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Report on the WMO-BIPM workshop on

Measurement Challenges for Global Observation Systems for Climate Change Monitoring

Traceability, Stability and Uncertainty

30 March – 1 April 2010
WMO Headquarters
Geneva, Switzerland

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World Meteorological Organization
Bureau international des poids et mesures

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WMO- BIPM workshop on Measurement Challenges for Global Observation Systems for Climate Change Monitoring: Traceability, Stability and Uncertainty.

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Foreword

Changes in the world's climate and the influence of human activity on our planet are of key concern. Increasingly, world leaders are faced with important decisions on environmental matters, which often have vast economic implications, and they wish to rely on the most accurate scientific observations of the state of the global environment. This need for scientific observations of ever increasing accuracy and complexity is placing stringent demands on the accuracy of global observing systems and on the traceability of measurement results to internationally agreed units of measurement and standards. Furthermore, the need to accurately interpret small changes in long-term environmental data series requires measurement standards with well-characterized uncertainties and well-monitored and maintained stabilities.

Recognizing this need, the World Meteorological Organization (WMO) and the International Bureau of Weights and Measures (BIPM) jointly hosted the WMO-BIPM workshop on Measurement Challenges for Global Observation Systems for Climate Change Monitoring: Traceability, Stability and Uncertainty. The workshop gathered scientists from the Earth observing systems and the metrology communities to discuss ways in which they can collaborate so as to deliver ever more accurate and reliable observations of the Earth's climate.

Requirements for high-quality observational data and their world-wide compatibility were a governing principle when the International Meteorological Organization (IMO) was established in 1873. They also have been the foundations for the technical references in collecting and exchanging world-wide meteorological and climate observations since the establishment of WMO, the IMO successor, in 1950. Since that time, standardization responsibilities of the WMO Commission for Instruments and Methods of Observations, including defining technical standards, conducting instrument intercomparisons, testing and calibration and implementing quality control procedures, have been significantly expanded to cope with the fast development of measuring technology, in order that the traceability of measurements to the International System of Units (SI) could be guaranteed. Today, many of the challenges faced by climate science are indeed measurement challenges, for example, assessing the trends in concentrations of greenhouse gases and their regional sources and sinks, assessing the radiative impacts of these gases, and assessing the resulting changes in surface and atmospheric temperature.

Assessing climate change will depend crucially on the uncertainties associated with measurements and the robustness of climate data and their compliance with the internationally agreed climate monitoring principles of the Global Climate Observing System. Measurement uncertainties can only be determined, and hence minimized, if proper consideration is given to the metrological traceability of the measurement results to stated standards. National Metrology Institutes have traditionally provided primary measurement standards to underpin a wide range of physical and chemical measurements.

These standards often require many years of research and development to realize and are subject to constant refinement. The International Bureau of Weights and Measures, which is mandated to provide the basis for a single, coherent system of measurements throughout the world, traceable to the SI, organizes and facilitates the international comparison of these standards in order to ensure international consistency.

Stringent requirements for the stability of primary measurement standards remain a key objective for the WMO in order to meet data quality objectives. For example, the activities of Central Calibration Laboratories and World Calibration Centres within the WMO Global Atmosphere Watch Programme, or the World Radiation Centre within the WMO World Weather Watch Programme, have been important components of the quality assurance programme for key atmospheric and environmental measurements. These activities have been the recent focus of increased collaboration between the meteorology and measurement science communities to ensure, within the framework of the WMO Integrated Global Observing System, the development of standards and the delivery of highly accurate data for atmospheric and climate monitoring in support of the implementation of the Global Framework for Climate Services, which was established by the World Climate Conference-3, held in Geneva from 31 August to 4 September 2009.

The concept of metrological traceability is achieving a higher profile in the planning of climate monitoring systems, but much work remains to be done to ensure that future climate science is based on the most robust metrology currently achievable across all measurement classes.

The workshop brought together the relevant communities to debate and review the status of applied meteorology, with respect to metrological traceability, in eight specific theme areas. The goal was to identify key measurement issues in climate science, Earth observation and numerical weather prediction models where there is a requirement to develop or improve the underpinning metrology, and explore the ways in which the metrology and Earth observation communities can work together to reduce uncertainties and thus ensure the accuracy and comparability of climate science measurements both now and in the future. The workshop was convened to strengthen the links between our communities and identify activities that will act as examples for the future development of measurement science in the field of Earth observation.

Michel Jarraud & Andrew Wallard

Executive Summary

The WMO-BIPM workshop on 'Measurement Challenges for Global Observation Systems for Climate Change Monitoring: Traceability, Stability and Uncertainty' was held at the WMO Headquarters from 30 March to 1 April 2010, and brought together over 120 scientists active in long term measurements relevant to climate change monitoring and metrologists responsible for developing standards as references to which such measurements could be traceable.

The objectives of the workshop were:

- To identify key measurement issues in climate science, Numerical Weather Prediction (NWP) Models and earth observation where there is a requirement for improved underpinning of measurement science (metrology).
- To foster closer links and to develop dialogue between the metrology and the earth observation systems communities.
- To drive agenda-setting and road-mapping within National Metrology Institutes (NMIs).
- To inform the earth observation systems community about the capabilities and plans of the NMIs.

These objectives will ensure that future measurement science provides the necessary underpinning for climate science, NWP and earth observation.

The workshop was organized to identify examples of measurement traceability and uncertainty issues, as it was not possible to cover all such topics in the field of Global Observation Systems for Climate Change Monitoring within a first workshop. Bearing this in mind, the workshop was a starting point for future activities.

The workshop included a framing plenary session during which four key presentations addressed general key issues relevant to the workshop objectives; including the WMO global observing systems, Metrology, climate change, and metrological traceability. Following the plenary session, eight breakout sessions were organized, covering examples of key measurement areas, notably:

- Session A: Climate trends from satellite sounding data.
- Session B1: Stable time series for key greenhouse gases and other trace species.
- Session B2: Remote sensing of atmospheric composition and traceability issues in spectroscopic data.
- Session C: Radiation and Earth energy balance.
- Session D: Earth surface (land and water) temperature.
- Session F: Microwave imagery data in climate and NWP.
- Session G: Surface properties: Albedo, land cover, and ocean cover.
- Session H: Ocean salinity.

An additional introductory presentation on Aerosol composition and radiative properties was included in the opening plenary session.

The breakout sessions resulted in fifty nine presentations with forty three major issues identified and forty one recommendations made on how to address these issues.

The recommendations made during the workshop are grouped here into four distinct activities, notably:

1. **The coordination of metrological services for the meteorological community, including recommendations to:**

- Continue activities and collaborations for the provision of standards and comparisons for atmospheric composition, to ensure the long-term stability and reproducibility of reference materials, and explicitly defined calibration scales and their SI traceability.
- Continue collaboration to make best use of established infrastructure, capability and funding to meet the requirements for standards arising from verification activities resulting in an increase in interest in monitoring GHGs with a consequent increase in the number of sites.
- Ensure the availability of appropriate surface sites for validation of satellite remote sensing measurements.

As well as a number of targeted recommendations, including to:

- Perform quantitative analysis of the performance, over the long term, of the piecemeal renormalization approaches versus on-orbit traceability to better inform agencies on the priority for achieving traceability on-orbit for climate missions (to be coordinated through CEOS).
- Include NMI experts in the pre- and post-launch calibration of satellite sensors.
- Enable traceability requirements for pre- and post-launch sensor calibration and post-launch validation activities to be met.
- Maintain and improve *in situ* systems, such as buoy and ship-based infrared radiometer networks independent of individual satellite instrument programmes to ensure the ability to link climate records across potential satellite data gaps.

2. **The development and implementation of guidelines and operating procedures, including recommendations to:**

- Develop criteria for WMO-GAW Central Calibration Laboratory (CCL) performance and a mechanism for their external reviews.
- Document the performance of the Primary Standard and the uncertainty due to its propagation along with the Data Quality Objectives (DQOs) for WMO-GAW measured variables.

As well as a number of targeted recommendations, including to:

- Develop a consistent set of pre-launch measurements for microwave sounders for satellite agencies together with guidance to ensure SI traceability.
- Develop a recognized methodology for the post-launch validation of microwave sounders.
- Consider more stringent requirements on the accuracy of drifting-buoy measurements, with more systematic calibration of the instruments documented and traceable to the SI.
- Develop and implement calibration and validation strategies to strengthen on-orbit as well as *in situ* SI traceability to mitigate satellite data gaps for sea-surface temperature.
- Develop, for microwave imagers, a set of radiometric requirements, and metadata requirements, for each desired climate variable and models and error budgets for all sensors throughout their development and on-orbit lives.

3. **Research and development, including recommendations to:**

- Develop fundamental and applied research programmes to resolve issues affecting the accuracy of satellite measurements of atmospheric composition including: Molecular line/band parameters;

Line shapes (non-Voigt); Satellite pointing; Temperature and pressure profiles; Vertical and horizontal resolution; Retrieval algorithms; Aerosols, clouds, and surfaces.

- Further develop reanalyses as an important tool to combine the information from models and observations to produce global estimates of climate parameters.
- Improve the SI traceability of ground-based networks for solar spectral irradiance monitoring through the development of technology based standards for UV and IR.

As well as a number of targeted recommendations, including to:

- Capture requirements for and develop Blackbody emissivity standards, Tb observation standards and reflector surface property measurement standards.
- Develop improved designs of microwave sounders to achieve improved performance in terms of random noise, absolute accuracy and stability.
- Develop a density-based Salinity Standard to allow the measurement of Absolute Salinity traceable to the SI, and certified reference solutions for traceable measurement of pH and dissolved oxygen (DO).

4. Knowledge transfer activities between the metrology and meteorology communities, including recommendations to:

- Task the WMO to establish means to identify measurements and standards needs in the WMO community, and for the BIPM to consider a means of facilitating cooperative efforts involving the CIPM's Consultative Committees (CCs).
- Continue to exchange information and technology through exchange visits and cross-participation in workshops and committees.
- Better communicate the tools of the metrologists (measurement comparisons, robust uncertainty analysis, quality systems, language) as embedded for example in QA4EO to meteorologists through training, real-life demonstrations, collaboration, and compelling examples of the benefits.

As well as a number of targeted recommendations, including to:

- Publish a joint paper by practitioners from both communities explaining differences in vocabularies used.
- Share best practice between the communities, such as in dealing with the international transport of gas cylinders for comparison exercises.
- Organize the CEOS Microwave Sensors Sub Group (MSSG) to serve as the community repository and resource for protocols and best practices.
- Nominate representatives of the National Metrological Institutes (NMIs) to participate in the Group for High-Resolution Sea-Surface Temperature (GHRSST).

The closing session confirmed participants' satisfaction with the workshop in having brought together the metrology and meteorology communities, and identified issues which should be pursued and resolved through further cooperation and cross participation in the two communities' conferences and technical working groups. It was noted, however, that this first workshop only covered a certain number of examples enabling a first series of recommendations to be made and that follow-up workshops and activities were desirable to capitalize on the success of this first meeting. The outputs of the workshop would be communicated to both WMO and BIPM communities.

Plenary Session

Chair: Professor Andrew Wallard, Director, BIPM

Mr Michel Jarraud, Secretary General of the WMO, after his welcome to the participants, recalled the various areas where the WMO is active in producing standard measurements for the various climate system components. He spoke about the establishment of the Global Framework for Climate Services which was recommended by the World Climate Conference WCC-3. He pointed out that in this context, the WMO-BIPM workshop was timely and that addressing key measurements with a focus on climate change will enable both the WMO and BIPM communities to offer even more robust information for the policy and decision makers to help them make an optimal choice of solutions in climate change mitigation and adaptation. He assured participants that the WMO remains committed to working jointly with the BIPM community to implement the recommendations of the workshop for the mutual benefit of Members and Partners.

Dr Wenjian Zhang, Director of the WMO Observing and Information System Department provided an introductory key presentation on the role of observations in addressing current and future climate needs for monitoring, predictions and projections. He presented the various observation areas: *in-situ*, space based, marine and terrestrial, which are required for climate system monitoring. He provided an in-depth description of the WMO Integrated Global Observing System which aims at achieving standard methods for observations across the observing systems and networks in a cost-effective manner.

Three other key presentations were made subsequently by Dr Ersnt O. Göbel, president of the CIPM on Metrology for long term measurement data; Dr Jean Pascal Van Ypersele, Vice Chair IPCC, on Climate change and its impact; and Professor James G Anderson from Harvard College (USA) on the importance of metrological traceability for climate change assessment.

Summaries of the sessions

Session A: Climate trends from satellite sounding data.

Chair: Fuzhong Weng, NOAA NESDIS

Session *Rapporteur*: Roger Saunders, Met Office

Background

The credibility of numerical models to predict long term changes in climate can be best established by verifying their predictions against observations. However over decadal time periods changes in long term drifts are small, hence extremely accurate observations are needed to be able to validate model predictions. Directly comparing models with satellite observations on shorter timescales will facilitate model improvements in representing atmospheric and surface processes, enabling more reliable long-term forecast performance. Early warning of climate change is also dependent on highly accurate observations to have confidence in the inferred trends. Until such highly accurate instruments are developed and flown, we must rely on a series of demonstrably repeatable, very stable instruments, with sufficient satellite overlap periods to inter-calibrate the different sensors. Also, the future observing systems must be developed with SI traceable standards for stringent climate monitoring requirements. On 29 March to 1 April 2010, the World Meteorological Organization (WMO) and the Bureau International des Poids et Measures (BIPM) jointly organized its first historic workshop on Measurement Challenges for Global Observation Systems for Climate Change Monitoring at the WMO Headquarters, Geneva, Switzerland. The major findings from Session A were:

1. Numerous problems with past microwave radiometers clearly point out the need for improved design and pre-launch measurements. Several research groups in the United States have calibrated and cross-calibrated MSU/AMSU data for trending atmospheric temperature and they are now working closely with each other to understand the impacts of calibration algorithms (e.g. warm target correction, cross-calibrations, and orbit drift corrections) on the trending, and to formulate consensus and community best practices. Presently, the trends for temperature of the mid-troposphere, derived from these groups, still differ substantially.
2. In the new microwave sounding instrument design and pre-launch testing phases, the calibration and characterization of instruments are now more comprehensively attended to by instrument scientists, metrologists, and users to cover the manufacturer tests, identify possible anomalies in orbits, and understand the stability requirements in the context of climate monitoring, and to link the engineering tests with the long-term instrument performance stability.
3. The key sensor parameters of the Advanced Microwave Sounding System (ATMS) on future NPP and JPSS satellites are specified and in general meet the NWP user requirements. The pre-launch test will show that all the parameters meet specification. It remains unclear how ATMS performance will meet the stability requirements for climate monitoring.
4. The user community is now combining the information from models and observations to produce global estimates of climate parameters. The approach can expose and reduce uncertainties in observations. The latest data assimilation methods, for example, can remove the inconsistent information between models and observations. The residual biases from the reanalysis and observations can be saved as the metadata to improve the future satellite data reprocessing.
5. A holistic approach that uses as many methods or data as possible, is now utilized to diagnose the SDR and EDR data quality. The methods include SNO, SCO, CLARREO, temperature and water

vapour correlation, GRUAN, GPS TCWV, ground-based MW radiometer, specific calibration sites (Amazon forest, Dome C, deserts, etc).

Recommendations from Session A:

1. For the microwave sounding system design, calibration involves many factors: characterization of antenna pattern, corrections of spill-over, antenna emission, warm target irregularities, uncertainties in earth incident angle related to spacecraft attitude/altitude. A consistent set of pre-launch measurements of a microwave sounder should be defined for satellite agencies together with guidance to ensure SI traceability. Similarly post-launch validation should follow a recognized methodology (e.g. comparison with NWP models, reference to CLARREO, SNOs etc).
2. Many calibration residual errors remain in the data sets and affect the user applications in climate research. Since GPS/RO data are SI traceable and the temperature profiles from several systems (COSMIC, Champ, GRAS) are unbiased, these data sets should be uniquely qualified for calibrating the microwave sounding channels and identifying the calibration anomalies.
3. For climate monitoring and future NWP applications, we need improved design of microwave sounders to achieve: random noise less than 0.3 K for tropospheric sounding channels and 0.5 K for stratospheric channels, and an absolute accuracy of 0.5 K. For climate applications, a stability of 1/5 of the decadal trend is required for climate trend analysis (i.e. ~0.04 K).
4. The user requirements (e.g. for NWP forecasting, satellite product quality, and climate trending) should be related through some geophysical models to the instrument specification of accuracy, precision, and stability.

   Reanalyses should be used as an important tool to combine the information from models and observations to produce global estimates of climate parameters. They can expose uncertainties in observations. They still require a SI traceable reference dataset to anchor the evolution of the system. If the reference data are not traceable then the reanalysis is not traceable.

Session B1: Stable time series for key greenhouse gases and other trace species.

Chair: Robert Wielgosz, BIPM

Session *Rapporteur*: Martin Milton, NPL

Background

Extended time-series of the concentration of carbon dioxide and methane in the atmosphere have played a seminal role in the identification of the causes of global climate change. They also provide a basis for monitoring and planning future mitigation strategies. These time-series depend on the use of stable standards, with demonstrated comparability among measurement sites, to achieve the validity and stability required for them to be used to identify trends and distributions in the atmosphere.

In addition, observations of other species including ozone and volatile organic compounds (VOCs) are being coordinated by the WMO Global Atmosphere Watch (GAW) Programme. The central calibration laboratory function for VOCs is provided by the BIPM/CCQM. This collaboration between the metrology and meteorological communities is effective and provides a model for interactions in other fields.

Future challenges in the area will include the development of standards for new analytes such as the oxides of nitrogen, oxygen and selected monoterpenes as well as facilitating the expansion of global networks to increasingly remote locations whilst maintaining the accuracy of the measurement standards used. The objectives of the session were:

1. To summarize the state-of-the-art and consider what level of trend detection is achievable based on current measurements and the present availability of standards.
2. To identify priorities for new analytes and improvements to the accuracy of measurements of existing analytes.
3. To explore the relationship between measurements referred to "SI traceable" measurement standards and those referred to measurement "scales".
4. To review the use (or "assimilation") of "SI traceable" data into atmospheric chemical models and the consequences on the accuracy and quality of the results.
5. To discuss the relationship between measurement data of atmospheric composition taken at one or a few points to the results of column or range-resolved measured data.

Resolutions and recommendations from Session B1:

1. **The long-term, stability and reproducibility of reference materials, and explicitly defined calibration scales, are critical to the study of temporal change.**

- Enormous scientific value arises from the comparability of data from different stations in global networks.
- The global records of GHGs may come under greater scrutiny during the preparation of the 5th Assessment Report of the IPCC.
- The SI is maintained in the long term by the BIPM and the NMIs and provides a basis for measurements that are stable, comparable and coherent.
- Small changes in measured concentrations can have very significant influence on estimated fluxes.
- Atmospheric measurements are being used to quantify fluxes and will be used to validate emissions inventories.
- There is a need for necessary redundancy and the use of independent approaches to retain a robust system.

Recommendations:

- The WMO, BIPM and academic communities should continue to work together to increase redundancy through the development of independent approaches to the provision of standards and carry out necessary comparisons.
- That measurement results be traceable to the SI where practical.

2. **External review of the WCCs, the CCLs and of PSs may become a requirement.**

- Criteria for CCL/PS performance are not documented.
- The signature by the WMO to the CIPM MRA will introduce requirements for externally reviewed quality systems within the delegated laboratories of the WMO.

Recommendations:

- The WMO, BIPM and academic communities should continue to work together to develop criteria for CCL performance.
- The WMO and BIPM communities should continue with efforts towards establishing necessary external review of CCL performance.

3. Data Quality Objectives – their justification, definition and use.

- DQOs provide the requirements for measurements in the field.
- There is generally no specific statement of *inter alia* the uncertainty due to the propagation of the Primary Standard (PS) to field measurements.

Recommendation:

That the required performance of the PS and the uncertainty due to its propagation be considered explicitly and documented along with the DQOs.

4. Verification – the future challenge.

- The scope and complexity of mitigation efforts will vary nationally, regionally and locally.
- This is now leading to an increase in interest in monitoring GHGs with a consequent increase in the number of sites.
- Requirements for the performance of these sites will differ according to their location.

Recommendation:

That the WMO and BIPM communities collaborate to make best use of established national and international infrastructure, capability and funding to meet the requirements for standards that will result from increased mitigation efforts.

5. The vocabularies in use by the different communities differ.

- There are published glossaries and vocabularies.
- The approaches to the expression of measurement uncertainty are different.
- The practical consequence of these differences in usage is not always recognized.

Recommendation:

That a paper, prepared jointly by practitioners from both communities, be written and published.

6. The methods and techniques in use for the preparation and dissemination of standards by the two communities differ.

- The methods and techniques in use by WMO-GAW CCLs and WCCs represent the state-of-the-art in their fields.
- The methods and techniques in use by the NMIs represent the state-of-the-art in their fields.

Recommendation:

That exchange of information and technology continue to be encouraged through: exchange visits and cross-participation in workshops and committees.

7. Practical issues

- The international transport of gas cylinders for comparison exercises is often hampered by customs and air freight regulations.

Recommendation:

Best practice in dealing with these difficulties be shared between the BIPM and WMO communities.

Session B2: Remote sensing of atmospheric composition and traceability issues in spectroscopic data.

Chair: James Whetstone, NIST

Session *Rapporteur*: Robert Wielgosz, BIPM

Background

Satellite observations have the potential to provide dense, global measurements of greenhouse gases, adding to the highly precise surface observations used to monitor trends in atmospheric composition, and to infer sources and sinks with the help of atmospheric transport models.

There are significant technical challenges to delivering space-based remote sensing observations of atmospheric greenhouse gases with well-characterized uncertainties and traceability to established reference standards. These include requirements for:

- absolute radiometric calibration of high-spectral resolution infrared, near infrared and visible radiances;
- reference standard spectroscopic data for the retrieval algorithms that transform radiance measurements into estimates of atmospheric trace gas concentrations;
- validation of the retrieved trace gas concentration estimates to ensure that biases and accumulated uncertainties are less than the required targets.

The session reviewed existing and planned satellite instruments that measure greenhouse gas concentrations, including water vapour, carbon dioxide, methane, nitrous oxide, ozone and halogenated species. The challenges in achieving sub-1 % precisions for atmospheric concentrations, as well as the calibration and validation of vertical profiles were described, and requirements for laboratory derived reference data for atmospheric concentration retrieval algorithms elaborated. The objectives of the session were:

1. To summarize the state-of-the-art and consider what level of trend detection is achievable based on current measurements and the present availability of standards.
2. To explore the challenges in obtaining precise "SI traceable" measurement data from remote sensing platforms and ways of addressing these challenges.
3. To review the accuracy and use of spectroscopic reference standard data in retrieving atmospheric concentrations and their vertical profiles from remote sensing data.

4. To discuss the relationship between atmospheric composition measurements taken at a few points to the results of column or range-resolved measurements.
5. To discuss current activities and future requirements for the validation of remote sensing data.

Issues and recommendations from Session B2:

Issue 1: Accuracy of Satellite Measurements

Satellites offer dense global coverage lacking from other platforms, but better absolute accuracies and improved vertical and horizontal coverage are required for these techniques. They form part of a complementary and necessary multi-platform (surface, air-borne, and space based) global observation system.

Systematic errors arise from a lack of complete knowledge or approximations made in any of the following elements:

- Molecular line/band parameters
- Line shapes (non-Voigt)
- Satellite pointing
- Temperature and pressure profiles (needed for concentration retrievals)
- Vertical and horizontal resolution
- Retrieval algorithms
- Aerosols, clouds, and surfaces

Recommendation:
Fundamental and applied research programmes are required to resolve these issues. The WMO, BIPM and academic communities should work together to solve these problems.

Issue 2: Validation of Satellite Measurements

Satellite remote sensing measurements require independent validation with ground-based, aircraft, balloon measurements and comparison with other satellites.

Recommendations:

- Appropriate implementations, including prioritization and emerging technologies, should be pursued using techniques traceable to the SI, with open availability of validation data.
- Ensure the availability of appropriate surface sites for validation of satellite remote sensing measurements.

Issue 3: Traceability requirements for consistency of *in situ* and remote sensing measurements of GHGs

Consistent reference standards are required for direct comparison and simultaneous assimilation of the different measurands from atmospheric *in situ* and remote sensing measurements of GHGs.

Recommendations:

- All atmospheric measurements of GHGs should demonstrate traceability to established reference standards.

- Quantified uncertainties should be reported for all atmospheric models and measurements of GHGs.
- Optical standards traceable to SI units and quantum mechanical formulae should be established for and verified with results traceable to independent standards.

Issue 4: Traceable Spectroscopic Data

Current spectroscopic reference standards do not possess the absolute accuracy required to support atmospheric GHG remote sensing with sub-1 % uncertainties.

Consistent and consolidated spectral reference data are not available, e.g. Ozone absorption cross sections for UV (Hartley, Huggins), Visible (Chappuis) and NIR (Wulf band) and IR (10 µm, 5 µm) do not agree within their reported uncertainties.

Recommendations:

- Spectroscopic reference standards should be validated against both laboratory and atmospheric reference spectra.
- Benchmark spectra recorded by different NMIs and laboratories should be made freely available to the research community for testing and verification.
- Spectroscopic reference standards must yield consistent results across all applicable wavelength ranges (UV, Visible, IR).
- Molecular spectroscopic reference standards should use validated, standardized algorithms for line shapes, line mixing, speed dependence, etc.

Issue 5: Increased Community Collaboration

WMO-GAW (Global Atmosphere Watch Programme) and CIMO (Commission for Instruments and Methods of Observations) could be a focal point for cooperative efforts in measurements and standards for the NMI, WMO, and academic communities.

Recommendation:

Facilitate cooperation by:

- Should CIMO form an editorial review board for the CIMO Guide, it should include a representative(s) from the NMI community and should establish means to identify measurements and standards needs in the WMO community.
- BIPM should consider a means of facilitating cooperative efforts involving the CIPM CC's; e.g., CCM, CCT, CCPR, and CCQM.

Session C: Radiation and Earth energy balance.

Chair: Werner Schmutz, PMOD/WRC

Session *Rapporteur*: Dave Young, NASA

Background

The temperature of the Earth responds to changes in the radiative energy balance maintained between the incoming solar radiation and the outgoing reflected solar radiation and emitted thermal radiation. Accurate total and spectral space and surface measurements of these radiation components at various spatial and temporal scales are critical for understanding the long-term trends in the Earth's climate. Moreover, these measurements must be tied to the SI to ensure their comparability independent of time, locale, or sensor. The measurement problem is extremely challenging since the accuracy required is commensurate with the state-of-the-art for spectral radiance and irradiance measurements performed in environmentally controlled laboratories at National Metrology Institutes. The presentations and discussions during this session reviewed the current state-of-the-art in Earth radiation measurements and efforts to improve their accuracy and strengthen their ties to the SI.

The critical need for achieving accuracies beyond the current capabilities of the observing system was illustrated explicitly in two of the talks. Joanna Haigh (UK) provided an overview of the current understanding of climate sensitivity to solar variability. Of particular concern, recent results from the Spectral Solar Irradiance (SSI) measurements from the Solar Radiation and Climate Experiment (SORCE) indicate solar cycle spectral trends very different from current models. In order to understand the extent to which, and the mechanisms whereby, solar variability influences the climate of the lower atmosphere, we need continuous, well-calibrated, long-term observations of solar total and spectral irradiance, stratospheric temperature and composition. Atsumu Ohmura (Switzerland) provided a summary of the global dimming/brightening controversy and the related issues dealing with the accuracy of the surface networks. In order to resolve such issues in the future, the climate observing system requires accurate, traceable, and complete data.

