E.1) to identify appropriate groups to establish links with the Space Agencies developing FRM concepts for the cryosphere variables and to link this to the work with the technical groups of WMO/INFCOM/GCW. **[2-4 years]:** These collaborations should establish optimal methods to determine uncertainty values for different measurement applications. This work should focus first on reference measurements (lowest uncertainty values, for both FRM and GCW reference networks – which are different communities doing ground-based reference measurements) and then consider broader observations. Guidance should be developed through research projects and comparisons and shared with the right WMO/INFCOM/GCW and CEOS technical groups so that they can be reflected in formal recommendations. **[5 years +]** Collaboration between WMO technical groups and the satellite community (when needed), with metrologists, should perform the research needed to establish protocols on how to define the degree of representativeness of a measurement result, and how to scale

Number	Issue	Recommendation
	and metrology communities. Specific areas needing new approaches include: • Selection of appropriate (fit-for-purpose) instruments and how to use instruments according to their application regime. • Definition and quantification of the degree of representativeness in spatial/temporal scales for long-time series and comparisons. • Definition of the factors of influence in the field measurements and their inclusion in the total uncertainty budget. • Definition of siting and exposure requirements for but also influences on the measurements. • Definition of fit-for-purpose requirements regarding instrumentation, calibration procedures, verification procedures, instrument maintenance, measurement procedures and the establishment of tiered networks with reference/FRM measurements supported by local observations. Improved consistency in metadata/data format.	between *in situ* measurements, air- and waterborne measurements, satellite observations and model cells. Also, these technical groups should identify influence factors for ground-based measurements and should define procedures for the quantification of these influence factors, for their inclusion in the total uncertainty budget. It is likely that research activities will be needed, which the technical groups can recommend.
1E.5 **[e]**	**Sea ice:** Observations utilizing satellite remote sensing techniques are the primary source of data for monitoring of sea ice extent/edge, sea ice thickness and sea ice drift/motion. Related parameters such as snow thickness on sea ice, and derived products such as sea ice trajectories, deformation parameters and sea ice age are also monitored. Ground based measurements of sea ice variables carried out on the sea ice itself, using coastal, ship-borne and/or airborne platforms and/or from moored and/or submarine devices are essential. These measurements usually have lower uncertainties, serve as a key indicator of climate change and complement the satellite observations, and are needed for satellite product development and evaluation. Many different groups contribute to such measurements. However, despite initial attempts to establish best practices and measurement guidelines, the use of metrological terminology, and the definition and the units of some of the sea-ice variables are not yet consistent and need to be	**[Within 2 years]:** The cross-disciplinary group (recommendation 1E.1) should initiate a process to build links between metrological experts and the Sea Ice Watch Expert Team in WMO/INFCOM/GCW or/and (when needed), communities that connect those developing satellite and FRM products for all types of sensors, different retrieval procedures and numerical modellers (e.g., ESA CCI Sea Ice, CRYORA, SIN'XS). The initial goal would be to reach consensus in terminology, definition of the sea ice quantities, the corresponding units, and uncertainties. **[2-5 years]:** For in situ (non-satellite) observations a collaborative group, involving the Sea Ice Watch Expert Team, or/and (when needed), researchers working for satellite product validation (e.g., FRMs) should recommend collaborative research activities, comparisons and methods for establishing traceability, uncertainty models and calibration procedures. For satellite observations, the task group could recommend projects to extend the work of, e.g., FDR4ALT, to apply rigorous metrological

Number	Issue	Recommendation
	improved. The homogenization of the measurement protocols needs to be revised and enhanced. In addition, for satellite measurements: Methods to propagate uncertainties for satellite-based sea-ice products need to be improved and developed further and agreed upon by the sea ice community. Further, a better understanding and quantification of space/time correlation length scales of both, the sea ice variables and their uncertainties are needed. Issues that came up during the workshop include in particular: • Strategies to better sample the actual spatio-temporal distribution of freeboard, ice thickness, snow thickness and other snow parameters such as grain size from floe to basin scale need to be improved in view of satellite remote sensing capabilities and product evaluation needs as well as demands from the modelling community. • Components related to sea ice dynamics require enhanced and homogenized definition of measurands, improved understanding of uncertainty sources across scales and a definition of best practices for their evaluation.	uncertainty analysis to all sea ice products derived from satellites. Metrologists should be involved in SIN'XS to provide a metrological basis to comparisons. Efforts should be made to connect to all the relevant space agencies (ESA, NASA, JAXA, EUMETSAT, CNSA, ISRO). **[5+ years]:** The task group working on in situ (non-satellite) observations would recommend research activities for the establishment and/or improvement of uncertainty models and ground-based measurement procedures for sea ice variables. In addition, new measurement techniques should be studied at this stage. These activities will be performed after reviewing the state-of-the-art of procedures, such as guidelines to carry out measurements of physical parameters on sea ice and protocols to estimate sea ice parameters from ship-based observations. For satellite observations, the established collaborations between space agencies, product developers and metrologists will lead to enhanced incorporation of traceability chains into CDR production – with particular emphasis on improved assessment of product uncertainties. It could also influence the design of next generation sensors.
1E.6 **[f]**	**Permafrost:** The Earth Energy Balance topic described the importance of permafrost measurements in understanding the Earth heat inventory and observing climate tipping points (see 1C-11). Observations of permafrost variables are extremely diverse because of the different environments and forms in which permafrost occurs. This diversity has driven development and application of a wide range of measurement techniques and instruments, specifically tailored to the respective measurement needs of several specialist groups worldwide. The degree of the implementation of metrological principles in observing the different permafrost variables is very diverse. While the measurements of some permafrost variables are already performed	**[Years 1-3]:** The cross-disciplinary group (recommendation 1E.1) should review the different permafrost variables [1] to determine the most appropriate metrology communities to address the metrological needs in each of the permafrost variables and BIPM should invite permafrost experts (nominated by WMO) to take part in the appropriate CIPM/CCs. While WMO should promote the involvement of the metrology community in the task group on permafrost in WMO/INFCOM/GCW. Links should also be made with the International Permafrost Association (IPA) that already developed a Global Terrestrial Network for Permafrost (GTN-P). The initial goal of these

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	with calibrated instruments, other permafrost variables do not yet have an agreed definition. Metrological work on terminology, definition of permafrost variables, units, and procedures is still needed, bearing in mind the above-mentioned large diversity of permafrost zones and measurement techniques (and the need enhanced cross-disciplinary collaboration). Agreed measurement procedures need to be defined for the different permafrost zones such that measurements can be compared efficiently to promote global monitoring of permafrost extent, required in the GCOS implementation plan 2016. Common strategies to store data, to define and store metadata, the ownership of measured data; data set curation; data set rescue are now demanded by the scientific community.	collaborations would be to reach consensus in terminology, definition of the permafrost variables and the corresponding units. **[Years 2-5]:** At medium stage, this collaborative group will recommend research activities, whose conclusions will be used for the establishment of traceability chains, uncertainty models and calibration procedures. **[Years 5+]:** At a later stage, this group will detect factors of influence for ground-based measurements and will recommend research activities, whose conclusions will be used for the establishment of uncertainty models and ground-based measurement procedures and/or guidelines for permafrost variables.
1E.7 **[g]**	**Ice sheets and caps, Ice shelves and glaciers:** Different variables have been defined inside these domains to characterize each of the different forms of ice located in the polar and sub-polar regions and in high-mountain areas. Long-term monitoring of these components of the Earth's cryosphere is essential because of their role as freshwater sources and as a key contributor to sea level change. Measurements of ice evolution and ice characterization are extremely important in defining the appropriate policies about climate change adaptation. These measurements are increasingly important as climate change accelerates ice melt and glacier disintegration. Such melting also poses a particular challenge for long-term measurements of ice variables describing their status (e.g. thickness, speed). The unwanted termination of observational time series as glaciers retreat is becoming increasingly likely with time. While good practices exist for the relocation of observation sites (of climatological relevance) for, e.g., meteorological parameters (establish a secondary site, same equipment, 3-year overlap period of	**[Years 1-3]:** The cross-disciplinary group (recommendation 1E.1) should review the different variables used for the characterization of glaciers, ice caps, ice sheets and ice shelves [1]. This review will determine the most appropriate metrology communities to address the needs in each of these variables and to determine the collaborative frame needed to reach fruitful results. In parallel, WMO should promote the involvement of metrology community in the task group on glaciers and ice caps in WMO/INFCOM/GCW. Connections should be made with the World Glacier Monitoring Service and the Global Terrestrial Network for Glaciers (GTN-G), GCOS network. The initial goal of these collaborations would be to reach consensus in terminology, definition of these domains' variables and the corresponding units. For satellite measurements, we recommend identifying representatives of the satellite community and respective communities working in glaciology. Starting points could be contact the Global Land Ice Measurements from Space Initiative (GLIMS), and organizations / projects such as IMBIE, IACS, SCAR, and IUGG. Similar to

Number	Issue	Recommendation
	measurements) these practices appear to be impractical for ice sheet and glacier sites for several reasons. Understanding the most suitable traceability chains, uncertainty models and measurement procedures are urgently needed in order to further optimize monitoring techniques and adapting them to the changing environment. Specific examples are: • The need for a systematic end-to-end treatment of uncertainty that starts with the data telemetered by the satellite and propagates uncertainties through to final estimates of elevation and mass change. • The need to develop improved and community-agreed measurement procedures and instrument calibration procedures for collecting data from the subglacial environment – similar to the needs formulated in recommendation 1E.6.	recommendation 1E.5 this working group should establish closer links and enhanced collaboration between space agencies / level-1 data providers and research organizations deriving relevant products for monitoring glaciers and ice caps and sheets. **[Years 3-5]:** At a medium-term stage, this collaborative group will recommend research activities, whose conclusions will be used to establish traceability chains, uncertainty models and calibration procedures. **[5+ years]:** At a later stage, this group will detect factors of influence for ground-based measurements and will recommend research activities, whose conclusions will be used for the establishment of improved uncertainty models and ground-based measurement procedures for these domains' variables.
1E.8 **[h]**	**Snow:** Snow is characterized by multiple variables [1], with different measurement techniques needed for different applications. Monitoring for avalanche warning is not the same as monitoring for hydrological purposes. Probably this is the reason there is still no global, coordinated monitoring of snow on the ground. Snow monitoring is also an important quantity in correctly analysing all the other cryosphere subdomains. Snow characterization would particularly benefit from fit-for-purpose procedures (covering traceability chain, appropriate calibrations, uncertainty models. Definitions of some snow variables are still missing, establishment of the traceability chains, calibration procedures, measurement procedures, along with corresponding uncertainty models need deeper study and research into new technologies, such as snow	**[Years 1-3]:** The cross-disciplinary group (recommendation 1E.1) should review the different variables used for the characterization of Snow [1]. This review will determine the most appropriate metrological communities to address the metrological needs in each of these variables and BIPM should invite experts in the several snow variables (nominated by WMO) to take part in relevant CIPM/CCs. In parallel, WMO should promote the involvement of metrology community in the Expert Team on Snow Observation in WMO/INFCOM/GCW. The initial goal of these collaborations would be to reach consensus in terminology, definition of this domain's variables and the corresponding units. One element of this activity would be to review the content of the International Classification for Seasonal Snow on the Ground (ICSSG). The cross-disciplinary group (1E.1) should also promote links with satellite CDR production institutions such as Rutgers University Global

