Committee on Earth Observation Satellites

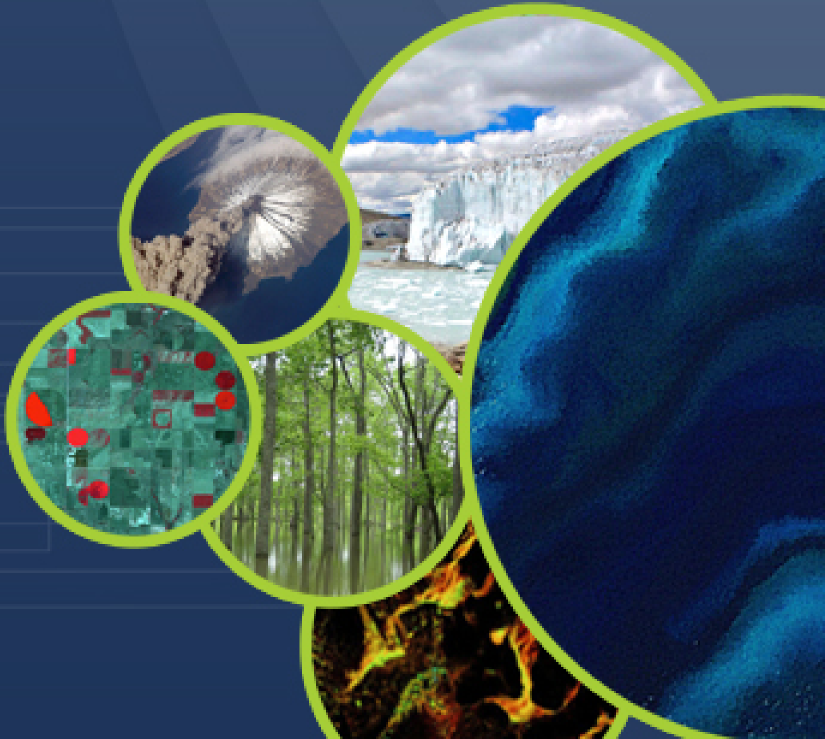
AC-VC – GHG Constellation

Report to CEOS SIT

April 2017

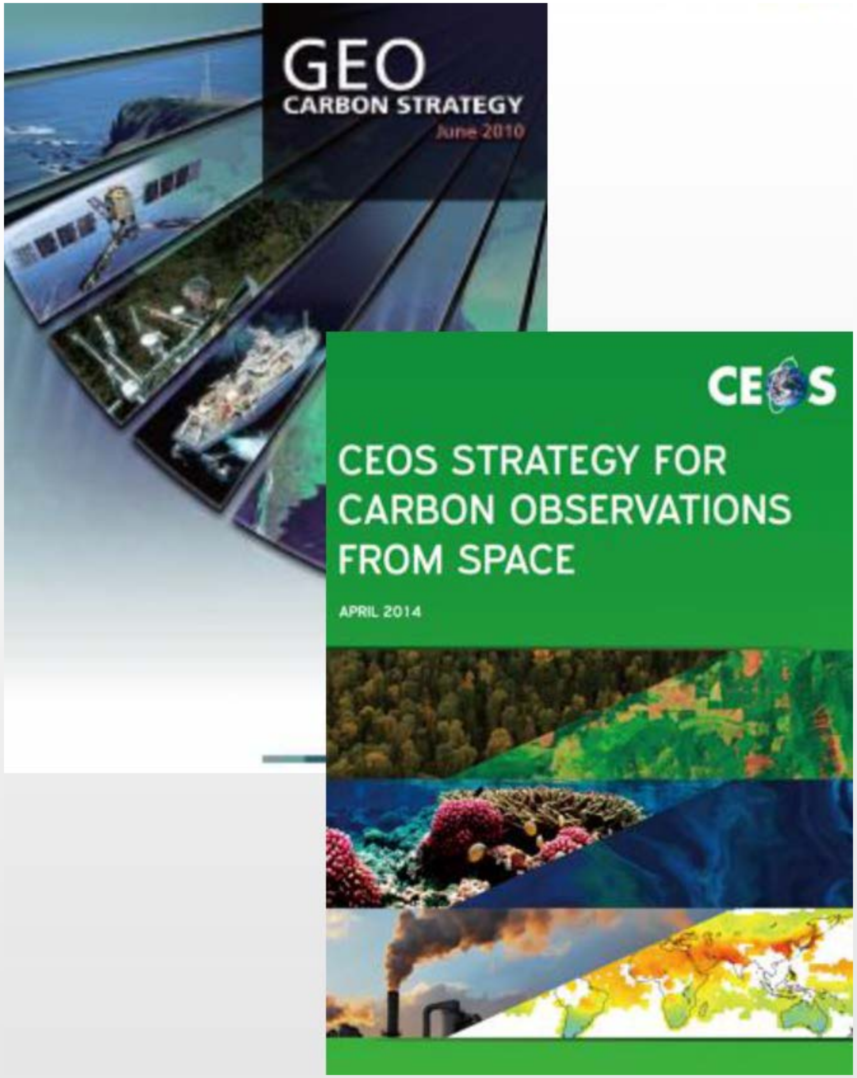
David Crisp (JPL/Caltech)