Progress is being made to address these issues. Bruce Forgan (Australia) reviewed the history of the traceability standards used for infrared and visible surface-based radiation measurements, particularly those made by the Baseline Surface Radiation Network (BSRN). There have been significant instrument and sampling changes at the BSRN sites during the time series, with major improvements in the measurement accuracies. It was recommended that the WMO and BIPM both play a role in fostering "meteorological metrology" through common nomenclature, updating the CIMO guide, providing practical examples of GUM analyses, and continued development of WRR and WISG traceability to the SI.

Similarly, advances are being made in the measurement of solar irradiance. Werner Schmutz (PMOD/WRC) presented an overview of the past, present and future of Total Solar Irradiance (TSI) measurements. Werner Schmutz reviewed the current state, including the history of space-based measurements, their disagreement in absolute accuracy, and the challenges in developing a composite record. Greg Kopp (US) echoed these concerns and described steps being taken to develop accuracy goals, compare instruments more thoroughly on the ground, and to develop end-to-end ground irradiance validations against an SI traceable reference. The goal is to improve absolute accuracy to 100 ppm, but to maintain sensors with stabilities of <10 ppm/year (plus continuity) until that is achieved. Greg Kopp also described the new TSI Radiometer Facility (TRF) system that is being used to attain these accuracies. Jeff Morrill (US) provided a description of similar efforts to TRF that are being made at the NRL Cryogenic Radiometer Facility. Jerald Harder (US) presented a summary of the current state-of-the-art and potential future of space-based solar spectral irradiance measurements. In order to address the issues raised by the spectral solar cycle trends observed by SIM, pre-flight calibration of future instruments must be improved to 0.2 %-0.5 % using systems such as the NIST SIRCUS along with redundant spectrometers and detectors to measure on-orbit degradation. Wolfgang Finsterle (PMOD/WRC) and Rainer Winkler (UK) addressed the issue of radiometric standards. Wolfgang Finsterle presented the history and future of the World Radiometric Reference (WRR). The WRR is at risk due to instrument availability and gaps in the instrument record. In the future, the SI traceability should be improved through the development and dissemination of a technology-based standard. Rainer Winkler presented a potential solution, the Cryogenic Solar Absolute Radiometer (CSAR). CSAR is being designed to become the new standard for TSI within next 10 years, with an accuracy that is 10 times better than that of the current standard.

New climate missions are being planned that incorporate on-orbit traceability to the SI in the instrument and mission design. Bruce Wielicki (US) presented an overview of the NASA satellite mission called Climate Absolute Radiance and Refractivity Observatory (CLARREO), a mission that will provide benchmark climate records of spectrally resolved outgoing terrestrial IR and reflected solar radiation along with GNSS RO refractivities that are SI traceable and verified on orbit. The instrument accuracies have been rigorously defined from the goal of detection of decadal trends relative to natural climate variability and NASA is partnering with NIST in planning and development. Missions such as CLARREO and the Traceable Radiometry Underpinning Terrestrial- and Helio-Studies (TRUTHS) mission are necessary to achieve trusted climate data records for future policy decisions concerning climate. Issues addressed in Session C were:

1. Current state-of-the-art in the measurement of total solar irradiance and key challenges for the future.
2. Quantitative requirements and potential solutions for long-term climate benchmark measurements of the Earth’s energy balance.
3. Terrestrial radiation networks: Climate need and traceability.
4. Climate sensitivity to solar variability (total and spectrally resolved): Uncertainty drivers.
5. The Earth’s energy balance: The current record.
6. Metrological challenges and specific uncertainty specifications.
7. Barriers to international collaboration.

Findings from Session C:

1. The current climate data records of radiation and the Earth’s energy balance, such as space based TSI, SSI, Earth radiation budget, and the ground-based radiation networks, such as the BSRN, continue to be dependent on stability and continuity and are therefore at risk of data gaps.
2. Absolute accuracy tied to SI traceable standards must be achieved to eliminate the risk of data gaps of these critical climate data records.
3. Metrological advances are being incorporated into missions such as the CLARREO and TRUTHS to achieve accuracies and on-orbit traceability for climate measurements.
4. Solar spectral irradiance shows unexpected results and needs improved accuracy for future instruments.
5. The WRR standard is an excellent long-term reference, but it is at risk.

Recommendations from session C:

1. Metrological advances must be developed and applied to establish on-orbit SI-traceable data records with absolute accuracies required for climate measurements of radiation and the Earth energy budget.
    a. The community must maintain data records dependent on continuity until the required accuracies are achieved.
    b. Multiple, independent measurements are needed whenever possible (equivalent to key comparisons).
    c. Facilities for end-to-end characterization of instruments must be improved and used for all instruments.
2. Space-based spectral solar irradiance must be continued and achieve the accuracies needed for climate models by improved ground calibration and on-orbit traceability.
3. The SI traceability of ground-based networks should continue to be improved through the development of technology-based standards for UV and IR.
4. The WRR should be transitioned to a technology based standard such as CSAR.

Session D: Earth surface (land and water) temperature.

Chair: Pascal Lecomte, ESA

Session *Rapporteur*: Jerry Fraser, NIST

Background

The change in temperature of the Earth's surface, particularly the Oceans but of increasing importance, Land, is a key indicator of climate change, as well as providing data for operational meteorological services. Remote sensing from space of infrared spectral radiance provides (through Planck's law) global temperature data sets. The sea surface temperature community is well coordinated and is particularly advanced in terms of metrology and traceability. Driven by the need to detect subtle changes, of < 0.01 K over decades, they provide good examples of best practice. However, the uncertainties are still highly challenging and there are issues about reliably linking current sensors to future ones with large variations between measurements based at different sites. Findings from Session D were:

1. Drifting-buoy measurements of sub-surface sea-surface temperature (SST) are critical for the derivation and validation of satellite SST measurements, yet seem to suffer from a large uncertainty of ±0.2 K (k = 1), a factor of 4 greater than the target accuracy of ±0.05 K (k = 1) required to support targets for satellite regional and temporal SST accuracy. It should be noted that this level of uncertainty was fit for purpose previously. Improved uncertainty is technically possible now and there is, at least from the satellite community, a strong requirement for the improved uncertainty.
2. Intercomparisons of radiometric scales associated with skin SST measurements are of great importance, particularly when linked to the radiometric scales encountered in satellite SST measurements.

3. Metrologists work in an idealized laboratory environment with equipment not generally suitable for field use. To meet the needs of the EO community, metrologists must work in collaboration with the EO community to transition their research successes from the laboratory bench to the ocean, desert, rainforest, air or space.
4. The lack of robust, on-orbit, SI traceability of satellite SST measurements increases the risk of breakage in continuous data records due to a satellite data gap. Additionally, calibration/validation networks of buoys, radiometers and other instrumentation also face interruption when tied to specific satellite sensors, compounding the impact of a satellite data gap.
5. The Earth Observation and metrology foundations for land surface temperature measurements need strengthening and the societal and scientific needs for such measurements must be better articulated.

Recommendations from Session D:

1. Intercomparisons of drifting-buoy measurements for different manufacturers are essential to assess measurement accuracy. More systematic calibration of the instruments should be performed, traceable to the SI, and documented. More stringent requirements on the accuracy of drifting-buoy measurements should be considered and support from the National Metrological Institutes (NMIs) sought where appropriate to help achieve this. Accuracy claims should be unequivocally demonstrated and validated.
2. Measurement comparisons would benefit from metrologists and meteorologists collaborating on the development of uncertainty budgets. Such analyses should recognize the limits in measurement accuracy due to instrumental, geophysical and sampling issues.
3. The tools of the metrologists (measurement comparisons, robust uncertainty analysis, quality systems, language) as embedded in QA4EO need to be better communicated to the meteorologists through training, real-life demonstrations, collaboration, and compelling examples of the benefits.
4. Continuity of SST satellites at appropriate levels of uncertainty is critical for the continuity of climate data records. Calibration and validation strategies to strengthen on-orbit as well as *in situ* SI traceability would mitigate satellite data gaps. Additionally, *in situ* systems, such as buoy and ship-based infrared radiometer networks should be maintained and improved independent of individual satellite instrument programmes to ensure the ability to link climate records across potential satellite data gaps. This concept of 'Generic Validation' - concentrating on the geophysical parameter rather than a specific measuring system - is particularly important, because, currently, their deployment is almost always linked to the life-cycles of specific satellite missions and, also, the instruments and their deployment methods lend themselves well to the need for traceability.
5. A representative of the National Metrological Institutes (NMIs) should participate in the Group for High-Resolution Sea-Surface Temperature (GHRSST). SST is a compelling and relatively mature environmental measurement that may benefit from strengthening of the metrological foundations. The CEOS "Miami" Infrared Radiometry comparisons demonstrate the benefits of collaboration between "oceanographers", meteorologists and metrologists in SST.
6. A pre-GHRSST should be considered for Land Surface Temperature (LST).

Session F: Microwave imagery data in climate and NWP.

Chair: Karen St. Germain, IPO JPSS

Session *Rapporteur*: William Bell, ECMWF

Background

Microwave imagers (MWI) in polar orbit, operating in the range 6 GHz to 183 GHz, provide information on a range of atmospheric variables, including water vapour, cloud liquid water, precipitation, ocean surface winds, sea ice and sea surface temperature. Data from operational satellite missions have been used for climate research and Numerical Weather Prediction (NWP) for more than 10 years. The use of this data for climate trend analysis is well established. Cal-Val programmes, as well as increasingly sophisticated use of the data in NWP assimilation systems, have highlighted a number of instrument calibration problems with several previous imager missions. As with microwave sounders, improved traceability for pre-launch testing and calibration is one important aspect of a wider effort to improve the consistency of the satellite data record. Agencies in the US, Europe, Japan, India, China and Russia have plans to launch imager missions over the next 10 years. The aims of Session F were:

1. Review the current use of the data in NWP and climate research and review the measurement uncertainty requirements associated with these applications.
2. Review instrument calibration issues uncovered to date and on-orbit radiometric performance of current imaging missions.
3. Review current practice in pre-launch characterization and in microwave metrology.
4. Establish best practice for future missions.
5. Specify requirements for improved underpinning metrology in order to provide a focus for national and international metrology programmes.
6. Foster improved international collaboration between users, agencies, instrument teams and the metrology community, in order to reduce risks for future missions.

Findings and recommendations from Session F:

Finding 1:

Microwave imagers can deliver measurements of essential climate variables related to the hydrological cycle (total column water, cloud liquid, precipitation, sea ice, snow), however:

- The accuracy and stability requirements for these applications are not currently fully articulated by all agencies and captured in sensor requirements.
- Requirements for metadata standards (e.g. all inputs to environmental data product retrieval process) are not fully documented.

Recommendation 1:

Develop a set of radiometric requirements, and metadata requirements, for each desired climate variable (to agency mission expert advisory groups). Encourage cross-agency consultation in the development of these requirements, to ensure homogeneity, where possible.

Finding 2:

Given the challenges of 'whole dish calibration on-orbit', the group cannot see a near-term path to fully SI traceable observations from microwave imagers, either at the Brightness Temperature or Environmental Data Product levels. In addition, the radiometric uncertainties achievable using current standards in National Metrology Institutes (NMIs) in-lab are at the same level as required from satellite sensors on-orbit.

Recommendation 2:

- In the short- to medium-term (1-10 years) continue to develop and implement "consensus" approaches to sensor calibration (may already be good enough for some climate observations), including strong support for reference *in situ* observations *e.g.* sondes, buoys. For example, the GRUAN network. Emphasis should be placed on traceability, where this is achievable.
- In parallel, where standards and protocols can be applied at the instrument level, develop and disseminate international "best practices". (see Recommendation 4 for specifics).
- NMIs should continue to develop primary radiometric standards to meet the current and future requirements of climate missions. Achieving appropriate levels of uncertainty is a longer term goal which requires sustained resourcing within NMIs.

Finding 3:

For NWP, some simple radiometric biases are tolerable and automatically managed, but some other types of errors are significantly more difficult to correct and compromise the utility of the data. For example: time varying, scene dependent, orbital, or scan position dependent errors.

Recommendation 3:

Near-term efforts at the sensor level should focus on reducing these varying systematic errors identified to date from a number of microwave imager missions, for example TMI, SSMIS and AMSR-E (see Recommendation 4 for specifics).

Finding 4:

Significant advancements in the understanding of radiometric error sources are available to inform the design and characterization of future sensors. These advances have been made through detailed lab-based investigations as well as comprehensive Cal-Val campaigns. Examples include:

- Receiver Performance: linearity, gain stability, frequency stability.
- Reflector Performance: antenna patterns, surface materials characterization.
- Flight and Test Blackbody targets: emissivity characterization, temperature measurement.

In addition, it was recognized that internationally established sensor characterization best practices and standards may help defend against the cost and schedule pressures that often limit sensor test programmes.

Recommendation 4:

- Sensor models and error budgets should be rigorously developed for all sensors, throughout their development and on-orbit lives. Good examples should be made available.
- NMIs should capture requirements for, and develop, Blackbody emissivity and Tb observation standards.
- NMIs should capture requirements for, and develop, reflector surface property measurement standards.

- The CEOS Microwave Sensors Sub Group (MSSG) should serve as the community repository and resource for these protocols and best practices. There is a need to strengthen the presence of passive microwave experts, including wide international representation.
- During sensor development, solid modeling and graphical visualization tools that represent the instrument and satellite platform geometry (including major structures like solar panels), and view of the system from the sun should be used at the Critical Design Review to demonstrate full system engineering compliance.
- The uncertainty in Climate data products will be reduced if instruments are flown in stable (non-precessing) orbits, therefore agencies should consider this in mission planning.

Finding 5:

Without fully SI traceable sensors, at least three approaches exist for establishing sensor-to-sensor consistency:

- Selection of a particular sensor as the reference to which other sensors are matched.
- Explicit calibration to a common reference (a physically-based realization of a stable Tb, for example, cold calm ocean, or rainforest scenes) on a sensor-by-sensor basis.
- NWP reanalysis to identify sensor/channel biases.

The uncertainties in long term trend estimates from these approaches are difficult to quantify, although this problem is being addressed. The relative benefits of these *ad-hoc*, piecemeal renormalization approaches, versus traceable observations needs to be quantified (‘*with traceability you gain with time*’?).

Recommendation 5:

Perform quantitative analysis of the performance, over the long term, of the piecemeal renormalization approaches versus on-orbit traceability to better inform agencies on the priority for achieving traceability on-orbit for climate missions (to be coordinated through CEOS).

Session G: Surface properties: Albedo, land cover, and ocean cover.

Chair: Nigel Fox, NPL

Session *Rapporteur*: Carol Johnson, NIST

Background

Knowledge of the reflective properties of the Earth’s surface is critical to understanding the Earth’s radiation budget and also for climate change studies. In particular land cover classification and its change with time, together with ocean chlorophyll, through spectrally resolved measurements of solar reflected radiation allow for investigations of the carbon cycle.

A fundamental issue in the determination of surface properties is the perturbation due to atmospheric absorption and scattering. The correction for this perturbation is a source of uncertainty in establishing traceability between radiance/reflectance measured at the top of the atmosphere and that leaving the surface. Demanding uncertainties are now being requested by the climate science community, and future weather and climate models will endeavour to incorporate land-cover information as the spatial grids reduce in scale. The findings and recommendations resulting from presentations and discussions are organized according to the aims of the session and are presented below:

1. **Critical uncertainty drivers and key sensor characteristics for pre- and post-launch calibration of satellite sensors.**

Findings:

Systematic effects generally dominate the sensor's uncertainty budget, and their impact is amplified when the sensor performance functions are unknown or poorly characterized. Although the launch process itself may introduce changes in the radiometric responsivity, a major issue is given by the difficulty to obtain laboratory system performances equivalent to those of the space system. Desired radiometric uncertainties are at, or exceeding, the state-of-the-art and therefore are not easily able to be met by NMIs with current methods and technologies. Thorough uncertainty assessment is underpinned by a complete understanding and documentation of sensor performance, and unfortunately the rigour and completeness of this activity is frequently dictated by programme schedule, good fortune, and the flexibility and dedication of the underlying teams. An example presented was the recent characterization of VIIRS, with NIST leadership, using portable, laser-based, calibrated sources.

A second finding was that although the sensor performance functions (e.g., spatial or polarization response) are well known, complete assessment of uncertainties from output counts to data products is lacking.

Recommendations:

The awareness of the NMIs of the priorities of the metrological issues of the climate change monitoring community is the responsibility of this community: establish mechanisms (e.g., user groups) to state priorities, identify upcoming requirements, and provide guidance to the NMIs. At the same time, establish mechanisms to facilitate direct participation by NMI staff on core and critical calibration/validation instrument teams for the full life cycle of the mission. This activity should be centred on measurements, not review of procedures or documentation.

2. **Traceability requirements for pre- and post-launch sensor calibration and post-launch validation activities.**

Findings:

Traceability is a general concept and more specific guidance may be necessary, e.g., what does establishing traceability for measurements from orbit entail? The traceability and instrument characterization for field measurements (from ground, sea, aircraft, balloon, etc.) is not being addressed adequately. Determination of radiance or reflectance quantities of the Earth's surface is an active area of research and the participants presented examples of the difficulties and challenges of modelling the physical effects realistically. The validation activities, which involve both rigorous, targeted field campaigns and use of established networks, suffer from instability in funding, adequacy of spatial representation, and issues relating to data access.

Recommendations:

Ensure traceability by direct involvement of the major NMIs, encourage and support participation in standards committees, development of procedures, and adherence to international quality assurance protocols (e.g., the GUM). Validate claims of traceability by evaluation of the results of measurement comparisons designed specifically with this objective in mind. Seek to establish a full hierarchy of institutes, in terms of traceability, to facilitate efficient and cost effective dissemination of scales traceable back to the major NMIs. Field campaigns should be comprehensive and interdisciplinary so that all the necessary ancillary data needed for interpreting the results is acquired. Take care to maximize the benefit to the broadest community and design the experiment to provide the basis for the removal of systematic effects present in the natural environment. Validate the results of *in situ* measurements by using multiple means of approach for the same desired result or product. Expand and continuously maintain networks of validation sites and activities.

3. Equating top of the atmosphere (TOA) radiances or reflectances to true surface variables at all spatial scales.

Findings:

The correction process that accounts for perturbing sources in the measurement problem (scattering, absorption and emission in the atmosphere; sun glint; shadows; etc.) is a necessary step for equating top of the atmosphere (TOA) signal to surface variables like radiances, reflectances, or products derived from these latter quantities. This procedure introduces uncertainty arising from natural variability in the environment, modelling parameters, and the completeness of the physical model applied. Because there is a lack of robust uncertainty estimates in both the surface variables derived from on-orbit measurements, and the *in situ* results, it is difficult to assess the degree of equivalency in these results.

Recommendations:

Establish end-to-end approaches, working with the community to develop case studies and assess traceability for Level 2 products and above. Clarify the assumptions and methods for validation and vicarious calibration approaches in the various remote sensing applications. For instance in the ocean colour radiometry approach for global mapping of phytoplankton biomass, vicarious calibration and atmospheric correction rely on the use of same atmospheric models and algorithms assuming aerosol optical properties are correctly modelled (or at least modelled with the uncertainties). Develop techniques to account for temporal and spatial sampling effects that impact comparisons from space and *in situ*.

4. The establishment of operational, global data sets and sensor-to-sensor interoperability.

Findings:

Success in climate investigations requires 10 years or more of high quality data. This results in a substantial effort that must rely on international cooperation, multiple reprocessings including changes in the calibration and characterization of the on-orbit sensor, the use of common algorithms for inter-sensor studies to isolate instrument performance artefacts from algorithm performance, and evaluation of global and regional Level 3 trends to provide a means to assess instrument temporal stability.

Recommendations:

Establish mechanisms for the international collaboration for establishment and maintenance of *in situ* data, including issues such as full access and comparison of results. Establish new *in situ* sites that are needed to cover the full dynamic range of the sensors. Promote international quality assurance procedures and protocols. Recognize the long term nature of the effort by granting stable scientific resources.

5. **Specification of metrological uncertainties originating from understanding and monitoring the impact of the carbon cycle.**

Findings:

Specification is not possible at this time. Radiances or reflectances are measured and the derived products are related to variables such as chlorophyll concentration, not amounts of organic or inorganic carbon. The term carbon is too narrow, it is the global biogeochemical cycle that needs to be addressed.

Recommendations:

Forward planning for upcoming sensors requires more interdisciplinary thinking to ensure that the sensors are designed to meet the needs of the broad climate change community. For example, more emphasis should be placed on a proper description of land/atmosphere and ocean/atmosphere interfaces, e.g., gas fluxes.

Session H: Ocean salinity.

Chair: Klaus-Dieter Sommer, PTB

Session *Rapporteur*: Petra Spitzer, PTB

Background

The global circulation of seawater, which is driven by density fluctuations, has a large impact on the climate. Salinity, a measure for dissolved material in water, is, in addition to pressure and temperature, used to calculate the density of seawater. Salinity, linked to the overall water cycle including the ocean-atmosphere interaction, constitutes one of the key climate variables. Salinity is an important input quantity in oceanographic models.

The Practical Salinity Scale, PSS-78, and the International Equation of State of Seawater (EOS-80), which expresses the density of seawater as a function of practical salinity, temperature and pressure, have served the oceanographic community for thirty years.

However, practical salinity defined in terms of relative conductivity measurements is not traceable to SI units.

In 2009 the Intergovernmental Oceanographic Commission (IOC) endorsed the new Thermodynamic Equation of Seawater 2010 (TEOS-10), from which accurate algorithms for calculating density of seawater, and many other thermodynamic properties (i.e. heat content), are available. Oceanographers now have consistent and accurate formulations to quantify the transport of heat in the ocean and the exchange of heat between the ocean and atmosphere. Part of the new thermodynamic treatment of seawater involves adopting absolute salinity. In contrast to practical salinity, absolute salinity is expressed in SI units and incorporates the small spatial variations of the composition of seawater in the global ocean. Absolute salinity is also appropriate for the calculation of freshwater fluxes and for calculations involving the exchange of freshwater with the atmosphere and with ice.

The algorithm that calculates absolute salinity from knowledge of the practical salinity and the spatial location should however be refined on the basis of more SI traceable ocean measurements.

Measurements and parameters discussed:

1. Sea-surface and sub-surface salinity.

These are measured to document:

- The ocean's storage and global transport of heat and fresh water.
- Ocean-atmosphere exchange of heat and fresh water.
- Long term trends in sea level change.
- Ocean carbon sources and sinks.

2. Traceability and comparability of measurements.

- Absolute Salinity is estimated from Practical Salinity, given on the Practical Salinity Scale PSS-78. Practical Salinity is calculated from conductivity measurements. The measurement results are related to the conductivity of a defined potassium chloride (KCl) solution, but they are not traceable to the SI. The only internationally recognized transfer standard for the calibration of salinity measurement devices is IAPSO Standard Seawater, provided by the Standard Seawater Service, and calibrated with respect to the KCl solution.
- The reproducibility of a KCl solution is doubtful with respect to decadal timescales, as needed in oceanography.
- Differences have been reported between platforms (e.g. Argo profilers, Thermosalinographs (TSG), CTDs, tropical moored buoys, gliders, surface drifters) providing near-surface salinity. The differences were caused, among others, by sensor accuracies, real time data availability, and quality control procedures.
- The definition of Absolute Salinity as an SI variable makes it mandatory to link its estimates to the SI unit "kilogram". This cannot be done on the bases of a non SI measurement quantity. Thus, there is a strong need to link Practical Salinity, and therefore Absolute Salinity, results to stable SI measurement standards.
- SI traceable measurements of the conductivity and density of Baltic Sea samples indicate that the density of seawater can be measured under laboratory conditions with a significantly smaller relative uncertainty, 3×10^{-6}.
- There is a lack of data and understanding of vertical salinity gradients near to the ocean surface due to missing links between sub-surface salinity and surface salinity measurements.
- The measurement of ocean acidification is not yet metrological underpinned.
- Thermodynamics of water-air-systems in the ocean and atmosphere are not uniform, e.g. RH definition by WMO and CCT.

3. Uncertainty of measurements.

- Good reproducibility of Practical Salinity measurement results in the order of 0.00005 (PSS-78) can be provided. This is the required level of accuracy to be achieved. However, the Seawater Standard is doubtful with respect to climatic time-line.
- Currently, only conductivity can be measured traceable to the SI with a relative standard uncertainty of 0.0001.

- There is a lack of uncertainty-evaluation skills, tools and appropriate approaches for modelling and field-measurement evaluation to link all sub-surface and surface salinity results.

4. Suggested ways to improve methodologies and measurement uncertainties.

A new oceanographic salinity measure is required that:

- Measures absolute salinity within the required relative target uncertainty of 5×10^{-5} traceable to the SI.
- Is consistent with current oceanographic practice (e.g. Argo Network).
- Is consistent with marine chemistry and biology.
- Is long-term stable on climatic time scales.
- Is accurate and repeatable for oceanographic needs.
- Accounts for regional and temporal composition anomalies.

Recommendations from Session H:

1. Development of the scientific basis and practical implementation of a density-based Salinity Standard which will allow measurement of Absolute Salinity within the required relative target uncertainty of 5×10^{-5} traceable to the SI.
2. Development of advanced calibration procedures and certified reference solutions for traceable measurement of pH and dissolved oxygen (DO).
3. Application of the same thermodynamic standard equations and equation of states for water, water vapour, ice, seawater and humid air in oceanography, meteorology, climatology, metrology and industry as a prerequisite for SI traceable measurement results.
4. Development of uncertainty-evaluation skills, tools and appropriate approaches for modelling and field-measurement evaluation of *in situ* and satellite-derived measurement results as a prerequisite for combining the data to derive high quality sea surface salinity data.
5. NMIs should be encouraged to cooperate with the GOSUD and Argo programmes and be more future oriented with SMOS and AQUARIUS missions.

Through the use of reliable absolute salinity data, the influence of the spatially varying composition of seawater can systematically be taken into account. This will substantially improve the quality of data necessary to provide regular and comprehensive descriptions of ocean fields such as temperature, salinity and currents at high temporal and spatial resolution. Global oceanic data assimilation and forecasting projects in which circulation and climate of the ocean are modelled (e.g. ECCO, MERCATOR or OMCT) will benefit from traceable salinity data.

Joint research and training activities of BIPM and WMO communities to cover the above mentioned topics should to be launched.

Abstracts from the sessions

Session A: Climate trends from satellite sounding data

A1. Climate trends from microwave sounding data: Lessons learned - a post-launch perspective

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Deep-layer atmospheric temperatures have been continuously measured by satellite-borne microwave sounders since the launch of the first Microwave Sounding Unit (MSU) on the TIROS-N satellite in late 1978. Eight subsequent MSUs, as well as seven Advanced Microwave Sounding Units (AMSUs) continue this record through to the present. In the future, similar measurements will be made by the Advanced Technology Microwave Sounders (ATMSs). Before measurements from the different instruments can be assembled into long-term datasets, a number of time varying biases must be characterized and removed. These biases include small offsets in absolute temperature, the effects of the dependence of the radiometer calibration on the temperature of the warm calibration target, and the effects of the drift in local measurement time due to changing orbital parameters. In addition, several satellites exhibit calibration drifts for some channels that are currently unexplained. The complexity of these adjustments, the small signals that need to be measured, the lack of unassailable *in situ* validation data, and the political nature of climate change science have made this process challenging and controversial.

Both the MSU and AMSU instruments are continuously calibrated on orbit by noting the signals produced when viewing cold space and a thermistor-instrumented warm calibration target. These measurements are used to remove gain and offset changes that occur on orbit. By comparing measurements made by co-orbiting satellites, Christy *et al*. [1] noted errors that remain after this procedure that are correlated with the temperature of the warm calibration target. These could be caused by a number of factors, including receiver non-linearity, errors in the measured warm target temperature, or antenna spill over to warm parts of the satellite. Whatever the cause, the error structure can be characterized by a detailed analysis of measurements from co-orbiting satellites. Several approaches to this analysis have been tried by various groups [1-4].

