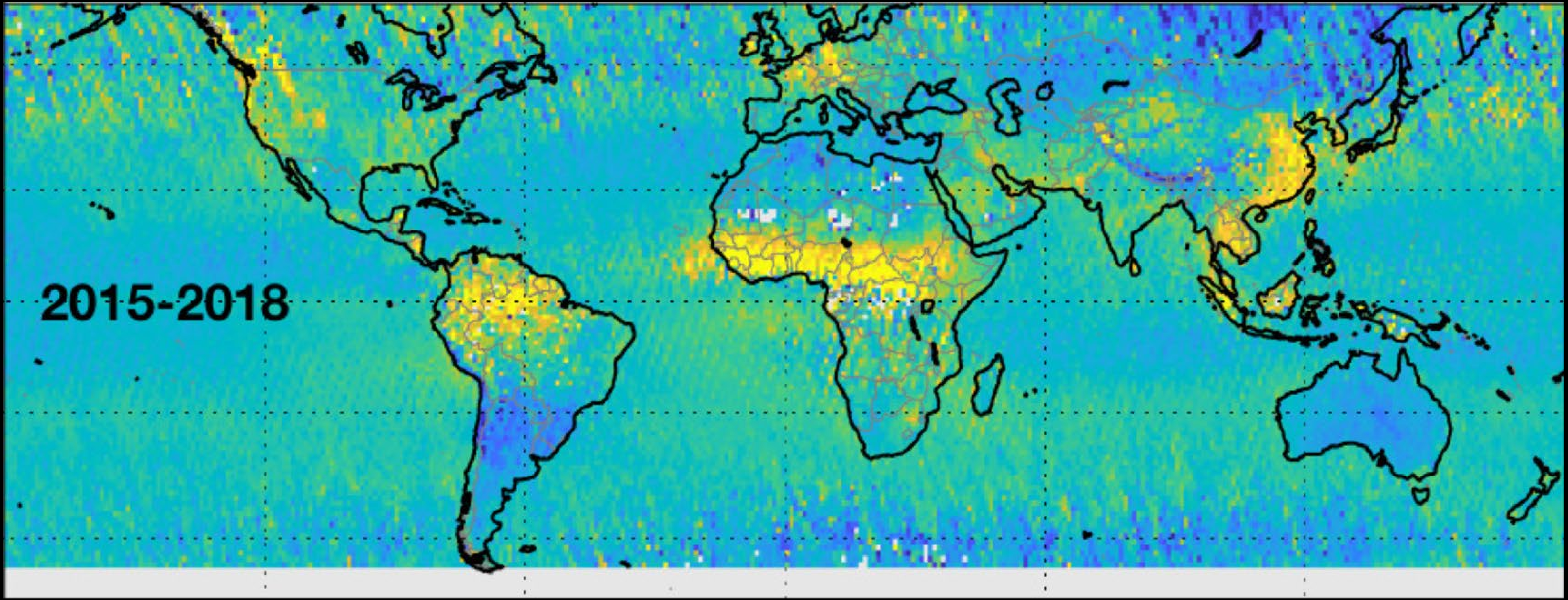
Ongoing Efforts to Develop Top-Down Atmospheric Flux Inventories for CO_2 and CH_4



David Crisp (Jet Propulsion Laboratory, California Institute of Technology)

for the CEOS AC-VC Greenhouse Gas Team, 4 June, 2019

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

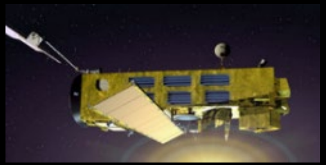
- Atmospheric CO_2 and CH_4 measurements provide an integrated constraint on the exchanges of these gases between land, ocean and atmosphere and their trends
- Fluxes inferred from atmospheric CO_2 and CH_4 measurements are not as source-specific as those used in bottom-up GHG inventories, but include contributions from sources often omitted or poorly characterized in bottom-up inventories

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

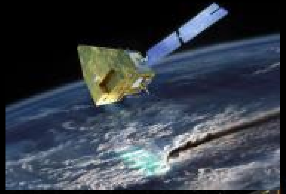
- At global scales, CO_2 and CH_4 concentrations are well characterized by precise, ground-based *in situ* measurements from surface and airborne sensors
- Estimates of column-averaged CO_2 and CH_4 dry air mole fractions (XCO_2 and XCH_4, respectively) from space-based measurements can augment the resolution and coverage of the *in situ* measurements