AC-VC GHG Lead



CEOS Carbon activity
-History and Background

- Group on Earth Observations (GEO) Carbon Report developed in June 2010 by team led by Ciais et al. (GCP)
- *CEOS Strategy for Carbon Observations from Space*–written in response to above, completed in March 2014 –*Wickland et al.*
- **Deliveries:**
  - Merged CARB AI 16+18: AC-VC to support the organization of yearly IWGGMS (FMI (Helsinki, Finland) on 6-8 June 2017
  - Merged CARB AI 17+19+23: AC-VC will prepare a white paper within 2 years
  - CARB AI 20: AC-VC will write a Technical Note within 2 years



14 February 2017 Letter from the CEOS SIT

Committee on Earth Observation Satellites

USGS science for a changing world

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14 February 2017

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Dear CEOS AC-VC Lead,

Thank you for your support in implementation of the *CEOS Strategy for Carbon Observations from Space*. The ability to accurately measure atmospheric CO2 and CH4 will be critical to our implementation of this strategy, and we thank you for agreeing to develop a white paper on this topic. We kindly request that the following areas be given specific attention in your work:

- Based on existing requirements, define the key characteristics of a global architecture for carbon (CO2, CH4) measurements from space.
- Consider observational needs for both composition and fluxes, natural and anthropogenic.
- Include known plans and considerations from space agencies worldwide in overall system architecture to ensure global consistency of design.
- Incorporate potential observations from both GEO and LEO potential missions in an optimal system, and consider optimal acquisition strategies across the system including orbits, equator crossing times, sensor characteristics etc.
- Include instrument on-orbit calibration and geophysical validation aspects.
- Build on work already undertaken by AC-VC in response to the CEOS Carbon Strategy.
- Provide a reference architecture against which individual agencies can develop their plans to optimize joint implementation.
- Identify top priorities for implementation based on the requirements and gaps identified.

We request that interim reports be provided at forthcoming CEOS SIT meetings, SIT Technical Workshops, and the 2017 CEOS Plenary, with a final report to be provided at the 32nd CEOS Plenary to be held in the 4th quarter of 2018.

We have also written to CGMS asking them to nominate, if they wish, additional people to participate in development of the report. We will pass on any such nominations to you and encourage you to work closely with them.

We welcome your feedback and look forward to a very significant and impactful report.

