Measurement Science and the Environment

Martin Milton
Director, BIPM.

NCSLI, August 2014
The International Bureau of Weights and Measures

- Intergovernmental organization
- Established in 1875 to:
  - “ensure and promote the global comparability of measurements, including providing a coherent international system of units (the SI)”
- 70 staff members
- Annual budget of approximately 12 Meuro
- 56 Member States and 41 Associate States/economies, who operate 245 NMIs and Designated Institutes, organised into 5 Regional Metrology Organisations.
Examples from the work programme:

- Disseminate UTC
- Maintain the International Prototype of the kg
- Develop and use transportable quantum devices.
- Maintain international facilities for comparing: measurements of radioactivity and ozone.
- Coordinate the 10 consultative committees of the CIPM.
Measurement Science and the Environment

- What are we trying to measure – and why is it different?
- How are measurements made?
- Examples from: temperature, noise, radioactivity, greenhouse gases, earth observation
- What can we expect next?

- What is the role of measurement data that is traceable to the SI?
Addressing policy issues

- Global policy
- National policy
- Local/site policy
Addressing policy issues

- Global policy
- National policy
- Local/site policy

- Strong academic interest too.
Environmental measurements often influence decisions with large $ values

- Cost of compliance
- Carbon reduction targets
Environmental measurements often influence decisions with large $ values.

"All approaches require the measurement of carbon emitted, but the burdens of measurement differ":
- CDM - project specific, against a project specific baseline
- Carbon Tax – at point of use
- Cap-and-trade – higher up the chain

Strategic options for climate change mitigation
Global cost curve for greenhouse gas abatement measures

Cost of reducing greenhouse gas emissions by 2030
Euros per tonne of CO₂ equivalent avoided per year

Strategies sorted by cost-efficiency
- Savings
- Costs

This graphic attempts to show 'all in one': the various measures for greenhouse gas reduction with both reduction (in CO₂ equivalent) and cost (in Euros) quantified.
Read from left to right it gives the whole range of strategic options ranging from low hanging fruit, such as building insulation, in green (coming with economic savings) to the increasingly higher hanging ones, such as afforestation, wind energy, in red.

* Carbone Capture and Storage
Environmental measurements often influence decisions with large $ values

- Carbon reduction targets
- Cost of compliance
- Ecosystem services
Measurement accuracy is crucial when detecting trends

- A direct link can be made between the value of a data set and its measurement stability/accuracy and therefore cost.

- “The requirement for stability is 1/5 of the predicted change that is sufficient to narrow down the spread of current climate model simulations”
The scale of applications presents challenges for their accuracy

- Length scales
- Time scales
- Unusual quantities
  - Dimensionless quantity that characterizes plant canopies
  - **leaf area index** - "the one-sided green leaf area per unit ground surface area"
Environmental measurements - summary

- Address policy issues
- Very significant costs
- Can effect high-value decisions
- “Scale” of measurements is very large

- Where are the challenges for metrology?
- What is the basis of traceability?
Using observational records for climate monitoring

IPCC 5th Assessment Report 2015

❖ “The vast majority of historical (and modern) weather observations were not made explicitly for climate monitoring purposes.

– Measurements have changed in nature as demands on the data, observing practices and technologies have evolved.
– The uncertainty in observational records encompasses instrumental/recording errors, effects of representation (e.g., exposure, observing frequency or timing), as well as effects due to physical changes in the instrumentation (such as station relocations or new satellites).

❖ Because there is no unique, unambiguous, way to identify and account for non-climatic artefacts in the vast majority of records, there must be a degree of uncertainty as to how the climate system has changed.

❖ The only exceptions are certain atmospheric composition and flux measurements whose measurements and uncertainties are rigorously tied through an unbroken chain to internationally recognized absolute measurement standards (e.g., the CO₂ record at Mauna Loa; Keeling et al., 1976a)”.
Dealing with uncertainty in the temperature record

Introduce “points” with traceable measurements to the system
eg simultaneous calibration of temperature, pressure and humidity

“to facilitate creation of the best possible surface air temperature records over land to meet the myriad of data demands by science and society”
Establishing reference quality data

- Traceable sensor calibration
- Uncertainty of input data
- Transparent processing algorithm
- GRUAN Measurement: Best estimate and Uncertainty
- Black box software
- Disregarded systematic effects
- Proprietary methods

Literature:
- Guide to the expression of uncertainty in measurement (GUM, 1980)
Predicting and measuring environmental noise

- Noise sources are typically modelled and mapped in isolation to maintain simplicity.
- Measurement data can validate modeling results.
- Measurements can then be used to supplement and improve modelling in specific regions.