Number	Issue	Recommendation
	surveys carried out using unmanned autonomous vehicles or drones, needs metrological input. Requirements detected during the workshop related to snow include: • A more specific quantitative definition of the factors that discriminate snow from firn and/or ice is needed to optimally adapt measurement procedures. Links to newer satellite approaches are also needed. Altimeter satellites can provide differences in surface elevation measured at different radar frequencies or by combining radar and laser to infer snow thickness and better discriminate between snow and ice, but this requires further investigations at the ground. • Improve the homogenization of measurement procedures for snow quantities, such as for snow water equivalent, extremely important for hydrology community and water management • An improved consideration of the effects of canopy, snow type and snow redistribution by wind on the representativity of a measurement needs to be included in the measurement procedures. • The effect automation of measurement procedures has on the observed snow parameter needs to be better understood, particularly regarding snow water equivalent.	Snow Lab or Environment Climate Change Canada (ECCC) and organizations / projects dealing with snow on land such as the WSL Institute for Snow and Avalanche Research (SLF) or SnowPEX. There should also be closer links and enhanced collaboration between space agencies / level-1 data providers and research organizations deriving relevant terrestrial snow products. **[Years 3-5]:** At a medium-term stage, the collaborative groups (established in the previous period) will recommend research activities, whose conclusions will be used for the establishment of traceability chains, uncertainty models and calibration procedures. **[5+ years]:** At a later stage, these groups will detect factors of influence for snow ground-based measurements and will recommend research activities, whose conclusions will be used for the establishment of improved uncertainty models and ground-based measurement procedures for snow variables.
1E.9 **[i]**	**Surface Meteorology at CryoNet stations, Solid precipitation and Complementary variables involved in all the cryosphere domains:** For solid precipitation, the measurement of snow falling still needs a better deal with the under-catch of solid precipitation measurements when using rain gauges – particularly in areas prone to high wind speeds / mountain areas. The establishment of the traceability chains, calibration procedures, measurement procedures, both with the corresponding uncertainty models are still to be deeper studied. In	**[Years 1-3]:** The cross-disciplinary group (recommendation 1E.1) should review the different variables important for the cryosphere science but not included in the domains previously described. Examples of these variables are solid precipitation, air temperature, wind speed and wind direction, solar albedo. This review will identify the most appropriate metrological communities to work on these variables. In parallel, WMO should promote a higher involvement of metrology community in the WMO/INFCOM/GCW expert teams. The initial goal of this collaboration would be to reach consensus in terminology, definition

Number	Issue	Recommendation
	addition, research about new technologies, for solid precipitation measurements are still a field to be metrologically developed. In solid precipitation, the SPICE project [3] launched by WMO CIMO, evaluated a certain number of gauges and windshields available on the market and provided a set of recommendations on their use and operation. Also, transfer functions were developed to correct the wind induced error to the level of the reference measurement performed within a Double Fence Inter-comparison Reference (DFIR). The final report of the SPICE project includes different recommendations (e.g., heating of the instrument, snow capping, etc.). These recommendations need implementation and could benefit from metrological involvement. In Cryosphere science, there are variables that cut across all the domains already explained have additional value. Observations of these meteorological parameters such as air-temperature, wind speed and direction, snow albedo, and others over climate relevant time scales is particularly challenging in the (sub-)polar and high-mountain environment. Instruments used are facing extreme weather conditions, with (expected) big impact on these measurements. Validity of the instrument's calibration and its measurement capabilities might therefore encounter a larger (unwanted) drift, enhancing their contribution to the uncertainty budget of a single measurement – as a function of, e.g., location, time, frequency of particularly extreme events. There are also difficulties in performing on field measurements under such extreme conditions, developing high stresses on the sensor systems and conditioning the measurement procedures. Also, research into alternative technologies more suitable for these extreme environments should be considered in the near-term future.	of variables and the corresponding units. Links should be promoted with the partners of WMO/CIMO SPICE project by WMO. **[Years 3-5]:** The selected metrology communities should perform a survey about the current metrology implementation on these variables and will detect the WMO/INFCOM expert teams on these variables. BIPM should invite experts in the already mentioned variables [1] (nominated by WMO) to take part in the corresponding CIPM/CCs. **[Years 4-7]:** At medium timescales, the collaborative groups developed during the previous period will recommend research activities, whose conclusions will be used for the establishment of traceability chains, uncertainty models and calibration procedures. Additional research and investigations on better quantifications of the influence of polar extreme weather conditions on climate/meteorological measurements, in terms of drift and in terms equipment response to such extreme weather conditions should be promoted by the cross-disciplinary group (1E.1) and WMO by the organization of common workshops with the aim of detecting metrological needs. **[Years 7+]:** At longer timescales, these collaborative groups will detect factors of influence for these variables' measurements and will recommend research activities, whose conclusions will be used for the establishment of uncertainty models and measurement procedures. For a better understanding of these variables CIPM should encourage to NMIs the involvement of metrologist into field campaigns and in-field comparisons.

References

[1] WMO No. 8. Guide to Instruments and Methods of Observation. Volume II- Measurement of Cryospheric variables, 2018 Edition. https://library.wmo.int/doc_num.php?explnum_id=9870

[2] GCOS ECVs and implementation plan

[3] WMO Solid Precipitation Intercomparison Experiment (SPICE) (2012 - 2015) https://community.wmo.int/en/activity-areas/imop/intercomparisons/spice

Links and notes

[a]: From presentations T1-E1,T1-E5,T1-E10, T1-E16 and discussions

[b]: From all presentations and discussions

[c]: From presentations T1-E3, T1-E5, T1-E8, T1-E10, T1-E12 and discussions

[d]: From presentations T1-E6, T1-E5, T1-E7, T1-E12, T1-E8, T1-E15 and discussions

[e]: From presentations T1-E1, T1-E3, T1-E5, T1-E8, T1-E11, T1-E12, T1-E13, T1-E14, T1-E15, T1-E17, T1-E18 and discussions

[f]: From permafrost discussion in workshop led by Christian Hauck, input from the Energy Balance theme (see 1C-11), and von Schuckmann et al., (2022), and Lenton et al. (2020), https://www.nature.com/articles/d41586-019-03595-0

[g]: From presentations T1-E4, T1-E10, T1-E16, and discussions.

[h]: From presentations T1-E1, T1-E6, T1-E19, and discussions. Also Haberkorn 2019, “European Snow Booklet”, available at : https://www.slf.ch/en/publications/european-snow-booklet.html

[i]: From presentations T1-E7, T1-E9 and discussions.

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

7.1. Theme 2 Organizing Team

Theme 2 Chairs

- Philip L. DeCola, University of Maryland, Department of Atmospheric and Oceanic Sciences (USA)
- Alex Vermeulen, Lund University, Director ICOS Carbon Portal (Sweden)
- James R. Whetstone, National Institute of Standards and Technology, Special Assistant to the Director for Greenhouse Gas Measurements Program (USA)

Topic Chairs and expert groups

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

- Jennifer Carney (NIST, USA)
- Dave Worton (NPL, UK)

Topic B: State of play in integrated approaches for advanced GHG emission estimates and the way forward to operational services

- Fouzi Benkhelifa (NEXQT, France)
- Thomas Lauvaux (University of Reims Champagne-Ardenne, France)

Expert Contributors:

- Hratch Semerjian (NIST, USA)
- Maurice Cox (NPL, UK)
- Lesley Ott (NASA USA)
- Frédéric Chevallier (LSCE, France)

Topic C: Novel GHG concentration and flux methods and sensors

- Felix Vogel (Environment Climate Change Canada)
- Hong Lin (NIM, China)

Expert Contributors:

- Dr. David Long (NIST, USA)
- Mr. Tom Gardiner (NPL, UK)
- Dr. Tim Arnold (NPL, UK)
- Mr. Olivier Laurent (LSCE, France)

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

- Eric A, Kort (University of Michigan, USA)
- Eric L. Shirley (NIST, USA)

Expert Contributors:

- David Crisp (CRISP Spectra LLC, USA)
- Annmarie Eldering (NIST, USA)
- David Long (NIST, USA)
- Charles Miller (NASA JPL, USA)

7.2. What Theme 2 Covers

Theme 2 addresses measurement science advances and metrology usage needs in support of actions to mitigate climate change. These advances, and those resulting from continuing and future measurement science research and technology developments, are aimed at supporting effective climate change mitigation through measurement-based monitoring to locate, quantify and thereby manage greenhouse gas emissions and removals. Improved quality and number of measurements producing data and information across a range of geographic areas with varying temporal specificity and accuracy requirements, and the use of advanced analysis tools will target effective mitigation opportunities and track the efficacy of these emission reduction measures. This theme encompasses current activities and research ranging from GHG concentration standards that are the foundation of all

GHG emissions measurements to a variety of measurement and estimation tools useful for the management of mitigation actions and assessment of their effectiveness.

There are many methods to obtain climate data, e.g., from point-sources, airborne and satellite remote-sensing, socio-economic sources, etc. The complementary nature of different types of data provides the climate change community with challenges as well as added benefits regarding knowledge to be gained. All such data can add value to the community's understanding of climate change and suitable recommendations to address it. Each class of data entails its own limitations and uncertainties that need to be appropriately handled in data analysis. Uncertainty estimation is a critical aspect of all measurement components and can be random as well as systematic in nature. Biases in data can be constant as well as varying in time and location. Data sets can also vary in their global coverage, ranging from nearly uniform coverage of the entire earth surface, to emphasizing equatorial or polar latitudes, or to addressing high intensity GHG source/sink activity in a few locations, e.g., cities or agricultural areas. In terms of altitude, satellite measurements often report GHG concentrates in a way that intrinsically integrates entire atmospheric columns, whereas airborne and surface measurements might furnish spatially resolved data that gives better insight into altitude distributions of GHGs and phenomena that take place at the surface (human activity in particular).