In addition to the calibration problems, drifts in local measurement time can alias the diurnal cycle into the long-term record. While we attempt to model and remove the effects of the diurnal cycle before merging the data from the different satellites together, it is likely that the accuracy of our final products is limited by errors in this procedure, particularly for the channels with large weights in the lower troposphere, where the diurnal cycle is relatively large. After mid 2002, the launch of the AQUA satellite (which includes an AMSU instrument) in a controlled, non-drifting orbit, significantly reduced the impact of the diurnal adjustment on the final data products.

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A2. Reanalysis, climate trends and an evaluation of the satellite sounding data record

Dick Dee, European Centre for Medium-Range Weather Forecasts, UK

Reanalysis combines and interpolates measurement data from multiple sources in the context of a global circulation model, to produce a complete and dynamically coherent record of geophysical parameters. Using tools and techniques originally developed for numerical weather prediction, reanalysis provides an excellent framework for integrating and reconciling diverse sources of information about the recent climate. The use of a state-of-the-art forecast model as a unifying context ensures that the various climate parameters that can be derived from reanalysis data are not only consistent with the observations, but also with the laws of physics, and therefore with each other.

The most difficult scientific challenge in reanalysis, as with all observation-based climate studies, is to properly deal with the multitude of changes in the observing system that have occurred throughout the period of interest. Uncertainty assessments, quality control, and bias corrections of observations are essential elements needed to produce meaningful estimates of trends and variability for climate parameters. Reanalysis has the advantage that all available observations, including *in situ* as well as remote-sensing data, can be consistently related to a well-defined state evolution constrained by the model equations. This provides a powerful means for integration, inter-comparison, and error assessment of otherwise incompatible observations.

As a concrete example, the presentation showed how satellite radiance data from various sensors on multiple platforms have been corrected for biases in the ERA-Interim reanalysis recently produced at ECMWF [1]. Using a variational approach, bias predictors associated with separate radiance channels were simultaneously and continuously adjusted during the reanalysis. This procedure amounts to an automatic statistical inter-calibration of satellites, sensors, and channels. The information used to anchor the bias corrections consists of all available data entering the reanalysis, including *in situ* observations from various sources, as well as the model forecasts used to propagate observational information forward in time. It was shown that the variational bias correction system works very well in well-observed situations, but has limitations where the model biases are not well constrained by anchoring data.

Reanalysis data are increasingly used for climate monitoring purposes, because of the comprehensive nature of the data, which include many auxiliary model-generated products as well as reconstructions of directly observed climate parameters. Accurate representation of trends and variability of climate signals is possible, as has been clearly demonstrated for the case of near-surface parameters such as 2 m temperature and humidity [2]. Upper-air trends are much more difficult to estimate with confidence, fundamentally because there is no single stable observing system that can serve as a reference for such estimates. The situation has improved in some respects with the advent of GPS radio occultation data in recent years. However, our ability to monitor future climate evolution, especially on regional scales, will depend on the availability of accurate and stable observing systems with known error characteristics.

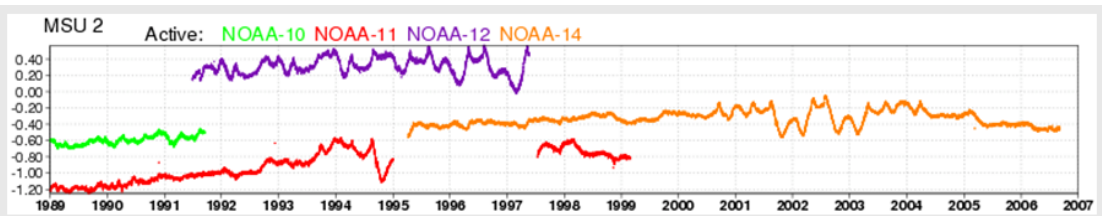

Figure 1. Global mean bias estimates (K) generated in ERA-Interim, for MSU channel 2 radiance data from NOAA-10, NOAA-11, NOAA-12, and NOAA-14

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A3. Improved atmospheric sounding with ATMS

William J. Blackwell, MIT Lincoln Laboratory, USA

A suite of sensors scheduled to fly onboard the NPOESS Preparatory Project (NPP) satellite in 2011 will both continue and improve the environmental data records provided by operational and research missions over the last 40 years. The Cross-track Infrared and Microwave Sounding Suite (CrIMSS), consisting of the Cross-track Infrared Sounder (CrIS) and the first space-based, Nyquist-sampled cross-track microwave sounder, the Advanced Technology Microwave Sounder (ATMS), will provide atmospheric vertical profile information needed to improve numerical weather and climate modelling. The ability of ATMS to sense temperature and moisture profile information in the presence of non-precipitating clouds complements the high vertical resolution of CrIS. Furthermore, the ability of ATMS to sense scattering of cold cosmic background radiance from the tops of precipitating clouds allows the retrieval of precipitation intensities with useful accuracies over most surface conditions.

An integral part of the CrIMSS pre-launch validation activities is the testing of operational software that will be used to process raw data counts into scientific data products. To ensure a smooth transition after launch to the operational production of temperature, sensor, and environmental data records, pre-launch test data are passed through the software processing system to identify any unforeseen issues in the processing flow. It is important for the test data to be as authentic as possible; therefore, “proxy” data are used. The term “proxy” refers to observed data (from an on-orbit sensor) that have been transformed spatially and spectrally to resemble, with some error, a future sensor. Atmospheric models may be inaccurate and incomplete, and therefore data simulated using only these models will be flawed. Alternatively, proxy data derived from actual radiometric observations of the atmosphere should preserve meaningful meteorological features that are difficult to accurately model.

This paper presented several assessments of the performance of ATMS and the geophysical quantities that are to be derived using ATMS measurements and compared the ATMS sensor with its heritage sensor the Advanced Microwave Sounder Unit (AMSU-A1 and A2) and Microwave Humidity Sounder (MHS). ATMS integrates the functionality provided by these three separate instruments into a single sensor, thereby reducing mass and power by 50 % and volume by 75 %. Pre-launch testing of ATMS has characterized the principal calibration parameters and has enabled predictions of on-orbit performance with high levels of confidence. Planned on-orbit characterization of ATMS will further improve both the measurement quality and the understanding of various error contributions. The presentation was organized as follows. First, an overview was given of the pre-launch radiometric calibration of ATMS. Key calibration parameters were discussed, as well as the error bars and dominant sources of uncertainty. Second, plans for on-orbit characterization of ATMS to further improve performance and reduce uncertainty were presented. Finally, preliminary assessments of ATMS data product performance were discussed, including vertical profile and precipitation products.

A5. Microwave sounding and imaging requirements for the future EUMETSAT Polar System

Peter Schlüssel, Eumetsat-Allee 1, 64295 Darmstadt, Germany

Preparations for the future EUMETSAT Polar System (Post-EPS), which is needed from 2020 onwards, have progressed from initial gathering of user requirements towards the formulation of observation mission requirements. The latter have been derived for a number of observation missions, to support operational meteorology, climate monitoring, atmospheric chemistry, oceanography, and other environmental services. Account has been taken to include the expected future evolution of various application areas. However, competing requirements from different application areas need to be evaluated on the basis of ranking of applications and technical feasibility. Important observation missions for which advanced studies are being carried out include microwave sounding and imaging. A range of prioritized radiometric, spectral, and geometric requirements have been specified, given by threshold, breakthrough, and objective values that allow for instrument concepts of different levels of complexity, ranging from plain heritage missions to highly innovative ones. Climate monitoring demands have been taken into account by requesting stringent bias requirements and their stability over the lifetime of the missions, and also continuity with respect to the spectral characteristics of heritage instruments. The mission requirements build the basis for instrument and system concept studies, being carried out by industry. Initial concepts have been elaborated, validating the mission requirements. More detailed feasibility analyses are ongoing to demonstrate possible breakthrough areas and shaping the envisaged overall payload complement for Post-EPS.

A6. A review of microwave metrology at NIST in support of satellite sounding missions

David Walker, NIST, USA

The Electromagnetics Division at NIST-Boulder is engaged in developing the metrology infrastructure to support improved calibration and validation (Cal-Val) of microwave remote-sensing radiometers. A primary goal is to develop a TB standard comprising a combination of two independent realizations of TB. The first is based on one of NIST's metrology-grade radiometers incorporating a cryogenic primary thermal noise standard connected (reversibly) to a well-characterized antenna. The second is based on a black-body target designed and constructed as a reference standard. Current activities at NIST were reviewed, including microwave absorber materials characterization, black-body target reflectivity (closely related to emissivity) and thermal uniformity evaluation, demonstration TB measurements of a heated black-body target using a NIST radiometer, radiometer nonlinearity issues, and advanced calibration techniques and uncertainty analyses. Once developed and deployed the TB standard and associated comparison methods will provide the means for tracing microwave remote-sensing instruments to national primary noise standards maintained by NIST. A discussion of the metrology challenges lying ahead concluded the presentation.

A7. Towards to standard pre-launch and post-launch calibration/validation of microwave sensors

Xiaolong Dong, NMRSL/CSSAR/CAS, China

The Microwave Sensor Subgroup (MSSG) is one of six subgroups of the Working Group on Calibration and Validation (WGCV) of CEOS. The main objectives of MSSG are to promote accurate calibration and validation of microwave sensors, through standardization of terminology and measurement practices. WGCV also provides a forum for discussion of current issues and for exchange of technical information on development of technologies for microwave sensors and their calibration/validation.

The work of MSSG covers all the remote sensing instruments operating in the microwave frequency band, including active and passive, while emphasis is placed on microwave radiometer, radar scatterometer and radar altimeters. MSSG is proposing standardization of the pre-launch calibration and post-launch calibration/validation procedures, by identifying existing standards and methods adopted by different organizations and coordinating development of better standards or procedures. The successful completion of this task will be dependent on the efforts and cooperation of both the sensor and applications communities. MSSG is calling for cooperation and coordination of all organizations concerned or interested.

In this presentation, some preliminary considerations from MSSG/WGCV were given. Microwave radiometers, imagers and sounders will have similar pre-launch calibration procedures but very different post launch cal-val procedures. For radar scatterometers, emphasis will be placed on the post-launch calibration by both artificial and natural targets and validation of retrieval models. For radar altimeters, emphasis will be placed on coordination of ground facilities for calibration/validation purposes and validation of retrieval models for geoscience and climate change applications.

Session B1: Stable time series for key GHGs and other trace species

B11. Greenhouse gas observations in the GAW programme

Oksana Tarasova, World Meteorological Organization, Switzerland

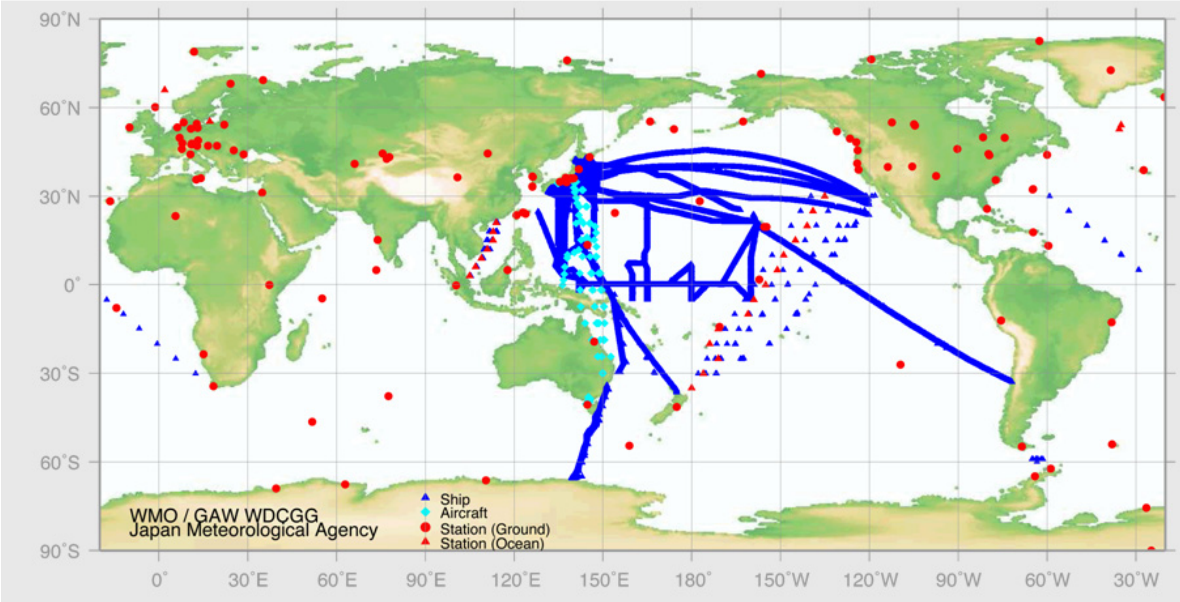
Understanding the global budget of the greenhouse gases in the atmosphere and predicting its evolution under future climate scenarios is one of the biggest challenges facing science today. It is important to distinguish between naturally and anthropogenically induced changes as only the latter can be controlled. To obtain a globally consistent picture, all the measurements have to be of a known quality and on a known scale. The WMO Global Atmosphere Watch (GAW) Programme (http://www.wmo.int/gaw) serves to provide a framework for reliable observations. It realizes a unique integrated approach through international coordination of atmospheric carbon cycle observations and research globally.

WMO GAW coordinates the activities of the greenhouse gas observational network contributed by the partner national organizations, in particular through a Quality Assurance Framework including Central Facilities operated by partners. Central Facilities serve to provide measurements comparability and quality within the network. A Central Calibration Laboratory maintains primary standards for CO_2, CH_4 and N_2O and the WMO World Reference Scale for greenhouse gases recognized by the International Bureau of Weights and Measures (BIPM). GAW World and Regional Calibration Centers maintained by WMO Members perform calibrations, inter-comparison campaigns and station audits. Standard operational procedures (SOPs) or measurement guidelines (MG) are developed under supervision of an international group of experts (SAG) and implemented by GAW stations. A rolling review process for the data quality objectives and measurement requirements is performed through biennial WMO/IAEA Expert Workshops.

The US NOAA/ESRL research group operates a WMO GAW contributing network and is a major partner in the comprehensive network. It hosts the WMO primary standards for CO_2, CH_4, and N_2O and serves as a World Calibration Centre for CO_2. Many other WMO GAW participants contribute to the comprehensive network following WMO GAW measurement guidelines and data quality objectives and supporting Central Facilities. The World Data Center for Greenhouses Gases (WDCGG) hosted by the Japan Meteorological Agency plays an important role in the integration of the observations serving for data submission, archiving and preparation of the assessments (e.g. the Annual Greenhouse Gas Bulletin).

Implementation of the Integrated Global Carbon Observing (IGCO) system needs a combination of the atmospheric composition observations coordinated through the GAW framework from different platforms, as well as flux tower networks and modelling activities. The surface-based and commercial aircraft component of the GAW integrated global network for carbon dioxide and methane observations is shown in Figure 1. It includes about 180 stations for CO_2 monitoring. Several projects and networks contribute to GAW by providing a three dimensional picture of the atmospheric greenhouse gas distribution in time and space. The need for traceability of satellite measurement data to the WMO World Reference Scale advanced the development of the remote sampling of GHG content, which is implemented in particular by the Total Carbon Column Observing Network (TCCON, www.tccon.caltech.edu). Further efforts are needed in integration of observations and development and support of Central Facilities and measurement networks to support a robust and transparent Carbon Tracking system and accurate Carbon Budgets at different scales.

Figure 1. CO_2 observational network based on the data submissions by September 2009 to the WMO GAW World Data Centre for Greenhouse Gases. Only locations where the measurements are continued for more than three years during 2005-2009 and those data are reported to the WDCGG are shown on the picture.



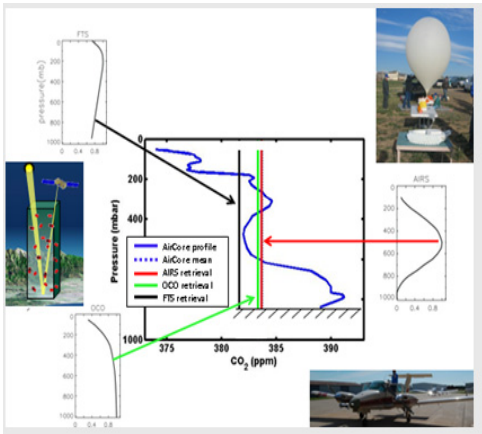
B12. Ensuring traceability and comparability of measurements for greenhouse gas monitoring

James H. Butler, NOAA Earth System Research Laboratory, USA

Global society will soon accelerate efforts to reduce greenhouse gas emissions in a variety of ways. These will likely involve international treaties, national policies, and regional strategies that will affect a number of economic, social, and environmental sectors. Some strategies will work better than others and some will not work at all. Because trillions of dollars will be involved in pursuing greenhouse gas emission reductions – through realignment of energy production, improvement of efficiencies, institution of taxes, implementation of carbon trading markets, and use of offsets – it is imperative that society be given all the tools at its disposal to ensure the ultimate success of these efforts. Providing independent, globally coherent, regional-scale information on the success of these approaches will give considerable strength to these treaties, policies, and strategies.

The closest thing the world currently has to a globally consistent, comprehensive, greenhouse gas observation network today is WMO's Global Atmosphere Watch Programme and the scientists who support it. Yet that network is currently neither scaled nor operated in such a way as to provide information at the required level of detail. The WMO and its partners are looking at how this might be done through enhanced observations, improved modelling, and ensemble reanalysis, but there is also a need to appraise their approach to calibration. Providing unimpeachable, regional-scale information requires consistent calibration scales and on-going comparisons of field measurements. The WMO currently addresses this need through its central calibration laboratories, world calibration centres, and quality assurance science activity centres. WMO calibration scales for the major greenhouse gases (CO_2, CH_4, N_2O) are currently maintained by NOAA, which also distributes calibration gases and provides quality assurance. This is done to ensure not only the accuracy of measurements, but comparability of measurements made at different sites. For carbon dioxide, for example, the goal for comparability is 0.1 ppm out of almost 400 ppm (0.025 %) in the atmosphere. This requires not only maintaining consistent calibration scales over long periods of time, but also that the mole fraction assigned to each cylinder is extremely precise and that each cylinder is analyzed in the central laboratory before, after, and sometimes during use. Traceability to SI units is ensured by using NIST scales for pressure, temperature, and weight in preparing the standards, but currently measurement comparisons of gases are not routinely conducted between NOAA and NIST.

A new problem for ensuring both traceability (NIST) and comparability (NOAA) of WMO measurements lies with emerging remote sampling techniques such as upward-looking FTIR and downward looking satellites. Because these techniques measure atmospheric column average mixing ratios, there is no simple way to make direct comparisons with the *in situ* measurements. If the WMO is to integrate remote and *in situ* measurements into a global greenhouse gas observation and analysis system, then a way must be developed to ensure both traceability and comparability of these two different techniques if bias of measurements is to be avoided.



B13. The World Calibration Centre for VOCs

Rainer Steinbrecher, Karlsruhe Institute of Technology (KIT), Germany

Volatile organic compounds (VOCs) are one of the major components involved in atmospheric chemistry. Through their reactive nature towards radicals such as HO, oxygen radicals, and NO_3 together with NO_x they contribute to ozone formation, leading to an approximate doubling of surface ozone concentrations by the end of the last century compared to pre-industrial levels. Ozone itself is a major air pollutant impacting human health and plant functioning, by lowering the carbon-sink in vegetation, as well as contributing to global warming by acting as important greenhouse gas itself. VOCs and their oxidation products are involved in radical recycling in the atmosphere and also contribute to the organic particulate matter (POM) load with consequences for solar radiation transfer to the earth surface and the global energy budget. Through these complex and significant actions in the atmosphere and their relevance for the earth climate system, VOCs have been recognized as an important atmospheric constituent to be monitored within the WMO-GAW Programme.

The principle WMO-GAW activities are related to: (1) to use internationally accepted methods and vocabulary to describe the uncertainty in measurements; (2) to harmonize measurement methodology at stations by using measurement guidelines (MGs) and standard operating procedures (SOPs); (3) to conduct regular performance and system audits by checking the station's agreement with the GAW quality assurance/quality control (QA/QC) protocol.

The objective of GAW-VOC monitoring is to produce high quality data with known uncertainty at specific representative sites for major biomes. Reported mole fractions and compound ratios of VOCs are then used for characterization of the photochemical age of air masses and transport processes. Furthermore, those data are needed as input for global/regional climate modelling based on Chemistry-Transport-Models (CTM) to validate their performance, e.g. for understanding the OH-radical, ozone and POM distributions, and for trend analysis.

VOCs are a complex mixture of several hundreds to thousands of compounds primarily originating from anthropological and biological sources of a wide range of chemical properties. The residence times in the atmosphere range from seconds to several years. For the GAW-VOC monitoring programme a key subset of 17 VOCs has been defined by an expert group and suitable analytical methods proposed.

The current WMO GAW-VOC network includes nearly 50 surface sites with regular *in situ* measurements of VOC and air samples collected within existing flask-sampling networks. For this network the world calibration center for VOC (WCC-VOC) coordinates the QA/QC activities and the implementation of central calibration laboratories (CCLs) for maintaining a traceable VOC scale. The QA/QC chain and the traceability of standards for the GAW-VOC network are shown in Figure 1. Further information about the WCC-VOC can be obtained from http://imk-ifu.fzk.de/wcc-voc/.

Recent results from site audits and inter-comparisons reveal that the tested *in situ* stations and central analytical facilities achieve the GAW-VOC guidelines for QA/QC for the hydrocarbon subset of VOC targets. Other GAW-VOC targets will be part of the next QA/QC sequence after the corresponding CCLs are in operation.

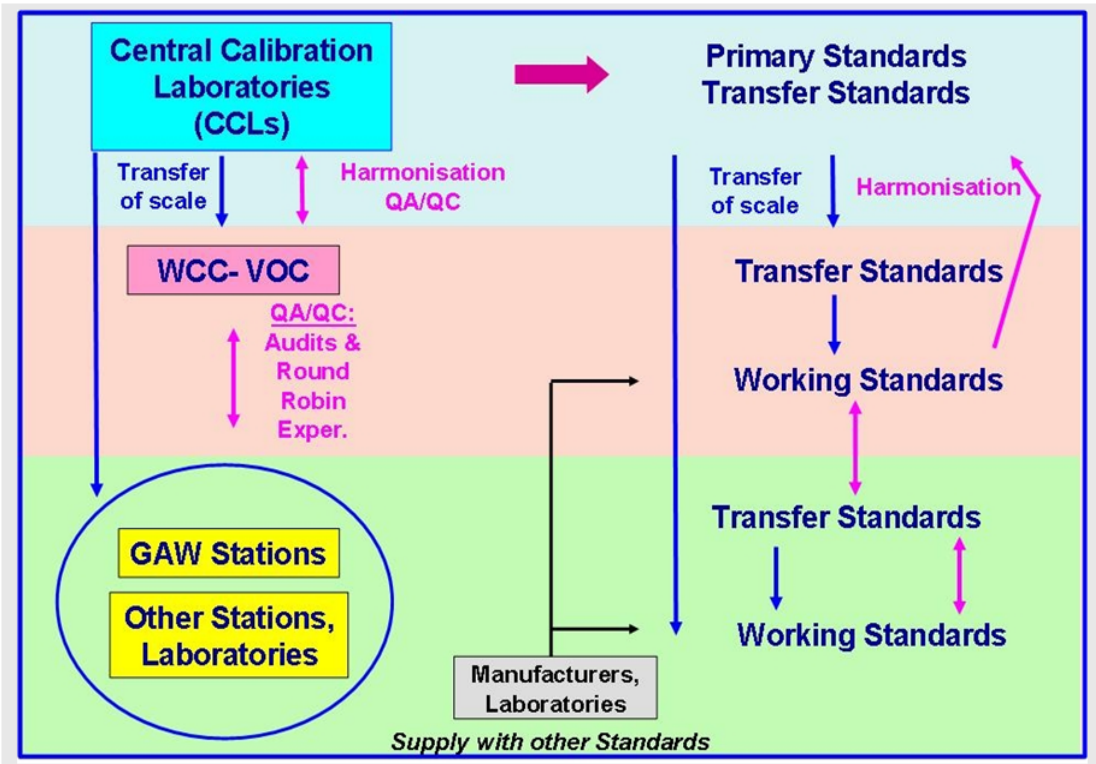


Figure 1. QA/QC chain in the WMO GAW-VOC programme and the traceability of standards.

B14. Supporting traceable global measurements through international comparison exercises

Martin J.T. Milton, National Physical Laboratory, UK

Long-term measurements of atmospheric components depend on the use of stable standards to enable them to be used to identify temporal trends and changes in spatial distributions. The principal role of NMIs around the world has always been to develop and distribute measurement standards that are stable, comparable and coherent. This talk gave examples of how NMIs are now collaborating to provide the standards needed to underpin global monitoring exercises. The overarching principle adhered to by the NMIs in the development and dissemination of standards is that they should be "traceable to the SI". The talk discussed how this approach is complementary to the "scale approach" used by established CCLs.

A particular example is the provision of the Central Calibration Laboratory (CCL) function for the Global Atmosphere Watch (GAW) network monitoring Volatile Organic Compounds (VOCs). The requirement for this CCL is to provide standards for nine species. Since this is a new and extensive task that overlaps with the demonstrated competencies of several NMIs; four NMIs are working together under the auspices of the Gas Analysis Working Group of the CCQM to meet the requirement.

A central feature of the operation of the NMIs is the organization of international comparison exercises, which provide an open, transparent, and comprehensive system for comparing their standards. The results of several recent comparisons of compounds of relevance to the climate change measurement community (e.g., CO_2, CH_4, N_2O and VOCs) were presented. These included results from several atmospheric monitoring laboratories that have participated following an agreement between the BIPM and the WMO.

The collaboration between the metrology and meteorological communities is proving to be effective and provides a model for interactions in other fields. Future challenges will include extending the collaboration to the development of standards for new analytes such as the oxides of nitrogen, selected mono-terpenes and oxygenated hydrocarbons.

B15. Calibrating measurements of long-lived atmospheric trace gases: The dominant importance of precision over accuracy and the role of defined calibration scales

Ray F. Weiss, Scripps Institution of Oceanography, USA

Measuring trends and distributions of environmentally important trace gases in the atmosphere can be an especially challenging problem for long-lived gases with low atmospheric abundances, small rates of change, and small vertical and horizontal concentration gradients. At the outset it is important to recognize that the atmosphere is a complex mixture of non-ideal gases with some highly-variable short-lived components, principally water vapour, and that the units of the measurement must be defined unambiguously to make the data comparable. For most such measurements, dry air mole fractions meet these constraints, but mixing ratios in units of parts by volume, even by dry air volume, do not because non-ideal gases do not mix ideally and the state of the volume measurement is not defined.

In order to meet the scientific needs for the detection of small spatial and temporal changes in trace gas abundances, it is important to recognize that with most measurement techniques it is possible to compare the dry air abundances of a trace gas in two different air samples or standard mixtures against each other with far greater relative precision than the accuracy with which the absolute abundance can be determined in either. This is especially true for comparisons that can be repeated a number of times to reduce statistical uncertainties, and for comparisons in which the abundances of the analytes and bulk compositions are similar, so that matrix effects and non-linearity concerns are minimized.

In order to take maximum advantage of these relationships it is important to define a specific calibration scale which is composed of an explicit set of maintained reference mixtures that have been shown to store conservatively and whose relationships to each other have been measured with high precision and with appropriate corrections for any measurement non-linearities. As has been done for atmospheric carbon dioxide and stable isotope research for many decades, the existence of such a defined scale makes it possible to measure exceedingly small changes in nature, even when the absolute values of the measurements are known with less certainty than the sizes of the changes being measured.