Mapping noise fields

- Although consumer product microphones are not fit-for-purpose as measurement devices...... MEMS microphones have inherent potential to meet requirements for high performance.
- Such systems provide the basis for a new approach to noise measurement using distributed sensor networks and address the vision for future noise measurement.
Environmental radioactivity

Traceability for specific activity (mBq/g) is underpinned by comparisons of reference materials at environmental levels: eg
- CCRI(II)-S9 (Rice)
- APMP.RI(II)-S3 (Brown rice)
- A planned comparison on a wheat matrix.

Figure B-VII. Measurement results of the airborne monitoring surveys conducted by MEXT (deposition density of $^{137}$Cs) [N18]
Environmental radioactivity

- Environmental radioactivity comparisons in matrix materials are undertaken as Supplementary Comparisons (at the RMOs or CCRI) to:
  - validate reference materials/methods in support of CMCs,
  - respond to specific needs (food contamination, fallout exposure)

- Problems of environmental materials:
  - variability of natural matrix
    - sampling, homogeneity, grain size,
    - water content, stabilization, density, ...
  - extraction of radionuclides from the matrix
  - preparation of the source: solid/liquid, measurement method(s)
  - low counting statistics, higher uncertainty

- Traceability for activity established for pure radionuclides:
  - BIPM.RI(II)-K1 (Système International de Référence - SIR)
  - allows NMIs to check the equivalence of primary methods on single radionuclide
Environmental radioactivity (eg in Cs-137 in seaweed)

Seaweed reference material needed for monitoring radioactivity in the marine environment. Organic material is widely available and naturally accumulates radionuclides from sea water.

CCRI(II)-S1 (seaweed)
- Piloted by NIST
- Major environmental aggregator
- 24 laboratories from 16 countries
- 13 radionuclides
- Typical uncertainties are ten times larger than for pure radionucleides.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Relative expanded uncertainty, % (k=2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$K</td>
<td>5.9</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>8.0</td>
</tr>
<tr>
<td>$^{210}$Pb</td>
<td>14.5</td>
</tr>
<tr>
<td>$^{212}$Po</td>
<td>7.3</td>
</tr>
<tr>
<td>$^{226}$Ra</td>
<td>13.9</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>12.7</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>11.2</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>11.7</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>6.2</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>4.2</td>
</tr>
<tr>
<td>$^{241}$Pu</td>
<td>3.9</td>
</tr>
<tr>
<td>$^{242}$Pu</td>
<td>5.8</td>
</tr>
<tr>
<td>$^{243}$Am</td>
<td>14.8</td>
</tr>
</tbody>
</table>

*Metrologia 2013, 50, Tech. Suppl., 06014*
Contributions to radiative forcing

- Radiative forcing for the period 1750–2011 based on emitted compounds (gases, aerosols or aerosol precursors) or other changes.
- The vertical bars indicate the relative uncertainty of the RF induced by each component. Their length is proportional to the thickness of the bar, that is, the full length is equal to the bar thickness for a ±50% uncertainty.
- The net impact of the individual contributions is shown by a diamond symbol and its uncertainty (5 to 95%).
- Ref IPCC - WG1 – AR5 Fig 8-17
CO₂, CH₄ and N₂O

Concentrations of Greenhouse Gases from 0 to 2005

- Carbon Dioxide (CO₂)
- Methane (CH₄)
- Nitrous Oxide (N₂O)

1980-2013

World Data Centre for Greenhouse Gases
The Global Atmospheric Watch

- GAW is a collaborative programme organized by the WMO
- include standards and quality assurance activities - the NMIs are now collaborating
Data Quality Objectives (DQOs) for GAW