Accurate data is foundational to improving the effectiveness of mitigation activities. For example, the targeting, quantifying, and tracking of emissions and removals and continued monitoring of their trends across local, regional, continental, and global scales. Identification and addressing of unmet measurement needs can improve national and subnational emission inventories and their reporting. Advances, particularly in precision, accuracy and granularity at sub-national scales, will contribute to increased consistency between locally determined emission and removal amounts and national inventory reports.

7.3. Theme 2 topic areas.

Theme 2 was organized around four topic areas:

- Topic 2A: Accuracy requirements for atmospheric composition measurements across economic sectors, and temporal and spatial scales
- Topic 2B: State of play in integrated approaches for advanced GHG emission estimates and the way forward to operational services
- Topic 2C: Novel GHG concentration and flux methods and sensors
- Topic 2D: Strengthening the linkage of remote sensing GHG concentration measurements to emission fluxes

Sessions were convened for each of these four topics in which topic leads and rapporteurs led discussions of the submitted oral and poster presentations. These discussions produced a set of conclusions and recommendations for advancing the objectives identified in each topic area and these results are tabulated below. Each topic area is introduced with an overview and followed by recommended actions. Recommendations have been presented in the form of identifying stakeholder communities (who needs or uses a recommend action), communities thought to be providers of such capabilities, and estimated time frames for their provision.

The subsequent sections of the report summarize the issues and recommendations that emerged from oral and poster presentations and discussions during the four topic areas. Recommendations are tabular and identify issues such as what needs to advance, who will benefit from the advancement, and why the advancement is valuable to the community being served. Recommendations also identify the likely provider of the necessary advancement of capabilities.

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

This topic addressed issues and requirements necessary for robust and comparable measurements of key greenhouse gas compounds in the atmosphere over large spatial domains and over multi-decadal time horizons. The following guidance was proposed for presentations and discussion for Topic 2A:

- Stakeholder requirements for accurate observations, input data and modelling tools
- The fundamental basis for accurate atmospheric composition observations of the greenhouse gases and co-emitted gases
- Standards and transfer of scales and their uncertainties
- Reports of recent related meetings, e.g., GGMT (WMO/IAEA Meeting on Carbon Dioxide, Other Greenhouse Gases, and Related Measurement Techniques)
- Uncertainty propagation in input data to modelling tools
- Impact on results and on their certification

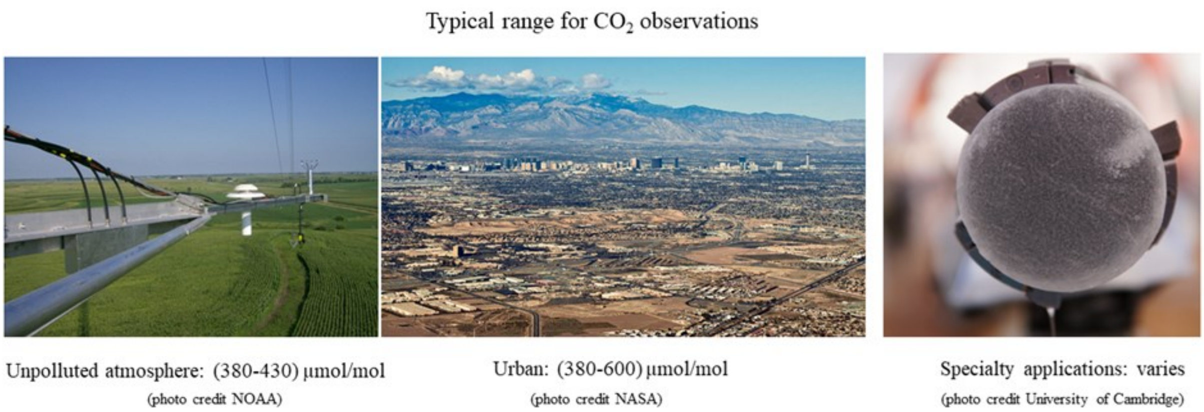


Figure 6: These images illustrate the challenges required to achieve robust and comparable measurements of key greenhouse gas compounds in the atmosphere over large spatial domains and multi-decadal time periods. The illustration on the left shows the instrumentation installed on the KWKB-TV tower in July 2007 and the WBI site's sampling of agricultural ecosystems in the corn belt (https://gml.noaa.gov/ccgg/insitu/). The centre figure shows the urban area of Las Vegas, Nevada, USA. Urban areas such as this are the subject of NASA's Orbiting Carbon Observatory-2 (OCO-2), which measures carbon dioxide levels. (https://climate.nasa.gov/news/2957/nasa-satellite-offers-urban-carbon-dioxide-insights/). The figure on the right shows a freshly drilled ice core in Antarctica. These ice cores provide ancient atmospheric samples that allow ice core scientists to reconstruct atmospheric compositions from up to 800,000 years ago. Photo credits: NOAA Global Monitoring Laboratory, Boulder, Colorado, USA; Bert Kaufmann; and Dr Christoph Nehrbass-Ahles, University of Cambridge.

Recommendations address a range of issues, identified organizations or communities with the capabilities to address these issues. Both National Metrology Institutes (NMIs) and Designated Institutes (DIs) including the WMO's Central Calibration Laboratories were primarily identified as critical contributors to the development of a much-strengthened global network of primary standards suppliers supporting the dissemination of the field standards needed for an anticipated significant increase in measurement and monitoring systems to effectively address climate mitigation actions. Specific areas identified were 1) stable and commutable gas reference materials, 2) identification of GHG purity analysis/methods and material limitations, and the need for improvements in measurements and standards for GHG isotopes. Some initially unanticipated issues were also addressed as can be seen in the table of recommendations for this sub-topic. Concentration standards for both greenhouse gases and an important proxy gas, carbon monoxide[2], were addressed.

[2] Carbon monoxide is important to the atmospheric modeling community as a proxy for incomplete combustion seen in some vehicle types due to tradeoffs necessary for air quality abatement. Two issues were identified as critical ones, stability of concentrations for carbon monoxide, a gas much more reactive that the

Workshop presentations and discussions focused on issues and requirements needed to make robust and comparable measurements of key greenhouse gas compounds in the atmosphere over large spatial domains and on multi-decadal time horizons. In all there were 14 pre-recorded presentations and 7 posters. Five general issues were covered:

- Stakeholder Needs
- Stable and Commutable Gas Reference Materials
- Purity Analysis/Method & Material Limitations
- Reference Material Availability and Comparability
- Isotopes

As an increased number of atmospheric GHG measurements are being made worldwide, it will become more important for NMIs/DIs to better understand the needs of the different monitoring communities. Increased communication and coordinated interactions and activities between WMO/GAW central facilities, NMIs/DIs, the BIPM, industry, and other expert organizations will provide the opportunity for improvements in both measurement science and measurement services providing improved confidence in data.

Development of guidance documents describing measurement objectives would steer development of appropriate reference materials. Research towards solving current reference material production limitations, material limitations, and analytical limitations will enable more reliable and consistent measurements in the future and the development of a strengthened operational infrastructure would support an expected increase in demand for standards.

There is also an indicated need to collate existing technical information and best practices in a readily accessible format and location to inform decision making and help establish documentary standards. More efficient advancements could be facilitated by increased cooperative efforts between institutions to address new and emerging measurement challenges.

GHGs are often seen to change concentration with time in the high-pressure cylinders used for their containment, and the need for recalibration of standards, both laboratory and field deployed.

	Issue	Recommendation	Sources
2A.1	NMIs need to better understand the needs of the different monitoring communities to develop and disseminate appropriate standards.	**[1-3 years]** Recommend World Meteorological Organization Global Atmospheric Watch (WMO-GAW) provide guidance surrounding Data Quality Objectives (DQOs) relevant in different areas (clean southern hemisphere air vs terrestrial field studies vs urban areas) and how they are established (precision of instrumentation vs evaluation of network compatibility) would be valuable. Better understanding by National Metrology Institutes (NMIs) / Designated Institutes (DIs) of the different needs of the various monitoring communities would facilitate standards development/dissemination supporting various segments of the atmospheric community to make the best measurements possible. It is understood that some DQOs are difficult to achieve, however useful information still comes from measurements whose objective is to meet the DQOs as DQOs drive innovation. A better understanding of how to assess whether DQOs are met or exceeded would be useful. Development of internationally recognized assessment criteria is critical for comparing to the DQO. **[1 year]** Recommend NMIs/DIs, and other reference material producers review and reference relevant statements of user requirements for reference materials from the last published Carbon Dioxide, Other Greenhouse Gases and Related Measurement Techniques (GGMT) meeting (GAW report), the latest GGMT meeting when the report is available (September 2022) and other relevant additional sources of information (e.g., IG3IS) as an additional source of input.	Climate Action Workshop discussions
2A.2	Globally, the atmospheric monitoring community needs stable and commutable gas reference materials that are compatible with each other and over time and space to assure consistent measurements across sites and programs.	**[1-3 years]** Recommend Consultative Committee on Amount of Substance (CCQM) Gas Analysis Working Group (GAWG) to establish a new task group to collate knowledge regarding adsorption/reactive losses of Greenhouse Gases (GHGs) and other important non-GHG species in compressed gas cylinders [classify by material, passivation/surface treatment, adsorbate type, carrier gas mix]. The task group could also connect to modeling/theoretical explanations as current knowledge is fragmented and often inconsistent. The aim would be to create a central information repository. **[5+ years]** Recommend NMIs/DIs consider forming collaborations (with other NMIs/DIs, the specialty gas industry, and cylinder manufacturers) to perform studies evaluating the potential influence of all material in contact with the standard gas. Investigations into what materials/metals are being used in cylinder manufacturing[(a)] as well as the effects of gas transfer from high-pressure cylinder to analyzer keeping in mind other equipment utilized such as the pressure regulator, cylinder head valves, and drying units.	T2-A6, T2-A3, T2-A10, T2-A11, T2-A18

