Stable and accurate measurements to quantify the causes of global climate change

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Outline

• A few fundamentals
• Monitoring challenges
• How we do this
• Comparisons
• The future
A Few Fundamentals . . .
### Radiative Forcing
IPCC 5th Assessment Report (2014)

<table>
<thead>
<tr>
<th>Emitted compound</th>
<th>Resulting atmospheric drivers</th>
<th>Radiative forcing by emissions and drivers</th>
<th>Level of confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>CO₂</td>
<td>1.68 [1.33 to 2.03]</td>
<td>VH</td>
</tr>
<tr>
<td>CH₄</td>
<td>CO₂ H₂O₂O₃ CH₄</td>
<td>0.97 [0.74 to 1.20]</td>
<td>H</td>
</tr>
<tr>
<td>Halo-carbons</td>
<td>O₃ CFCs HCFCs</td>
<td>0.18 [0.01 to 0.35]</td>
<td>H</td>
</tr>
<tr>
<td>N₂O</td>
<td>N₂O</td>
<td>0.17 [0.13 to 0.21]</td>
<td>VH</td>
</tr>
<tr>
<td>CO</td>
<td>CO₂ CH₄ O₃</td>
<td>0.23 [0.16 to 0.30]</td>
<td>M</td>
</tr>
<tr>
<td>NMVOC</td>
<td>CO₂ CH₄ O₃</td>
<td>0.10 [0.05 to 0.15]</td>
<td>M</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrate CH₄ O₃</td>
<td>-0.15 [-0.34 to 0.03]</td>
<td>M</td>
</tr>
<tr>
<td>Aerosols and precursors</td>
<td>Mineral dust Sulphate Nitrate Organic carbon Black carbon</td>
<td>-0.27 [-0.77 to 0.23]</td>
<td>H</td>
</tr>
<tr>
<td>Natural</td>
<td>Changes in solar irradiance</td>
<td>0.05 [0.00 to 0.10]</td>
<td>M</td>
</tr>
</tbody>
</table>

**Total anthropogenic RF relative to 1750**

- 2011: 2.29 [1.13 to 3.33] (H)
- 1980: 1.25 [0.64 to 1.86] (H)
- 1950: 0.57 [0.29 to 0.85] (M)

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Radiative forcing relative to 1750 (W m⁻²)
Annual Greenhouse Gas Index
(Normalized Radiative Forcing)

• An information tool for the public
  ➢ US Physical Indicator of Climate Change

• Normalizes RF to 1990
  ➢ Kyoto target year

• Long-lived GHGs only
  ➢ No aerosols, ozone, BC, NO_x, SO_x

• CO_2 responsible for 84% of change in RF from long-lived GHGs over past decade

• Increase from minor gases exceeds decrease from CFCs
Atmospheric CO₂ - The Primary Driver of Climate Change

- Atmospheric CO₂ continues to increase every year
  - The trend is largely driven by fossil fuel emissions

- The growth rate increases decadally
  - Variability is largely driven by the Earth System

- The Earth System continues to capture 50% of emissions
  - Despite the increase in emissions
  - Do we understand carbon cycle?

Pre-industrial level of CO₂ was 280 ppm

+ 75 ppm within 50 years

Annual mean growth rate of CO₂ at Mauna Loa

Parts per million
Methane is confounding

- After ~10yr hiatus, CH₄ began increasing again in 2007
- Cause of this increase is uncertain
  - Sources of atmospheric CH₄ are legion
  - Renewed interest in extraction
- The recent trend seems to be largely driven by emissions in the tropics and subtropics
  - The arctic was significant only in 2007
  - Extraction does not seem significant – yet

Pre-industrial CH₄ was 700 ppb
Monitoring Challenges
Sub-continental Information Needed

• Global averages are robust and highly certain
  - 40+ marine boundary layer sites
  - Measurements are all made in the same laboratory
  - Calibrations are traceable to WMO World Standards

• Society needs robust information on “policy-relevant scales”
  - Much more difficult than global average
  - Requires more observations, better analysis, improved modeling
  - Must be globally coherent (thus bias can be a BIG problem)
How to compare sites around the world?

- Analyses must be constrained by atmospheric observations.
- Observations must be sufficiently dense.
- Observations must either be free of bias or the bias must be known.
How does bias impact annual net CO$_2$ surface fluxes?

- North America: $74.8 \pm 0.6$ (N=8)
- Extratropical Eurasia: $-25.1 \pm 0.9$ (N=8)

- More biospheric uptake if bias is negative.
- Less biospheric uptake if bias is positive.

Bias Run minus CT (TgC yr$^{-1}$)

Introduced CO$_2$ measurement bias at LEF (ppm)
Reducing Bias

- Lots of Observations
- Consistent calibrations over time and space
  - Common, traceable scale
  - Stability and reproducibility
  - Comparability
- Consistent measurements among sites
  - Comparable approaches?
  - Compatible sites
How we do this
WMO Measurement Guidelines

- General requirements for CCLs, WCCs, measurement laboratories
- Specific requirements for
  - Gases (CO₂, CH₄, N₂O, SF₆, O₂/N₂, CO, H₂)
  - Stable Isotopes (C,O,H)
  - ¹⁴CO₂
- Quality Control
- In situ measurements
- Data management and archiving
- Emerging instrumentation
Data Quality Objectives

Data Quality Objective (DQOs): Qualitative and quantitative statements that clarify the objectives of observations, define the appropriate type of data, and specify tolerable levels of uncertainty.