With kind regards,

Frank Kelly
2017 CEOS Chair

- In February 2017, the AC-VC received a formal request from the CEOS Chair, Frank Kelly
    - Included specific guidance on the content of the GHG White Paper
    - Requests interim reports be provided at forthcoming CEOS SIT meetings, SIT Technical Workshops, and the 2017 CEOS Plenary
    - Requests a final report to be provided at the 32nd CEOS Plenary to be held in the 4th quarter of 2018
    - Invited CGMS asking them to nominate, if they wish, additional people to participate in development of the report

Mandate for Satellite Carbon report content, undertaken by AC-VC

- **Based on existing requirements, define the key characteristics of a global architecture for carbon (CO_2, CH_4) measurements from space.**
- **Consider observational needs for both composition and fluxes, natural and anthropogenic**
- **Include known plans and considerations from space agencies worldwide in overall system architecture to ensure global consistency of design**
- **Incorporate potential observations from both GEO and LEO potential missions in an optimal system, and consider optimal acquisition strategies across the system including orbits, equator crossing times, sensor characteristics etc.**
- **Include instrument on-orbit calibration and geophysical validation aspects**
- **Build on work already undertaken by AC-VC in response to the CEOS Carbon Strategy**
- **Provide a reference architecture against which individual agencies can develop their plans to optimise joint implementation.**
- **Report at Plenary 2017, with interim report SIT (April 2017)**

Scope of the White Paper

- Define the key characteristics of a global architecture for carbon (CO_2, CH_4) measurements from space

- The CEOS perspective
  - Facilitate coordination of ongoing efforts by member agencies
  - Focus on calibration and validation of space-based data and products
  - Emphasize value of an open data policy and common product formats
  - Foster use of space-based greenhouse gas (GHG) observations
  - Consolidate data requirements for next-generation GHG satellites

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- Chapter 1: Need for space-based measurements of CO_2 and CH_4
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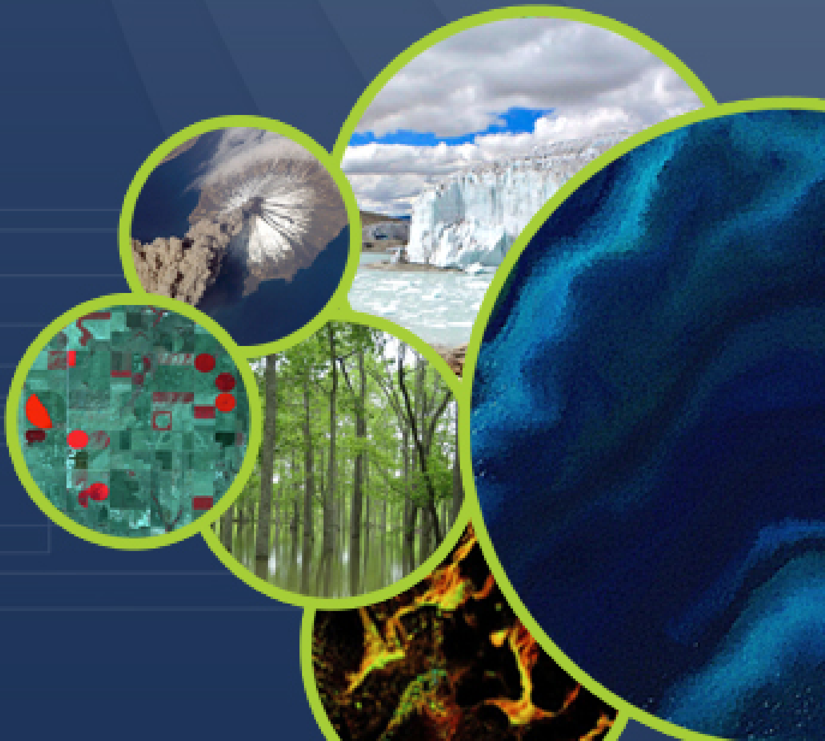
- Chapter 5: Defining GHG Constellation Requirements
- Chapter 6: Candidate Constellation Architectures
- Chapter 7: The EC/ESA CO2 Sentinels: an example of an operational greenhouse gas monitoring constellation
- Chapter 8: The Transition from Science to Operations
- Chapter 9: Conclusions