	Issue	Recommendation	Sources
		Documented guidance developed by principal investigators involved in studies and based on study results should offer advice on what materials are best for which gases. **[5+ years]** Recommend that NMIs/DIs collaborate to improve cylinder stability through studies on cylinder passivation. Recommend the NMI/DI community initiate collaborations through the formation of a new task group within CCQM GAWG to determine how to develop new passivation chemistries and publish these openly to allow better access to the best passivated cylinders for all.(b)	
2A.3	Gas reference materials are susceptible to trace amount fraction changes as the cylinder pressure is drawn down. There is a need to use experimental results in tandem with modeling to gain understanding of the limitations and factors critical for improving measurements.	**[1-3 years]** Recommend NMIs/DIs collaborate, and include, where appropriate, interested academic partners, to develop improved modeling which can fit experimental measurements, yielding adsorption fitting parameters that allow for other modeling, sensitivity testing, and examination of vessels with multiple adsorbing species. Future measurements could focus on competitive or co-adsorption with the intention of fitting the measured composition traces to a new model. More complex adsorption modeling may be necessary.(c)	T2-A10
2A.4	One important non-GHG where instability is a critical issue is in CO reference materials in air at ambient levels. The current observed drift of 1 nmol mol^{-1} yr^{-1} limits the ability of the atmospheric monitoring community to make un-biased measurements across programmes and time.	**[1-3 years]** Recommend that WMO-GAW expand the carbon monoxide (CO) scale beyond the current 500 nmol mol^{-1} upper limit to 1 µmol mol^{-1}, to help reduce the impact of drift in standards and bridge the gap between air quality and GHG monitoring communities. **[1-3 years]** Recommend the atmospheric monitoring community take advantage of the linearity of spectroscopic techniques and further investigate the use of higher amount fraction CO in air standards to reduce the impact of drift in ambient amount fraction CO in air reference standards.	T2-A3

	Issue	Recommendation	Sources
2A.5	A critical issue to be addressed is reference material re-calibration intervals to minimize the impacts of any drift in amount fraction.	**[3-5 years]** Recommend NMIs/DIs, and other expert organizations producing reference materials for the monitoring community engage with stakeholders to discuss the potential impact of drift in gas standards along with the importance of re-calibrating gas standards and understanding the individual history of re-calibrations. (d)	T2-A5
2A.6	NMIs/DIs need a uniform approach to purity measurements to assure reference materials are of sufficient quality to allow WMO/GAW DQOs to be met or exceeded.	**[1-3 years]** Recommend CCQM-GAWG Task Group on Purity to reconvene to develop guidelines for minimum requirements for purity (as an initial starting point for end users). **[3-5 years]** Recommend the CCQM-GAWG Task Group on Purity work towards developing a guidance document which focuses on outlining a standardized approach for purity analysis of pure gases including agreeing upon, documenting, and adopting best practices in purity analysis based on outcomes and lessons learned through key comparison activities. Most specifications of pure gases are conservative but other impurities may yet be present. Determining ways to measure and provide values other than 'less than' values is important.	T2-A8, T2-A15, T2-A18
2A.7	For governments to improve the quantification of urban or sector level emissions (and to evaluate emission reduction strategies) there is an urgent need for increased monitoring of atmospheric CO_2 at all spatial scales and this increase in measurements must be supported by readily available high-quality CO_2 in air field standards and in the chain of intermediate standards supporting their traceability to the SI.	**[1-3 years]** NMIs, DIs, and expert organizations, through the CCQM GAWG GHG Scales Task Group, should work to promote the understanding of scales (development, implementation, and propagation) and how they can benefit the monitoring community. **[1-3 years]** Recognizing that demand for high quality carbon dioxide (CO_2) gas standards may increase, recommend that NMIs/Dis, and other expert organizations establish additional well-maintained CO_2 scales, and distribute reference materials traceable to scales. Recommend that all institutes which develop and maintain scales ensure that scales are clearly defined and documented, and that relationships to commonly used scales (e.g., WMO GAW CCL) are well understood. **[5+ years]** Recommend that all institutes that develop and maintain scales and the atmospheric monitoring communities work together (the CCQM GAWG GHG Scales Task Group provides a framework for this) to ensure that the scale used is clearly defined and associated with all measurements and that guidance on the scale relationships is publicly available in a central repository on scale relationships. Recommend that this information be held at the Headquarters of the International Bureau of Weights and Measures (BIPM) and be made publicly available, e.g., in the key comparison database (KCDB).	T2-A5, T2-A6, T2-A9, T2-A13

	Issue	Recommendation	Sources
		[3-5 years] Recommend that the CCQM GAWG develop a strategy to define and maintain scale relationships over decadal time periods. This includes the need to determine, understand and define the optimum frequency of comparison studies (which will depend on the long-term stability of individual scales) and the best approach for these comparisons (cylinder exchange between institutes or comparisons at a centrally designated facility, e.g., at BIPM Headquarters). **[5+ years]** Recommend that the CCQM GAWG GHG Scales Task Group look to extend the scale approach taken for CO_2 to cover methane, nitrous oxide[(e)], and potentially other GHG as well such as halogenated compounds. It is recommended that those institutes developing CO_2 scales should be proactive and consider including methane in addition to CO_2 because many commonly used instruments measure CO_2 and CH_4 at the same time and users will benefit from standards that can be used to calibrate for both.	
2A.8	NMIs/DIs, and expert organizations need access to available and affordable high quality purified air/whole air matrix gases and certified zero air.	**[1-3 years]** Recommend that NMIs/DIs, and expert organizations work to increase the availability of high-quality purified air/whole air matrix gases through a definition of acceptable tolerance limits for the composition and the performance of measurement methods required to verify these limits and produce a technical specification recognizing that a comprehensive suite of tolerance limits may not be possible until more information on cross sensitivities are known. **[1-3 years]** Stakeholder engagement between CCQM and the Specialty Gas Industry (in the framework of the CCQM Task Group on Stakeholder Engagement) is needed to work towards enabling the specialty gas industry to provide the necessary volumes of high quality purified air/whole air matrix gases at required uncertainty levels.[(g)] Discussions between NMIs and the Task Group are needed to develop an agreed upon data quality mechanism, e.g., drawing from the NIST Traceable Reference Materials Program. **[3-5 years]** Recommend that ISO TC158 develop an international standard for high quality purified air/whole air matrix gases and zero air based on a developed technical specification. **[1-3 years]** Although zero gas is not used as a calibration point in GHG scales, it could be used to prove that calibrations extrapolate through zero. Given its use as a potentially useful diagnostic tool the quality of zero gas is very important. Recommend ISO TC158 to produce a best practice guide/technical specification on methods to certify critical GHGs in zero air.	T2-A4, T2-A6, T2-A7, T2-A11, T2-A14, T2-A19

	Issue	Recommendation	Sources
2A.9	The atmospheric greenhouse gas monitoring community needs clear language to describe the isotopic composition of atmospheric gases.	**[1-3 years]** Recommend that CCQM GAWG members that have an interest in isotopic ratio join the CCQM IRWG to strengthen the links between these two communities. **[1-3 years]** Recommend that CCQM IRWG establish a task group to enable NMIs/DIs, expert laboratories and representatives of user communities work toward developing unambiguous language, definitions, and symbols for describing measurement results of isotopic quantities, units, and scales.	Climate Action Workshop discussions
2A.10	The atmospheric monitoring community need access to traceable isotopic GHG reference materials to support verification of emissions measurements.	**[1-3 years]** Recommend that assignment of isotope ratio to reference materials should be accompanied by sufficient detail of the characterization and value assignment to enable accurate replication by other laboratories. For example, for CO_2 there are alternate procedures for performing the $\delta^{17}O$ correction. This could be addressed through the development of a standard method. **[3-5 years]** Recommend that ISO TC158 develop a standard calibration method for the determination of isotope ratio (e.g., which quantity to calibrate delta isotope or amount fraction of each isotopologue) including what metadata must be included to replication and to identify potential biases to address harmonization issues. **[5+ years]** Recommend that NMIs/DI, and other expert organizations (e.g., BIPM, IAEA) work towards establishing a robust metrological infrastructure for isotopically assigned GHG reference materials that are traceable to the existing accepted international scales. **[5+ years]** Recommend that NMIs/DIs work towards enabling SI traceability for isotope measurements and the provision of accessible primary isotope reference materials with improved uncertainties to meet the requirements of the atmospheric greenhouse gas monitoring community. **[5+ years]** Recommend that NMIs/DIs engage with the radiocarbon community to understand requirements for $^{14}CO_2$ in air reference materials.	T2-A4, T2-A6, T2-A7, T2-A11, T2-A14, T2-A19

	Issue	Recommendation	Sources
2A.11	Source apportionment of natural and manmade GHG emissions requires extensive long-term spatially dispersed measurements of isotope ratio of GHGs. Due to recent advances in optical spectroscopy, the atmospheric monitoring community now has requirements for larger volumes of calibration gases compared to those traditionally needed for IRMS.	**[1-3 years]** Recommend NMIs/DIs and expert laboratories (within the framework of a CCQM-IRWG/GAWG task group) work with instrument manufacturers and the specialty gas industry to agree and adopt a calibration strategy, cost effective routes of disseminating reference materials and to define a technical specification required for isotope ratio reference materials in order to produce measurements of CO_2 and CH_4 in air from both real time measurements using laser spectroscopy or offline flask sampling and mass spectrometric analysis. **[3-5 years]** Recommend that NMIs/DIs develop capabilities to enable the provision of low uncertainty and high-volume CO_2 and CH_4 gas reference materials traceable to stable realizations of the VPDB and VSMOW/SLAP scales for $\delta^{13}C$, $\delta^{18}O$, and $\delta^{2}H$ to underpin global measurements.	T2-A4, T2-A7, T2-A11, T2-A19
2A.12	Compatibility of $\delta^{13}C$ and $\delta^{18}O$ measurements have not been demonstrated at the required target levels and need to be improved.	**[5+ years]** Recommend that NMIs, DIs, and expert organizations work towards improving the network compatibility for CO_2 isotopes, including harmonization of methods and more links to the CCL-isoCO$_2$.[h]	

Notes:

- Synthetic cylinders made from woven materials; 3D printing with layers of different materials - this type of development and testing would probably require significant resources; composite materials (e.g., H_2 storage); treatment processes would need to pass DOT/PI regulations especially if these are bespoke/in-house.
- This is a large goal that would need significant resources and coordination. Work towards addressing currently observed instability issues in some CO_2 reference materials, and in reference materials of other important non-GHG species such as CO, by further investigating the internal cylinder surface reactions and/or improving alternative methods to provide traceable standards. Instability of CH_4 reference materials does not seem to be a big issue using current analytical systems, but drift in N_2O reference materials is becoming an issue as new analyzers with higher precision are being developed and become more-widely used. (Encourage sharing of information on new experimental data that is relevant). (One possibility is to extend gold plating (https://www.sharrettsplating.com/base-

materials/aluminum#:~:text=Gold%3A%20Although%20plating%20gold%20onto,devices%20made%20from%20aluminum%20alloys .) which is used for smaller components (e.g., cyrotraps) to cylinders. SilcoNert is also a possibility though not for aluminum cylinders due to the temperatures involved in treatment process though some issues have been observed for long term stability of SilcoNert cylinders. We refilled cylinders with SilcoNert coatings (methanol reference gases at low ppm levels), and the losses were much higher compared to other cylinder treatments while with new SilcoNert treated cylinders behaved very well. Further for NO_2 mixtures made in SilcoNert treated cylinders we also had issues (lots of HNO_3 formation).]

