Need for space-based measurements of CO$_2$ and CH$_4$

• Reduce uncertainty in fossil fuel emission inventories and their time evolution
  – Discriminate and quantify anthropogenic emissions in context of natural carbon cycle
  – Provide a consistent global method for validating GHG inventories
  – Address new requirements from UNFCCC Paris agreement (e.g. “global stocktaking”)

• Monitor and predict changes in the natural carbon cycle associated with climate change and human activities
  – Human Activities: Deforestation, degradation, biomass burning
  – Changes in CO$_2$ and CH$_4$ associated with drought, temperature stress, melting permafrost
  – Changes in ocean thermal structure and dynamics
Measuring CO₂ from Space

- **Record** spectra of CO₂ and O₂ absorption in reflected sunlight
- **Retrieve** variations in the **column averaged** CO₂ dry air mole fraction, \( X_{CO2} \), over the sunlit hemisphere
- **Validate** measurements to ensure \( X_{CO2} \) accuracy of 1 ppm (0.25%)
Retrieving $X_{CO2}$ from GOSAT and OCO-2 Data

GOSAT TANSO-FTS has been returning 300-1000 cloud free soundings/day since Apr 2009. The ACOS/GOSAT team has been using these data to retrieve $X_{CO2}$.

OCO-2 has been returning 25000 to 70000 soundings/day since Sept 2014. The ACOS/GOSAT algorithm was modified to retrieve $X_{CO2}$ from these data.
A Quick Look at the OCO-2 Prime Mission

Orbiting Carbon Observatory - 2
Atmospheric Carbon Dioxide Concentration (09/06/14 - 03/31/2017)
Creating a Combined Data Product: the OCO-2/GOSAT Collaboration

Vicarious Calibration

Retrieval Algorithm

Cross Validation

Forward Radiative Transfer Model
Spectra + Jacobians

Instrument Model
Spectral+Polarization

Inverse Model
• Compare obs. & simulated spectra
• Update State Vector

• Compare obs. & simulated spectra
• Update State Vector

ACOS GOSAT B7.3
OCO-2 v7

Vicarious Calibration

Retrieval Algorithm

Cross Validation

Forward Radiative Transfer Model
Spectra + Jacobians

Instrument Model
Spectral+Polarization

Inverse Model
• Compare obs. & simulated spectra
• Update State Vector

• Compare obs. & simulated spectra
• Update State Vector

ACOS GOSAT B7.3
OCO-2 v7
Lessons Learned from GOSAT and OCO-2: Cross-Calibration and Cross Validation

• Pre Launch:
  – Exchange information on best practice for pre-launch instrument characterization
  – Cross calibration of pre-launch radiometric standards
  – Exchange of gas absorption coefficient and solar data
  – Retrieval algorithm development/intercomparison
  – Validation system development (TCCON, aircraft)
  – Multi-Satellite OSSE’s – what do you gain with truly coordinated observations

• Post Launch:
  – Cross calibration of solar/lunar/Earth (vicarious: RRV+?) observations
  – Including exchange of solar and lunar standards
  – Cross validation: TCCON, EM27/Sun, and aircraft validation campaigns
  – Continued retrieval algorithm development/intercomparisons
Benefits: Quantifying Localized Sources

High spatial resolution and full coverage are critical for quantifying localized sources.


Alberta Tar Sands

Singrauli India
Oct 2014

Nassar et al. (GRL 2017)
Benefits: Anthropogenic Emissions

OCO-2 mean XCO₂ anomalies, 2014-2016

OMI mean NO₂ trop. columns, 2014-2016

Janne Hakkarainen et al. GRL (2016)
Solar Induced Chlorophyll Fluorescence (SIF)

OCO-2 SIF over Des Moines, Idaho

Sun et al. (Science 2017)
Lessons Learned from GOSAT & OCO-2

• High accuracy and low bias are both essential

• High spatial resolution (footprint area < 4 km²)
  – Critical for quantifying emissions from compact sources
    ▪ $X_{\text{CO}_2}$ anomaly associated with a given CO$_2$ injection is inversely proportional to the area of the footprint
  – Critical for gathering data in presence of patchy clouds

• Imaging rather than sampling the CO$_2$ and CH$_4$ field
  – Critical for tracking emission plumes and resolving anthropogenic emission sources from the natural background

• High resolution transport models for flux inversion
  – Critical for quantifying at the scale of cities and resolving anomalies associated with CO$_2$/CH$_4$ “weather”

• Proxies (SIF, CO, and NO$_2$) may be needed for attribution
Remote Sensing of CO₂ and CH₄ using Reflected Sunlight: The Pioneers

• **SCIAMACHY (2002-2012)** – First sensor to measure O₂, CO₂, and CH₄ using reflected NIR/SWIR sunlight
  - Regional-scale maps of X_CO₂ and X_CH₄ over continents