With a well-defined calibration scale in place, as techniques for absolute calibration improve it is possible to revise and improve the absolute values that are assigned to a specific scale, or even to have the option of choosing among different absolute calibrations, without jeopardizing the relative precision of measurements. These principles are well illustrated by their application to the relative and absolute calibration of long-term measurements of atmospheric greenhouse gases and ozone depleting substances in the Advanced Global Atmospheric Gases Experiment (AGAGE) programme.

B16. Trend analysis for greenhouse and reactive gases

Brigitte Buchmann, EMPA, Switzerland

High-quality and long-term comparable time series of the relevant atmospheric observations are the essential prerequisite to understanding the dynamic, physical and chemical state of the atmosphere from seasonal to multi-decadal time scales. The required data quality for analyses of long-term time series strongly depends on the objective trend estimation, both to verify international treaties and for scientific investigations. The required data quality can be defined in data quality objectives (DQOs) for the respective purpose.

CFCs, halons and long-lived chlorinated solvents for example, which are banned from usage in Europe under the terms of the Montreal Protocol, show a continuous decline in the continental background concentrations. For the HCFCs (their first-generation substitutes) concentrations are still increasing due to their emissions from refrigeration equipment and foams. When actual concentrations for these ozone-depleting substances are compared to those that theoretically would have been expected without the Montreal Protocol, a positive influence of the Protocol is obvious, but not only in view of the stratospheric ozone depletion but also for the abatement of climate change.

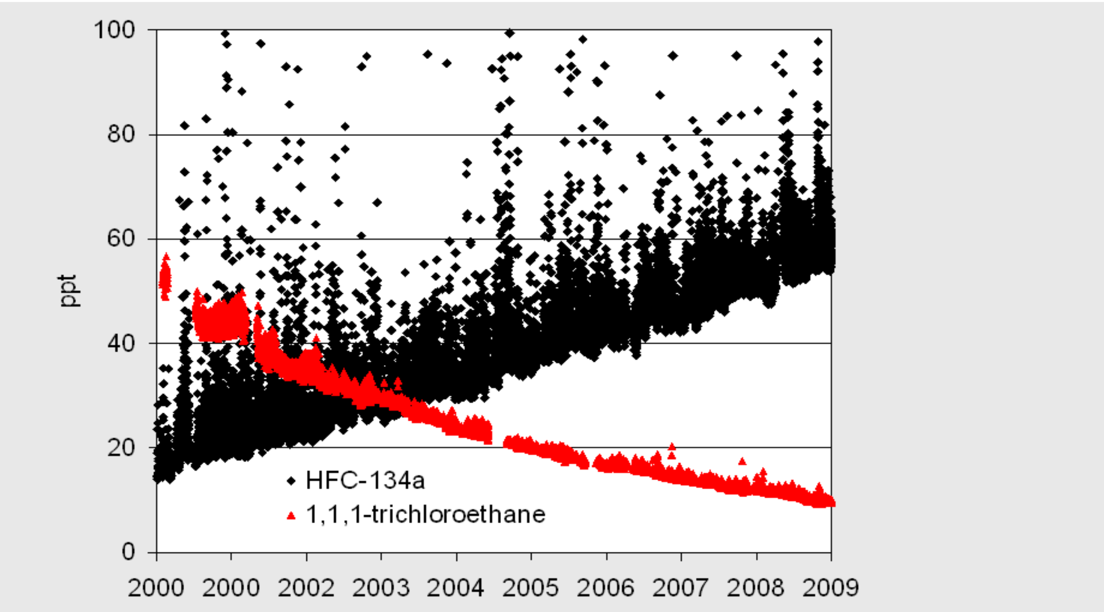


Figure 1. The cooling agent HFC-134, regulated in the Kyoto Protocol is still increasing by 5 ppb per year, meanwhile the solvent 1,1,1-trichloroethane due to its ban in the Montreal Protocol shows a clear decline of 2.5 ppb per year.

For HFCs, which do not reduce the ozone layer, but which are potent greenhouse gases, background concentrations are increasing continuously. This increase in the baseline concentration is superimposed by high peak concentrations. The most important HFC is HFC-134a, which is mainly used as refrigerant in stationary and mobile (i.e. vehicle) air conditioning. However, in the recent past the percentage increase in other important HFCs (i.e. HFC-125, HFC-152a, HFC-365mfc) has been higher, which points to their increasing importance.

Time series, combined with model approaches (dispersion, transport and receptor models), allow European sources allocation as well as verification of European non-CO_2 greenhouse gas emissions inventories.

Examples for trend analyses were presented, involving relevant parameters influencing the uncertainty of the trend estimation such as instrumentation and standards as well as characteristics of measurement sites.

B17. Ozone cross-sections and primary standards

Joële Viallon, BIPM

The reference method for the measurement of ground level ozone concentration is based on UV absorption at 253.7 nm. The ozone absorption cross section value at this wavelength is the value measured by Hearn in 1961 [1], and the expanded uncertainty of this value has recently been estimated as 2.12 % [2].

The NIST SRP ozone reference standard operates on the principle of UV absorption, and acts as the primary standard for numerous national and international ozone-monitoring networks (including the WMO-GAW stations). Several replicas of this instrument are maintained by the BIPM, one of them being the reference for international comparisons of national ozone standards coordinated by the BIPM.

During the last international comparison (2006), twenty-three UV absorption based ozone standards at ground level were compared with two realizations of an independent method for primary ozone concentration measurements based on gas phase titration systems developed by the NIES (Japan) and the BIPM. The 2 % to 3 % bias observed between the methods requires explanation and confirmation of the ozone absorption cross-section value, which represents the major uncertainty component in measurements based on UV photometry.

This issue is at the heart of a more global concern regarding the accuracy of the ozone cross-section in a larger wavelength range, which impacts world-wide ozone monitoring performed with various instruments (see Figure 1), as recognized by the ASCO (Absorption Cross-Sections of Ozone) committee, working under the umbrella of WMO and IO3C (International Ozone Commission) (see http://igaco-o3.fmi.fi/ACSO/index.html). The recent meeting of ASCO held in 2009 concluded with the request for more laboratory studies with improved control of the sources of uncertainty.

Using experience gained during a study of systematic biases and uncertainties in the NIST SRP [2], the BIPM is currently developing a laser based ozone photometer as a potentially new reference standard for ground level measurements. The instrument will also be used to measure the (absolute) value of the absorption cross-section of ozone at three different wavelengths in the Hartley band, around 250 nm. The target standard uncertainty for these measurements is 0.5 % relative, potentially the lowest uncertainty ever obtained

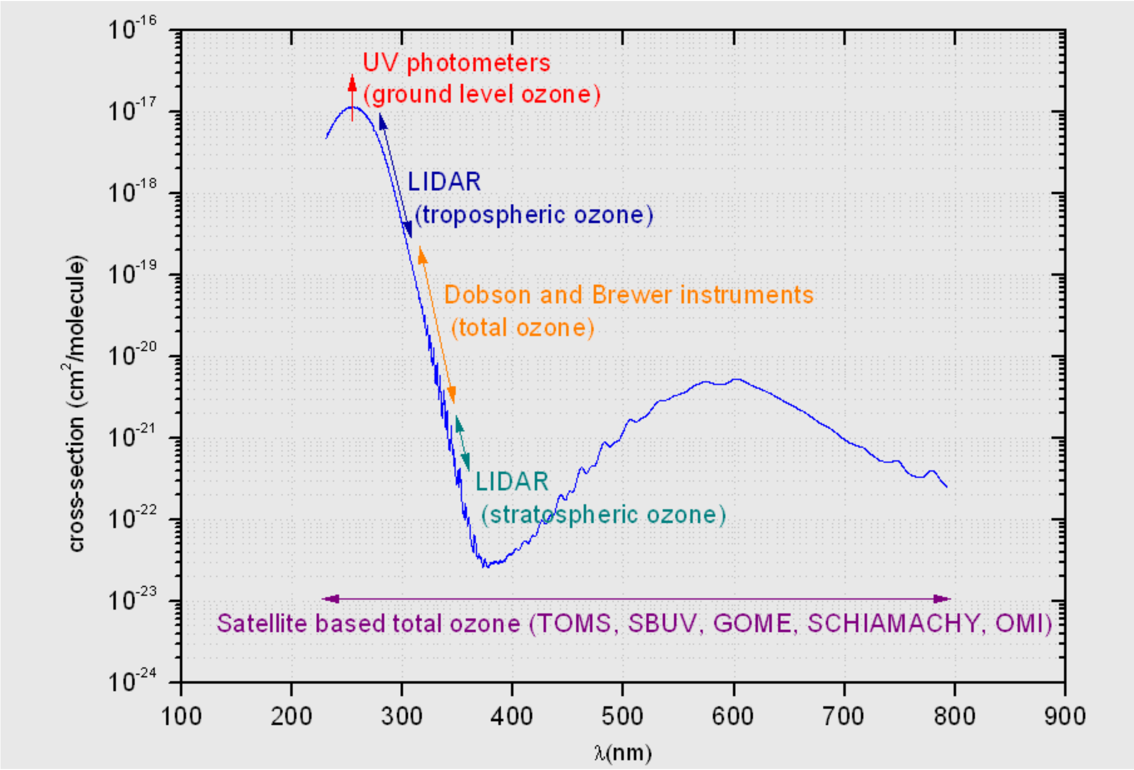


Figure 1. Parts of the absorption cross-section of ozone in the UV-VIS used within ozone monitoring instruments (data from GOME FM grating spectrometer at 293 K).

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Session B2: Remote sensing of atmospheric composition and traceability issues in spectroscopic data.

B21. Relating point measurements of atmospheric composition to integrated-path and range-resolved measurements

Bertrand Calpini, MeteoSwiss, Switzerland

Requirements for high-quality observational data and their world-wide compatibility were a governing principle when the International Meteorological Organization was established in 1873. So, it was necessary to define technical standards, conduct instrument inter-comparisons, testing and calibration and implement quality control procedures. These responsibilities were assigned to the Commission for Instruments and Methods of Observations (CIMO). Since then, the standardization responsibilities of CIMO have been significantly expanded, to cope with the fast development of measuring technology, so that the traceability of measurements to the International System of Units (SI) could be guaranteed.

The WMO Guide to Meteorological Instruments and Methods of Observation (CIMO Guide) is the most influential of WMO's publications as regards standardization of observations. The 1st edition of the CIMO Guide was published in 1954; the latest 7th edition (2008) covers the whole range of instruments, systems and techniques in regular use, from the simplest to the most complex and sophisticated. Its purpose is to give comprehensive and up-to-date guidance on the most effective practices for carrying out meteorological observations and measurements.

As an example of CIMO's contribution to meteorological standardization, the work performed with radiosonde developments was highlighted, the first World Comparisons of Radiosondes being carried out in MeteoSwiss Payerne in 1956 and followed by extensive studies in the development of guidance material applied to radiosonde development, testing, comparisons and compatibility.

It is of interest to mirror the work in CIMO down to the level of a National Meteorological service. This was done by showing the recent development at MeteoSwiss of an air quality security tool in case of a nuclear power plant release over the Swiss Plateau. The direct assimilation of remote sensing upper air observation into fine grid numerical weather prediction models and the improved NWP results was demonstrated even though the remote sensing observations have intrinsic limitations in absolute accuracy. This was presented in particular for wind profilers and lidars but was also extended to some discussion about still unresolved spectroscopic features in trace gas detection.

A time series of absolute humidity versus altitude range is given in Figure 1. A period of time of 10 days is shown comparing active remote sensing measurement by Raman LIDAR with passive microwave remote sensing data. On the same figure the integrated water vapour column is given by including satellite (GPS wet delay) and radiosonde (SRS) observation. These results were presented and discussed by considering absolute versus relative calibration issues.

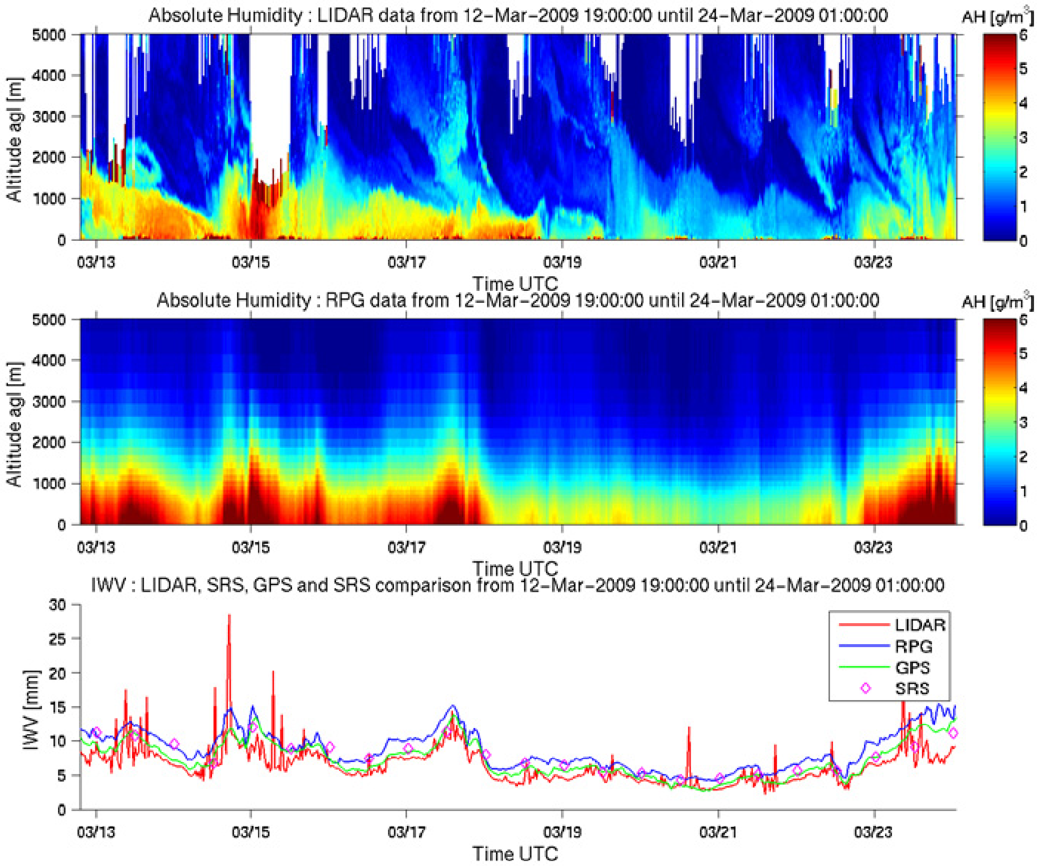


Figure 1. Time series of absolute humidity versus altitude range

B22. Satellite measurements of tropospheric species from GOSAT

Tatsuya Yokota, NIES, Japan

The Greenhouse gases Observing SATellite (GOSAT) was launched on 23 January 2009. The main target of the GOSAT observation is to obtain data for the global distribution and variation of tropospheric greenhouse gases; carbon dioxide and methane. A GOSAT sensor, Thermal And Near infrared Sensor for carbon Observation-Fourier Transform Spectrometer (TANSO-FTS) detects the signal of reflected solar light on the earth's surface in Short Wavelength Infra-Red (SWIR) regions as well as that of radiance emitted from the surface and the atmosphere in the Thermal Infra-Red (TIR) region. The TANSO-Cloud and Aerosol Imager (TANSO-CAI) is a CCD radiometer used to obtain information on cloud and aerosols that contaminate the FTS signals. Since June 2009, TANSO-FTS and CAI have made continuous observations. Retrieval of carbon dioxide and methane column abundances from SWIR spectra for cloud-free scenes are retrieved in several processing versions. Optically thick clouds within the field of view of TANSO-FTS (approximately 10 km diameter) are detected using the TANSO-CAI radiances and optically thin cirrus using the solar reflected spectrum in the strong water vapour absorption band in the TANSO-FTS 2.0 μm band. We applied an optimal estimation method (maximum *a posteriori* method) to the selected cloud-free scene data for retrieving column abundances of carbon dioxide and methane. At present, retrieved column abundances seem to be slightly underestimated, but global column-averaged concentration patterns and seasonal variations agree with the current knowledge. The GOSAT Level 2 data products (column abundances of carbon dioxide and methane) have indicated an estimation error bar (confidence width of retrieved value) for each retrieved scan. However, biases between GOSAT data and validation data have to be estimated independently. Data quality control and associated information, the present error estimation method and data validation were introduced.

B23. Reference standards for space-based remote sensing of carbon dioxide and greenhouse gases

Charles Miller, JPL, NASA, USA

Space-based remote sensing of atmospheric carbon dioxide (CO_2) and other greenhouse gases (CH_4, N_2O, etc.) with sub-1 % precisions have the potential to provide critical information for climate monitoring as well as treaty support and assessment. There are significant technical challenges to delivering these data with well-characterized uncertainties and traceability to established reference standards. Firstly, one must perform absolute radiometric calibration of high-spectral resolution (l/Dl ~ 1000 – 100 000) measurements of top-of-the-atmosphere infrared, near infrared and visible radiances to better than 5 %. Secondly, reference standard spectroscopic data are essential inputs for the retrieval algorithms that transform radiance measurements into estimates of atmospheric trace gas concentrations. Finally, one must validate the retrieved trace gas concentration estimates, e.g. total column CO_2, to ensure that biases and accumulated uncertainties are less than the targeted precision: ~1 ppmv (0.3 % of the background level of ~390 ppmv) for the case of CO_2. Similar requirements exist for remote sensing of methane (CH_4), nitrous oxide (N_2O), water vapour (H_2O) and ozone (O_3). Standard remote sensing standards and methods break down when sub-1 % precisions are desired, requiring innovative new approaches. This presentation discussed methods for attacking all of these reference standard challenges.

B24. Integration of column CO_2 measurements into the existing *in situ* network for greenhouse gases

T. Warneke, J. Messerschmidt, J. Notholt, P. Wennberg, D. Griffith, University of Bremen, Germany

CO_2 is the most important anthropogenic greenhouse gas. Human activities, primarily fossil fuel combustion and deforestation, are responsible for a continuing increase of its atmospheric concentration. The oceans and terrestrial ecosystems currently act as sinks for atmospheric CO_2 and absorb approximately half of the anthropogenic emissions. Inverse models have been used to infer the geographical distribution of the sinks from atmospheric measurements. Until recently inverse modelling studies were solely based on a network of *in situ* boundary layer measurement stations. This approach is limited by the sparse spatial coverage of the sampling sites and by the sensitivity of the sink estimates to the assumed vertical model transport.

Column measurements did not contribute to carbon cycle studies in the past because their precision was not sufficient. This situation has changed over the last years and column measurements of sub-percentage precision are now available for CO_2 from ground-based solar absorption measurements using FTIR-spectrometers and from space-borne sensors measuring reflected sunlight. Space-borne sensors provide global coverage and in addition the CO_2 column is not sensitive to vertical transport. Therefore these measurements overcome the limitations of the *in situ* network and have the potential to start a new era in atmospheric CO_2 research. Of critical importance for the success of column measurements are the calibration of the column measurements against the *in situ* standard and the ground-based validation of the satellites. A vital role for the calibration of the column measurements and the validation of satellite retrievals is played by the ground-based Total Carbon Column Observing Network (TCCON), consisting of solar absorption FTIR spectrometers. TCCON was founded in 2004 in view of the OCO mission and will establish a critically maintained and long timescale record of ground-based column measurements. Within TCCON the observations and retrieval are performed in a strictly coordinated way and the link to the *in situ* network has been established via aircraft profiling. The current status of the measurements within this network was presented.

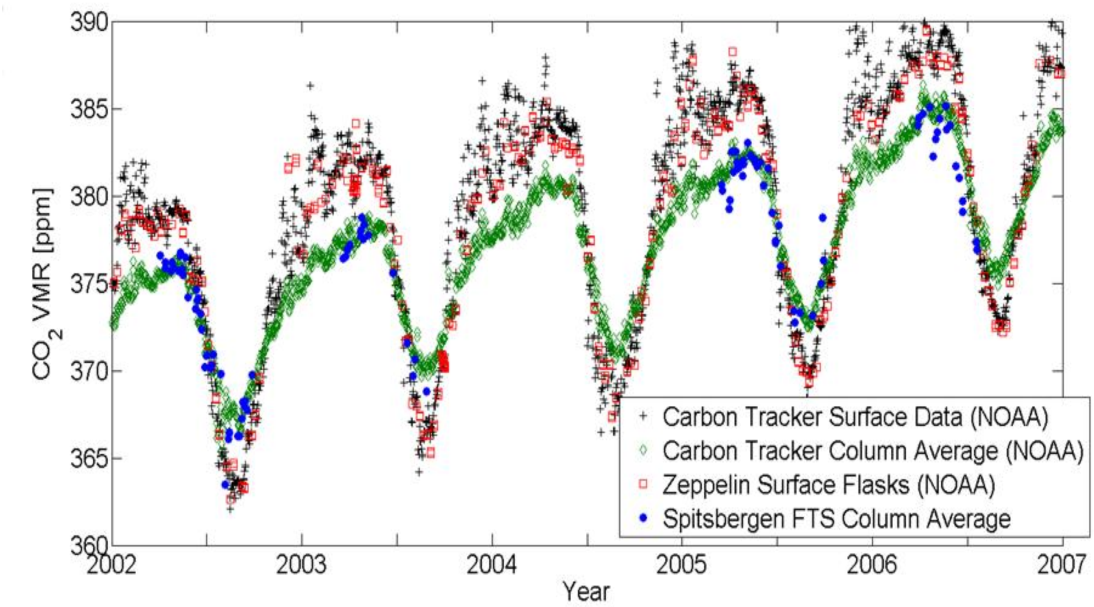


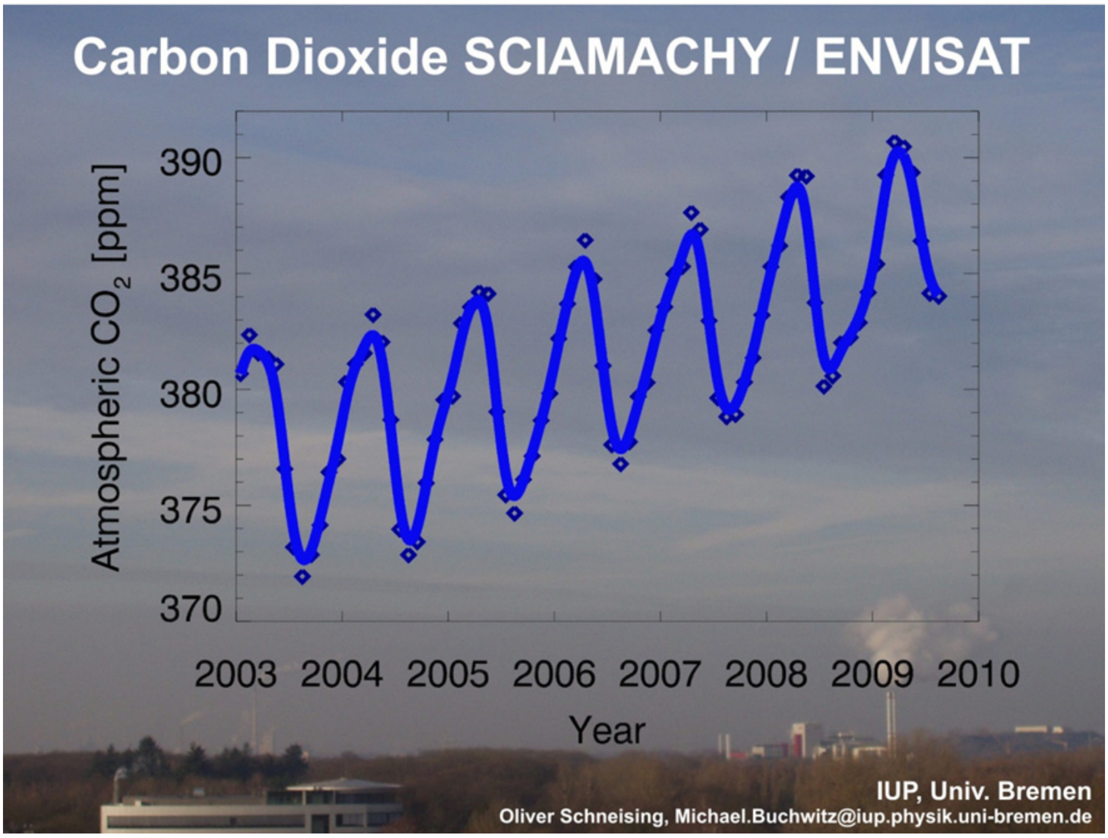
Figure 1. CO_2 measurements at Ny Alesund (79°N). Due to the vertical decrease of CO_2 in the atmosphere the seasonal amplitude of the column averaged CO_2 measured by ground-based FTIR spectrometry (blue) is smaller than the amplitude of the surface in situ measurements (red). At Ny Alesund the column and in situ measurements agree well with Carbon Tracker model simulations, suggesting that the vertical transport is well represented in the model.

B25. Global observations of greenhouse gases using SCIAMACHY

John P. Burrows, NERC Centre of Ecology and Hydrology and Istitute of Environmental Physics University of Bremen, Germany

The SCIAMACHY instrument is onboard the ENVISAT satellite, which was launched in February 2002 and began its measurements in August 2002. SCIAMACHY measures the up-welling of radiance from the atmosphere in different viewing geometries: nadir, limb and occultation. SCIAMACHY is a spectrometer having 8 spectral channels covering contiguously the spectral region from 214 nm to

1750 nm and channels around 2.0 microns and 2.3 microns. The spectral resolution varies between 0.2 nm and 1.4 nm. This talk focused on the retrieval of carbon dioxide, methane and water vapour from nadir measurements made by SCIAMACHY. The retrieval of the data products, their validation and their interpretation was discussed.



B26. Comparison of spectroscopic measurements of water vapour

Volker Ebert, Physikalisch-Technische Bundesanstalt PTB, Germany

Water is undoubtedly the most important greenhouse gas which strongly influences atmospheric chemistry, mass and latent heat transport as well as the water fluxes that interconnect atmosphere, oceans, pedo- (soil) and phytosphere. Even within the atmospheric compartment further complications arise through the need to describe the phase transitions of water, i.e. cloud and precipitation dynamics, which also influences heterogeneous atmospheric chemistry. Climate models thus require global coverage of the atmospheric water vapour distribution and simultaneously require fine spatial and temporal details. However, water provides persistent measurement difficulties due to its strong adsorption to almost any surface, its existence in multiple phases (gas, liquid, super-cooled liquid and ice phase), a huge dynamic concentration range within the troposphere and the large spatio-temporal variability (e.g. in clouds).

Numerous, very diverse techniques, ranging from a combination of photo-dissociation and OH-fluorescence detection, over well established frost point hygrometers to chemical (P_2O_5-based) water detectors, have been developed to quantify the atmospheric water vapour content. Especially for airborne sensing and other demanding field applications, spectroscopic techniques such as tuneable diode laser absorption spectrometers (TDLAS) are currently used and have been developed intensively as they offer the possibility of sampling-free H_2O detection in open absorption cells, thereby avoiding the complications of the sampling process [1]. The large sensor variability generates a strong need for homogenization and stringent intercomparison between the different sensor principles and sensor realizations to ensure comparability. Further, considerable differences are frequently documented between airborne water measurements especially in the UT/LS region of the atmosphere or within cirrus clouds, some of them only being explainable through new ice microphysics [2] or by sensor dysfunctions.