<table>
<thead>
<tr>
<th>Component</th>
<th>Inter-Laboratory comparability</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>± 0.1 ppm (± 0.05 ppm in the southern hemisphere)</td>
</tr>
<tr>
<td>δ¹³C-CO₂</td>
<td>± 0.01 %</td>
</tr>
<tr>
<td>δ¹⁸O-CO₂</td>
<td>± 0.05 %</td>
</tr>
<tr>
<td>Δ¹⁴C-CO₂</td>
<td>± 1 %</td>
</tr>
<tr>
<td>O₂/N₂</td>
<td>± 1 per meg</td>
</tr>
<tr>
<td>CH₄</td>
<td>± 2 ppb</td>
</tr>
<tr>
<td>CO</td>
<td>± 2 ppb</td>
</tr>
<tr>
<td>N₂O</td>
<td>± 0.1 ppb</td>
</tr>
<tr>
<td>H₂</td>
<td>± 2 ppb</td>
</tr>
<tr>
<td>SF₆</td>
<td>± 0.02 ppt</td>
</tr>
</tbody>
</table>

WMO method for CO$_2$ scale dissemination

Niwot Ridge air

Volumetric addition of pure CO$_2$, CH$_4$ etc

Repeatability ~ 100 ppb

Noise (1 sec) ~ 20 ppb

- Value on certificate comes from comparison of standard versus secondary standards
WMO sign the CIPM MRA (April 2010)

Three laboratories designated by the WMO

- NOAA/ESRL for CO₂, CH₄, N₂O, SF₆ and CO
- EMPA for surface ozone
- PMOD/WRC for solar irradiance

- will take part in future international comparisons organised by the NMIs

- gives visibility of the relationship between SI traceable values from the NMIs and the WMO scales

Shared objective:

to bring the WMO “scales” and NMI standards in line.
Demonstrating the comparability of standards and scales for CH₄ in air

Comparisons on Methane in air at atmospheric levels
(2 μmol mol⁻¹) for climate change monitoring

Comparison results vs. Data Quality
Objectives of WMO-GAW

DQO = ± 2 nmol/mol

For CCQM-K82:

Smallest \( u(x) = 0.5 \) nmol/mol

\( \sigma_{(CCQM-K82)} = 1.17 \) nmol/mol

For interchangeability of standards

\( u(x), \sigma_{(CCQM-Kxx)} \leq DQO/8 \)

\( u(x), \sigma_{(CCQM-Kxx)} \leq 0.25 \) nmol/mol
The basis for (environmental) measurements

Metrological traceability - “property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations each contributing to the measurement uncertainty” – VIM (2007)

<table>
<thead>
<tr>
<th>Traceability to the SI</th>
<th>Traceability to a “scale”</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rationale</strong></td>
<td><strong>Rationale</strong></td>
</tr>
<tr>
<td>Values disseminated that are traceable to the SI as realised by a primary method.</td>
<td>Values disseminated that are traceable to a collection (“family”) of artefacts carefully, monitored and maintained</td>
</tr>
</tbody>
</table>

**Benefits**
- Highly coherent and accurate
  - Good “absolute” data
- Possibility for more than one source.

**Disadvantages**
- Values may change (in absolute terms) within stated uncertainties but will always “improve”.

**Benefits**
- Highly consistent (“precise”)
  - Good trend data

**Disadvantages**
- Responsibility / cost of maintenance concentrated at one institution
- Impossible to regenerate or develop independently
- (May be) insensitive to drift in the reference artefacts

**But does “coherence“ matter in environmental applications?**

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**Bureau International des Poids et Mesures**
Why is ozone important?

- Ambient ozone – contributes to photochemical smog, severe irritant to asthma sufferers, damages plants etc
Reference method for (surface) ozone

\[ x = \frac{-1}{2\sigma L_{opt}} \frac{T}{P} \frac{R}{N_A} \ln(D) \]

- \( x \): Mole fraction of ozone in dry air (nmol/mol)
- \( T \): Temperature in the cells
- \( P \): Pressure in the cells
- \( L_{opt} \): Light path length
- \( \sigma \): Ozone absorption cross-section at 253.64 nm under standard conditions of temperature and pressure
- \( D \): Product of transmittance of the two cells
- \( R \): Gas constant
- \( N_A \): Avogadro constant
UV photometry and GPT traceability chains

Pure ozone concentration $c$ assessed by pressure measurements

$$\sigma(\lambda) = -\frac{1}{L_{opt} \cdot c} \ln\left(\frac{I}{I_0}\right)$$

Primary UV photometer

$$c' = -\frac{1}{L_{opt} \cdot \sigma(\lambda)} \ln\left(\frac{I}{I_0}\right)$$

NO standard

Chemiluminescence NO$_x$ analyser calibrated by gravimetric NO standard

Calibration of O$_3$ analyser

Future work – resolve this difference!
International comparison of ozone

\[ D_i = x_{LABi} - x_{BIPM} \]

(at 420 nmol/mol)
The value of the ozone absorption cross section at 253 nm has a direct influence on the cross section used at other wavelengths for other applications

**Do we want measurements of ozone to give different results according to what part of the atmosphere they are taken in!**
Essential Climate Variables

- GCOS has defined a list of 50 essential climate variables required to support UNFCC and IPCC.
- All are technically and economically feasible to monitor.
- How do we determine where the impact of providing traceability for ECVs will be greatest?