• **GOSAT (2009 ...)** – First Japanese GHG satellite
  - FTS optimized for high spectral resolution over broad spectral range, yielding CO₂, CH₄, and chlorophyll fluorescence (SIF)

• **OCO-2 (2014 ...)** – First NASA satellite to measure O₂ and CO₂ with high sensitivity, resolution, and coverage
  - High resolution imaging grating spectrometer small (< 3 km²) footprint and rapid sampling (10⁶ samples/day)

• **TanSat (2016 ...)** - First Chinese GHG satellite
  - Imaging grating spectrometer for O₂ and CO₂ bands and cloud & aerosol Imager
  - In-orbit checkout formally complete in August 2017
Remote Sensing of CO$_2$ and CH$_4$: The Next Generation

- **Feng Yun 3D (2017)** – Chinese GHG satellite on an operational meteorological bus
  - GAS FTS for O$_2$, CO$_2$, CH$_4$, CO, N$_2$O, H$_2$O

- **Sentinel 5p (2017)** - Copernicus pre-operational Satellite
  - TROPOMI measures O$_2$, CH$_4$ (1%), CO (10%), NO$_2$, SIF
  - Imaging at 7 km x 7 km resolution, daily global coverage

- **Gaofen 5 (2018)** - 2nd Chinese GHG Satellite
  - Spatial heterodyne spectrometer for O$_2$, CO$_2$, and CH$_4$

- **OCO-3 (2018?)** – NASA OCO-2 spare instrument, on ISS
  - First solar CO$_2$ sensor to fly in a low inclination, precessing orbit

- **GOSAT-2 (2018)** – Japanese 2nd generation satellite
  - CO as well as CO$_2$, CH$_4$, with improved precision (0.125%), and active pointing to increase number of cloud free observation
Future GHG Satellites

- **CNES/UK MicroCarb (2020)** – compact, high sensitivity
  - Imaging grating spectrometer for $O_2 A$, $O_2 ^1\Delta_g$, and $CO_2$
  - ~1/2 of the size, mass of OCO-2, with 4.5 km x 9 km footprints

- **CNES/DLR MERLIN (2021)** - First $CH_4$ LIDAR (IPDA)
  - Precise (1-2%) $X_{CH4}$ retrievals for studies of wetland emissions, inter-hemispheric gradients and continental scale annual $CH_4$ budgets

- **NASA GeoCarb (2022)** – First GEO GHG satellite
  - Imaging spectrometer for $XC_{O2}$, $X_{CH4}$, $X_{CO}$ and SIF
  - Stationed above 85° E for North/South America

- **Sentinel 5A,5B,5C (2022)** - Copernicus operational services for air quality and $CH_4$
  - Daily global maps of $X_{CO}$ and $X_{CH4}$ at < 8 km x 8 km

- **Sentinel 7 (2025+)** – Copernicus Operational CO2 Satellite
A multi-satellite GHG constellation could

- Exploit the benefits of observations from low Earth orbit (LEO), geostationary orbits (GEO), and Highly Elliptical Orbits (HEO)
- Reduce revisit times in the presence of optically-thick clouds
- Improve spatial coverage without requiring very broad swaths that
  - Are technically difficult and expensive to implement
  - Large atmospheric path lengths at the swath edges are more likely to be contaminated by clouds
- Collect coincident observations of proxies (CO, NO₂, SIF) to facilitate the interpretation of the measurements
- Provide resiliency to the loss/degradation of individual satellites
- Facilitate data quality improvements through cross calibration and cross validation

Partnerships will help realize these objectives
The coverage, resolution, and precision requirements could be achieved with a constellation that incorporates

- A constellation of (3 or more) satellites in LEO with
  - Broad (~200) km swath with mean footprint sizes < 4 km²
  - Single sounding random error near 0.5 ppm and small regional scale biases (< 0.1 ppm) over > 80% of the sunlit hemisphere
  - One (or more) satellites carrying ancillary sensors (CO, NO₂, SIF and/or a CO₂ or CH₄ Lidar)

- A constellation with 3 (or more) GEO satellites
  - Monitor diurnally varying processes (e.g. rush hours, diurnal variations in the biosphere)
  - Stationed over Europe/Africa, North/South America, and East Asia

- One or more and one or more HEO satellites to monitor carbon cycle changes in the high arctic
Summary

• Space-based remote sensing observations hold substantial promise for future long-term monitoring of greenhouse gases
  – These data complement existing ground-based and aircraft based in situ data with increased coverage and sampling density
• The GOSAT and OCO-2 missions are beginning to demonstrate these capabilities
  – GOSAT and OCO-2 teams have pioneered methods for cross-calibrating measurements and cross-validating products
  – Their products have been combined to produce an 8-year record that is now being used in studies of the global carbon cycle
• Over the next decade, a succession of missions with a range of CO₂ and CH₄ measurement capabilities will be deployed
  – Much greater benefits could be achieved if these sensors can be cross-calibrated and their products can be cross-validated so that they can be combined into a long, continuous GHG data record