Ongoing Efforts to Develop Top-Down Atmospheric Flux Inventories for CO₂ and CH₄

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Atmospheric Inventories in the Context of the Paris Agreement

• Atmospheric measurements of CO$_2$ and CH$_4$ from ground-, airborne- and space-based sensors could reduce uncertainty in national emission inventory reports by:
  • providing nations with timely, quantified guidance on progress towards their emission reduction strategies and pledges (NDCs)
  • identifying additional emission reduction opportunities; and
  • tracking changes in the natural carbon cycle caused by human activities (deforestation, degradation of ecosystems, fire) and climate change

• Atmospheric measurements support conventional, bottom-up inventories by:
  • Improving the frequency and accuracy of inventory updates for nations not well equipped for producing reliable inventories, and
  • helping to close the carbon budget by providing measurements over ocean and over land areas with poor data coverage (tropical forests, polar regions)
Building Atmospheric Greenhouse Gas Inventories

Top-Down atmospheric inventories can complement Bottom-Up GHG inventories

- Atmospheric CO$_2$ and CH$_4$ measurements provide an integrated constraint on the exchanges of these gases between land, ocean and atmosphere and their trends
- Fluxes inferred from atmospheric CO$_2$ and CH$_4$ measurements are not as source-specific as those used in bottom-up GHG inventories, but include contributions from sources often omitted or poorly characterized in bottom-up inventories

Need to combine surface-, airborne-, and space-based atmospheric measurements

- At global scales, CO$_2$ and CH$_4$ concentrations are well characterized by precise, ground-based \textit{in situ} measurements from surface and airborne sensors
- Estimates of column-averaged CO$_2$ and CH$_4$ dry air mole fractions (XCO$_2$ and XCH$_4$, respectively) from space-based measurements can augment the resolution and coverage of the \textit{in situ} measurements
Collecting GHG Observations from Space: The Evolving Fleet

• Space agencies have supported a series of pioneering space-based GHG sensors including:
  • ESA’s ENVISAT SCIAMACHY,
  • Japan’s GOSAT TANSO-FTS, NASA’s OCO-2, China’s TanSat AGCS, Feng Yun-3D GAS and Gaofen-5 GMI, Copernicus Sentinel 5 Precursor TROPOMI.

• Other space-based sensors have just been added to the fleet:
  • Japan’s GOSAT-2 TANSO-FTS-2 and NASA’s ISS OCO-3

• Others are under development:
  • CNES MicroCarb, CNES/DLR MERLIN, NASA’s GeoCarb

• The next step - Operational GHG constellations
  • GOSAT-3, Copernicus Sentinels (S4, S5, CO2M)
Persistent XCO$_2$ Anomalies Provide Insight Into Fluxes

See Hakkarainen et al.
The Committee on Earth Observations Satellites (CEOS) commissioned the Atmospheric Composition Virtual Constellation (AC-VC) team to write a white paper defining a global architecture for monitoring atmospheric CO₂ and CH₄ concentrations from instruments on space-based platforms

- 166-page document, 88 authors representing 47 organizations
- Executive Summary (2 pages)
  - Overview of objectives and approach
  - Intended for policy makers, CEOS/CGMS Agency leads
- Body of report (75 pages)
  - Science background and requirements, current and near-term mission heritage and system implementation approach,
  - Intended for program scientists and project managers
- Technical Appendices (42 pages)
  - “Textbook” summarizing state-of-the-art in measurements and models
  - Targeted for scientists, engineers, and inventory community

A Candidate Operational CO$_2$/CH$_4$ Constellation Architecture

The coverage, resolution, and precision requirements could be achieved with a constellation that incorporates:

- A constellation of 3 (or more) satellites in LEO with
  - A broad (> 250 km) swath with a footprint size < 4 km$^2$
  - A single sounding random error near 0.5 ppm, and vanishing small regional scale bias (< 0.1 ppm)
  - Ancillary sensors to identify plumes (CO, satellites NO$_2$)
- A constellation with 3 (or more) GEO satellites
  - Stationed over Europe/Africa, Americas, and East Asia
  - Monitor diurnally varying processes (e.g. rush hours, diurnal variations in the biosphere)
- This constellation could be augmented with
  - HEO satellites to monitor carbon cycle of the high arctic
  - Active sensors (lidars) to collect measurements at night
Developing Atmospheric GHG Inventories