More than 1/3rd of the ECVs are derived from primary radiometric parameters.
## Essential Climate Variables

<table>
<thead>
<tr>
<th>Instrument or mission type</th>
<th>Current or planned satellite missions including measurements of that category</th>
<th>Essential Climate Variable potentially supported</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO - Multi-purpose VIS/IR imagery and IR and MW sounding</td>
<td>NOAA series (NOAA)</td>
<td>Temperature, Water vapour, Cloud properties, Aerosols, Surface radiation budget, Albedo, Ozone, Methane, CO, CO₂, NO₂, Sea surface temperature, Permafrost, Snow cover, FAPAR, Leaf Area Index, Biomass, Fire disturbance, Precipitation</td>
</tr>
</tbody>
</table>
|                                                 | Meteor series (Roshydromet)  
|                                                 | Metop series (EUMETSAT)  
|                                                 | FY-1 and FY-3 series (CMA)  
|                                                 | GCCM-C series (JAXA)  
|                                                 | EOS-Terra and Aqua (NASA)  
|                                                 | NPP, JPSS series (NOAA)  
|                                                 | DMSP and DWSS series (DOD)  
|                                                 | Megha-Tropiques (ISRO, CNES)  |
| GEO - Multi-purpose VIS/IR imagery and IR sounding | GOES series (NOAA)                                                            | Water vapour, Cloud properties                                                  |
|                                                 | Meteosat (MF6, MSG, MTG) series (EUMETSAT)  
|                                                 | FY-2/FY-4 series (CMA)  
|                                                 | MTSAT/Himawari series (JMA)  
|                                                 | INSAT/ Kalpana series (ISRO/IMD)  
|                                                 | Elektro-L (Roshydromet)  
|                                                 | COMS series (KMA)  |
| LEO – Radio-occultation sounding                 | COSMIC-1, 2 (NOAA)                                                            | Atmospheric temperature, Water vapour, Cloud properties |
|                                                 | SAC-C and SAC-D (CNES)  
|                                                 | KOMPSAT-5 (KARI)  
|                                                 | Tandem-X (DLR)  
|                                                 | Meteor-M N3 (Roshydromet)  
|                                                 | Metop series (EUMETSAT)  
|                                                 | FY-3 E, G (CMA)  
|                                                 | Oceansat-2, 3 (ISRO)  
|                                                 | Megha-Tropiques (ISRO, CNES)  
|                                                 | CHAMP (DLR)  
|                                                 | GRACE (NASA/DLR)  |
| LEO and GEO - Earth radiation budget             | ACRIMSAT (NASA)                                                                | Earth radiation budget, Surface radiation budget                                 |
|                                                 | SORCE (NASA)                                                                  |                                                                                  |
|                                                 | JPSS-1 (NOAA)                                                                 |                                                                                  |
|                                                 | Earth care (ESA/JAXA)  
|                                                 | FY-3 A, B, C, E, G (CMA)  
|                                                 | Meteosat (EUMETSAT)  

**CEOS / WMO 2013**
Essential Climate Variables

• “In some areas (e.g., passive microwave observations), SI traceability of sufficient accuracy will not be achievable within the next 10 years as the radiometric uncertainties reached using current in-lab standards from National Metrology Institutes (NMIs) are at the same level as those required from satellite sensors in orbit”.