Collecting GHG Observations from Space: The Evolving Fleet

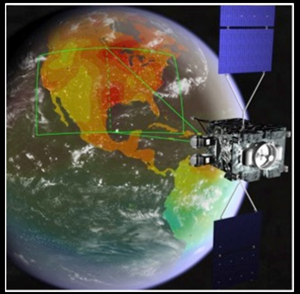
- **Space agencies have supported a series of pioneering space-based GHG sensors including:**
  - ESA's ENVISAT SCIAMACHY,
  - Japan's GOSAT TANSO-FTS, NASA's OCO-2, China's TanSat AGCS, Feng Yun-3D GAS and Gaofen-5 GMI, Copernicus Sentinel 5 Precursor TROPOMI.
- **Other space-based sensors have just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



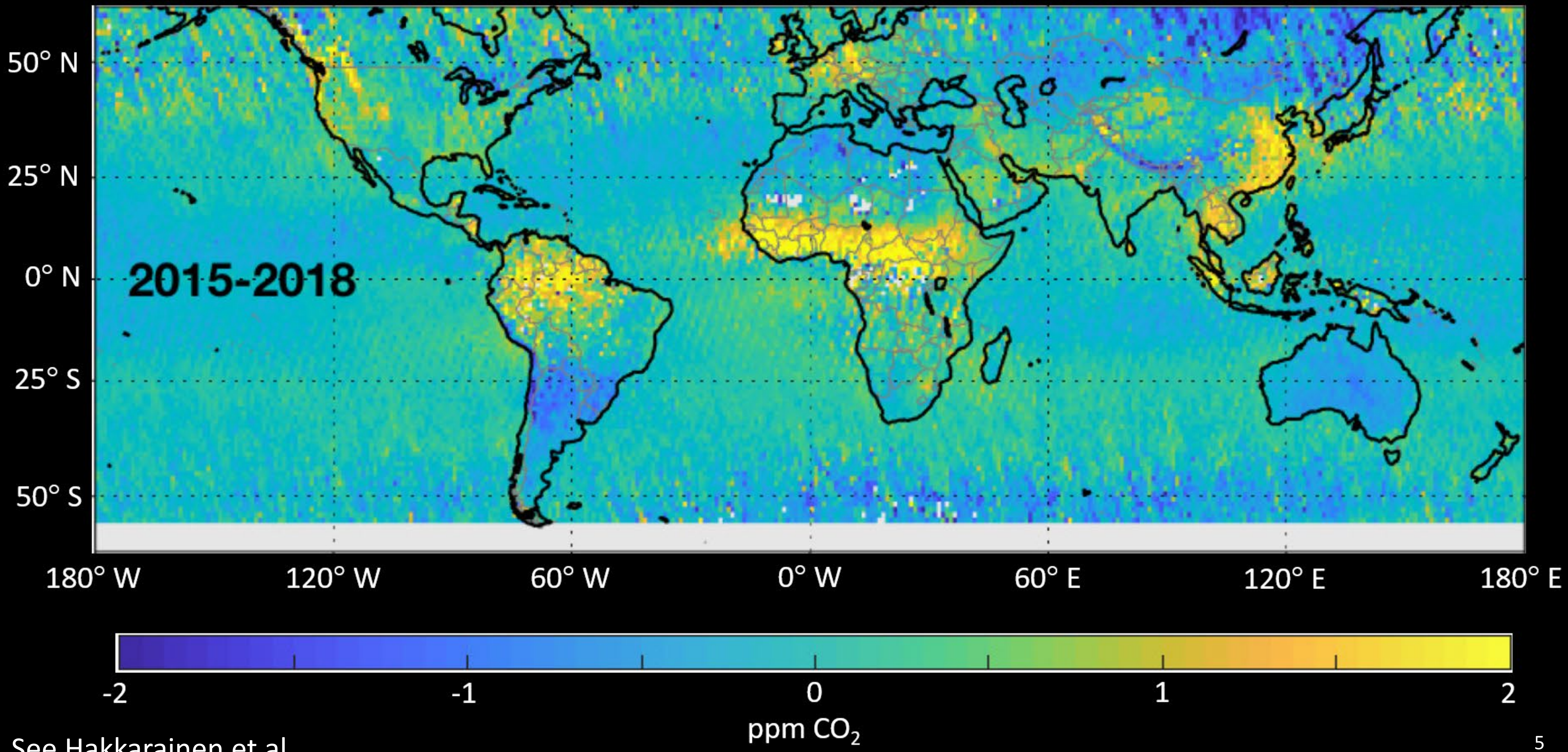






Persistent XCO_2 Anomalies Provide Insight Into Fluxes

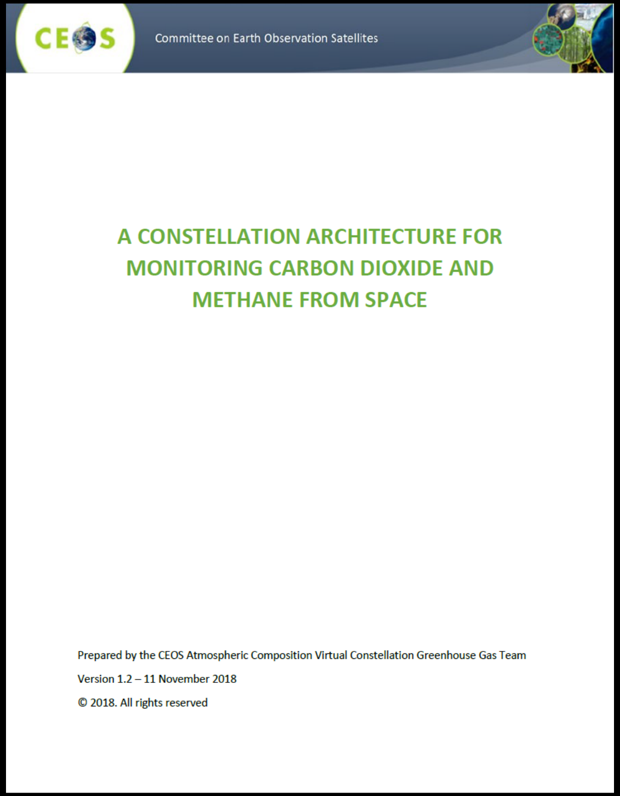


See Hakkarainen et al.

The CEOS AC-VC GHG White Paper

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 CO_2 and CH_4 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


CEOS Committee on Earth Observation Satellites

A CONSTELLATION ARCHITECTURE FOR MONITORING CARBON DIOXIDE AND METHANE FROM SPACE