The talk gave a short overview of the most important water sensing needs of atmospheric sciences, the currently used water vapour detection principles and analyzed the pros and cons of spectroscopic methods for water detection. The main part of the talk focused on the prospects of self-calibrating TDLAS-hygrometers for sampling-free, absolute atmospheric water detection (see Figure 1), and presented the results of the large, refereed and blind, international intercomparison campaign (AQUAVIT, [3]) of almost all important airborne water vapour instruments (realized at the world's largest cloud simulation chamber AIDA at the research centre Karlsruhe, Germany) from which the current capabilities (and future needs) in atmospheric water vapour detection will be derived.

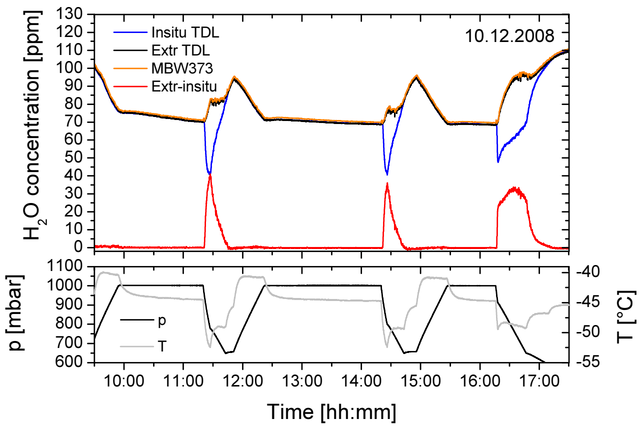


Figure 1. Simultaneous, absolute detection of water vapour (blue), total water (black), in comparison with a reference frost point hygrometer, (orange) and ice water (red) during cloud formation events (pressure , temperature below) at the AIDA-cloud chamber using a set of self-calibrating TDLAS-hygrometers [4].

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B27. Linking remote measurements of GHG concentrations to the SI through intrinsic molecular properties

Joseph T. Hodges and Roger D. van Zee, NIST, USA

Column-integrated greenhouse gas (GHG) concentrations in the atmosphere are typically retrieved from absorption spectra, using either passive (solar) or active (laser-based) methods. These types of long-path retrievals are predicated on the validity of the Beer-Lambert law and modelling the path-integrated absorption coefficient, that is, the fractional reduction in the radiation intensity per-unit-length along the direction of propagation. To ensure consistency and data continuity from measurement-to-measurement and through time, these measurements should be linked to the International System of Units (SI). Artefact standards of gas mixtures, used in many applications where gas-phase concentration measurement must be calibrated, have limited value in this application because of the large physical scales and variety of conditions (pressure, temperature, etc.) of a typical atmospheric retrieval. Standard reference data, linked to the SI through primary standards for state-variables, coupled with physical models for the absorption process offer a better approach for achieving traceability.

The approach we describe relies on a fundamental understanding of light-matter interaction and measurement of spectroscopic parameters under fully characterized thermodynamic conditions. At a given pressure, *p*, temperature, *T*, and gas mixture composition, *x*, the absorption coefficient, alpha depends on absorber number density, *n*, and the frequency-dependent absorption cross-section. Absent confounding perturbations, the latter quantity is equal to *nSiBi*(*T*) *g*(*v*-*vi*; *p*, *T*, *x*), where *Si* is the line strength of transition *i*, centred at frequency *vi* and *Bi*(*T*) is the relevant Boltzmann factor. The quantity, *g*(*v*-*vi*) is the corresponding frequency-normalized line shape function. Importantly *Si* depends only upon the specific quantum-mechanical transition moment of the absorber - an intrinsic molecular property. The approach discussed involves measuring *Si* under conditions where the pertinent thermodynamic parameters are linked to primary standards, and similarly characterizing the parametric dependence of *g*(*v*-*vi*). Measurements of alpha using such data provide a link to the mole, the SI unit for amount of substance, independent of any other reference to that quantity.

We discuss laboratory measurements of standard reference data validated against theoretical calculations and consider how these measurements and models can underpin SI traceability in remote sensing of atmospheric GHGs. We assess the accuracy of advanced laboratory measurements and models for line parameters of CO_2, H_2O and O_2. We find that because pressure, temperature and composition strongly influence line shapes, one must accurately model the influence of these parameters on the spectrum over the atmospheric column to avoid significant bias in the reported concentration.

B28. Satellite observations of greenhouse gases

Peter Bernath, University of York, United Kingdom

Satellite observations of greenhouse gases have the potential to greatly improve the quality of our estimates of climate change. In the past, highly precise surface observations of greenhouse gases have dominated the datasets used to monitor trends in atmospheric composition, and to infer sources and sinks with the help of models. Vertical profile measurements have been much more limited and are mainly from specific measurement campaigns, although some regular aircraft observations are available. Satellites offer the possibility of obtaining a global four dimensional dataset (location, altitude and time) of greenhouse gas concentrations.

A short review of existing and planned satellite instruments that measure greenhouse gas concentrations was provided. Most of the recent activity has been devoted to nadir sounders because of their higher temporal and spatial resolution. The vertical dimension has been largely neglected and was the primary focus of this talk. Vertical profiles of greenhouse gases are essential and atmospheric radiative properties cannot be calculated without them (e.g., tropospheric ozone is a much more potent greenhouse gas than stratospheric ozone). Limb sounders such as the Atmospheric Chemistry Experiment (ACE, see http://www.ace.uwaterloo.ca/) and MIPAS therefore have the potential to provide complementary height information to the observations made by nadir sounders. In this talk the full range of greenhouse gases were considered including water vapour, carbon dioxide, methane, nitrous oxide, ozone and halogenated species.

Session C: Radiation and Earth energy balance

C1. Climate benchmark missions: CLARREO

Bruce Wielicki, NASA, USA

CLARREO (Climate Absolute Radiance and Refractivity Observatory) is one of the four Tier 1 missions recommended by the recent NRC decadal survey report on Earth Science and Applications from Space (NRC, 2007). The CLARREO mission addresses the need to rigorously observe climate change on decade time scales and to use decadal change observations as the most critical method to determine the accuracy of climate change projections such as those used in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4). A rigorously known accuracy of both decadal change observations as well as climate projections is critical in order to enable sound policy decisions. The CLARREO mission accomplishes this critical objective through highly accurate and SI traceable decadal change observations sensitive to many of the key uncertainties in climate radiative forcings, responses, and feedback that in turn drive uncertainty in current climate model projections. The same uncertainties also lead to uncertainty in attribution of climate change to anthropogenic forcing.

The CLARREO breakthrough in decadal climate change observations is to achieve the required levels of accuracy and traceability to SI standards for a set of observations sensitive to a wide range of key decadal change variables. These accuracy levels are determined both by the projected decadal changes as well as by the background natural variability that such signals must be detected against. The accuracy for decadal change traceability to SI standards includes uncertainties of calibration, sampling, and analysis methods. Unlike most other missions, all of the CLARREO requirements are judged not by instantaneous accuracy, but instead by accuracy in large time/space scale average decadal changes.

Given the focus on decadal climate change, the NRC Decadal Survey concluded that the single most critical issue for decadal change observations was their lack of accuracy and low confidence in observing the small but critical climate change signals. CLARREO is the recommended attack on this challenge, and builds on the last decade of climate observation advances in the Earth Observing System as well as metrological advances at NIST (National Institute of Standards and Technology) and other standards laboratories.

The presentation summarized the planned CLARREO observations, science priorities, requirements, and the dual strategy to provide climate change benchmarks directly from CLARREO observations, as well as to serve as a set of reference spectrometers in orbit capable of improving the calibration of other weather and climate sensors.

C2. Total solar irradiance: Challenges for the future

Werner Schmutz, PMOD/WRC, Switzerland

Total Solar Irradiance (TSI) is measured by pyrheliometers. These instruments are either fully characterized and measure in absolute units or they are traceable to the World Radiometric Reference (WRR) at the World Radiation Centre in Davos. The WRR in turn is so far only traceable to the SI in power but not in irradiance. The added difficulty when discussing metrology of pyrheliometers in space is that the WRR is operated in air. Thus, so far, measurements of TSI in space rely on the full or partial characterization of the instruments and a fully traceable TSI measurement instrument has not yet flown.

This talk gave an overview of existing space observations of TSI and discussed the differences in the absolute and relative values between the various experiments. The challenge for future experiments is to get full traceability of the measurements in space. There are two upcoming experiments, PREMOS on PICARD and GLORY, which have the necessary traceable calibrations on the ground.

C3. Solar spectral irradiance: Current understanding and challenges for the future

Jerald Harder, University of Colorado, USA

The Spectral Irradiance Monitor (SIM) is a solar spectral radiometer that operates from 200-2400 nm and measures solar spectral irradiance variability over about 97 % of the solar spectrum. SIM has been operational on the SORCE satellite (Solar Radiation and Climate Experiment) since April 2003, and the second generation of the SIM instrument is scheduled for launch on NPOESS (National Polar-orbiting Operational Environment Satellite System) C1 in 2015 as part of the TSIS (Total and Spectral Solar Irradiance Sensor). Analysis of the measured spectral variability during the SORCE mission has prompted a number of instrument design refinements, and post-launch characterization of the SIM detectors and optical system has developed into a well-defined pre-flight calibration plan.

The pre-flight instrument calibration will be tied to SI irradiance standards by using the NIST SIRCUS (Spectral Irradiance and Radiance Calibration with Uniform Sources) facility. Critical component-level calibrations of detector sensitivity, prism transmission, and instrument profile area as a function of wavelength are measured separately and then introduced into a measurement equation to obtain the overall response function. An independent end-to-end calibration on the assembled instrument then validates this measurement equation. The unit-level calibration approach facilitates accurate on-orbit component specific degradation corrections. Absolute calibration of 0.2 % to 0.5 % can be achieved using the SIRCUS system over the full wavelength range.

Satellite-borne spectral radiometers exhibit wavelength dependent sensitivity degradation that must be corrected on-orbit. SORCE observations show very small and offsetting solar cycle trends that must be accurately separated from instrument degradation. This was done on SORCE by comparing 2 independent prism spectrometer channels each containing 4 separate detectors with overlapping wavelength ranges. One of these two channels is used for daily measurements while the other is exposed once per month; comparison of the time series from each spectrometer provides a correction for optical degradation. Each spectrometer employs an Electrical Substitution Radiometer (ESR) bolometric detector that is impervious to radiation damage and maintains the pre-flight radiometric calibration. The ESR corrects changes in radiant sensitivity to the less radiation hard photodiode detectors. This same design and operation philosophy will be implemented for TSIS, but a third, independent spectrometer channel operated every nine months will be used to unambiguously correct the degradation induced on the channel operated monthly. An improved mechanical design employing ultra-high vacuum technology will significantly reduce organic contaminants in the spectrometer cavity which contribute to optical degradation. These improvements will allow the instrument to achieve a long-term precision of 0.01 % to 0.05 % per year thereby greatly improving the ability to determine the long-term trends in spectral irradiance.

The findings were presented from the on-orbit observations of SORCE SIM and the performance enhancements that will be applied to the TSIS instrument to meet the needs for climate monitoring of solar spectral irradiance monitoring.

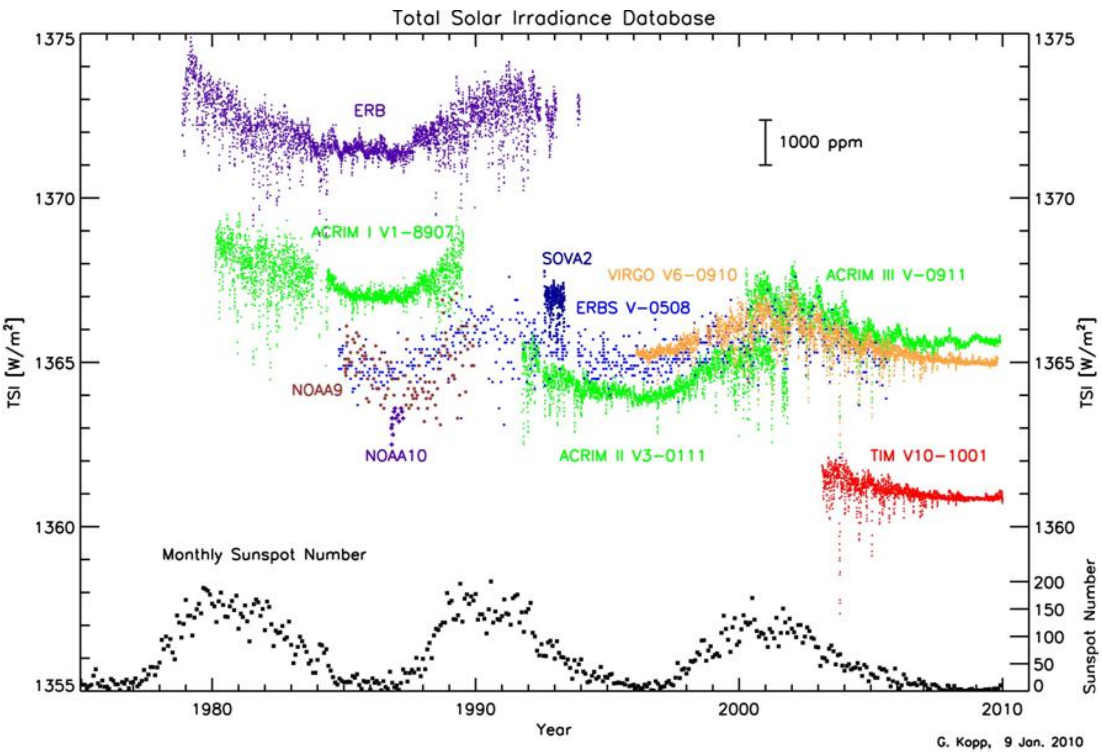
C4. TSI radiometer facilty to improve calibrations of total solar irradiance instruments

Greg Kopp, University of Colorado, USA

The total solar irradiance (TSI) data record includes measurements from more than 10 space borne instruments over the past 31 years. Overlap of on-orbit measurements allows adjustments for instrument offsets to create a composite time series used in estimating solar influences on Earth climate both via direct TSI measurements spanning 11-year solar cycles and via TSI proxies to estimate historical solar forcing. The offsets between different instruments are caused by calibration errors and are due in part to the fact that none of the current on-orbit instruments have been calibrated end-to-end to the desired accuracy levels, as no such calibration facility has existed.

The new TSI Radiometer Facility (TRF) built for NASA's Glory mission provides these new calibration capabilities. Via direct optical power comparisons to a NIST-calibrated cryogenic radiometer, this facility provides calibrations of a TSI instrument under flight-like conditions: in vacuum, at full solar irradiance power levels, and with uniform incident light needed for irradiance measurements. Control of the shape of the incoming beam facilitates instrument diagnostics such as validating optical power measurement accuracy and quantifying internal scatter and diffraction effects, helping determine the causes of instrument offsets.

Both the upcoming Glory Total Irradiance Monitor and the PICARD/PREMOS TSI instruments have been tested in the TRF. Their upcoming on-orbit measurements will establish a link between the existing 31-year TSI record and this ground-based reference calibration facility, providing a pre-flight benchmark against which future TSI instruments can be compared. This unique new calibration facility will improve the TSI climate data record by validating instrument absolute accuracy, diagnosing causes of instrument offsets, and mitigating against potential future data gaps.



C5. The history and the future of the WRR

Wolfgang Finsterle, Rainer Winkler, PMOD/WRC, Switzerland / NPL, United Kingdom

The World Radiometric Reference (WRR) was first defined in 1977 by the World Meteorological Organization (WMO) as the primary reference for solar irradiance measurements world-wide [1]. Since then the WRR was realized by the World Standard Group (WSG) of pyrheliometers, which are maintained and operated at the World Radiation Centre (WRC) in Davos, Switzerland. Currently the WSG consists of five absolute cavity pyrheliometers of different manufacture. The paper discussed potential future scenarios for the WSG with a focus on its possible replacement by a Cryogenic Solar Absolute Radiometer (CSAR) [2].

Introduction

In Resolution 11 of the 23rd meeting of the CGPM (2007), the BIPM and the World Meteorological Organization (WMO) agreed on the importance of SI traceable measurements to monitor climate change. However, the WRR cannot strictly provide SI traceability of solar irradiance measurements. This is mainly due to the limitation of current SI primary standards for radiant flux (i.e. cryogenic radiometers), which are optimized to measure monochromatic light at relatively low irradiance levels compared to the sun. While the latter can be overcome through relatively simple design modifications, the expansion of the spectral bandwidth and the ability to measure irradiance is a more challenging task. PMOD/WRC in collaboration with NPL and METAS are currently developing the Cryogenic Solar Absolute Radiometer (CSAR), which will provide the missing link in the traceability chain for solar irradiance.

Performance of the World Standard Group (WSG)

The WSG has served as the primary standard for solar irradiance measurements for more than 30 years. To date no major stability issues have been detected. The individual radiometers in the WSG are frequently compared to each other in order to reveal potential drifts or failures. This technique has proven to be successful in a number of cases, such as the detection of a drop of sensitivity by roughly 0.05 % of the HF18748, which occurred in spring 2006. The affected instrument is temporarily excluded from the WSG until the problem is resolved.

However, not all drifts can reliably be detected. Between the year 2000 and 2005 the sensitivity of one WSG instrument (PMO2) seemingly drifted with respect to the others by roughly +0.015 % per year. It was only during the 10th International Pyrheliometer Comparisons (IPC-X, 2005) [3] when it became apparent that PMO2 agreed well with 58 national and regional standard pyrheliometers and that instead the remaining WSG instruments appeared to have suffered from an annual drift of -0.015 %.

WRR to SI Comparisons

In 1990, 1995 and 2005 the WRR was found to be consistent (well within estimated uncertainties) with SI primary standards for radiant flux (cryogenic radiometers), although a small drift of the WRR was detected in the 2005 WRR-to-SI comparison [4, 5, 6]. This drift is consistent with the results of IPC-X [3].

Future scenarios for the WRR

The CIMO guide [7] requires the WSG to be populated by at least three absolute cavity radiometers of different make. All WSG instruments must have a proven long-term stability record. Out of the five radiometers that make up today's WSG, four were "founding members" of the original WSG in 1977 (i.e. PMO2, PMO5, CROM2L, PAC3). Here we sketch three scenarios to assure the future of the WRR:

1. The WSG will continue to provide the WRR in the future. Therefore it appears necessary to re-populate the WSG with newer instruments. Currently, two instruments from China (SIAR-2a and SIAR-2b) are undergoing long-term stability tests at the WRC. If they prove stable, the *ad-hoc* group of experts may recommend including them in the WSG after the IPC-XI (2010).
2. The WSG provides the WRR only during inter-IPC periods, i.e. during the five years between consecutive IPCs. During the IPCs all regional and national standard pyrheliometers with a sufficiently long history of IPC participation would form an "IPC standard group". This IPC standard group would then provide the new WRR correction factors which would be assigned to all radiometers, including the WSG. Today, most National and Regional Radiation Centers (NRC and RRC) use active cavity radiometers for solar irradiance measurements. Since RRCs are required to participate in the IPC all-regional and many national standard pyrheliometers would be available to form the IPC Standard Group.
3. The concept of the artefact based primary standard for solar irradiance (WSG) is dropped in favour of a new technology-based primary standard, such as the CSAR.

Discussion

Here we focus on scenario 3, which is the only scenario that requires substantial new developments in radiometry. In the past the CSAR has been proposed to fly in space [9]. Based on the original CSAR proposal, a collaboration between PMOD/WRC, NPL and METAS is designing and building a cryogenic radiometer for ground based solar irradiance measurements. The major hurdle in transferring solar cryogenic radiometry from space to ground is the need of a vacuum chamber, and hence an entrance window, which must then have a known transmittance [9]. We plan to have the ground-based CSAR ready by the autumn of 2010 to participate in IPC-XI. The technical specifications and details of the CSAR project have been presented to the NEWRAD 2008 conference [9, 10].

Replacing the WSG by the CSAR would indicate a paradigm shift from an artefact towards a technology-based primary standard for solar irradiance. Appropriate measures would need to be taken to assure smooth transition and the highest continuity between the primary standards. Once the transition is made the WRR (then CSAR) will be able to participate in BIPM key comparisons with other cryogenic radiometers, which is a mandatory requirement for primary standards. The WRR will benefit from the advantages of technology-based standards, such as the reproducibility in the case of failure or loss.

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C6. Climate sensitivity to solar variability

Joanna D. Haigh, Imperial College, United Kingdom

The Sun provides all the energy driving the Earth's climate system so it is important to understand how variations in solar output might induce climate change. The influx of solar radiative energy determines the Earth's mean temperature and radiation budget, while the latitudinal distribution of the absorbed radiation is the primary driver for atmospheric circulations. Photochemical processes in the atmosphere are fundamental to atmospheric chemistry so that the spectrum of incoming solar irradiance influences both the temperature and composition. Thus variations in the solar spectrum have the potential to affect the atmosphere in a complex and non-linear fashion.

This talk considered the evidence for a solar influence on the climate of the Earth's lower and middle atmosphere and discussed some of the processes whereby changes in solar radiation may introduce climate change. First, the energy balance of the Earth was discussed, and how variations in the total solar irradiance incident at Earth introduce a radiative forcing of climate. Then processes involving solar ultraviolet radiation, and how these are modulated by solar activity, were presented. In both cases the focus was on uncertainties and to what extent these depend on the availability and precision of measurements of the solar and atmospheric parameters.

C7. Radiation networks of the WMO: Traceability and meeting the needs of climate

Bruce W Forgan, Bureau of Meteorology, Australia

Radiation metrology as applied to meteorological observations in the WMO has progressed significantly in the three decades since the introduction of the World Radiometric Reference (WRR) in 1981. This has mainly been through the development of better measurement technologies, the World Climate Research Programme (WRCP), the Baseline Surface Radiation Network (BSRN), ISO's introduction of the Guide to the Expression of the Uncertainty of Measurement (GUM) and the regular updates of the Commission for Instruments and Methods of Observation (CIMO) Guide. However, relating climate change measurement requirements to operational metrology is difficult without knowledge of the application of appropriate uncertainty requirements and effective definitions of measurands. Examples were presented showing the utility of past and future radiation climate measurements within the WMO.

The core solar and terrestrial measurements at the WMO *in situ* surface sites are: direct solar irradiance (or exposure); diffuse solar irradiance (or exposure); downward terrestrial (longwave) irradiance; global solar irradiance; and daily sunshine hours. Some member states provide reflected solar irradiance or exposure data and others the net irradiance or net exposure. The most often measured are global exposure (with a pyranometer) and sunshine hours. With the advent of geostationary satellites, derived data provide a fourth tier of measurements.

The primary mechanisms to establish traceability of measurement in the WMO are: the introduction of the WRR and recently the World Infrared Standard Group at the World Radiation Center/PMOD, Davos; a traceability hierarchy through the Regional Radiation Centres; guidelines and advice from expert teams enunciated through CIMO and its Guide; and holding of the International Pyrheliometric Comparison every 5 years. As a result, self-audited WMO member networks provide solar and terrestrial (longwave) data typically related to time increments of hours to the World Radiation Data Centre (WRDC) in St Petersburg. WRDC provides regular feedback to data submitters after statistical quality assurance checks.

The WMO worked with the WRCP to establish the BSRN, now recognized at the Global Climate Observing System (GCOS) radiation network. The BSRN network, of high quality stations generating high frequency data made up of 1 minute statistics, has developed a high level of competence in routine network operation and put in place mechanisms to demonstrate quantitatively the traceability and uncertainty of measurements. The BSRN community has also played a leading role in improvements to instruments, processing algorithms, calibration practice and an introduction of uncertainty concepts to a wider community. Target uncertainties within BSRN for the four main radiation parameters are: direct solar irradiance 1.5 Wm^{-2} (or 0.5 %); diffuse solar irradiance 3 Wm^{-2} (or 2 %); downward longwave irradiance 3 Wm^{-2} (or 2 %); and global irradiance 5 Wm^{-2} (or 2 %). As target uncertainties, they have yet to be met for routine network operations within all of the BSRN. CIMO is working to integrate expanded targets and expressions of uncertainty for 2nd tier network operations to improve measurement practices.

In the 1980s from the guidelines on solar radiation measurement in the CIMO Guide, ISO standards were developed to provide standards for instrument calibration. These ISO standards are now under review and this is being assisted by the close links between CIMO and ISO on solar radiation matters.

C8. Global dimming/brightening and its metrological challenges

Atsumu Ohmura, ETH, Switzerland

During the last two decades three important advances have been made in the field of atmospheric radiation. The first was the discovery of the missing absorption, which led to the correction of the previously underestimated atmospheric absorption of the solar radiation. The second was the discovery of the decadal fluctuation of global solar radiation, and the third was the discovery of the increase in long-wave atmospheric counter radiation. All these discoveries were made owing to terrestrial radiation observations. This paper was mainly concerned with the second topic, which is often referred to as “Global dimming” and “Global brightening”. The article also touched on the third subject, as the change in long-wave radiation will alter the air temperature in combination with that in solar radiation.

It was in the late 1980s when a steadily decreasing trend of global radiation was first noticed in Europe, although the first publication reporting this trend was met with scepticism and a general rejection. Soon similar trends were found in other regions of the world. The magnitude of the decrease was about 8 Wm^{-2} for the 30 year period from the 1950s to the 1980s. In view of the accuracy of dynamometers in use at that time, this magnitude was clearly a detectable difference. The basis for this accuracy is due to the International Pyrheliometric Scale 1956 (IPS1956) and World Radiometric Reference (WRR), and the International Pyrheliometric Comparison (IPC) that recurs every five years. National level efforts to calibrate pyranometers on a regular basis also made an important contribution. The unwillingness to accept the reality of the decadal changes was due to a general belief, prevalent among the energy balance climatologists of the time, that radiation is a very stable component in the climate system. This belief was probably promoted by a widely read textbook written by Michael Budyko which stated that radiation is very stable and several years' observation suffices to characterize a geographical site. It was precisely because of the difficulty to characterize a site with longer observations that global dimming was discovered. The change was correlated with sunshine duration, and attributed to changes in clouds. This was later found to only partially explain the trend.

The decreasing trend, however, did not continue beyond the late 1980s, as in many regions of the world global solar irradiance started to recover in the early 1990s. It was fortunate that this time coincided with the start of the Baseline Surface Radiation Network (BSRN) of the World Climate Research Programme (WCRP) and the Global Climate Observing System (GCOS). The BSRN is not only the radiometric network with the highest accuracy, but with auxiliary atmospheric measurements such as synoptic and radiosonde observations. It was in this network that global brightening was first discovered, as well as in the data obtained under cloudless sky conditions. After this discovery, a component in the atmosphere that did not involve clouds, such as aerosols, had to be considered as a potential cause for the global dimming and brightening.

During the last half a century, we experienced about 30 years of dimming and 20 years of brightening. There are about a dozen locations in the world where global radiation and direct solar radiation have been simultaneously measured. By combining these data it is possible to separate the aerosol direct and indirect effect. Further, it is possible to evaluate the temperature sensitivity due to radiation change. This experiment shows that the aerosol direct and indirect effects are of about the same magnitude, and the temperature sensitivity is 0.06 K/Wm^{-2}. At a glance this sensitivity appears small in comparison with similar values obtained in GCMs. The observed sensitivity, however, contains the irradiance change, which includes all feedback processes. The present sensitivity yields about 1 K temperature increase when carbon dioxide is doubled. This finding coincides with the results of the experiments reached by best three GCMs that participated in AR4, IPCC.

During the last half century, the long-wave counter radiation has been steadily increasing at a rate from 1 Wm^{-2}/decade to 2.5 Wm^{-2}/decade, the latter of which was detected in the BSRN network for the period from 1992 to 2009. For this first detection of the increasing greenhouse effect in the present atmosphere, the establishment of the Infrared Radiometry Section of the World Radiation Centre (WRC-IRS) in Davos has played an important role. The increasing rate of 2.5 Wm^{-2}/decade comes close to the rate of 2.4 Wm^{-2}/decade simulated by ECHAM4 for the coming decades. The trend of total incoming radiation (solar and long-wave) fluctuated between positive and negative values, which ultimately caused the temperature fluctuations we saw over the last 50 years.