- Experiments using labelled water would be very interesting. Knowing more about how moisture impacts stability would be helpful. May need long-term studies of moisture in cylinders to fully understand equilibrium adsorption] moisture and stability, the AGAGE community has done work on this for the non-CO_2 GHGs, especially Cl containing gases.
- NOAA recommends recalibration periods of 2-3 years, but these are not always followed. Encourage users to obtain history of recalibrations. Best practice can be gas specific which has caused confusion, e.g., recalibration every 2 years needed for CO but not for SF6. It might also depend on the expected lifespan of the cylinder - all cylinders should have an end-of-life re-calibration. Expiration date on certificate (NMI) forces end user to return for recertification/repurchase if the cylinder has low pressure (<300 psi).
- Currently, it is challenging for the atmospheric monitoring community to meet the WMO DQO for N_2O of 0.1 nmol/mol. Improvements in measurement techniques/analytical methods are needed to allow more consistent measurements and increase the possibility of meeting or exceeding the WMO DQO through the use of the scale approach. For N_2O this is most likely addressed through the development of additional N_2O scales. This should be considered provided that the CO_2 scale development program currently underway in the CCQM GAWG GHG Scale Task Group is successful.
- Since measurements of a specific GHG by a specific method can be affected by matrix effects or (potentially ill-defined) cross-sensitivities to other components in the air, it should be considered to have whole air matrices that match the atmosphere being sampled (i.e., Southern vs. Northern Hemisphere - or city vs background). It is critical that the reference materials behave in the same way as the matrix that is being measured - this concept is termed commutability of the reference material.
- Market size expectation will be a key issue for specialty gas industry involvement. Large compressors for filling cylinders with whole air are available and affordable to industry as a potentially economically viable route, whilst the specific smaller compressor system used by laboratories is no longer manufactured. Small scale liquid nitrogen filling is a possibility but requires care and is not the preferred method.
- Require more consistent use of parameters, not just the agreed parameters, and establishing a link through the CCL-isoCO_2. Some suggestions for improving comparisons, and therefore compatibility, are: (1) Sharing the agreed, apparent and measured parameters used for the isobaric corrections, including a scheme for the application of the corrections. (2) One, or more, links to the CCL-isoCO_2 that can be compared with other laboratories. (3) Updating past comparison results when laboratory procedures are changed. (4) Assessment of traceability and inclusion of a robust uncertainty assessment that can be used to assess laboratory performance against the WMO compatibility goals in a consistent manner. (5) Validation, or revision, of the compatibility goals for stable isotopes of CO_2. [T2-A1]

9. Topic 2B: State of play in integrated approaches for advanced GHG emission estimates and the way forward to operational services.

This topic addressed emissions and removal measurement needs based both upon socio-economic activity and atmospheric methods from local to global scales. Advances in modeling approaches for detection and quantification of emissions and removals were presented and discussed. The following guidance was proposed for presentations and discussion for Topic 2B:

- Integrated emissions modelling and atmospheric observations at national, sub-national and industrial scales (e.g., inverse model analyses)
- Assessment of current capabilities and uncertainties, identification of gaps
- Analysis benefits & costs
- Application to National Inventory Reporting
- Applications to Land Use, Land Use Change, and Forestry
- Applications for Urban GHG Monitoring
- Observations to improve accuracy of emission factors and activity data
- Uncertainty propagation in methods for individual mitigation sectors
- Effects on uncertainty of differing temporal and spatial scales – atmospheric and emissions modelling methods
- Paths toward elements for certification of results

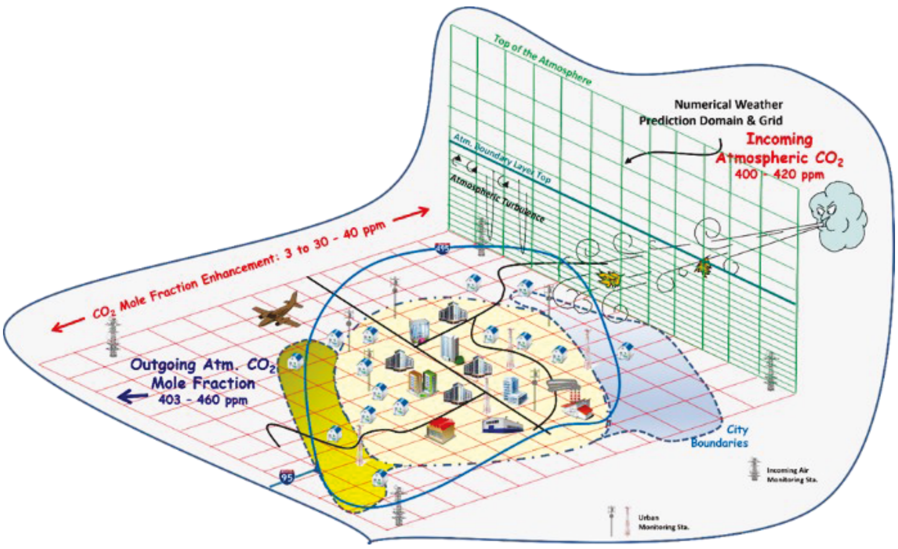


Figure 7: This figure presents the measurement needs for greenhouse gas (GHG) emissions and removals at different spatial scales, from local to global, considering socio-economic activities and atmospheric measurement methods. The atmospheric inversion approach is shown in the figure, which involves complex urban centres that have multiple sources of emissions and uptake, such as buildings, roads, industrial and power generation plants, etc. The background GHG concentrations mix with those of the city, and networks of concentration measurement sites provide data. These data, along with numerical weather prediction and dispersion models, and optimization methods, aid in quantifying incoming, outgoing, and internally produced GHG emissions. Image credit: James R. Whetstone (NIST).

The recommendations address needs for a unified approach to quality assurance of inverse atmospheric modeling approaches, the need for an easily implemented transparent framework to assess inversion modeling results, improvement in atmospheric transport model skills, and improvements in satellite data. This session noted the need for improved interactions between the global carbon cycle science community and climate negotiators, private sector stakeholders (e.g., for those using ESG ratings in finance), and the need for a comprehensive capability to provide data for methane emissions. At least one recommendation addresses the need to start international standardization efforts, that is the development of documentary standards, most likely developed under the umbrella of ISO, the International Organization for Standardization (https://www.iso.org/home.html).

Methods for assessing and monitoring the contributions of each socio-economic activity to global GHG emissions, whether at the national level (IPCC - Taskforce on National Inventories) or at the local level (such as the GHG protocol for corporations or cities), rely essentially on the collection of activity data or official statistics. These self-reported inventories are very useful for raising awareness or holding public and private organizations accountable but are missing the point about comparability and accuracy as it's highly dependent on the reliability and completeness of local data sources. In addition, these methods do not meet the growing demand for accurate and actionable information on GHG emissions (location, real time) induced by new national or regional regulations (methane leakage, carbon tax at borders, etc.), the renewed ambition of cities to accelerate their decarbonization (carbon neutral cities alliance, EU 100 climate neutral and smart cities, etc.) or the increased transparency demanded by sustainable finance players (ESG reporting, ESG funds, impact finance, etc.)

New approaches have been developed for modelling GHG emissions based on recent scientific advances in the detection and quantification of GHG emission fluxes for a range of sources and sinks. These advances include emissions from unknown or significantly underestimated large point sources, from urban areas, atmospheric and satellite monitoring methods, modelling of biogenic CO_2 sources and sinks, modelling of atmospheric transport, and data analysis methods.

Different combinations of these techniques are being used in locations around the globe. These advanced methodologies are poised to provide the private sector and governments with GHG emissions data that would enable assessment of the impact of mitigation efforts and quantify the expected returns on their investments. However, there are no established, internationally recognized standards to ensure the accuracy, reliability, consistency, and mutual recognition of GHG measurements.

Based on the participants' input, the following four subtopics were identified and addressed within the recommendations given below:

- Inverse atmospheric modeling
- Methane emission tracking
- Urban GHG emission estimates
- Business and standardization issues

	Issue	Recommendation	Sources
2B.1	The national greenhouse gas emissions inventory community needs a unified approach to quality assurance of inverse atmospheric modeling and data, as the difficult comparison between various methodologies leads to a reluctance to endorse/integrate these scientific data products in their official communications.	Development by WMO/IG3IS of specific guidelines for national scale atmospheric inversions and inventories, is needed and should include: **[1-2 years]**: Definition of key metrics to document the accuracy and precision of inverse fluxes. **[1-2 years]**: Transparency framework to access to shared inputs (data and prior). **[3-5 years]**: Transparency framework to access the performance of codes.	T2-B2 T2-B4 T2-B8
2B.2	The UNFCCC Expert reviewers of national greenhouse gas emissions inventory need an easily implemented transparency framework (e.g., a checklist) to assess the quality of inversion-based greenhouse gas emission inventories, as the underlying science required for this technique is still a scientific niche and research to advance inversion-based methods continues and would benefit from acceleration of efforts.	**[1-2 years]**: Development by WMO-IG3IS under UNFCCC/SBSTA's and/or IPCC-TFI umbrella and of an auditability / accountability framework for national-scale inversion-based GHG emission inventories.	T2-B2 T2-B4 T2-B8