Prepared by the CEOS Atmospheric Composition Virtual Constellation Greenhouse Gas Team

Version 1.2 – 11 November 2018

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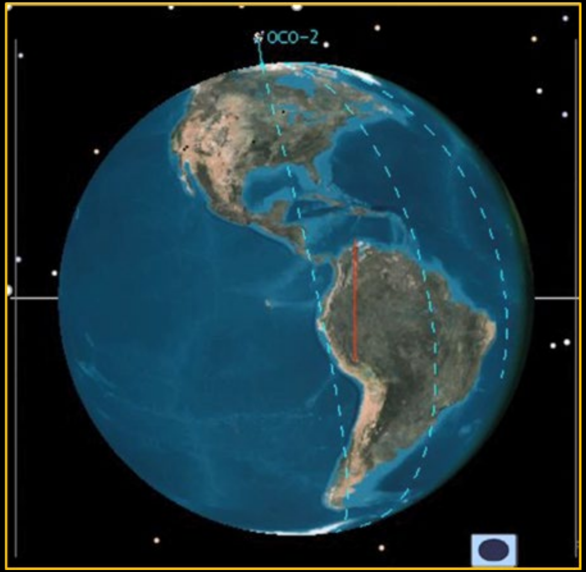
http://ceos.org/document_management/Virtual_Constellations/ACC/Documents/CEOS_AC-VC_GHG_White_Paper_Publication_Draft2_20181111.pdf

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

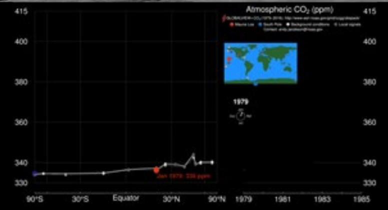


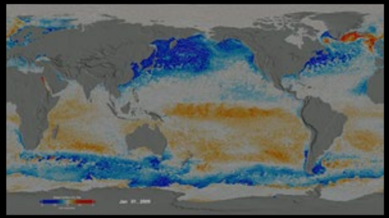
Developing Atmospheric GHG Inventories

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 CO_2 and CH_4

Ground and Airborne Measurements of CO_2 and CH_4

Meteorology
Satellite & in-situ

Auxiliary Data
Satellite observations of CO, NO_2, clouds, aerosols …

Prior Information

Fluxes, model parameters, emission reports, economic statistics.