Milestones for GHG White Paper Development

- 25-28 April: CEOS SIT, Paris, France
  - Present a report on the GHG White Paper progress and plans
- 6-8 June: IWGGMS-13, Helsinki, Finland
  - AC-VC participation in Organizing Committee and opportunities to enlist participation in GHG White Paper among space-based GHG measurement and modeling communities
- 11-16 June: GHG report to the CGMS-45, Jeju Korea
  - Opportunity to solicit input on GHG White Paper from operational agencies
- 28-30 June: CEOS AC-VC, CNES HQ, Paris, France
  - Breakout session to harmonize mission requirements (GEO, GCOS, CEOS)
  - Finalize GHG White Paper outline and writing assignments
- 21-25 August, ICDC10, Interlaken, Switzerland
  - First drafts of all chapters due
- 11-14 September, 2017 SIT Technical Workshop, Frascati, Italy
  - Present a report on the GHG White Paper scope and contents

Chapter 1: Need for space-based measurements of CO_2 and CH_4



Need for space-based measurements of CO_2 and CH_4

- Reduce uncertainty in fossil fuel emission inventories and their time evolution
  - Review origin, content, and limitations of present GHG inventories
  - New requirements from UNFCCC Paris agreement (e.g. “global stocktaking”)
  - Summarize challenges of discriminating and quantifying anthropogenic emissions in context of natural carbon cycle
- Monitoring and predicting changes in the natural carbon cycle on seasonal to interannual time scales associated with climate change and human activities
  - Deforestation, degradation, fire
  - Changes in CO_2 and CH_4 associated with drought, temperature stress, melting permafrost
  - Ocean thermal structure and dynamics

Supporting success of post-COP21 actions to reduce climate-disrupting GHG emissions

The overall goal is to develop a sound, scientific, measurement-based approach that:

- reduces uncertainty of national emission inventory reporting,
- identifies large and additional emission reduction opportunities, and
- provides nations with timely and quantified guidance on progress towards their emission reduction strategies and pledges (Nationally Determined Contributions, NDCs)

In support of these efforts, atmospheric measurements of greenhouse gases from satellites will

- Improve the frequency and accuracy of inventory updates for nations not well equipped for producing reliable inventories, and
- help to “close the budget” by measurement over ocean and over areas with poor data coverage

These objectives require spaceborne measurements with reduced uncertainty

New Delhi Declaration: 3 April 2016

- “Following the COP 21agreement in Paris, “there will be a growing need to implement an independent Measurement, Reporting and Verification system (MRV) … for verifying national INDCs (Intended Nationally Determined Contributions).”
- “operational LEO and GEO constellations measuring greenhouse gases in the atmosphere have the potential to be an essential element for future MRV systems.”
- “At present, several space agencies have invested in research satellites that pave the way for future operational satellites dedicated to Green House Gases monitoring …”
- “Operational measuring capabilities based on satellites will also require coordination between space agencies and with the surface in-situ monitoring network, so that instruments in orbit can be cross-calibrated and their measurements cross-validated.”
- “An international independent way of estimating emission changes for all world countries based on internationally accepted data would create a level playing field and an independent basis for further reductions.
- Space agencies from around the world reaffirm their commitments to work together in the right international framework on these matters.