Session D: Earth surface (land and water) temperature

D1. GHRSST as a model for deriving climate data from operational sources

Peter J. Minnett, RSMAS, University of Miami, USA

The Global Ocean Data Assimilation Experiment (GODAE) High Resolution Sea Surface Temperature Pilot Project (GHRSST-PP) was an international collaboration of operational and research individuals and agencies set up to produce a new generation of sea-surface temperatures (SSTs), using retrievals from infrared and microwave scanning radiometers on satellites, and *in situ* observations. The need for such an activity arose from the requirements of GODAE, and the GHRSST fields now available are used in NWP, ocean forecasting, ecosystem applications, and climate research.

One of several major foci of GHRSST was to establish the uncertainties of the derived satellite SSTs, based on extensive comparisons with independent data. Previously the accuracies of the satellite-derived SSTs were expressed as a mean and standard deviations of discrepancies between the satellite retrievals and in the *in situ* measurements on a global basis, but now these are expressed in a parametric form with explicit dependences on governing variables. As a result each SST value derived from the satellite measurements is accompanied by estimates of its uncertainties. This is very valuable information for guiding the appropriate application of the data. Another focus was to deliver SST fields from a range of satellite sensors in a common file format, thus allowing easier accessibility to different data sets, easier comparison of different fields, and easier experimentation on the fields. Part of the SST GHRSST product definition is the inclusion of several parameters, derived from satellite data or analysis fields that can influence the SST value or its retrieval from the top-of-atmosphere measurements by the satellite radiometers. GHRSST has also stimulated collaborative research into the physics of the Upper Ocean and Air Sea exchanges, including the ocean thermal skin layer and diurnal variability.

All of these activities, especially the emphasis on determining the accuracies of the retrievals, and efforts to understand what the limiting factors are, lead the way to the generation of Climate Data Records of SST. A necessary requirement for CDRs based on measurements of many satellite instruments over decades is the knowledge of the absolute, not relative, accuracies of the retrieved SSTs, and this has been accomplished by traceability of the measurements of ship-based radiometers used in the validation of the satellite retrieval to a national SI standard, the NIST (US National Institute of Standards and Technology) Transfer Radiometer (TXR) through a series of international workshops at the University of Miami.

The success of the GHRSST-PP was based not only on the enthusiasm and expertise of those involved, but also on the individual national or international funding sources that have facilitated this project.

Although the GHRSST-PP has run its course, the collaborations cemented during this programme continue in the form of the Group for High Resolution Sea Surface Temperature (also GHRSST) and we look forward to continuing co-operation in research, in transitioning research results into the operational environment, and assessing the impact of improved knowledge, and data sets, on a range of applications.

D2. Extending benchmark measurements of traceable SST measurements: SLSTR (Sentinel 3)

David L. Smith, Rutherford Appleton Laboratory, United Kingdom

The Sea and Land Surface Temperature Radiometer (SLSTR) instrument for the GMES Sentinel-3 mission is being designed to continue the Sea-surface temperature records produced by the Along Track Scanning Radiometer (ATSR) series. The sensor includes IR channels at 3.74 μm, 10.8 μm and 12 μm for measuring emitted thermal IR radiances and VIS-SWIR channels at 0.555 μm, 0.659 μm, 0.870 μm, 1.374 μm, 1.6 μm and 2.25 μm to measure reflected solar radiation for cloud and aerosol detection. SLSTR has a wider swath width than its predecessor (1400 km for nadir, 800 km for dual view) to give improved coverage, and higher spatial resolution (500 m) for the visible to short wave infrared channels. To meet its scientific goals, the instrument must measure radiances to an accuracy equivalent to a temperature error less than 0.1 K for all pixels with radiometric noise must be less than 0.08 K at 3.7 μm and 0.05 K at 11 μm and 12 μm, for a scene temperature of 270 K.

Achieving these accuracies requires the system be designed so that it can be calibrated, such that any biases can be measured to a known accuracy either before launch or in-orbit. At IR wavelengths, calibration of the radiometric signals will be achieved through the use of on-board blackbody sources designed to give a known radiance. Two sources based on ATSR design heritage, with high emissivity > 0.999, accurate thermometry, good long term stability and spanning the expected range of scene temperatures, will be used to provide an offset and gain measurement. A particular challenge for infrared sensors is the control of stray light sources due to self-emission and great care has been taken in the design to ensure that the on-board calibration can account for the instrument thermal background.

To ensure the traceability of the measurements a rigorous characterization and calibration programme will be performed, including: characterization and calibration of the subsystems, a full instrument level test campaign under simulated orbital conditions and signals from ground calibration sources that are traceable to SI units. The procedures to be used will draw extensively from the lessons learned from the pre-launch calibration activities of the Along-Track Scanning Radiometer (ATSR) series of instruments.

In order to provide an important reference point between the series of ATSR instruments and the SLSTR calibrations, the two blackbody sources originally provided by the UK meteorological office for the ATSR series will be reused. These sources were designed to illuminate the full pupil of the instrument with an emissivity ~ 0.999 and known to < ± 0.0004 to give a worst case temperature uncertainty of ± 0.02 K at 310 K. When calibrated, the blackbody thermometry is accurate to ± 0.01 K, traceable to ITS90 and has negligible self-heating to give an overall calibration accuracy of these targets of < 0.04 K. This paper described the procedures to be used to ensure the traceability of the instrument calibration to international standards.

D3. Global and local measurements of SST: Harmonization and traceability

Christopher J. Merchant, University of Edinburgh, United Kingdom

Satellite retrievals of sea surface temperature (SST) are becoming more sophisticated, as is the interpretation of the retrieved SST. In this context, the importance of *in situ* accuracy and metadata are increasing, and both *in situ* and satellite observations are being looked at more critically in the context of validation. A key area is understanding how *in situ* and satellite observations inter-relate. The real geophysical differences between these types of observations cannot now be neglected, and the Group for High Resolution SST definitions that are now widely used, have been helpful in clarifying this area. Satellite-buoy comparisons can now be made that adjust for vertical stratification of temperature in the upper ocean, and for temporal change (diurnal cycle) between observation times. The ocean thermal skin dominates *in situ* to satellite differences during the night. The skin behaves differently during the day, and acts simultaneously to the tendency for near-surface stratification. Models exist that can reconcile *in situ* and satellite observations for such effects, although the accuracy of these needs to be improved. These models need information about the depth of observation of buoy observations, particularly under low-wind regimes. The relationship between buoy accuracy and apparent satellite SST uncertainty is discussed. Some analyses are shown that support the view that the best satellite SSTs have comparable accuracy to drifting buoys, which challenges the traditional view of "validation". Rather, the need is for a two-way flow of information between satellite and *in situ* systems to assist uncertainty characterization and quality control. Therefore, increased dialogue between satellite and other observers is desirable.

D4. *In situ* temperature measurements

Etienne Charpentier, WMO, Switzerland

The majority of the sea surface temperature (SST) observations come from drifters, moored buoys, and ships. SST measurements are also being made from rigs and offshore platforms, coastal stations, and tide gauges, or can be derived from upper ocean thermal profiles obtained from Argo floats, tropical moorings, and XBTs. However, only SST observations from drifters, moorings, and ships are addressed here.

Much effort in recent years has gone into standardizing drifter measurements using Lagrangian drifters. Because of the technology used, the quality of the observations is influenced by the sea state and the height of the waves. The DBCP is regularly conducting inter-comparisons of drifters from different manufacturers, and is keeping track of the quality of the observations. Recent studies indicate a quality of SST observations in the order of 0.2K RMS.

Observations from moored buoys are normally more accurate (in the order to 0.1K RMS) than those from drifters because the measurements are less influenced by the waves. However, except for the tropical moorings where the standardization is strong, efforts remain to be made to ensure better traceability of the SST measurements from meteorological buoys and coastal moorings.

The historical Voluntary Observing Ship scheme (VOS) has provided more than 150 years of ocean observations from ships. Many observation techniques have been used over the period and the accuracy of the measurements has been evaluated. Despite early perceptions that the VOS data quality is low, much work has been done in the research community to characterize estimates of SST data uncertainties, and for those well characterized observations, bias adjustments can be made provided appropriate ship metadata are available. The VOS Climate (VOSClim) Project is providing for higher quality data addressing the requirements for climate change monitoring. Automatic Weather Systems (AWS) are also increasingly being used on ships permitting the collection of higher resolution data using certified instruments.

Standards for the VOS scheme are defined in relevant WMO Publications. Classes of VOS have been introduced to standardize measurements and track certification of the instruments. Most of the VOS scheme is “selected ships” and all report SST. Recently, it has been proposed to add a VOSClim class of vessel, and an Automatic Weather Station (AWS) sub-class for all classes. A network of Port Meteorological Officers (PMO) is assisting in the recruitment of vessels, and verification that recommended observing practices are being followed.

Quality of VOS data and SST in particular is routinely monitored by meteorological centres and inter-comparison of VOS data acquisition systems and electronic logbooks are being promoted to enhance standardization and improve data quality. Collecting platform/instrument metadata are collected for interpreting the data correctly, ensuring traceability to standards, enhancing coherence of data records, and facilitating quality monitoring activities.

The so called "ship masking" issue remains a concern for the ocean community, in particular impacting quality monitoring and bias correction. Measures are being taken to minimize impact for the end users of the data.

The WMO Integrated Global Observing System (WIGOS) is developing and aiming in particular at facilitating standardization of ocean *in situ* measurements, enhancing the traceability of those measurements to standards, and facilitating assessment of the stability of the measurements, evaluation of the uncertainties, and the quality of those measurements.

D5. Establishing climate quality data: Traceability needs and issues

David T. Llewellyn-Jones, University of Leicester, United Kingdom

Recently, the technology of satellite instrumentation has been demonstrated in several cases to be well capable of making the type of accurate quantitative measurements that are required. However, in order to acquire a long time-series of data it may be necessary to use records from a series of sensors which, although they measure nominally the same parameters, may have been procured by a number of separate agencies using, perhaps, very different engineering designs and, almost certainly, differing procedures for characterization and calibration of the sensors. For climate applications, especially, this can be a major obstacle to acceptance by the user communities of satellite data records.

The QA4EO Initiative has led to a set of guidelines which aims to set out realistic and practical procedures which can be followed in the calibration and validation of earth-observing satellite sensors. If these guidelines, which now enjoy a certain level of widespread support and endorsement in principle, could be accepted and adopted, many difficult issues of traceability and inter-operability will be effectively addressed.

To accomplish this vision, starting from a system of disparate systems that were built for a multitude of applications, requires the establishment of an internationally coordinated operational framework to facilitate interoperability and harmonization of methodologies used in data collection, particularly with respect to the calibration and validation of data. There can be little doubt that this is likely to be more easily said than done. However, the current need for effective and consistent climate monitoring are now such that the general acceptance and implementation of traceable standards and repeatable procedures must be regarded as mandatory.

There are major implementation issues which can and, in some cases, will inhibit the general adoption of this concept and it is essential that standards applied are not only agreed by the participants, but that the procedures advocated and used are practical as well as manifestly justified.

This paper highlighted some of the practical issues which might be encountered and recommended some possible ways forward. Problems of inter-sensor calibration and of the respective roles of satellite and *in situ* data records, both of which are of great importance to climate records, were described and discussed. Examples were taken from current and future programmes, with particular emphasis on the Along-Track Scanning Radiometer space instruments, of which the current sensor is the AATSR on ENVISAT. These sensors were specifically designed to be capable of producing measurements of the accuracy and stability required for climate applications.

D6. Validating post-launch instrumentation: CEOS comparison of brightness temperature instrumentation

Evangelos Theocharous, Nigel Fox and Eric Usadi, NPL, United Kingdom

The measurement of the Earth's surface temperature and more fundamentally, its temporal and spatial variation is a critical operational product for meteorology and an essential parameter for climate monitoring. Satellites have been monitoring global surface temperature for some time. However, it is essential for long-term records that such measurements are fully anchored to SI units. Field-deployed infrared radiometers currently provide the most accurate surface based measurements which are used for Cal-Val. These radiometers are in principle calibrated traceably to SI units, generally through a blackbody radiator. However, they are of varying design and are operated by different teams in different parts of the world. It is essential for the integrity of their use, that any differences in their measurements are understood, so that any potential biases are removed and are not transferred to satellite sensors.

A comparison of terrestrial based infrared (IR) radiometric instrumentation used to support calibration and validation of satellite borne sensors with emphasis on sea/water surface temperature was completed in Miami in 2001. However, eight years had passed and as many of the satellite sensors originally supported were nearing the end of their life, a similar inter-comparison was repeated in 2009. The objectives of the 2009 comparison were to establish the "degree of equivalence" between terrestrially based IR Cal-Val measurements made in support of satellite observations of the Earth's surface temperature and to establish their traceability to SI units through the participation of national standards laboratories.

During the 2009 comparison, NPL acted as the pilot laboratory and provided traceability to SI units during laboratory comparisons in Europe. NPL was supported by the Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami, acting as hosts and by NIST providing traceability to SI units during laboratory measurements at RSMAS. The 2009 comparison consisted of two stages in order to allow maximum participation and enable the traceability chain to be established to both NPL and NIST. Stage 1 took place at NPL in April 2009 and involved laboratory measurements of participants' blackbodies calibrated using the NPL reference transfer radiometer (AMBER), while participants' radiometers were calibrated using the NPL variable temperature blackbody. The performance of 4 blackbodies and 8 radiometers operating on 24 measurement channels was compared during Stage 1. Stage 2 took place at RSMAS in May 2009 and involved laboratory measurements of participants' blackbodies calibrated using the NIST Thermal-Infrared Transfer Radiometer (TXR), while participants' radiometers were calibrated using the NIST water bath blackbody (WBBB). The performance of 9 radiometers operating on 14 measurement channels was compared during Stage 2. Stage 2 also included the testing of the same radiometers alongside each other, completing direct day-time and night-time measurements of the skin temperature of the Ocean. Because AMBER and the NPL variable temperature blackbody were not readily portable, linkage between the two stages was established though participants radiometers used in both stages, serving as transfer standards.

During the 2009 comparison, all participants were encouraged to develop uncertainty budgets for all measurements they reported. In order to achieve optimum comparability, lists containing the principal influence parameters for the measurements were provided to all participants. All measurements reported by the participants, along with their associated uncertainties were analysed by the pilot laboratory and were reported at the WMO-BIPM workshop.

D7. Establishing climate surface temperature quality data: Traceability needs and issues

Richard W. Reynolds, NCDC, NOAA, USA

To obtain surface temperatures, land and ocean temperatures are usually processed separately. Over land, air temperatures at the surface are measured directly by thermometers. Over the ocean, sea surface temperatures (SST) are used instead of marine air temperatures, because of large biases in the marine air temperatures during the day due to ship deck heating. SSTs are measured using thermometers in buckets, ship engine intake temperatures, ship and buoy hull contact temperatures, hydrographic ocean profile temperatures, and by infrared and microwave satellite instruments. Both land temperatures and SSTs are analyzed to produce complete gridded fields for many purposes such as climate monitoring. An example of annual averaged SSTs is shown in Figure 1 with error estimates.

Data processing is similar for the land and the ocean. Over land, measurements are produced at stations. It is important to correct biases caused by changes in station location and to eliminate any individual observations with large errors. Processing of SST observations is more complicated than land because of large instrumental changes. *In situ* SST data were made from ships using uninsulated buckets in the earliest part of the record. Over time the uninsulated buckets were replaced by insulated buckets, hull contact sensors and engine intake temperatures. Each type of measurement has biases associated with it. Unfortunately, metadata are often missing so correction is difficult. Recently (beginning in the late 1970s) SST observations from drifting and moored buoys were added to the *in situ* archive. In addition, beginning in 1981, accurate infrared satellite retrievals became available and were supplemented in 1997 with accurate microwave satellite SST retrievals.

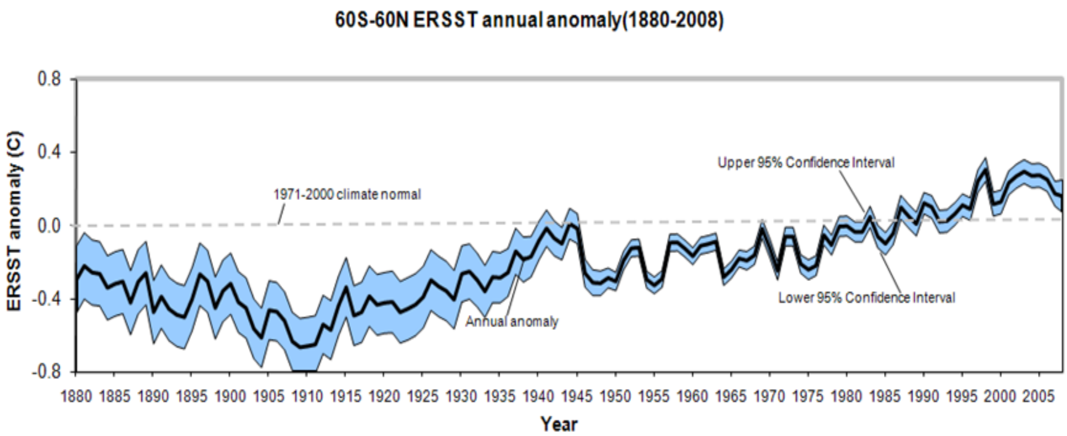


Figure 1. Annual averaged anomaly SSTs between 60°S and 60°N. Anomalies are computed as departures from a 1971-2000 climatology.

After the data are processed to either correct large errors, if possible, or to eliminate them, the observations are usually averaged in time and space. This results in a relatively noisy gridded field with missing grid boxes. The purpose of an analysis is to fill in the missing boxes and to smooth the final result. Analysis procedures typically include methods such as optimum interpolation (OI) which produces an analysis when the analysis error covariance and the observational noise-to-signal ratios are defined. The OI procedure is typically used for recent periods when the data are fairly dense due to the availability of satellite data. Other analysis procedures involve the fitting of predefined modes to data. In this fitting procedure the modes are defined by the covariances of data in recent periods when data are plentiful. These modes are then fitted to data in earlier periods. This fitting procedure is frequently used for historic analyses prior to the satellite era when only sparse *in situ* data were available.

Session F: Microwave imagery data in climate and NWP

F2. Microwave imager data in NWP

William Bell, ECMWF, United Kingdom

The importance of microwave sounding (MWS) data from measurements in the 50 GHz to 60 GHz spectral range, providing information on atmospheric temperature, is well established. Until recently these measurements gave the largest contribution to NWP forecast skill from all available data in many areas of the globe. Data from microwave imaging (MWI) instruments provides the most important information on oceanic lower tropospheric water vapour in NWP models. This data also provides information on cloud water, precipitation and ocean surface wind speed. MWI data is assimilated, usually in the form of radiances, at most NWP centres. The current use of the data at several NWP centres was reviewed. For example, at ECMWF data from SSMI and AMSR-E have been actively assimilated for some time and data from TMI, SSMIS, Coriolis-Windsat and FY-3 MWRI has been monitored passively. The brightness temperatures from these instruments are corrected using variational bias correction (see MWS session talk A2 by D. Dee), which permits an assessment of the comparability of the measured radiances. Differences of several Kelvin are common.

For NWP applications the radiometric requirements (noise performance and accuracy) for imager channels are currently less stringent than those for sounder channels, but still present a challenge for conical scanning instruments.

NWP models have also proved to be very useful in the assessment of data quality from a number of recent imager and imager/sounder missions and have led to the identification of several sources of instrumental biases. Examples were presented for SSMIS and TMI. In these cases the complex orbital biases have hampered efforts to exploit the data in operations and highlight the need for more accurate pre-launch calibration and testing.

More generally the prospects for the future exploitation of MWI data in NWP and reanalysis were presented and the anticipated accuracy requirements for these applications were reviewed.

F3. NPOESS microwave imager/sounder (MIS) sensor development

David Kunkee, The Aerospace Corporation, USA

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO) is developing a multi-channel conical-scanning Microwave Imager/Sounder (MIS) for the NPOESS C2 mission. The NPOESS MIS will continue and improve upon the legacy microwave brightness temperature measurements of the Defense Meteorological Satellite Program's (DMSP) Special Sensor Microwave Imager/Sounder (SSMIS). Key features of the MIS radiometer include channels at 6- and 10-GHz and improved horizontal spatial resolution compared to SSMIS. The MIS will include Atmospheric Vertical Moisture Sounding (AVMP) and Vertical Temperature Profiling (AVTP) up to the 10 mb pressure level. The second MIS sensor will include the full Upper Atmospheric Sounding (UAS) capability up to 0.01 mb continuing the SSMIS measurement capability. Overall, MIS will fulfil 17 Environmental Data Records (EDR) including AVMP, AVTP, Sea Surface Wind Speed and Direction (SSWS/D), soil moisture, and Sea Surface Temperature (SST).

Performance priorities for the MIS sensor are subdivided into five categories: 1) Core imaging capability representing the legacy SSM/I imaging channels plus the 10-GHz vertically- and horizontally-polarized channels, 2) AVTP and AVMP capabilities at the performance level of SSMIS, 3) all-weather sea surface temperature including 6-GHz vertically- and horizontally-polarized measurements with RFI mitigation to ensure uncontaminated brightness temperature observations over land as well as over ocean, 4) polarimetric channels for retrieval of sea surface wind vector and 5) upper atmospheric temperature profile.

This presentation described the key performance characteristics and design priorities of the MIS radiometer to achieve required Sensor Data Record (SDR) and EDR performance for the next generation operational microwave imager and sounder. Assessment of MIS EDR impacts to weather forecasts and climate studies was also addressed.

F4. Lessons learned from AMSR and plans for GCOM-W

Haruhisa Shimoda and Keiji Imaoka, EORC, JAXA, Japan

The Advanced Microwave Scanning Radiometer (AMSR) and the AMSR for the Earth Observing System (AMSR-E) are the multi-frequency passive microwave radiometers developed by the Japan Aerospace Exploration Agency (JAXA). The AMSR instrument was onboard the Advanced Earth Observing Satellite-II (ADEOS-II). Although the mission life was shorter than expected due to a satellite problem, the instrument, together with other onboard instruments including the Global Imager (GLI) and SeaWinds, gathered about seven month's global data. The AMSR-E instrument on NASA's Aqua satellite has been continuing its successful observation since May 2002. The two instruments have several characteristics which enable the unique measurements. The large main reflector (1.6 m and 2.0 m for AMSR-E and AMSR, respectively) provides better spatial resolution, which is an advantage in measuring small scale features including precipitation and sea ice. The 6.925 GHz channels provide a capability of global and all-weather sea surface temperature (SST) measurement. Particularly for operational weather applications, AMSR-E observations from the afternoon orbit are beneficial since most of the microwave radiometers are in the morning orbit.

The most significant calibration issue of AMSR and AMSR-E originates from the High Temperature noise Source (HTS), or warm calibration load. Due to the design, there exists a time-varying, physical temperature non-uniformity over the calibration load. Therefore, simple two-point calibration does not work. To derive the brightness temperatures, we are currently using the combined approach of a multiple regression method and a receiver temperature-referenced method. Also, non-linearity correction is applied particularly for the lower frequency channels. To assess the validity of brightness temperatures, inter-comparison or cross-calibration with other similar instruments including the Special Sensor Microwave/Imager (SSM/I) and the TRMM Microwave Imager (TMI) is indispensable. Year-to-year stability of brightness temperature is being monitored over homogeneous ground areas such as rainforest areas, ice sheets, and oceans. Based on the activities, we are still updating the calibration of AMSR-E products.

The Global Change Observation Mission (GCOM) is JAXA's long-term monitoring concept and consists of two satellite observing systems and three generations, to achieve global, comprehensive, and long-term Earth monitoring. The first satellite of the GCOM-W (Water) series will be GCOM-W1 with the Advanced Microwave Scanning Radiometer-2 (AMSR2) onboard. AMSR2 is a successor of AMSR and AMSR-E. Basic performance of AMSR2 will be similar to that of AMSR-E, based on the data continuity requirement of AMSR-E, with several enhancements including a larger main reflector (2.0 m), additional channels in the C-band receiver, and improved calibration. Experiences through the

AMSR and AMSR-E development, calibration, and algorithm investigations can be directly utilized in the AMSR2 programme. JAXA is participating in inter-calibration activities such as the GPM cross calibration working group to enhance the data uniformity and consistency. The current target launch date of GCOM-W1 is in Japanese fiscal year 2011.

F5. Pre-launch testing, calibration and on-orbit performance of the METEOR-M N1 microwave imager/sounder

A.B. Uspensky, I.V. Cherny, State Research Center on Space Hydrometeorology "Planeta", Russia

The presentation described the space-borne microwave radiometer MTVZA-GY on board the Meteor-M N 1 spacecraft. This spacecraft was launched on 17 September 2009 on a sun-synchronous orbit at an altitude of 830 km. The instrument MTVZA-GY is a microwave imager/sounder. It will be used as the meteorological imaging system for remote sensing of ocean and land surface parameters as well as for measuring global atmospheric temperature and water vapour profiles together with some integrated parameters of atmosphere and clouds.

The instrument operates at frequencies of 10.6 GHz, 18.7 GHz, 23.8 GHz, 31.5 GHz, 36.5 GHz, 42 GHz, 48 GHz, and 91 GHz, oxygen lines 52 GHz to 57 GHz, and water vapour line 183.31 GHz. The instrument is a conical scanning device looking aft. The swath width is 1500 km. The spatial resolution is 16 km to 198 km.

The pre-launch testing and calibration of the microwave imager/sounder MTVZA-GY was discussed. The on-orbit performance and absolute calibration of the microwave imager/sounder MTVZA-GY are considered separately for the imager and for the sounder channels.

F6. Calibration issues of microwave imagers

Shannon Brown, JPL, USA

The pre-launch calibration of microwave radiometers involves careful characterization of both the antenna and receiver sub-systems. In general, the radiometer output is referenced to high quality microwave blackbody calibration targets, but often, the plane of calibration is not the same as the plane of the measurement, requiring several additional corrections prior to obtaining the calibrated main beam brightness temperature. This talk surveyed pre-launch calibration techniques that have been applied to microwave radiometers as well as post-launch calibration techniques, focusing on the relationship between the two. Recently, the demand for high quality calibrated microwave radiances has increased due to direct assimilation of the radiances into numerical weather prediction models and for climate change studies. These studies have revealed many previously unknown or undetected calibration issues that were caused by inadequate pre-launch characterization, instrument design or processing algorithm limitations. Examples include receiver linearity errors, calibration target instability, reflector surface emission and scan dependent errors. In response to these issues, new pre-launch calibration and characterization techniques have been developed in an attempt to mitigate these errors. This talk discussed these pre-launch calibration techniques along with the post-launch calibration techniques used to detect calibration anomalies. Both pre-launch and post-launch calibrations have limitations and it is vital that they are planned and executed in collaboration to maximize the effectiveness of each.