Integration & Attribution

Estimation system
Data assimilation and uncertainty estimation

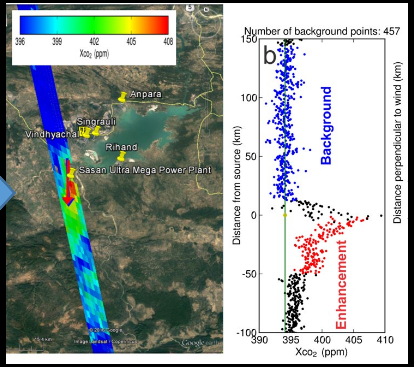
Models
Transport, land & ocean carbon cycle, fossil fuel emissions.

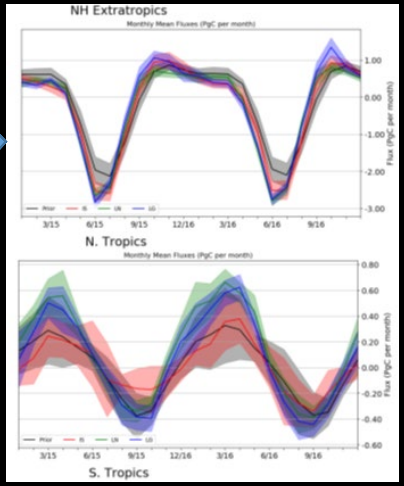
Outputs

CO_2 and CH_4 emissions & removal Hot-spots with uncertainties

Country/region CO_2 and CH_4 emissions & removals with uncertainties

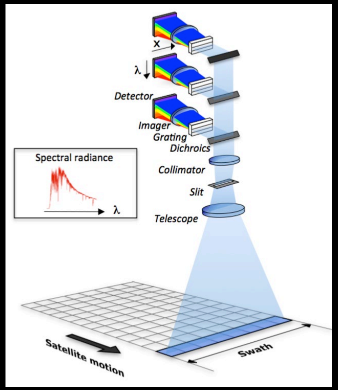
Other Carbon Cycle Products

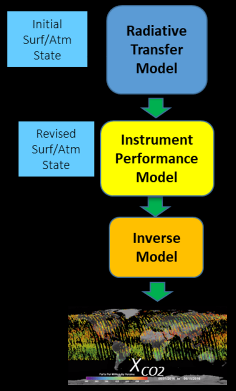


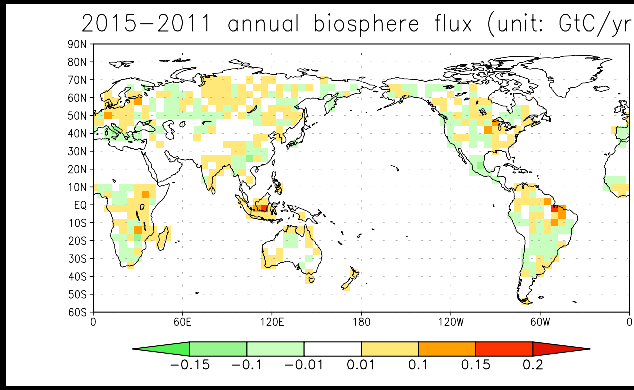


Other Tools Needed for Atmospheric GHG Inventories

- **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 XCO_2 Data Record

- CO_2 was chosen for the prototype atmospheric inventory due to the maturity of the GOSAT and OCO-2 XCO_2 products
- The GOSAT and OCO-2 teams have cross calibrated the their spectra
  - Annual vicarious calibration campaigns in Railroad Valley Nevada, USA
    - Kuze et al., Long-Term Vicarious Calibration of GOSAT Short-Wave Sensors: Techniques for Error Reduction and New Estimates of Radiometric Degradation Factors, IEEE TGRS, 52, 2014.
    - Bruegge et al., Vicarious Calibration of Orbiting Carbon Observatory-2, IEEE TGRS 2019.
  - Comparisons of coincident spectra in spatially uniform regions
    - Kataoka et al., The Cross-Calibration of Spectral Radiances and Cross-Validation of CO2 Estimates from GOSAT and OCO-2, Remote Sens. 9, 1158, 2017.
- The OCO-2 Team is using the standard OCO-2 XCO_2 version 9 retrieval algorithm to process the entire 10-year GOSAT data record to produce a harmonized XCO_2 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 CO_2 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 XCO_2 product, with a target delivery date at the end of 2019
  - This product will be compared to results generated by the Copernicus CO_2 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