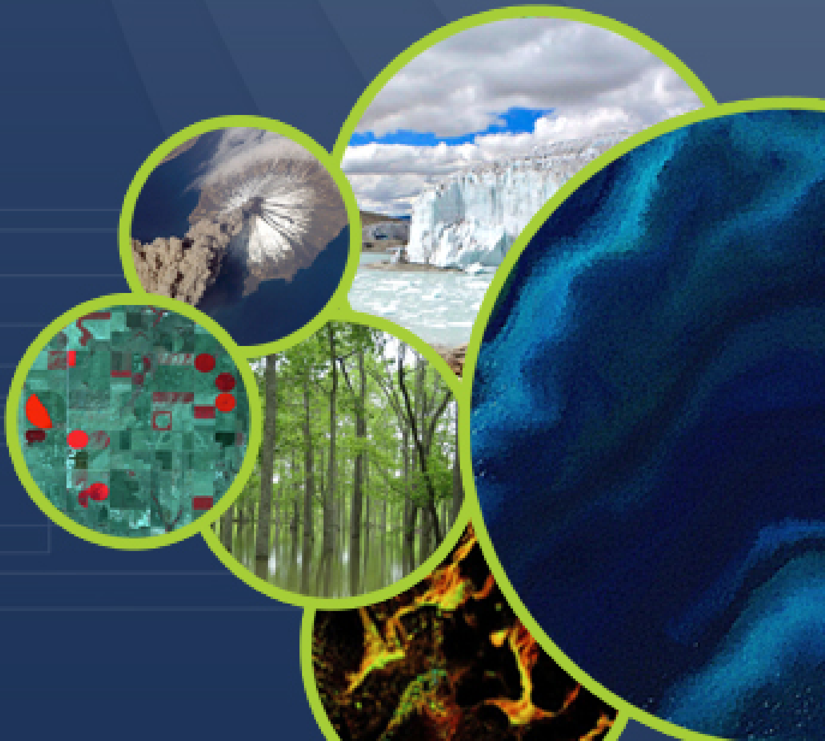
Existing space-based GHG measurement requirements

- A number of international organizations have recommended requirements on space-based GHG measurement precision, accuracy, resolution, coverage, and repeat frequency (see backup)
  - GEO Carbon Strategy Report (Ciais et al. 2010)
  - CEOS Strategy for Carbon Measurements from Space
  - GCOS (4ppm, 10 km, 3-hour repeat cycle)
  - EC CO_2 Report (Ciais et al. 2015)
- Many of these requirements were documented before space based GHG measurements were available for flux inversion experiments
  - Most were based on OSSE studies that provide insight into the role of random error (precision), spatial and temporal resolution, and coverage, but less insight into the role of systematic spatially- and temporally varying biases
  - Most such studies have not focused on constraining GHG inventories on national scales
  - Most provide little or no insight into how one might validate a GHG inventories inferred from space based GHG concentration data

Quantifying anthropogenic emissions to improve inventories

- Deriving estimates of anthropogenic GHG emissions from space-based measurements of GHG concentrations with the accuracy needed to improve inventories is especially challenging
  - Anthropogenic CO_2 emissions are superimposed on an active natural carbon cycle that emits and reabsorbs almost 20 times as much CO_2 as human activities, as well as > 50% of the human contributions
  - High spatial resolution images of plumes are needed to estimated emissions from compact urban areas, which are the dominant source of anthropogenic CO_2 emissions and a significant source of CH_4
  - While anthropogenic CO_2 sources are often spatially localized and intense, natural CO_2 sinks and many CH_4 sources are weaker and more broadly distributed
  - Optically thick aerosols and clouds often preclude full-column observations of GHGs for weeks or months
  - As human activities emit CO_2 and CH_4 into the air, these gases are entrained and dispersed by the prevailing winds
- The proposed GHG constellation must address these issues

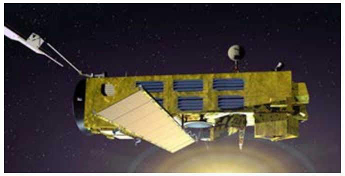
Chapter 2: Existing space-based GHG Satellites and near term plans



Existing space-based GHG Satellites and near term plans

- Past: SCIAMACHY: 2002-2012 – first NIR/SWIR X_{CO2}, X_{CH4}
- Existing GHG satellites: GOSAT, OCO-2, and TanSat
  - Evolution of measurement capabilities: precision, accuracy, resolution, coverage, data availability
  - Progress toward a constellation: cross calibration of measurements and cross validation of products against internationally recognized standards
- Near-term Missions: Gaofen 5, Sentinel 5p, Feng-Yun 3D, GOSAT-2, OCO-3, MERLIN
- Missions in formulation: MicroCarb, GeoCarb, Sentinel 5, GOSAT-3, Sentinel -7 GHG mission