F7. A plan for developments of climate data records from Special Sensor Microwave Imager (SSM/I) and Sounder (SSMIS)

Fuzhong Weng and Chris Kummerow, NOAA, NESDIS, USA

Satellite measurements from the Defense Meteorological Satellite Program's (DMSP), Special Sensor Microwave/Imager (SSM/I) is the longest term series of satellite microwave imagers in existence, beginning in July 1987 and continuing today (20 years of continuous data). These observations are being followed with a nearly identical sensor, the Special Sensor Microwave Imager/Sounder (SSMIS), which will continue to operate for at least the next decade. This sensor package will ultimately be replaced by something comparable on the converged NOAA/DMSP polar satellite programme, NPOESS, continuing this record of passive microwave measurements well beyond 2020 (at present, this sensor package is under review). This long term series of SSM/I sensors has to be well calibrated for intersensor bias, sensor degradations, and diurnal variations, in order to generate high quality and self-consistent climate data records (CDRs). Without cross-calibration, the trend of climate variables derived from SSM/I are inconsistent. At NOAA, we will examine the data quality related to all the SSM/I instruments in these following areas:

1. Characterize in-orbit performances of DMSP SSM/I series on their noise magnitudes, telemetric data and calibration targets,

2. Characterize the pattern of interference on several individual SSM/I from special operations, and unspecified targets,

3. Perform inter-sensor calibration of the entire SSM/I and SSMIS time series (eight satellites at present) to remove the inter-sensor biases. Special treatment for the F-16/17 SSMIS antenna emission will be required,

4. Develop a metadata database that will contain all necessary information on the sensor so that the newly developed calibration information can be repeated by the science community. This data will be archived at NCDC,

5. Utilize the full swath of fundamental climate data records (FCDRs) to generate improved environmental data records (EDRs). These will form the initial thematic climate data records (TCDRs) using the legacy algorithms already in place,

6. Use newly developed algorithms to improve the TCDRs, as well as some potential new products such as emissivity over land, snow and ice; ice and cloud water content over land, and soil wetness index.

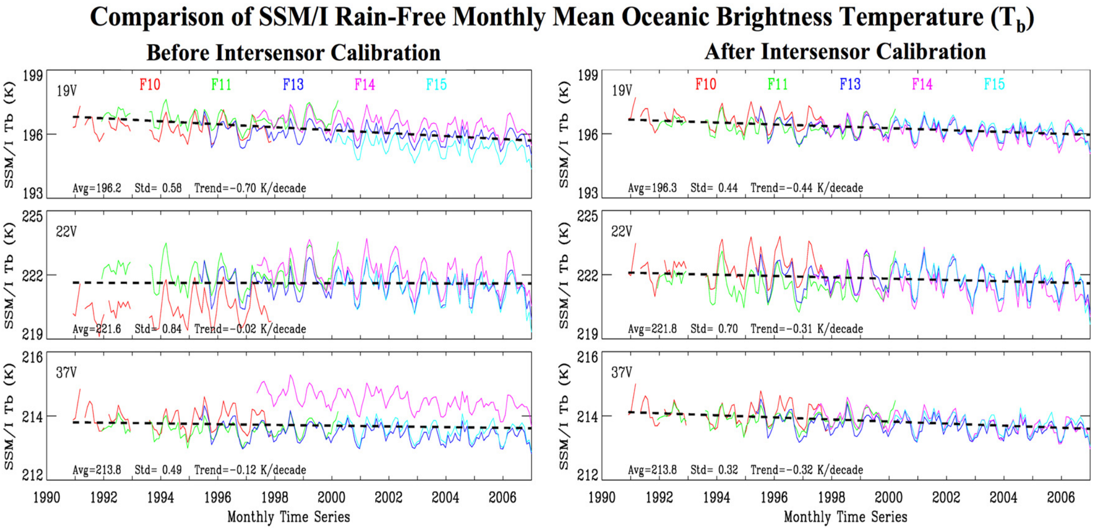


Figure 1. Time series of the SSM/I rain-free monthly mean brightness temperature (T_b) over ocean at 19V GHz (top panel), 22V GHz (middle panel) and 37V GHz (bottom panel) channels for before (left panel) and after (right panel) intersensor calibration.

Session G: Surface properties: Albedo, land cover and ocean colour

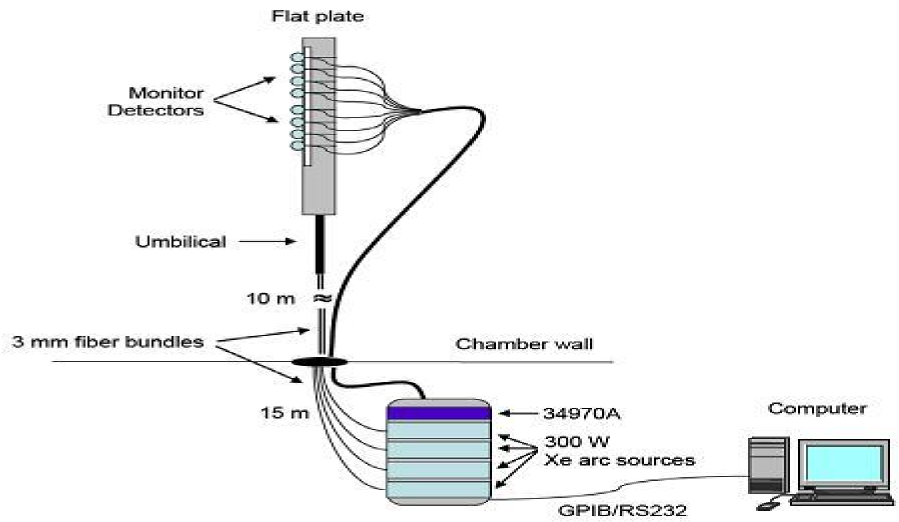
G1. Metrology considerations for the next generation of satellite sensors

Bruce Guenther, NOAA, USA

The National Oceanic and Atmospheric Administration (NOAA) is developing two advanced satellite systems in the United States. One satellite system will be launched into low earth orbits (LEO) at about 830 km altitude and one system will be launched into Geo-synchronous orbit (GEO). The LEO mission is the National Polar-orbiting Operational Environmental Satellite System (NPOESS) under development jointly with the US Department of Defense and the National Aeronautical and Space Administration (NASA). The first flight for the NPOESS is the NPOESS Preparatory Project (NPP) and includes 5 sensors. The GEO system is the Geosynchronous Operational Environmental System-R Series (GOES-R). GOES-R is in development jointly with the NASA and is now slated to include 6 instruments.

Information was presented about new testing strategies for the Visible Infrared Imaging Radiometric Suite (VIIRS) under development at the US National Institute of Standards and Technology (NIST) and funded jointly by the NPOESS Program and NIST. The VIIRS characterization areas are for improved spectral testing for large aperture sensors and system-level end-to-end testing to determine the effective Bi-directional Reflectance Distribution Function (BRDF) of the Solar Diffuser. These technologies also support improved in-vacuum radiometric trending. The key technology is the use of commercial flat plate illumination strategies that are fed with fibre optic bundles. Other work that was described included improved measurements of spectral emissivity in the infrared for the Cross-track Infrared Scanner (CrIS) and improvements in the calibration and characterization of microwave sensors (also described by Blackwell, in Session A: Climate Trends from Microwave Sounding Data).

Our Flat Plate Illuminator is based on commercial technologies for the terminator illuminator plate, various lamp sources of monochromatic and polychromatic outputs, and a fibre optic bundle that transmits the signal onto the (flat) illuminator plate. (We are using an integrating sphere for some applications of this technology.) An important advantage of this application for ground testing of spaceflight measurement systems is that the high power sources are isolated outside a vacuum chamber where cooling of the source may be accomplished easily, and the requirement for power dissipation within the vacuum environment is relatively easy to accomplish. The perturbation for power dissipation on VIIRS for these uses is about 10 % of the sensor total power dissipation.



The research and operations User Community for both NPOESS and GOES-R involve atmosphere, land and ocean studies. Several of these studies and members of our user community were on the agenda of the meeting. We are conducting a survey of both the NPOESS and GOES-R User Communities to identify where they need metrology improvements to meet their mission objectives and the results of this survey were presented.

G2. Advances in traceability for pre-flight calibration

B. Carol Johnson, NIST, USA

The Optical Technology Division (OTD) at NIST has the goal of providing the measurement science and standards to ensure that satellite measurements of the Earth's infrared and optical radiation meet the stringent requirements for climate-change science, weather forecasting, and other applications. It is recognized that instrument calibration, characterization, and stability are of primary concern with respect to these requirements. As a result, the OTD actively investigates application of novel technologies and new protocols or approaches to scale realizations. This talk reported on recent developments in the Spectral Irradiance and Radiance Responsivity of Uniform Sources (SIRCUS) facility, the facility in development for reflectance metrology, advances in infrared measurement science, a description of the Hyperspectral Image Projector (HIP), development of a detector-based, spectrally tunable, broadband or quasi-monochromatic source, and gave examples of recent efforts.

G3. Post-Launch calibration and validation needs for ocean colour sensors

Giuseppe Zibordi, JRC, Italy

The term ocean colour identifies remote sensing of the sea in the visible and near infrared to primarily determine the radiance emerging from the sea-surface, the so called water leaving radiance (Lw), from the top-of-atmosphere radiometric signal. By exploiting the spectral distribution of Lw, the goal of satellite ocean colour is the determination of the concentration and optical properties of those seawater constituents absorbing and scattering light, such as phytoplankton, suspended sediment and coloured dissolved organic matter, which are all relevant to climate studies and water quality monitoring.

At the most favourable wavelengths, Lw is generally less than 5 % of the top of the atmosphere radiance. Thus the accuracy of the absolute calibration of the space sensor and of the so-called atmospheric correction applied to remove the perturbing effects of the atmosphere from the top-of-the-atmosphere signal, are both elements largely conditioning the accuracy of the derived products.

Target uncertainty for the calibration of satellite ocean colour sensors is ideally better than 0.5 %. This value results from:

- The 5 % uncertainty requirement for Lw in the blue spectral region for oligotropic regions
- The consideration that any uncertainty in top-of-the-atmosphere radiance produces an uncertainty approximately ten times higher in derived Lw.

This demanding calibration requirement imposes:

- A pre-launch absolute calibration and characterization of the space sensor
- A continuous assessment of changes with time in the sensitivity; and additionally

- The adjustment of calibration coefficients through vicarious calibration relying on highly accurate *in situ* data together with the mission specific atmospheric correction code.

As a result, pre-launch calibration and characterization provides traceability to space observations; detection and fixing of sensitivity changes with time ensures traceability to the sensor absolute calibration beyond the launch date; and finally vicarious calibration minimizes the effects of residual uncertainties in the absolute calibration of the space sensor as well as inaccuracies of the atmospheric correction process.

Clearly the vicarious adjustment factors, once determined at a specific site, might not be equally accurate at the global scale because of the existence of peculiar conditions challenging the atmospheric correction process. This is likely to occur in coastal regions which might be characterized by aerosol types not accounted for in the atmospheric correction model. Because of this, vicarious adjustment factors are generally determined using sites pertaining to the most common marine regions on the globe (i.e., oligotropic and mesotropic deep waters) which are likely to be dominated by oceanic aerosols. This intrinsic limitation of the calibration process imposes the assessment of the accuracy of remote sensing radiometric products at the global scale to verify their suitability to determine high level products. Such a global validation effort requires high quality *in situ* data with specific features: traceable to reference standards and with defined uncertainties; globally distributed to represent the wide range of geophysical conditions that remote sensing sensors are expected to observe; continuous to ideally embrace successive space missions; cross-site consistency to have comparable uncertainties at the various measurement sites for similar measurement conditions; and finally accessible to any calibration and validation programme through a suitable data policy.

G4. Measurement uncertainties of surface albedo and need for traceability

Jan-Peter Muller, MSSL, United Kingdom

A land surface broadband albedo map of the entire Earth's land surface (snow and snow-free) is required for use in Global Climate Model initialization and verification. The ESA has sponsored the production of such a GlobAlbedo product for the 15 years from 1995-2010. A prototype albedo retrieval system was previously generated within the MERIS AlbedoMap project which employed MODIS BRDF and magnitude inversion for four common spectral bands. This data fusion assumed that sensor inter-calibration was known to sufficient accuracy and that small sensor differences due to different spectral ranges were negligible. However, inter-comparisons especially between instantaneously derived NASA MISR and MODIS with MERIS spectral albedos showed significant differences which could only partly be explained by radiometric calibration differences.

To generate the GlobAlbedo product by temporal compositing at 1 km and lower resolution on both equal area and latitude, longitude grid requires both sufficient directional looks and the very precise correction of top-of-atmosphere radiances to "at surface" directional reflectances (SDRs). In addition, such a map requires precise radiometric calibration of different sensors and the computation of radiative transfer coefficients to derive broadband SDRs from input narrowband SDRs and given sufficient angular sampling from the all the directional looks within a given temporal window, derive a suitable BRDF and DHR (Direct Hemispherical Reflectance known as "black-sky") and BHR (BiHemispherical Reflectance, known as "white-sky"). The final albedo product will be integrated in three spectral broadband ranges, namely the solar spectrum (400 nm-3000 nm), the visible (400 nm-700 nm) and the near- and shortwave-infrared (700 nm-3000 nm).

To achieve the aim of deriving independent estimates using European only assets, GlobAlbedo sets out to create a 15 year time series by employing ATSR2, SPOT4-VEGETATION and SPOT5-

VEGETATION2 as well as AATSR with MERIS. Legacy algorithms for deriving SDRs using an optimal estimation approach were outlined as well as a novel system for gap-filling using ten year mean estimates derived from US sensors.

Traceability is required for this product as well as sensor inter-calibration with pre-existing US sensors from AVHRR, MODIS and MISR. To achieve this aim the QA4EO protocols over the Antarctic DOME-C site (Cao *et al*., 2010, submitted; Mackin *et al*., 2010, submitted) is employed for December 2008/January 2009 for a bright surface using both nadir and multi-directional looks using SeaWiFS as the reference sensor owing to its frequent lunar calibration. There is a need to expand this sensor inter-calibration back to 1995 as well as to dark surfaces. The challenges to perform this task were discussed and possible solutions described.

G5. Improving field spectroradiometric measurements for optical land surface imager calibration and product generation

Michael E. Schaepman, University of Zurich, Switzerland

Field spectroradiometers have improved substantially over the past decades. However, spectroscopic measurements remain the least reliable of all physical measurements. Field spectroscopy has become established as an important technique for characterizing the reflectance of natural and man-made surfaces *in situ*, for supporting the vicarious calibration of airborne and satellite sensors, and for providing a means of scaling-up measurements from small areas to composite scenes. The presentation described the physical basis of the subject and evaluated the different methods, uncertainties and instruments which have been employed. The development and use of field goniometers was described, and related to methods for estimating the bidirectional reflectance distribution function (BRDF) from directional reflectance measurements in the field. This ultimately leads to the capability of assessing not only radiance based satellite data, but also higher level products, such as a variety of surface albedo products. Field measurements and methodologies presently used, including spectral databases and advanced calibration methods were presented. Comparison examples were given with the explicit calibration of MERIS on ENVISAT, as well as intermediate scaling instruments, such as the airborne APEX. The prospects for the future of field spectroscopy were considered in relation to the increasingly important contribution that field spectral data will make to EO-based global measurement and monitoring systems, specifically through their assimilation into numerical models. Potential uncertainties of assimilating reflectance instead of clear-sky albedo into these models were discussed. However, for this to be achieved it is essential that the data are of high quality, with stated levels of accuracy and uncertainty, and that common protocols are developed and maintained to ensure the long-term value of field spectroscopic data. The importance of employing a precise terminology for describing the geometric configuration of measurements was highlighted in relation to issues of repeatability and reproducibility. Through such refinements in methodology, field spectroscopy will establish its credentials as a reliable method of environmental measurement, underpinning quantitative Earth observation and its applications in the environmental and Earth sciences.

G6. The oceans, the carbon cycle and the establishment of a climate data record

Sean Bailey, NASA, USA

The US National Research Council defines a climate data record (CDR) as “a time series of measurements of sufficient length, consistency and continuity to determine climate variability and change." Discerning the role of the ocean in the Earth's carbon cycle requires a global perspective, such as that provided by satellite-based measurements. The satellite record of ocean colour is approaching "sufficient length" to be considered a CDR. The "consistency and continuity" of this data record, however, need consideration prior to its designation as a CDR.

Obtaining consistency in data products that are relevant to carbon cycle studies (e.g., concentrations of chlorophyll-a, particulate inorganic carbon, particulate organic carbon, and coloured dissolved organic matter, etc.) requires consistent satellite radiometry. This is no small task, as the desired radiometric signal, the spectral radiance exiting the water mass, is a fraction of the total top-of-atmosphere (TOA) signal measured by the instrument. Extracting the ocean surface signal from the TOA signal requires the use of complex radiative transfer algorithms that account for sensor and solar geometries, polarization, Rayleigh and aerosol atmospheric path radiance and gaseous absorption, and instrument-specific characterizations, such as out-of-band response, response versus scan angle, and polarization sensitivities. Each aspect of this complex process maintains uncertainties.

Satellite ocean colour radiometers are typically designed to operate for five years, a time scale far too short for an individual instrument to provide a CDR. Multiple missions are required to meet the criteria of "sufficient length" for the time series. No viable mission to date has an instrument design that is identical to any previous mission. As such, sensor and data processing differences exist, which impedes satisfaction of the criteria for continuity, not only from an instrument design perspective, but also with respect to data products. For example, while two missions - SeaWiFS and MODIS - both provide a chlorophyll-a data product, differences in the sensor designs force the chlorophyll-a algorithms employed by each mission to differ accordingly. A common processing code base has been shown to help reduce inter-mission uncertainties.

From the proof-of-concept CZCS through the current suite of SeaWiFS, MODIS, MERIS, OCM and the soon to be launched NPP/VIIRS, sensor capabilities have largely improved, while the number of available data products has increased. Future missions will continue this trend. The overarching challenge will be generating consistent time series from this inconsistent instrument suite with sufficiently small uncertainties to allow for the detection of real geophysical change. Equally critical to the production of a consistent long-term time series is the ability to track long term sensor stability on orbit. Various methods have been employed to accomplish this, including on-board solar diffuser measurements and lunar observations.

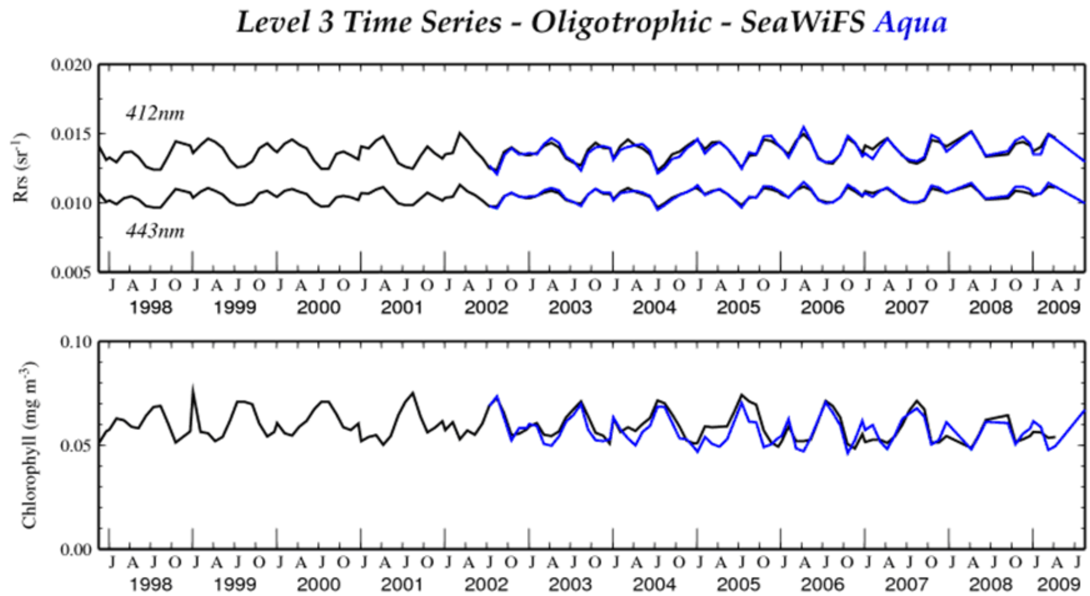


Figure 1. Oligotrophic water Radiance and Chlorophyll time series – SeaWIFS through MODIS Aqua.

G7. Remote sensing of the earth: Propagation through and correction for the atmosphere

Menghua Wang, NOAA, USA

In the satellite remote retrieval of the ocean (and inland) water near-surface optical and biological properties, it is crucial to accurately remove the atmospheric and water surface effects from sensor-measured signals. This process, which usually corrects for more than 90 % of satellite sensor-measured signals, is termed as atmospheric correction. The NASA standard atmospheric correction algorithm for Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) uses two near-infrared (NIR) bands for retrieval of aerosol properties with assumptions of the black water at the NIR wavelengths and non- or weakly-absorbing aerosols. A similar algorithm has also been used for producing global open ocean colour products from various satellite sensors, e.g., the Medium Resolution Imaging Spectrometer (MERIS) from the European Space Agency (ESA), the Global Imager (GLI) from Japan Aerospace Exploration Agency (JAXA), the Polarization and Directionality of the Earth's Reflectances (POLDER) from Centre National d'Etudes Spatiales (CNES), etc., SeaWiFS (1997-present) and MODIS-Aqua (2002-present) have been producing high quality ocean colour products over global open oceans. For the turbid waters in the ocean coastal regions, however, water could have significant contributions in the NIR bands (violation the NIR black ocean assumption), leading to significant errors in the satellite-derived water property products. In addition, aerosols in coastal regions are sometimes strongly absorbing (violation of the assumption for non- or weakly absorbing aerosols). These two issues are primary challenges for ocean colour remote sensing in the coastal regions. In this presentation, an overview was provided of the SeaWiFS/MODIS atmospheric correction algorithm that is currently used for deriving the global ocean colour products. Some new approaches for dealing with the coastal turbid waters and strongly absorbing aerosols were reviewed and discussed. In particular, a recently developed new approach using the shortwave infrared (SWIR) bands for atmospheric correction for dealing with the turbid waters was described in detail. Advantages of the new approach by comparing water optical and biological property results derived from the SWIR atmospheric correction algorithm and from the standard (NIR) algorithm were demonstrated. Some specific applications for deriving ocean colour products along the China east coastal regions, as well as for monitoring and assessment of Lake Taihu blue-green algae bloom during the spring of 2007, were presented and discussed.

Session H: Ocean salinity

H1. TEOS-10: International Thermodynamic Equation of Seawater 2010

Rainer Feistel, Institut für Ostseeforschung, Germany

Very accurate empirical thermodynamic potential functions are available for fluid water, ice, seawater and humid air covering wide ranges of temperature and pressure conditions, including those of the terrestrial hydrosphere and atmosphere. They permit the consistent computation of all equilibrium properties as, for example, required for coupled atmosphere-ocean models or the analysis of observational or experimental data (Feistel *et al*. 2008, 2010). These potential functions are formulated as international standards endorsed (humid air in preparation for 2010) by the International Association for the Properties of Water and Steam (IAPWS).

A new seawater standard, referred to as the International Thermodynamic Equation of Seawater 2010 (TEOS-10), was adopted in June 2009 by UNESCO/IOC as recommended by the SCOR/IAPSO Working Group 127 (WG127) on Thermodynamics and Equation of State of Seawater (IOC 2010). TEOS-10, which has been in force since January 2010, has replaced the previous 1980 International Equation of State of Seawater, EOS-80, by a combination of IAPWS documents. To support the adoption process, WG127 developed a comprehensive source code library for the thermodynamic properties of liquid water, water vapour, ice, seawater and humid air, referred to as the Sea-Ice-Air (SIA) library.

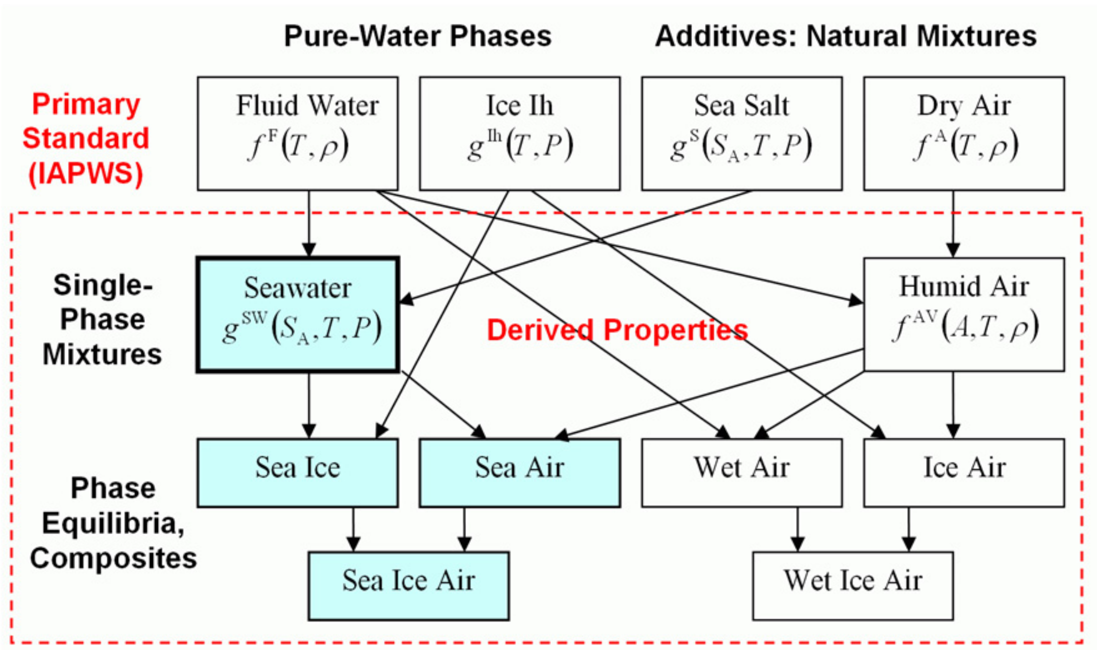


Figure 1. Modular architecture of the TEOS-10 standard for seawater thermodynamics

The modular architecture (Figure 1) of TEOS-10 and its supporting SIA library is guided by the axiomatic principles of consistency, independence and completeness of the primary standard. Virtually unlimited sets of property equations for the geophysical substances and their mutual phase equilibria can be derived from the primary standard by rigorous thermodynamic relations and their numerical implementation, without additional empirical constants or correlation equations. Among the derived quantities are, e.g., Gibbs functions for composite systems such as sea ice, or enthalpy potentials for the convenient description of adiabatic oceanic or atmospheric processes. Linked via a well-defined interface, the algorithms for the derived properties are unaffected by future partial update, substitution or extension of the primary standard. Similarly, the set of derived quantities is easily and arbitrarily extendible to provide additional required properties without modification of the primary standard. Alternatively, the modular semi-order structure in combination with the mutual independence of the primary standard modules permits the separation of smaller, self-contained sub-libraries from TEOS-10 that are restricted to special tasks. For speed-critical applications, tailored equations or look-up tables can be compiled with high accuracy for arbitrary parameter combinations.

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H2. Salinity calibration standards adopted in the international Argo programme

Birgit Klein, BSH, Germany

The international Argo programme operates an autonomous *in situ* observing network in the global oceans consisting of more than 3000 drifting instruments. These floats drift in the ocean interior for several years and measure temperature and salinity throughout the global oceans down to 2000 m. They deliver their data in real-time for operational users and the scientific research community. The programme is made up of contributions from 23 different countries, which results in a diversity of float manufacturers, float deployers and data management centres. To create a unified data set it was essential to standardize all quality control and data processing procedures. Because of the speed at which the data are required, the quality control procedures applied to the real-time data must run in an automated mode and cannot deal with calibration issues (i.e. sensor drift). A delayed mode quality control system has been set-up to catch sensor drifts, which is most relevant for salinity observations. The global Argo data centres provide climatological reference data sets which are used in the *in situ* calibration of the measured float salinities. The inherent oceanic variability and possible changes in salinity due to climate change requires a robust statistical analysis to distinguish between a slowly varying salinity sensor drift and spatial/temporal variability in the oceanic fields. Objective mapping procedures are applied to extract a reference salinity from the climatological data sets which are compared to the reported salinity by the float. Filtered time-series of differences between the reference fields and the observed float salinities are then used to quantify the behaviour of the salinity sensor. Independent measurements as satellite altimetry or other *in situ* systems are finally used to verify the consistency of the global Argo fields.