	Issue	Recommendation	Sources
2B.3	The diversity of methodologies for modeling atmospheric transport of greenhouse gas emissions at different scales (regional, national, sub-national, local, point source) does not facilitate the recognition, use and economic valuation of these data by public and private actors who need a recognized and stable framework.	**[1-3 years]**: The atmospheric observing community, through WMO and WMO/IG3IS, to define quantitative needs for atmospheric transport simulation and determination of the uncertainty inherent to it. **[3-5 years]**: The GHG measurements and inventory communities should work within ISO standardization efforts to improve performance of atmospheric transport models and data analysis methods to determine GHG fluxes and source apportionment.	T2-B2 T2-B4 T2-B8 Discussion during the workshop
2B.4	Satellite based atmospheric monitoring is not yet responsive enough to fit with needs (timely release of in situ/ remote sensing data for calibration/validation) of GHG emission inventory makers due to lack or constrained access to large scale computing facilities.	**[1 year]**: Launch an international joint initiative to ease access to national or regional scale computing facilities or private cloud service (WMO / UNFCCC / Philanthropic initiatives of cloud service companies).	T2-B2 T2-B11 Discussion during the workshop

	Issue	Recommendation	Sources
2B.5	The carbon cycle scientific community, to inform the institutions in charge of climate negotiations and their follow-up, and private actors (ESG rating agencies, investors, corporates, NGOs) need a comprehensive view of the observation data on methane leakage (CH_4) initially. This to be followed by other GHG emissions data) currently disseminated on different public and private platforms.	**[1-2 years]**: Governments, perhaps through UNFCCC organizations should develop a unified database on CH_4 observations open to the international climate community with the support of Global Methane Hug, WMO IG3IS/GGMI, UNFCCC, IEA Global Methane Tracker, Space Agencies, and new space start-ups such as Carbon Mapper. **[3-5 years]**: Governments, perhaps through UNFCCC organizations, should work toward developing a unified database on CO_2, HFCs and N_2O emission observation open to the international climate community with the support of WMO IG3IS and GGMI, UNFCCC, Space Agencies, and new space start-ups such as Carbon Mapper.	T2-B2 T2-B14 Discussion during the workshop
2B.6	The carbon cycle scientific community has not a clear visibility on access to controlled release test facilities which prevent from having methane detection techniques comparable results.	**[1-3 years]**: (BIPM/WMO/ GAW/IG3IS, Global Methane Hub, IEA Global Methane Tracker, NASA, ESA, and other interested parties should form an organization to design a suite of an international controlled release test facilities. Implementation funds should be obtained from UN and global business and philanthropic communities. This organization should provide open access to these facilities.	T2-B2 T2-B14 Discussion during the workshop

	Issue	Recommendation	Sources
2B.7	Investment and action in measuring, monitoring, and tracking methane emissions from agriculture and waste management sectors, both for super-emissions from point sources and diffuse emissions, are insufficient relative to the investment and work occurring for the oil-and-gas sector, which makes these sectoral activities less accountable in the efforts to reduce GHG emissions.	**[1-2 years]**: The WMO and CIPM should initiate a process to develop an international roadmap for non-O&G sector methane emission tracking (agriculture, waste management, wastewater treatment, etc.) with the support of WMO, UNEP, National EPAs, and UNFCCC.	T2-B2 T2-B14 Discussion during the workshop
2B.8	States and local governments have not yet fully grasped the transformative capacity of independent scientific tracking of methane leakage for innovative regulations, monitoring, and effective and appropriate economic incentives.	**[1-2 years]**: WMO/IG3IS, BIPM working with partners, e.g., the Global Methane Pledge, IEA, WRI, WBCSD, etc. should develop a toolkit of model methane emissions control policies. These are to be based on independent near-real-time monitoring techniques and are to be useful for national/subnational governments, covering methane emissions regulation, fraud detection, fiscal mechanisms, and innovative revenue models (market and non-market based).	T2-B2 T2-B14 Discussion during the workshop

	Issue	Recommendation	Sources
2B.9	High-resolution urban GHG emission inventory operators (university labs, start-ups) need spatialized data with high update frequency to estimate road transport flows and speeds, but face very costly private offerings initially dedicated to urban logistics actors that penalize the feasibility of such science-based and action-driven tools for cities.	**[1-2 years]**: Launch of international initiative to ease access to free mobility data (floating car data, mobile geolocation data, GSM data) for the climate science community (IG3IS, ICLEI, C40, CDP, GSM Association, Philanthropic initiatives of mobility data providers).	T2-B7 T2-B13 T2-B15 Discussion during the workshop
2B.10	Pilot cities that are experimenting with implementation of high-resolution urban GHG monitoring platforms have data definitions that are not necessarily aligned with the practices of the GHG protocol for cities community, which may create future barriers for new cities.	**[1-2 years]**: BIPM and WMO/IG3IS to form a working group on definition harmonization (boundary, scope, sector) to ease comparability between SRI and science-based approaches (WMO/IG3IS, CDP, GCOM, City Climate Intelligence RMI).	T2-B1 T2-B3 T2-B7 T2-B13 T2-B15

	Issue	Recommendation	Sources
2B.11	Cities need a unified approach to quality assurance of high-resolution emissions inventories, as the difficult comparison between different methodologies could lead to a reluctance to approve inventories and the decision-making process based on this family of tools.	**[1-2 years]**: Development of a WMO/IG3IS guideline to define key parameters documenting the accuracy and precision of the high-resolution emissions inventory. This work will prefigure the QA/QC component of a future ISO standard.	T2-B1 T2-B3 T2-B7 T2-B13 T2-B15
2B.12	Cities cover 70 % of GHG emission but have received less than 1 % of the Kyoto Protocol carbon credits. The lack of information systems providing measurable, reportable, and verifiable (MRV) impact data on GHG reduction for city managers is one of the major explanations for their very poor access to carbon finance tools and the still insufficient cooperation with business actors.	**[1-2 years]**: Development of an ISO standard on quality criteria for spatialized and frequently updated city-wide GHG emission inventories for MRV purposes for urban emission reduction projects, to facilitate access to carbon finance tools and city business cooperation.	T2-B13 T2-B15

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

This topic addressed new and/or novel methods for measurement emission fluxes and concentrations with a focus on new sensing approaches. The following guidance was proposed for discussion and presentations for Topic 2C:

- Surface, airborne, and space-based air composition methods
- Advances in and quality control of direct flux observations and linkages to larger spatial scales

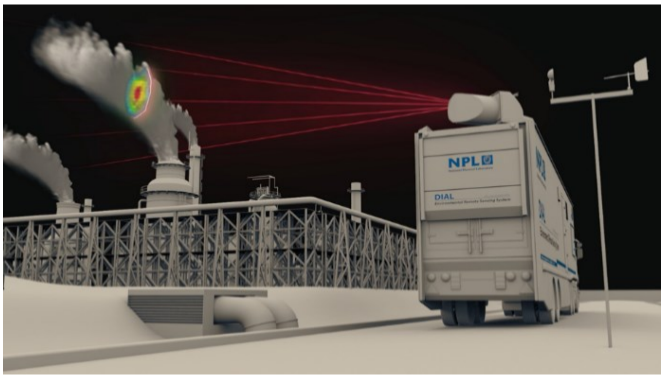


Figure 8: This figure illustrates an innovative method for measuring greenhouse gas (GHG) emission fluxes and concentrations, by using new sensing approaches. The image displays a mobile Differential Absorption Lidar (DIAL) facility for scanning emissions from chimneys. This system can monitor atmospheric pollutants remotely, at ranges of up to 1 km. DIAL measurements are real-time, directly traceable to primary standards of gas concentration and are free from interference and contamination.

For more information see: https://www.npl.co.uk/products-services/environmental/absorption-lidar-dial.

Image Credit: T.Gardiner (NPL)

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. The need for standardization was also cited. Rendering sensing advances made by the scientific community into measurement technologies has potential to address the global need to close the GHG data gap. Due to its nature, method development and integrating novel GHG sensor technology has a continuously changing landscape of stakeholders, practitioners and developers. The recommendations provided should be regarded as a snapshot of current needs that have to be addressed. However, they should be implemented in a way that allows enough flexibility to also integrate sensor and methodological developments that cannot be foreseen now but are certain to happen in the future.

The core issue across recommendations is a need for mutually accepted ways to improve coordination, communication and method development across the GHG science, BIPM expert and stakeholder communities.

	Issue	Recommendation	Sources
2C.1	**Better coordination** between atmospheric science community and instrument developers [Instrument developers need 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.) to design suitable systems]	**[1-2 years]** For background observations of atmospheric Greenhouse gases, the WMO/GAW GGMT guidelines exist. Some urban and some small-scale applications are covered in the WMO/IG3IS best research practice guidelines. Both documents should be disseminated more broadly by WMO/GAW. For novel or specialist applications, e.g., drones or isotopes for source apportionment, more information is required. WMO/GAW or scientific bodies like EGU/AGU should be approached to lead efforts towards a synthesis of current requirements over the next 2 years. This progress can be made in partnership with efforts such as the OPTICA (formerly OSA) Global Environmental Measurement and Monitoring (GEMM) initiative and others. https://www.gemminitiative.org/en-us/.	Discussion during the workshop
2C.2	**Better coordination** between data users and science community [The atmospheric science community lacks understanding of the needs of stakeholders, e.g., how precise do flux/emission rate estimates have to be to be useful]	**[1-2 years]** Establishing an ongoing dialogue between science and user community is challenging. WMO/IG3IS has made progress in creating such a link, thus their experience should be leveraged. Furthermore, new initiatives like UNEP/IMEO also aim for stakeholder-oriented science. Both organizations should be approached to see if they can facilitate better information flow between these communities more broadly.	Discussion during the workshop

	Issue	Recommendation	Sources
2C.3	**Calibration methods and comparability/traceability** of GHG abundance measurements needs to be ensured [The atmospheric modelling community needs to be able to use GHG observations from different data sources, e.g., *in situ*, mobile systems, ground-based remote sensing, satellites]	**[1-2 years]** An NMI-led working group should be set up with participation of WMO and other scientists. Ideally, the lead organization should have experience with both *in situ*, open-path, and remote sensing instruments (e.g., NPL, ICOS-Mlab). The lead organization should host a series of comparison experiments at different locations (with high and low natural variability of atmospheric GHG levels) in the coming 4 years, to assess different calibration approaches, their uncertainties and traceability.	Discussion during the workshop
2C.4	**Calibration methods and comparability/traceability** of different flux measurement methods needs to be ensured. [The scientific community needs the ability to demonstrate that different flux/emission rate estimation techniques are equivalent or comparable to ensure reliable data can be produced for decision makers.]	**[1-2 years]** It is important to recognize that atmospheric-based emission estimates cannot always be (easily) compared to one another or existing inventory-based techniques. However, it is critical that real world data is collected to demonstrate the reliability of different emission estimation techniques. The investigation into the consistency between atmospheric techniques should be led by practitioners and the WMO research community. **[3-5 years]** The task to work towards creating equivalency of inventory-based and atmospheric techniques could benefit from recent efforts launched by IPCC-TFI. The TSU and WMO should be approached to identify the best lead for such a project. The timeline should be aiming for results before the next global stock take.	Discussion during the workshop