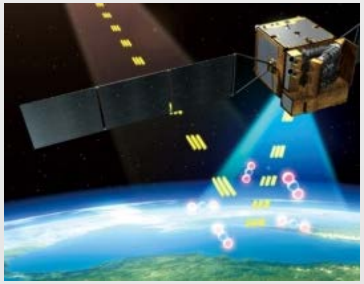
Remote Sensing of CO_2 and CH_4 using Reflected Sunlight: The Pioneers



- **SCIAMACHY (2002-2012)** – First sensor to measure O_2, CO_2, and CH_4 from reflected NIR/SWIR sunlight
  - Regional-scale maps of X_{CO2} and X_{CH4} over continents on seasonal time scales

- **GOSAT (2009 - ?)** – First Japanese GHG satellite
  - FTS optimized for spectral coverage (O_2, CO_2, CH_4)
  - High spectral resolution over broad spectral range yields high sensitivity to CO_2, CH_4, and chlorophyll fluorescence

- **OCO-2 (2014 - ?)** – First NASA satellite designed to measure O_2 and CO_2 with high sensitivity, resolution, and coverage
  - High resolution imaging grating spectrometer with agile pointing (glint, nadir, target), small (< 3 km^2) footprint and rapid sampling (10^6 samples/day)



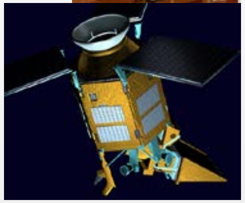
- **TanSat (2016-?) -** First Chinese GHG satellite
  - Uses same O_2 and CO_2 bands and similar orbit as OCO-2
  - Cloud & Aerosol Imager: 0.38, 0.67, 0.87, 1.38 and 1.61µm channels

Remote Sensing of CO_2 and CH_4: The Next Generation

- **Feng Yun 3D (2017)** – Chinese GHG satellite on operational meteorological bus
  - GAS FTS for O_2, CO_2, CH_4, CO, N_2O, H_2O

- **Gaofen 5 (2017)** - Chinese GHG Satellite
  - Spatial heterodyne spectrometer for O_2, CO_2, and CH_4

- **Sentinel 5p (2017)** - Copernicus pre-operational Satellite
  - TROPOMI measures O_2, CH_4 (1%), CO (10%), NO_2, SIF
  - Imaging at 7km x 7 km resolution, daily global coverage

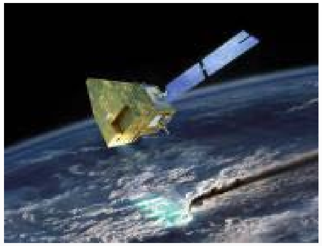


- **OCO-3 (2018)** – NASA OCO-2 spare instrument, on ISS
  - First solar CO_2 sensor to fly in a low inclination, precessing orbit

- **GOSAT-2 (2018)** – Japanese, High precision CO_2, CH_4, CO
  - Improved precision (0.5 ppm), spatial resolution, and range of ocean glint observations expected to improve coverage

Future GHG Satellites

- **CNES MicroCarb (2020)** – compact, high sensitivity
  - Imaging grating spectrometer for O_2 A, O_2 $^1\Delta_{g}$, CO_2
  - ~1/2 to 1/3 of the size, mass (< 200 kg) of OCO-2, with similar sensitivity in 4.5 km x 9 km footprints