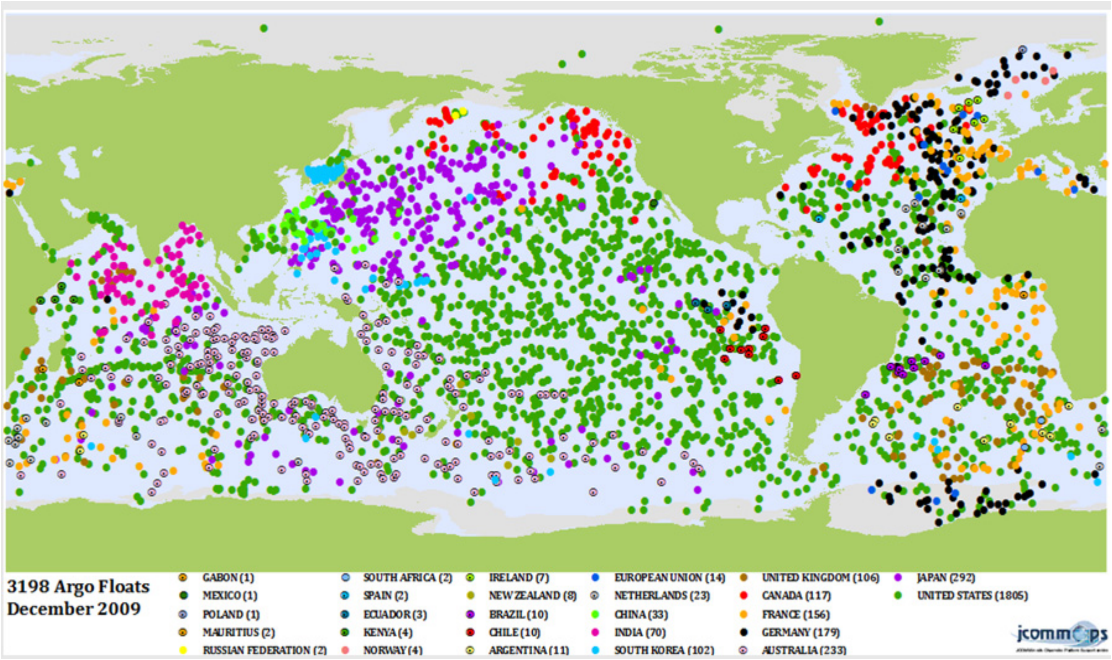

Figure 1. Status of the Argo network

H3. Sea-salt composition and oceanographic salinity scales

Rainer Feistel, Institut für Ostseeforschung, Germany

The subsequent oceanographic salinity standards of 1902 (Knudsen Salinity, S_K), 1942 (Chlorinity, Cl) and 1978 (Practical Salinity PSS-78, S_P) refrained from specifying a chemical composition model of sea salt and ignored the spatial and temporal composition variability in the world ocean and in coastal waters. In contrast, the 2010 standard TEOS-10 is expressed on the Reference-Composition Salinity Scale (RCSS, Millero *et al*. 2008) which provides the current best estimate for Absolute Salinity of IAPSO Standard Seawater (SSW). TEOS-10 allows regionally anomalous solutes such as silicate in the North Pacific or lime the Baltic Sea to be accounted for. To date, salinity measurements rely on SSW as a reference material and are not traceable to the SI (Seitz *et al*. 2008).

The common definition of Absolute Salinity, S_A, being the "mass fraction of dissolved material in seawater" is ambiguous with respect to chemical solute-solvent reactions. No established practical method is available for the determination of S_A. To provide a more rigorous and conservative salinity measure, RCSS-2008 counts the molar masses of the given Reference-Composition species at a given chlorine concentration of the solution, which in turn can be derived from the conductivity of SSW consistent with PSS-78.

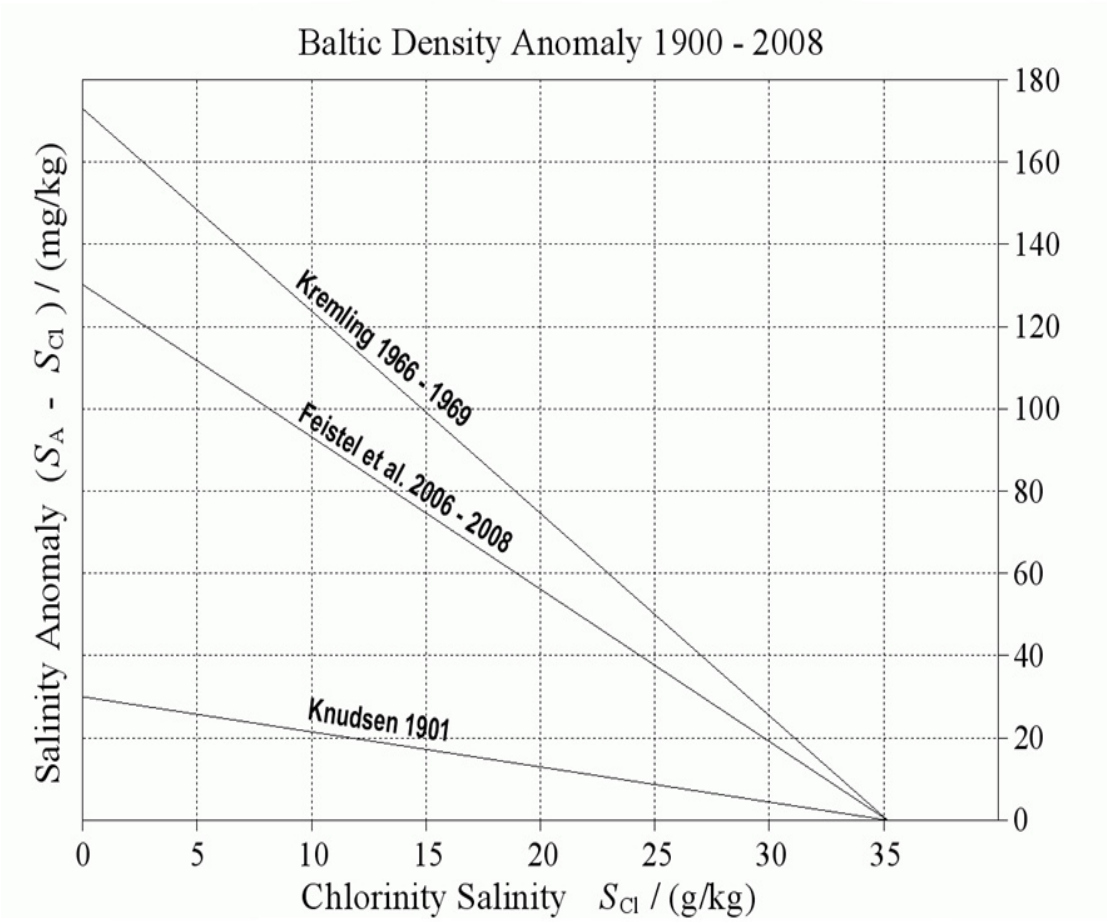

Figure 1. Decadal variability of the Baltic Sea composition anomaly. Using TEOS-10 equations, Chlorinity Salinity, S_{Cl}, computed from measured Chlorinity, and Absolute Salinity, S_A, estimated from measured density, are parameterized by linear correlation (Feistel et al. 2010)

Composition anomalies with respect to RCSS result in deviations regarding in particular

* the TEOS-10 salinity - density relation (McDougall et al. 2009, Feistel *et al*. 2010)

* the PSS-78 Chlorinity - conductivity relation (Pawlowicz 2009)

* the conservation of conductivity-based salinity (Feistel and Weinreben 2008)

By Millero's Rule, improved estimates for Absolute Salinity can be obtained from direct, SI-traceable density measurements (Figure 1) with small uncertainty (< 2 ppm, Feistel *et al*. 2010).

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H4. Global climate and ocean observing systems, opportunities and challenges

Prof. Dr. Martin Visbeck, Leibniz-Institut für Meereswissenschaften IFM-GEOMAR, Germany

The Global Climate Observing System (GCOS) and the Global Ocean Observing System (GOOS). Have provided a framework to advance the provision of routine and sustained global information on the marine environment sufficient to meet society's needs for describing, understanding and forecasting marine variability (including physical, biogeochemical, ecosystems and living marine resources), weather, seasonal to decadal climate variability, climate change, sustainable management of living marine resources, and assessment of longer term trends. A variety of space based observations and *in situ* global networks exist. The community came together in 2009 to express their needs and provide a vision for the coming decade for sustained ocean observing system needs during the OceanObs'09 conference. In solidarity, the Conference:

(1) Calls on all nations and governments to fully implement by 2015 the initial physical and carbon global ocean observing system originally envisioned at OceanObs'99, and refined at OceanObs'09.

(2) Calls on all nations and governments to commit to the implementation and international coordination of systematic global biogeochemical and biological observations, guided by the outcomes of OceanObs'09, and taking into account regional variations in ecosystems.

(3) Invites governments and organizations to embrace a framework for planning and moving forward with an enhanced global sustained ocean observing system over the next decade, integrating new physical, biogeochemical, biological observations while sustaining present observations. Recommendations on this Framework, considering how to best take advantage of existing structures, will be developed by a post-Conference working group of limited duration.

(4) Urges the ocean observing community to increase our efforts to achieve the needed level of timely data access, sensor readiness and standards, best practices, data management, uncertainty estimates, and integrated data set availability.

(5) Asks governments, organizations, and the ocean observing community to increase their efforts in capacity-building and education.

The multi-national arrangements and diversity of platforms pose significant challenges for data integration, quality control and the adherence to standards.

H5. The sea surface salinity observation system

Thierry Delcroix, Bob Keeley and Loic Petit de la Villéon, IRD, France

Quantifying sea surface salinity (SSS) changes is of critical importance for monitoring and understanding climate variability at different time scales, for analysing the related changes in heat, fresh water, momentum and CO_2 fluxes between the ocean and the atmosphere, and for marine species and ecosystem studies. SSS has thus been recognized as an essential climate variable of the global climate observing system (GCOS, 2010).

As a background, this talk gave examples of features of SSS changes in some well-sampled regions, and analysed causes as well as consequences for these changes, focussing on data collected in recent decades. The emphasis was put on key climate signals, such as ENSO in the tropical Pacific and long-term trends in the global ocean. Key observed climate signals in SSS were then compared with state-of-the-art (IPCC) model simulations, stressing the importance of SSS as a possible extra candidate for assessing model performance.

The present existing networks contributing to the above analysis of SSS changes were then described. The discussion included strengths and weaknesses of most of the platforms providing near-surface salinity measurements in recent years: Argo profilers, Voluntary Observing Ships (VOS) fitted with thermosalinographs (TSG), surface drifters, tropical moored buoys, research vessels, VOS XCTD, gliders, etc. It was shown that there are differences in these platforms, chiefly because of the sampling regions, sampling depths, time and space resolutions, available technology, sensor accuracies, real time data availability, etc. Taking VOS TSG measurements as an example, the issue of quality control procedures, data management, and data sharing policy, as performed through the GOSUD (Global Ocean Surface Underway Measurements) pilot project supported by IODE was addressed.

The ongoing efforts to demonstrate the feasibility of measuring SSS from space, through the ESA SMOS and NASA Aquarius Missions, was briefly described, stressing the need and the challenge for 'adequately' combined *in situ* and satellite-derived measurements to derive standard-quality SSS data for climate change monitoring and understanding.

H6. Traceable salinity measurements

Petra Spitzer & Steffen Seitz, PTB, Germany

Salinity linked to the overall water cycle, including the ocean-atmosphere interaction, constitutes one of the key climate variables. The salinity of seawater is routinely measured relative to certified Standard Seawater samples using the 1978 Practical Salinity Standard. Salinity determined as practical salinity and defined in terms of relative electrolytic conductivity measurements, is not traceable to the SI (Seitz *et al*, 2010). It was shown that the claimed small measurement uncertainty of practical salinity values linked to the conductivity ratio of the Standard Seawater reference is not creditable if results are compared on climatic time scales.

The numerical value of practical salinity differs from the absolute salinity, defined as the mass of dissolved solids per unit mass of seawater. The difference arises because of the more recent knowledge about the seawater composition is not reflected in the definition of practical salinity, which was chosen to maintain historical continuity with previous measures, and because of spatial and temporal variations in the relative composition of seawater (Pawlowicz, 2009). The currently stated uncertainty of practical salinity values does not indicate the uncertainty in the estimate of absolute salinity based on practical salinity measurements (Millero *et al*. 2008).

In order to solve these problems, a calibration hierarchy was discussed, linking practical salinity values to primary standards of density. Density can be measured traceable to the SI at an uncertainty level acceptable for oceanographers. Moreover, it can be linked to absolute salinity via the new formulation of the thermodynamic equations of seawater, TEOS-10 (McDougall *et al*. 2009). Such an approach can guarantee long term comparability of practical salinity and absolute salinity results. It is expected that an advantage of the proposed traceability chain will allow continuation of the established measurement and calibration procedure for salinity.

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H7. Role of the oceans in global cycles of carbon and nutrients

Chen-Tung Arthur Chen, IGBP

It has long been realized that the world's oceans are the sleeping giant of carbon dioxide (CO_2) control. There is 20 times more carbon dissolved in seawater than is found on land, and the release of just 2 % of that stored in the oceans would double the level of CO_2 in the atmosphere. Furthermore, each year around 15 times more CO_2 is taken up and released by natural marine processes than the total that is produced by the burning of fossil fuel, deforestation, cement production and other human activities.

The global carbon cycle is regulated by the oceans which cover around 60 % of the Earth's surface in the northern hemisphere and over 80 % in the southern hemisphere. The amount of CO_2 entering and leaving the oceans over an annual cycle is usually close to a balance. Ocean circulation patterns and other physico-chemical conditions, such as temperature and wind speed, govern CO_2 solubility, gas transfer rates across the sea surface and the bulk transport of carbon within the oceans. Superimposed on, and strongly influenced by, these effects are two basic biological processes: carbon fixation by photosynthesis, whereby plants use CO_2 and solar energy to produce complex organic compounds, and CO_2 release through respiration, whereby the breakdown of organic materials provides metabolic energy transfers which are essential for life.

Photosynthesis is limited to the sunlit, upper ocean while respiration occurs throughout the water column. Phytoplankton, bacteria, protozoa and other forms of life, unseen except with a microscope, have changed the Earth: over geological periods of time, marine plankton have been responsible for the vast accumulation of carbon in the oceans and in sediments. The role of the continental margins is particularly important in the transfer of materials, including carbon (C), nitrogen (N) and phosphorus

(P). Although the continental margins occupy less than 10 % of the total sea surface, they are disproportionately important because they are regions of active biogeochemical interactions between land and the open sea. These regions provide a pathway for receiving, transferring and transporting large amounts of natural and anthropogenic terrigenous materials from land to the open seas. The rate of biological production of the continental margin per unit area can be several times higher than that in the open ocean, due to nutrient inputs from land, coastal upwelling, cross-shelf exchanges, and so forth. In addition, the growth of various types of marine organisms in shallow waters accounts for about half of the calcium carbonate production in the marine environment.

As a final note, the oceans have been sequestering about 2 Peta gC per year from the atmosphere, leading to a steady decrease in the pH of seawater. As a result, conductivity of seawater will increase, complicating the issue of conductivity-based salinity measurements.

List of speakers (in alphabetical order)

James G. Anderson, Harvard College, USA

Sean Bailey, NASA, USA

William Bell, ECMWF, UK

Peter Bernath, University of York, UK

William J. Blackwell, MIT Lincoln Laboratory, USA

Shannon Brown, JPL, USA

Brigitte Buchmann, EMPA, Switzerland

John P. Burrows, NERC Centre of Ecology and Hydrology and Institute of Environmental Physics University of Bremen, Germany

James H. Butler, NOAA Earth System Research Laboratory, USA

Bertrand Calpini, MeteoSwiss, Switzerland

Etienne Charpentier, WMO, Switzerland

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Thierry Delcroix, IRD, France

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Volker Ebert, PTB, Germany

Rainer Feistel, Institut für Ostseeforschung, Germany

Wolfgang Finsterle, PMOD/WRC, Switzerland

Bruce W Forgan, Bureau of Meteorology, Australia

Ernst O Göbel, PTB, Germany

Bruce Guenther, NOAA, USA

Joanna D. Haigh, Imperial College, UK

Jerald Harder, University of Colorado, USA

Joseph T. Hodges, NIST, USA

B. Carol Johnson, NIST, USA

Birgit Klein, BSH, Germany

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David T. Llewellyn-Jones, University of Leicester, UK

Carl A. Mears, Remote Sensing Systems, USA

Christopher J. Merchant, University of Edinburgh, UK

Charles Miller, JPL, NASA, USA

Martin J.T. Milton, National Physical Laboratory, UK

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Petra Spitzer, PTB, Germany

Rainer Steinbrecher, Karlsruhe Institute of Technology (KIT), Germany

Graeme L Stephens, Colorado State University, USA

Oksana Tarasova, WMO, Switzerland

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David Walker, NIST, USA

Menghua Wang, NOAA, USA

Thorsten Warneke, University of Bremen, Germany

Ray F. Weiss, Scripps Institution of Oceanography, USA

Fuzhong Weng, NOAA, NESDIS, USA

Bruce Wielicki, NASA, USA

Rainer Winkler, NPL, UK

Jun Yang, CMA/CMSC, China

Chen Yunmei, BIRMM, China

Tatsuya Yokota, NIES, Japan

Jean-Pascal van Ypersele, IPCC, Switzerland

Wenjian Zhang, WMO, Switzerland

Giuseppe Zibordi, JRC, Italy

List of acronyms and initialisms

ACE	Atmospheric Chemistry Experiment
ADEOS	Advanced Earth Observing Satellite
AGAGE	Advanced Global Atmospheric Gases Experiment
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
AREP	Atmospheric Research and Environment Programme
ASCO	Absorption Cross-Sections of Ozone
ATMS	Advanced Technology Microwave Sounders
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
AVMP	Atmospheric Vertical Moisture Sounding
AVTP	Atmospheric Vertical Temperature Profiling
AWS	Automatic Weather Station
BIPM	International Bureau of Weights and Measures/Bureau International des Poids et Mesures
BRDF	Bi-directional Reflectance Distribution Function
BSRN	Baseline Surface Radiation Network
Cal-Val	Calibration and Validation
CC	Consultative Committee
CCD	Charge Coupled Device
CCL	Central Calibration Laboratory
CCM	Consultative Committee for Mass and Related Quantities/ Comité Consultatif pour la Masse et les Grandeurs Apparentées
CCPR	Consultative Committee for Photometry and Radiometry/Comité Consultatif de Photométrie et Radiométrie
CCQM	Consultative Committee for Amount of Substance – Metrology in Chemistry/Comité Consultatif pour la Quantité de Matière – métrologie en chimie
CCT	Consultative Committee for Thermometry/Comité Consultatif de Thermométrie
CDR	Climate Data Records
CEOS	Committee on Earth Observation Satellites
CFC	Chlorofluorocarbon
CGPM	General Conference on Weights and Measures/ Conférence Générale des Poids et Mesures
CHAMP	Challenging Minisatellite Payload for Magnetic & Gravity Field Measurement
CIMO	Commission for Instruments and Methods of Observations

CIPM	International Committee for Weights and Measures/ Comité International des Poids et Mesures
CIPM MRA	CIPM Mutual Recognition Arrangement
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CNES	Centre National d'Etudes Spatiales, France
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
CrIMSS	Cross-track Infrared and Microwave Sounding Suite
CrIS	Cross-track Infrared Sounder
CSAR	Cryogenic Solar Absolute Radiometer
CSSAR	Center for Space Science and Applied Research, China
CTM	Chemistry-Transport-Models
CZCS	Coastal Zone Colour Scanner
DBCP	Data Buoy Cooperation Panel
DHR	Direct Hemispherical Reflectance
DMSP	Defense Meteorological Satellite Program, USA
DO	Dissolved Oxygen
DQO	Data Quality Objectives
ECCO	Estimating the Circulation and Climate of the Ocean
ECMWF	European Centre for Medium-Range Weather Forecasts, UK
EDR	Environmental Data Records
EMPA	Swiss Federal Laboratories for Materials Testing and Research, Switzerland
ENSO	El Niño/Southern Oscillation
ENVISAT	Environmental Satellite (ESA satellite)
EO	Earth Observation
EOS-80	International Equation of State of Seawater
ESA	European Space Agency
ESR	Electrical Substitution Radiometer
ESRL	Earth System Research Laboratory, USA
ETH	Swiss Federal Institute of Technology/Eldgenössische Technische Hochschule
EUMETSAT	The European Organisation for the Exploitation of Meteorological Satellites
FCDRs	Fundamental Climate Data Records
FTIR	Fourier Transform, Infrared
GAW	WMO Global Atmosphere Watch Programme
GCM	Global Climate Model
GCOM	Global Change Observation Mission

GCOS	Global Climate Observing System
GEO	Geo-Synchronous Orbit
GHG	Greenhouse Gases
GHRSST	Group for High-Resolution Sea-Surface Temperature
GLI	Global Imager
GNSS	Global Navigation Satellite System
GODAE	Global Ocean Data Assimilation Experiment
GOES	Geostationary Operational Environmental Satellite, USA
GOME	Global Ozone Monitoring Experiment
GOOS	Global Ocean Observing System
GOSAT	Greenhouse Gases Observing Satellite
GOSUD	Global Ocean Surface Underway Data Pilot Project
GPS	Global Positioning System
GPS RO	GPS Radio Occultation
GRAS	GNSS Receiver for Atmospheric Sounding
GRUAN	GCOS Reference Upper-Air Network
GUM	Guide to the Expression of the Uncertainty of Measurement
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HIP	Hyperspectral Image Projector
HMEI	Association of Hydro-Meteorological Equipment Industry
HTS	High Temperature noise Source
IAEA	International Atomic Energy Agency
IAPSO	International Association for the Physical Sciences of the Ocean
IAPWS	International Association for the Properties of Water and Steam
IFM-GEOMAR	Leibniz-Institut für Meereswissenschaften/Leibniz Institute of Marine Sciences, Germany
IGBP	International Geosphere-Biosphere Programme
IGCO	Integrated Global Carbon Observing system
IMO	International Meteorological Organization
IO3C	International Ozone Commission
IOC	Intergovernmental Oceanographic Commission
IPC	International Pyrheliometer Comparison
IPCC	Intergovernmental Panel on Climate Change
IPO	Integrated Program Office

IR	Infrared
IRD	Institut de recherche pour le développement, France
JAXA	Japan Aerospace Exploration Agency, Japan
JPL	Jet Propulsion Laboratory, USA
JPSS	Joint Polar Satellite System
KIT	Karlsruhe Institute of Technology, Germany
LEO	Low Earth Orbit
LIDAR	Light Detection and Ranging
LST	Land Surface Temperature
Lw	Water Leaving Radiance
MERIS	Medium Resolution Imaging Spectrometer
METAS	Federal Office of Metrology, Switzerland
MG	Measurement Guidelines
MHS	Microwave Humidity Sounder
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding
MIS	Microwave Imager/Sounder
MODIS	Moderate Resolution Imaging Spectroradiometer
MSSG	Microwave Sensors Sub Group
MSSL	Mullard Space Science Laboratory, UK
MSU	Microwave Sounding Unit
MWI	Microwave Imaging
MWS	Microwave Sounding
NASA	National Aeronautical and Space Administration, USA
NCDC	National Climate Data Center, USA
NESDIS	National Environmental Satellite Data and Information Service, USA
NEWRAD	New Developments and Applications in Optical Radiometry Conference
NIES	National Institute for Environmental Studies, Japan
NIR	Near-Infrared
NIST	National Institute of Standards and Technology, USA
NIST SIRCUS	NIST Spectral Irradiance and Radiance Calibration with Uniform Sources facility
NMI	National Metrology Institute
NOAA	National Oceanic and Atmospheric Administration, USA
NPL	National Physical Laboratory, UK
NPOESS	National Polar-orbiting Operational Environment Satellite System, USA

NPP	NPOESS Preparatory Project
NRC	National Research Council
NRC	National Radiation Center
NWP	Numerical Weather Prediction
OCM	Ocean Colour Monitor
OI	Optimum Interpolation
OMCT	Ocean Model for Circulation and Tides
OTD	Optical Technology Division (NIST)
PMO	Port Meteorological Officers
PMOD/WRC	Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, Switzerland
POLDER	Polarization and Directionality of the Earth's Reflectances
POM	organic particulate matter
PREMOS	Precision Monitoring of Solar Variability instrument
PS	Primary Standard
PSS-78	Practical Salinity Scale
PTB	Physikalisch-Technische Bundesanstalt, Germany
QA/QC	Quality Assurance / Quality Control
QA4EO	A Quality Assurance Framework for Earth Observation
RCSS	Reference-Composition Salinity Scale
RH	Relative Humidity
RMS	Root Mean Square
RRC	Regional Radiation Center
RSMAS	Rosenstiel School of Marine and Atmospheric Science
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SDR	Sensor Data Record
SDRs	"At Surface" Directional Reflectances
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SI	International System of Units
SIA	Sea-Ice-Air
SIM	Spectral Irradiance Monitor
SLSTR	Sea and Land Surface Temperature Radiometer
SMOS	Soil Moisture and Ocean Salinity
SNO	Simultaneous Nadir Overpass
SOP	Standard operational procedure

SORCE	Solar Radiation and Climate Experiment
SRP	Standard Reference Photometer
SSI	Spectral Solar Irradiance
SSM/I	Special Sensor Microwave/Imager
SSMIS	Special Sensor Microwave Imager/Sounder
SSS	Sea Surface Salinity
SST	Sea-Surface Temperature
SSW	IAPSO Standard Seawater
SSWS/D	Sea Surface Wind Speed and Direction
SWIR	Shortwave Infrared
TANSO-CAI	Thermal And Near infrared Sensor for carbon Observation-Cloud and Aerosol Imager
TANSO-FTS	Thermal And Near infrared Sensor for carbon Observation-Fourier Transform Spectrometer
TB	Brightness Temperature
TCCON	Total Carbon Column Observing Network
TCDRs	Thematic Climate Data Records
TCWV	Total Columnar Water Vapour
TDLAS	Tuneable Diode Laser Absorption Spectrometers
TEOS-10	International Thermodynamic Equation of Seawater 2010
TIR	Thermal Infrared
TIROS	Television Infrared Observation Satellite
TMI	TRMM Microwave Imager
TOA	Top of the Atmosphere
TRF	TSI Radiometer Facility
TRUTHS	Traceable Radiometry Underpinning Terrestrial- and Helio- Studies
TSG	Thermosalinograph
TSI	Total Solar Irradiance
TSIS	Total and Spectral Solar Irradiance Sensor
TXR	Transfer Radiometer
UAS	Upper Atmospheric Sounding
UK	United Kingdom
UNESCO	United Nations Educational, Scientific and Cultural Organization
USA	United States of America
UT/LS	Upper Troposphere/Lower Stratosphere

UV	Ultraviolet
VIIRS	Visible Infrared Imaging Radiometric Suite
VOCs	Volatile Organic Compounds
VOS	Voluntary Observing Ship
WBBB	Water Bath Blackbody
WCC	World Calibration Centre
WCC-VOC	World Calibration Centre for Volatile Organic Compounds
WDCGG	World Data Center for Greenhouses Gases
WG127	SCOR/IAPSO Working Group 127
WGCV	Working Group on Calibration and Validation
WIGOS	WMO Integrated Global Observing System
WISG	World Infrared Standard Group of Pyrgeometers
WMO	World Meteorological Organization
WRC	World Radiation Centre
WRCP	World Climate Research Programme
WRDC	World Radiation Data Centre
WRR	World Radiometric Reference
WSG	World Standard Group
XBT	Expendable Bathythermograph

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