The CEOS AC-VC GHG White Paper recommends the following approach:

1. Foster collaboration between the space-based and ground-based GHG measurement and modeling communities and the bottom-up inventory and policy communities to refine the requirements and implementation plans for top-down atmospheric flux inventories;

2. Exploit the capabilities of the Committee on Earth Observation Satellites (CEOS), Coordination Group on Meteorological Satellites (CGMS) and the WMO Integrated Global Greenhouse Gas Information System (IG3IS) to produce a prototype atmospheric CO$_2$ and CH$_4$ flux product that is available in time to inform the bottom-up inventories for the 2023 global stocktake; and

3. Use the lessons learned from this prototype flux product to refine the requirements for a future, purpose-built, operational, atmospheric inventory system that more completely addresses the inventory process in time to support the 2028 global stocktake.
Space-based Measurements are Only One Component of an Atmospheric GHG Inventory System

Observations
- Satellite Measurements of CO₂ and CH₄
- Ground and Airborne Measurements of CO₂ and CH₄
- Meteorology Satellite & in-situ
- Auxiliary Data Satellite observations of CO₂, NO₂, clouds, aerosols...

Prior Information
- Fluxes, model parameters, emission reports, economic statistics.

Integration & Attribution
- Estimation system
  - Data assimilation and uncertainty estimation
- Models
  - Transport, land & ocean carbon cycle, fossil fuel emissions.

Outputs
- CO₂ and CH₄ emissions & removal Hot-spots with uncertainties
- Country/region CO₂ and CH₄ emissions & removals with uncertainties
- Other Carbon Cycle Products
Other Tools Needed for Atmospheric GHG Inventories

• **Improved precision, spatial resolution, and coverage**
  - **Accuracy/Precision:** Improved calibration
  - **Resolution/Coverage:** LEO and Geo GHG constellations

• **Improved remote sensing retrieval algorithms**
  - **Optical properties:** gas absorption and aerosol scattering
  - **Retrieval methods:** Optimized to analyze solar spectra

• **Better coordination with ground-based/aircraft networks**
  - **Validation:** TCCON, EM27-Sun, AirCore, Aircraft
  - **Complementary coverage:** polar regions, cloudy regions

• **Improved atmospheric inversion models**
  - **Transport:** Adequate resolution of mesoscale transport
  - **Assimilation techniques:** Incorporating ground-, aircraft-, and space-based GHG data and transport fields
Progress and Near Term Plans: Harmonized GOSAT/OCO-2 XCO₂ Data Record

- CO₂ was chosen for the prototype atmospheric inventory due to the maturity of the GOSAT and OCO-2 XCO₂ products
- The GOSAT and OCO-2 teams have cross calibrated their spectra
  - Annual vicarious calibration campaigns in Railroad Valley Nevada, USA
  - Comparisons of coincident spectra in spatially uniform regions
- The OCO-2 Team is using the standard OCO-2 XCO₂ version 9 retrieval algorithm to process the entire 10-year GOSAT data record to produce a harmonized XCO₂ product spanning 2009 - 2019
  - A preliminary analysis of this product is under way
Progress and Near-term Plans: Flux Inversion

• The OCO-2 team is performing a multi-model intercomparison to retrieve CO₂ fluxes on regional scales from *in situ* and OCO-2 observations (Crowell et al. Atmos. Chem. Phys. 2019)
  • Global annual carbon sink: 3.7±0.5 PgC (1.5±0.6 PgC from land)
    • Best agreement in northern hemisphere extratropics, which are well sampled by the surface networks
    • Largest difference over tropical Africa - few *in situ* measurements

• Plans: An atmospheric GHG inventory for 2023 Paris Stocktake
  • The OCO-2 flux inversion team is developing a prototype high resolution global inversion using the OCO-2 version 9 XCO₂ product, with a target delivery date at the end of 2019
  • This product will be compared to results generated by the Copernicus CO₂ Human Emissions (CHE) project and other teams provide a more comprehensive assessment of fluxes and their uncertainties
  • Results from this effort will guide the development of an updated atmospheric flux inventory that will be delivered early in 2021