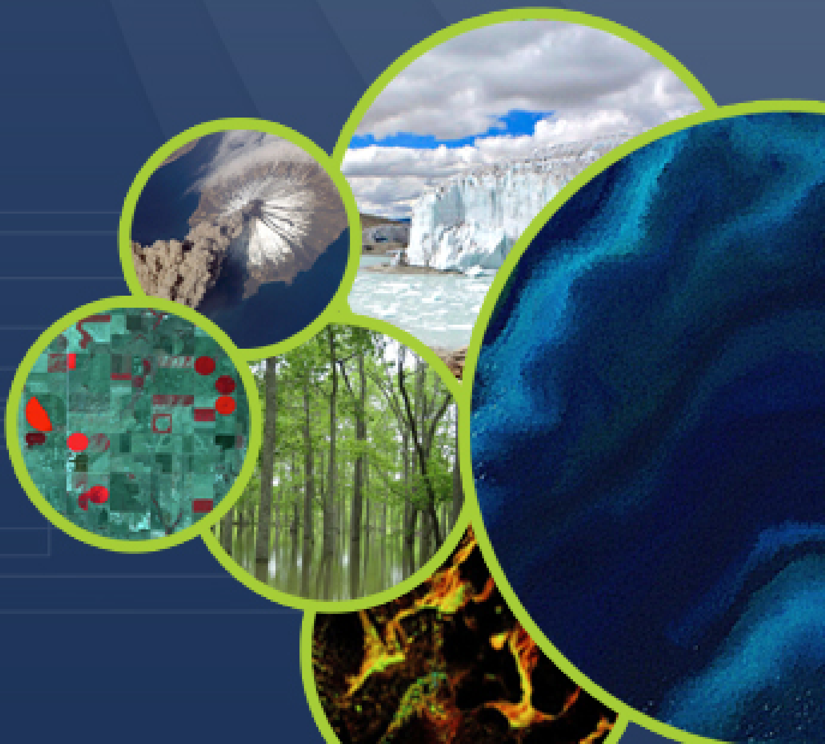


- **CNES/DLR MERLIN (2021)** - First CH_4 LIDAR (IPDA)
  - Precise (1-2%) X_{CH4} retrievals for studies of wetland emissions, inter-hemispheric gradients and continental scale annual CH_4 budgets

- **NASA GeoCarb (2022)** – First GEO GHG satellite
  - Imaging spectrometer for XCO2, XCH4, XCO and SIF
  - Stationed above 85° E for North/South America

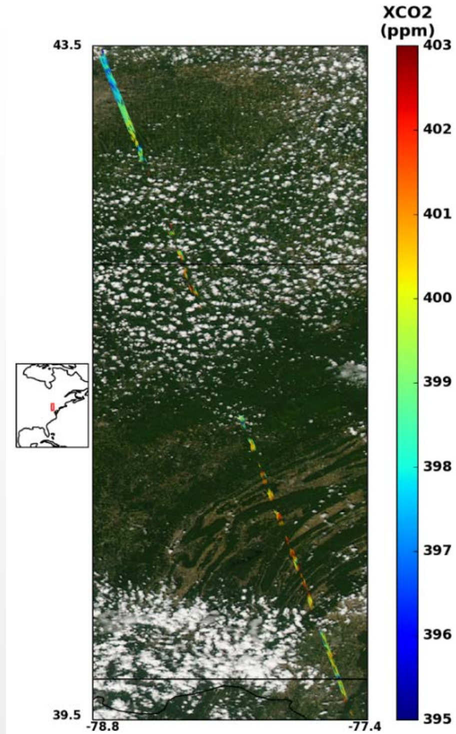
- **Sentinel 5A,5B,5C (2022)** - Copernicus operational services for air quality and GHG
  - Daily global maps of X_{CO} and X_{CH4} at < 8 km x 8 km

Chapter 3: Lessons Learned from GOSAT and OCO-2

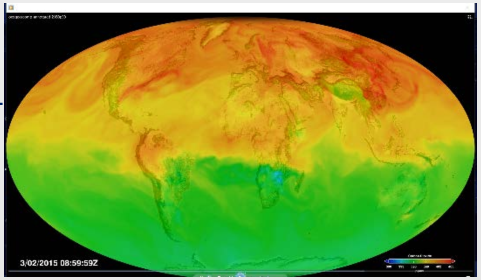


Lessons learned from GOSAT and OCO-2 CO_2 and CH_4 Measurements

- High accuracy and low bias are both essential
- High spatial resolution (footprint area < 4 km^2)
  - Critical for quantifying emissions from compact sources
    - X_{CO2} 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
  - Needed for resolving anomalies associated with CO_2/CH_4 "weather" from local sources and sinks
- Proxies (SIF, CO, and NO_2) may be needed for attribution