CEOS / WMO 2013
The measurand can be difficult to define

- Oceans are a big heat sink of energy; temperature changes very slowly,
- an indicator of climate warming and leads to expansion and hence sea level rises
- Climate models predict SST to change by approximately 0.2 K per decade

How to measure?
- Ship sampling
- Buckets
- Hull thermometers
- Radiometers
- Ocean buoys
- Drifting
- Tethered
- Robotic
- Satellites

But, they all different.
Many ECV’s are bio-geo-physical parameters

- Measured quantity is a proxy or first step to the desired measurand
- Assessing uncertainty on that parameter (e.g. Leaf Area Index (LAI) or carbon stored in a forest) requires retrieval algorithms.
- Scaling can be a major issue (leaf scale to 300 m pixels to global)
Raw measurement to required Information

FAPAR (Fraction of Absorbed photo-synthetically active Radiation)
An ECV for which GCOS requires uncertainty <10% and stability <3%

FAPAR calculated using same input satellite data different methods.

Dodorico et al
Rem Sens of Env 142, p 141 (2013)
Reconciling “bottom-up” with “top-down” measurement data

Courtesy of: J. Whetstone (NIST) “Greenhouse Gas and Climate Science Measurements Research at NIST” Talk in Session 1
Reconciling top-down and bottom-up measurement data

Courtesy of: J. Whetstone (NIST) “Greenhouse Gas and Climate Science Measurements Research at NIST” Talk in Session 1
Orbiting Carbon Observatory (2) - validation

Launch – July 2014

TCCON - Ground-based FTS instruments with clear-sky rms calibrated $X_{\text{CO}_2}$ accuracy of $\leq 0.3\%$.

Aircraft and balloon overflights calibrated to WMO standards.
Data assimilation – a “different paradigm”

“Data assimilation is the combining of different sources of information to estimate at best the state of a system. These sources generally are observations and a numerical model”.

Advantages:
- Data for different measurands can combined in the model,
- Sparse data, distributed unevenly, from different instruments to be used
- Chemical models can be used to link chemical parameters

BUT - the model becomes the basis for the “accuracy” of observations.
Metrology for the 2020s

A foresight project - “In the 2020s, metrology will develop in four areas”

http://www.npl.co.uk/2020vision/
### Metrology for the 2020s

**Examples of metrology in the 2020s applied to Monitoring the state of the planet**

<table>
<thead>
<tr>
<th>The new quantum SI</th>
<th>Direct traceability for Earth observation systems at uncertainties of 0.01% for incoming and 0.3% for reflected radiation to enable detection of decadal climate change.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurements at the frontiers</td>
<td>Sensitive and accurate methods developed to measure the long-term integrity of carbon capture and storage facilities, for example by monitoring carbon dioxide at ambient levels with ppb accuracy.</td>
</tr>
<tr>
<td>Smart and interconnected measurement</td>
<td>Networks of self-calibrating sensors monitoring chemical species in the atmosphere. Such networks will make use of new mathematical strategies that exploit the ‘internet of things’ to provide real-time data verification and quality assurance.</td>
</tr>
<tr>
<td>Embedded and ubiquitous measurement</td>
<td>Traceable environmental data publicly accessible in real time from sensors embedded in vehicles and mobile devices. For example, providing data for citizens to minimise their personal exposure.</td>
</tr>
</tbody>
</table>

http://www.npl.co.uk/2020vision/
New challenges - “Citizen science”

- **Noise Tube**
  - “Turn your mobile phone into an environmental sensor and participate in the monitoring of noise pollution”

- **Air quality egg**
  - “The Air Quality Egg is a sensor system designed to allow anyone to collect very high resolution readings of NO2 and CO concentrations outside of their home”.

- **How radioactive is our ocean?**
  - “Help us by mobilizing your community, to raise the money it takes to analyze 20 liters of seawater for signs of radiation from Fukushima. We’ll send you everything you need to take a sample and return it to us”.

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What standards are needed/used?  
How is quality assured?
Why traceability to the SI?

Measurement results (and uncertainties) that are traceable to the SI are:

- **Stable**
  - The same measurement made against the same references will be stable over time.

- **Comparable**
  - Results of the same measurements against the same references in a different laboratory will be comparable (the same!).

- **Coherent**
  - Results of the same measurements against different references will be coherent (the same!).

- Environmental measurements require all three of these.
- Other approaches to standardisation only provide the first two
Conclusions

- There are many examples of good measurement informing us about the state of the environment.

- To have further success we must:
  - Build the case for measurement results that are traceable (to the SI)
  - Develop new ways to disseminate traceability (eg reference networks)
  - Prepare for new approaches to measurement (eg citizen science, big data – network of things)
  - Expect high standards from society for transparency
Thank you