- repeatability
- reproducibility
- calibration transfer

Network Compatibility Goal: Scientifically desirable level of compatibility for well mixed background air.

In a sense, these represent the largest “artificial” gradients in surface mole fraction that would be “tolerable” for inverse modeling.

- Some compatibility goals are not achievable with current methods.

New in GGMT Report 2013 (Beijing): Extended compatibility goals for localized (not global) studies.
Example: For two measurement sites 500 km apart, a mean bias of 0.2 ppm CO$_2$ would result in an error of 50 g C m$^{-2}$ yr$^{-1}$ on inferred fluxes.

Further, an under estimate of the flux in one region will lead to an overestimate somewhere else.

Reproducibility of Primary Standard Curve

Difference between mean 2012/2013 results and WMO-CO2-X2007 scale

mean diff = 0.01 ppm
One primary standard shows evidence of drift.
### Primary Standards at the Central Calibration Laboratory

<table>
<thead>
<tr>
<th>Gas</th>
<th>Standard Uncertainty, Single Primary Standard</th>
<th>Compatibility Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>~0.025%, (0.1 μmol/mol)</td>
<td>0.1 μmol/mol (N.H.)</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.13%, (2.5 nmol/mol)</td>
<td>2 nmol/mol</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.12%, (0.4 nmol/mol)</td>
<td>0.1 nmol/mol</td>
</tr>
<tr>
<td>CO</td>
<td>0.3%, (0.3 nmol/mol)</td>
<td>2 nmol/mol</td>
</tr>
<tr>
<td>SF₆</td>
<td>0.5%, (0.04 pmol/mol)</td>
<td>0.02 pmol/mol</td>
</tr>
</tbody>
</table>
Scale Transfer

Primary

Secondary

Tertiary

WMO/GAW needs stable and consistent Tertiary standards
How to estimate reproducibility?

1) Want to know reproducibility under **ideal** and **real world** conditions
   - e.g. with/without dedicated regulators
2) At what level can we identify drift?
3) Provide guidance to users … e.g. are differences significant?

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**Graph:**

- **SF6 Target Tanks (X2014)**
- **SF6 (ppt):**
  - std dev 0.01 ppt
  - std dev 0.006 ppt
Estimate reproducibility from database of tertiary analysis results. Out of 700 cylinders in the SF$_6$ database, 160 have been analyzed more than once.

Take differences: $X_i - X_0$ (total of 282 SF$_6$ data pairs)

std. dev. under ideal conditions (just target tanks) was 0.01 ppt from 2006-2010
For cylinders analyzed more than 1 yr apart, Pressure > 300 psi

1995-2013
N = 2238 pts, 95%ile = 0.17 ppm
Select surveillance cylinders analyzed more than 10 times, with history extending at least 10 years.

Observe drift in positive and negative direction.

Drift range: $+0.0057 \pm 0.0009$ ppm/yr
- $-0.0073 \pm 0.0018$ ppm/yr
No evidence of systematic bias in WMO scale over time scales of decade or less. No significant change of reproducibility over time.
## Reproducibility (95%ile)

<table>
<thead>
<tr>
<th>Gas</th>
<th>Reproducibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>0.06 $\mu$mol mol$^{-1}$</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>0.84 nmol mol$^{-1}$</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>0.22 nmol mol$^{-1}$</td>
</tr>
<tr>
<td>CO</td>
<td>0.8 nmol mol$^{-1}$</td>
</tr>
<tr>
<td>SF$_6$</td>
<td>0.03 pmol mol$^{-1}$ (after 2010)</td>
</tr>
</tbody>
</table>

at near-ambient mole fractions
Comparisons
WMO Round Robin Comparison

WMO RR: 5; Circuit: all

Lab minus NOAA (ΔCO₂, ppm)

Created: 2013-11-12

Butler et al.,
20 November 2014
NOAA-hosted website: contributors can view comparisons in various forms, create custom plots

credit: Ken Massarie and Kirk Thoning for tools

site: Alert, Canada

co-located meas. sample exchange
same air (flask exchange): NOAA and CSIRO at Gape Grim, Australia
The Future . . .
Conceptual Cooperative Global Network

Monitoring the Causes of Climate Change
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ICOS

Atmospheric measurement sites in the CorboEurope IP (in prep.)

NOAA

TCCON

WMO Global Atmospheric Watch
Monitoring Stations for Carbon Dioxide (CO₂)

ICOS

NOAA

TCCON

WMO Global Atmospheric Watch
Monitoring Stations for Carbon Dioxide (CO₂)

AGAGE

WMO Global Atmospheric Watch
Monitoring Stations for Carbon Dioxide (CO₂)
Coordinating Networks in Developing Countries

- Emerging Networks anchored with WMO/GAW stations
- Using WMO/GAW Standards
- Taking part in GAW QA/QC Activities
- Sharing Data Openly
- Placing Data into World Data Centre for Greenhouse Gases
Monitoring the Causes of Climate Change

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Satellites

“Carbon Weather”

Questions?

TCCON

Current Network

China

Earth Networks

Brazil

SE Asia