	Issue	Recommendation	Sources
2C.5	**Closing the observational data gap**. Novel sensors and measurement techniques need to be deployed rapidly and widely to support better climate science. [A plethora of new sensors and techniques have emerged in recent years. The scientific community now needs to find the right partners to deploy suitable systems as soon as possible]	**[3-5 years]** The task of closing the observational gap will require the development of an integrated GHG monitoring system that leverages all existing and novel techniques, ranging from low-cost sensor networks to satellite constellations. Key organizations that need to be involved are WMO, TCCON, COCCON, GEOSS, CEOS, AirCORE community, etc. **[3-5 years]** Ideally, the WMO INFCOM initiative on systematic global GHG observations could be leveraged.	Discussion during the workshop
2C.6	**Existing guidance needs to develop into standards**, especially for private sector involvement. [The scientific community has developed many useful techniques and produced some guidelines/reference documents. However, to be able to ensure newcomers and private sector actor can (and do) perform to the required levels documentary standards on GHG observations should be developed]	**[1-2 years]** The BIPM community (whichever sub-entity is most suitable) should lead the translation of the existing guidelines into documentary standards. NIST has begun such a process for urban observations and ICOS, NIM-China and others have also worked towards this goal and should be involved (or co-lead) in the process.	Discussion during the workshop

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

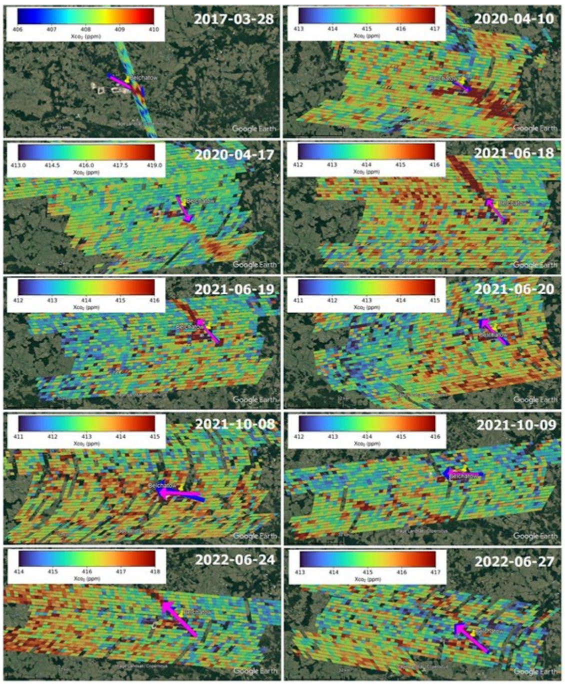
This topic addressed the need to improve the ability to use remote sensing data as valuable inputs to analytical methods for producing estimates of GHG emissions and fluxes. Discussions included significant use of atmospheric modeling of several types. The following guidance was proposed for discussion and presentations for Topic 2D:

- Use of surface and airborne data in validating space-based, path integrated concentrations
- Atmospheric quantification of GHG emissions methods from urban to global scales
- Challenges in using satellite path integrated GHG concentrations for emission and uptake flux determinations
- Opportunities of using data from low Earth and geosynchronous orbit instruments for emission flux determinations.

Recommendations addressed issues involving NMIs, the carbon cycle science / greenhouse gas measurement communities and stakeholders. Needs for improvements in remote sensing capabilities and improved connections between the major players in these three areas. Stakeholder needs for robust uncertainty estimates and supporting analysis methodologies were cited with particular emphasis on both CO_2 and methane as was the need for accessible and more easily understood information from the national to the local level were identified.

Remote sensing of greenhouse gases from space is a new capability developing in the 21st century. Space-based remote sensing provides a potentially optimal observation capability for estimating greenhouse gas measurements over a range of spatial and temporal scales. From space the same observations can be made globally, and with high revisit frequency, thus conceptually supporting operational systems with physical measurements useful for quantifying emissions, be they focused on facility-scale point source emissions, or larger aggregated emission from regional to national scales. With the newness of these observations, capabilities are improving rapidly both instrumentally and in the methods that link to space-based observations. It is important that standards and evaluative practices are continually developed and advanced in this dynamic environment to ensure credibility of space-based remote sensing in its various use cases. It is important that efforts continue to link emissions measured and estimated on the surface more firmly with remote-sensing observational data, and that the uncertainties in both approaches be quantified transparently. The term ‘carbon community’ in this topic area means the combination of the communities of carbon science research, emissions monitoring providers, emissions data compilation and reporting and similar stakeholders.

Several general conclusions emerged from the presentations and discussions in Topic 2D. Space-based remote sensing promises exciting potential to inform greenhouse gas emissions over a range of scales, and to provide the same measurement and methodology across different nation states. These approaches are rapidly improving, advancing, and multiplying. Currently, well characterized point-source quantification capabilities are multiplying and, particularly in the case of methane, provide a near-term pathway towards actionable information for governments, business, and industry. Development of standardized methodologies for quantifying point-source emissions, e.g., via known controlled releases, would provide a robust near-term pathway to developing and enhancing credibility for use of this data. To estimate area emissions and support assessments of nationally determined contributions, advancing the technological linkages of ground and air-borne measurements in conjunction with space-based observation will be critical to better define uncertainties and capabilities and provide credible greenhouse gas information.



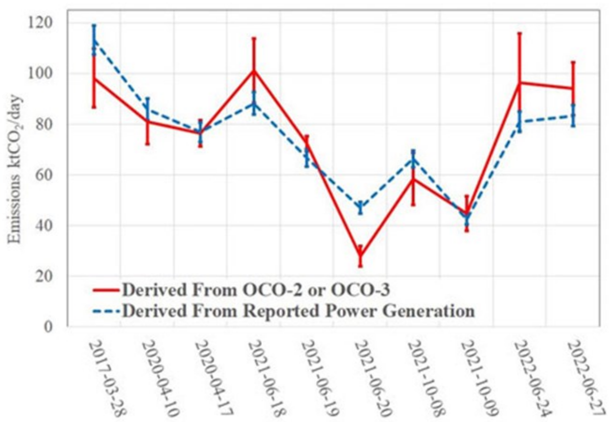


Illustration of quantifying power plant CO_2 emissions from space.
Left: Satellite observation of CO_2 from OCO-2 and OCO-3 capturing power plant CO_2 plume from Belchatow (indicated). Purple arrow shows wind direction.
Right: Quantified power plant emissions from these observations compared with reported.
Adapted From Nassar et al., https://doi.org/10.3389/frsen.2022.1028240

Figure 9: Bełchatów Power Plant overpasses from OCO-2 (2017-03-28) and OCO-3 (all others). Colored parallelograms are bias-corrected XCO2 footprints with customized color scales, overlaid on Google Earth Landsat/Copernicus satellite surface imagery. The power plant location is the yellow tack and the MERRA-2 (blue) and ERA-5 (pink) wind vectors are shown as arrows of length proportional to wind speed. The spatial scale is indicated in the lower left of each panel.

Plot: Time series of emissions expected based on ENTSO-E reported power generation and OCO-2/OCO-3 observations each with 1σ error bars.

	Issue	Recommendation	Sources
2D.1	Reliable and traceable remote-sensing observations are needed to serve as an input to a greenhouse gas emissions monitoring system.	**[1-5 years]** Recommend the continuation and expansion of frequent profiling of atmospheric greenhouse gas concentrations in an ongoing fashion, including satellite, airborne (research and commercial platforms), and surface-based methods, and increased participation form the metrology community in these activities. Key constituents for collaboration with BIPM, WMO and their members are national space agencies and CEOS, national ministries of environment and Earth sciences.	Climate Action Workshop discussions T2-C6
2D.2	NMIs and the carbon cycle science community need better connection to enable robust development of greenhouse gas measurement and monitoring technologies including credible standards.	**[1-3 years]** Recommend an increase in collaboration among and across communities, starting with regular workshops led by NMIs to link with the greenhouse gas community. This would work toward to implementation of uniform measurement protocols endorsed by NMIs and other organizations that include use of measurements traceable to the International System of Units (the SI). These interactions could be conducted in junction with international workshops and conferences, such as GSICS, IWGGMS, and CALCON. Topics should include measurement techniques, calibration, and traceability to the International System of Units (SI).	T2-C2, T2-D6, T2-D9
2D.3	Stakeholders need robust estimates with defined uncertainties on facility scales for point sources of methane and carbon dioxide.	**[1-4 years]** Recommend that NMIs contribute their measurement expertise to design and develop (or identify) calibrated emissions sources to support validation and confidence in space-based estimates of point source emissions. This could include power plants with accurate ultrasonic stack flow metering and CO_2 concentration measurements as well as ongoing methane-controlled release experiments and controlled flaring. Implementation activities should be in collaboration and coordination with space agencies coordinated through CEOS as well as WMO Commission for Infrastructure and Research Board.	Discussion during the workshop

	Issue	Recommendation	Sources
2D.4	Stakeholders need estimates of area (up to nation-state) emissions with defined uncertainties of methane and carbon dioxide concentrations and fluxes.	**[3-7 years]** The greenhouse gas community should establish calibration areas/regions with well characterized emissions data based on combining emissions modelling (bottom-up) and atmospheric observation and analysis (top-down). This should be done by NMIs interfacing with other government agencies and applicable partners, such as research universities. We recommend that the development of these regions consider varying emitter composition in both space and time to aid space-based observational analysis. These should consider cities as well as predominately biogenic areas – agricultural and forested regions, wetlands. The accounting for ocean carbon fluxes should also not be neglected. The communities should combine use of tower-based networks for these with periodic aircraft observations and analyses, with data integration in regional areas assessed by relevant NMIs and other organizations. The work should include robust statistical analysis. CIPM should coordinate such an effort via the CCs in coordination with the WMO.	Discussion during the workshop
2D.5	All communities have a need for improved connectivity and ability to communicate and collaborate.	**[1-3 years]** Through ongoing workshops led by NMIs, the NMIs and the carbon community should develop common language, communication changes, agreement on units of measurements, encourage data "interoperability" and utilize increased digitalization. Protocols should be developed via collaboration of the metrology and carbon communities for data commerce. These must contain clear definitions for measured quantities, traceability to the SI, and measurement uncertainties. Measurement scientists in all sectors should be encouraged to provide data in both processed and as unprocessed a form as practicable to facilitate cross-checking by others.	Discussion during the workshop
2D.6	Stakeholders need simpler, more accessible information from national to local levels.	**[3-7 years]** The NMI and carbon/GHG communities in partnership develop and provide general-public-level explanations of approaches, measurement methods, and results aimed at reducing uncertainty in inventory reports from the national to local levels. Articulating the advantage of the use of the combined bottom-up and top-down emissions determination approach is a critical messaging need for NDC applications and national inventories and other stakeholders.	Discussion during the workshop

Glossary of Terms

A

ACTRIS: Aerosol, Clouds and Trace Gases Research Infrastructure

AGAGE: Advanced Global Atmospheric Gases Experiment; a long-term project

AGU: American Geophysical Union

AI: Artificial Intelligence

AirCORE: An innovative atmospheric sampling system

ASELSU: Assessment Sea level rise stability uncertainty; a project

ARCSTONE: Calibration of Lunar Spectral Reflectance from Space; a mission concept

Argo: international program that measures water properties across the world's ocean using a fleet of robotic instruments that drift with the ocean currents and move up and down between the surface and a mid-water level.

B

BIPM: International Bureau of Weights and Measures

BIPM Headquarters: Scientific and technical staff and facilities at the Pavillon de Breteuil of the International Bureau of Weights and Measures

BSRN: Baseline Surface Radiation Network

C

CALCON: The Characterization and Radiometric Calibration for Remote Sensing Annual Meeting

CCL: Central Calibration Laboratory; of WMO-GAW

CCL-isoCO_2: Central Calibration Laboratory for CO_2 stable isotopes

CCPR: Consultative Committee for Photometry and Radiometry

CCQM: Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology

CCT: Consultative Committee for Thermometry

CDP: Carbon Disclosure Project

CDR: Climate data record

CERES EBAF: Clouds and Earth's Radiant Energy Systems (CERES) Energy Balanced and Filled (EBAF)

CEOS: Committee on Earth Observation Satellites

CGMS: Coordination Group for Meteorological Satellites

CIMO: Commission for Instruments and Methods of Observation

CIPM: International Committee for Weights and Measures

CIPM/CC: International Committee for Weights and Measures Consultative Committees

CIPM-MRA: International Committee for Weights and Measures - Mutual Recognition Arrangement (CIPM MRA)

CITAC: Guide to Quality in Analytical Chemistry

CLARREO: Climate Absolute Radiance and Refractivity Observatory; a space mission, a SITSat

CMA: China Meteorological Administration

CNSA: China National Space Administration

COCCON: Collaborative Carbon Column Observing Network

CRYORA: Cryosphere Observing Requirements Task Team

CryoNet: GCW surface observation network

CTD: Conductivity, Temperature and Depth

C40: Cities Climate Leadership Group

D

DI: Designated Institute

DIAL: Differential Absorption Lidar

DIC: Dissolved inorganic carbon

DFIR: Double fence intercomparison reference

DLR: Downward Longwave Radiation

DOT/PI: Department of Transportation/Pi (regulated marking of gas cylinders)

DQO: Data Quality Objective

E

ECCC: Environment Climate Change Canada

ECV: Essential Climate Variable

EEB: Earth energy balance

EGU: European Geosciences Union

EMS: extinction minus scattering

ENSO: El Niño-Southern Oscillation

EO: Earth Observations

EOVs: Essential Ocean Variables

EPA: Environmental Protection Agency

ESA CCI/Climate-Space: European Space Agency Climate Change Initiative; a programme

ESG: Environmental, Social and Governance

ET-ACMQ: Expert Team of Atmospheric Composition Measurement Quality

ETSI: Expert Team on Sea Ice

EURAMET: Regional Metrology Organization (RMO) of Europe

F

FAPAR: Fraction of Absorbed Photosynthetically Active Radiation

FDR: Fundamental Data Records

FDR4ALT: Fundamental Data Records for Altimetry; a project

FIDUCEO: Fidelity and Uncertainty in Climate data records from Earth Observations, a project

FLUXNET: International "network of networks," tying together regional networks of earth system scientists.

FORUM: Far-infrared Outgoing Radiation Understanding and Monitoring; a satellite mission

FRM: Fiducial reference measurement

FRM4VEG: Fiducial Reference Measurements for Vegetation; a project

G

GAW: Global Atmosphere Watch

GAWG: Gas Analysis Working Group

GCOS: Global Climate Observing System

GCO M: Global Covenant of Mayors for Climate & Energy

GCW: Global Cryosphere Watch

GEISA: Management and Study of Atmospheric Spectroscopic Information

GEMM: Global Environmental Measurement and Monitoring

GeoHab: Marine Geological and Biological Habitat Mapping

GEOSS: Global Earth Observation System of Systems

GEWEX: Global Energy and Water Exchanges

GGMI: Greenhouse Gas Monitoring Infrastructure

GGMT Greenhouse Gases and Measurement Techniques

GHGs: Greenhouse gases

GLIMS: Global Land Ice Measurements from Space Initiative

GMSL: Global mean sea level

GSICS: Global Space-based Inter-Calibration System

GSM: Global System for Mobile Communications

GTN-P: Global Terrestrial Network for Permafrost

GTN-G: Global Terrestrial Network for Glaciers

GUM: Guide to the expression of Uncertainty in Measurement

GUM4EO:Guide to uncertainty of measurement for earth observation

H

HITRAN: High-resolution transmission molecular absorption database

I

IACS: International Association of Cryosphere Sciences

IAEA: International Atomic Energy Agency

ICLEI: International Council for Local Environmental Initiatives

ICOS: Integrated Carbon Observation System

ICSSG: International Classification for Seasonal Snow on the Ground

IEA: International Energy Agency

IGACO: Integrated Global Atmospheric Chemistry Observation

IG^3IS: Integrated Global Greenhouse Gas Information System

IMBIE: Ice sheet Mass Balance Intercomparison Exercise

IMEO: International Methane Emissions Observatory

INFCOM: Commission for Observation, Infrastructure and Information Systems

IPA: International Permafrost Association

IPCC: Intergovernmental Panel on Climate Change

IPCC-TFI: IPCC's Task Force on National Greenhouse Gas Inventories

IRMS: Isotope ratio mass spectrometry

IRWG: Isotope Ratio Working group of the CCQM

ISO: International Organization for Standardization

ISRO: Indian Space Research Organisation

IWGGMS: International Workshop on Greenhouse Gas Measurements from Space

IUGG: International Union of Geodesy and Geophysics

J

JAXA: Japan Aerospace Exploration Agency

JCGM: Joint Committee for Guides in Metrology

K

KCDB: Key comparison database

KWKB-TV: KWKB Television station

L

LCS: Low-Cost Sensors

LPV: Land Product Validation

LST: Land Surface Temperature

LTER: long-term ecological research

LULUCF: Land-use, land-use change, and forestry

M

MBES: Multibeam echo sounders

MERRA-2: Modern-Era Retrospective analysis for Research and Applications, Version 2

ML: Machine Learning

MRV: Measurable, reportable, and verifiable

N

NASA; National Aeronautics and Space Administration

NDACC: Network for the Detection of Atmospheric Composition Change

NDC: Nationally determined contribution

NEON: National Ecological Observatory Network

NGO: Non-governmental organization

NIM: National Institute of Metrology, China

NIST: National Institute of Standards and Technology

NMIs: National Metrology Institutes

NOAA: National Oceanic and Atmospheric Administration

O

O&G: Oil and Gas

OA: Ocean acidification

OBPS: Ocean Best Practices System

OCO-2: Orbiting Carbon Observatory-2

OCO-3: Orbiting Carbon Observatory-3

OSA: Optical Society

OPTICA: Optical Society

P

PEMS: Portable Emissions Measurement Systems

PTI: Photo-thermal interferometry

Q

QA4EO: Quality Assurance Framework for Earth Observation; endorsed framework

QA4ECV: Quality Assurance for Essential Climate Variables; a project

QA/QC: Quality assurance/quality control

R

R&I: Research and Innovation

R&D: Research and development

RMI: Rocky Mountain Institute

RMOs: Regional metrology organizations

RTMs: Radiative transfer models

S

S_A: Absolute Salinity

Sag: Scientific Advisory Group

SBSTA: Subsidiary Body for Scientific Technological Advice

SCAR: Standing Committee for Antarctic Research

SI: International System of Units

SIN'XS: Sea Ice-thickness product iNter-comparison eXerciSe; a project

SITSats: SI-Traceable Satellites

SLAP: Standard Light Antarctic Precipitation

SLF: Institute for Snow and Avalanche Research

SnowPEx: Satellite Snow Product Intercomparison and Evaluation Exercise

SPICE: Solid Precipitation Intercomparison Experiment

SRI: Self Reported Inventories

SSI: Spectral solar irradiance

SWE: Snow Water Equivalent

T

TA: Total alkalinity

TCCON: Total Carbon Column Observing Network

TEOS-10: Thermodynamic Equation of SeaWater 2010

TERN: terrestrial ecosystems research network

ToA: Top of the Earth's atmosphere

TRUTHS: Traceable Radiometry Underpinning Terrestrial-and Helio-Studies; a satellite mission, a SITSat

TSI: Total solar irradiance

TSU: Technical Support Unit of the IPCC Task Force on National Greenhouse Gas Inventories

U

UNEP: United Nations Environment Programme

UNFCCC: United Nations Framework Convention on Climate Change

V

VIM: International Vocabulary of Metrology

VOC: Volatile Organic Compound

VPDB: Vienna Pee Dee Belemnite

VSMOW: Vienna Standard Mean Ocean Water

W

WBSCD: World Business Council for Sustainable Development

WCRP: World Climate Research Programme

WGCV: Working Group on Calibration & Validation

WMO: World Meteorological Organization

WRI: World Resources Institute

WRMC: World Radiation Monitoring Center

X

XCO2: Carbon dioxide column-averaged dry-air amount fraction

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ISBN: 978-92-822-2286-7
https://doi.org/10.59161/Rapport202303