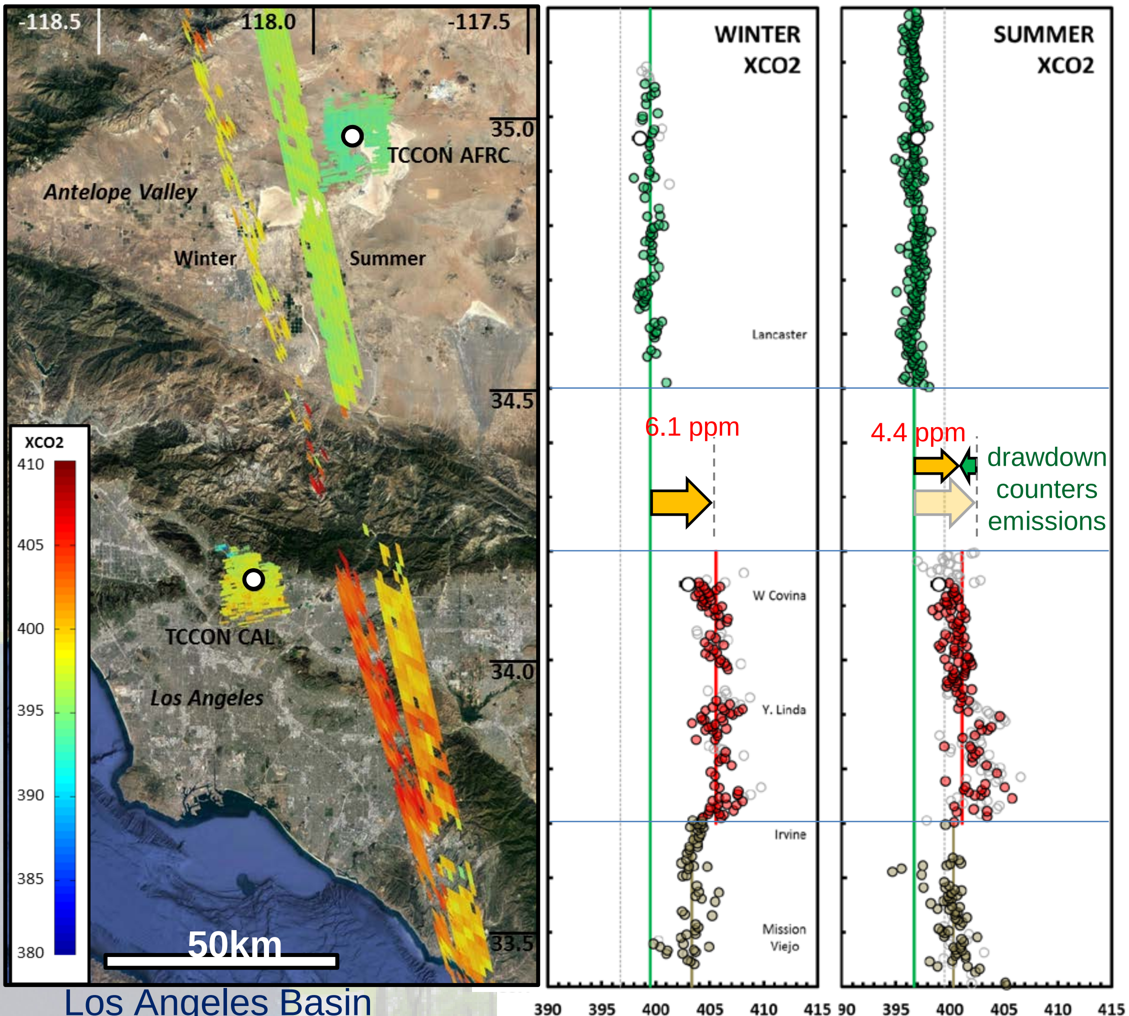


OCO-2 track through patc
hy clouds in NE U.S.

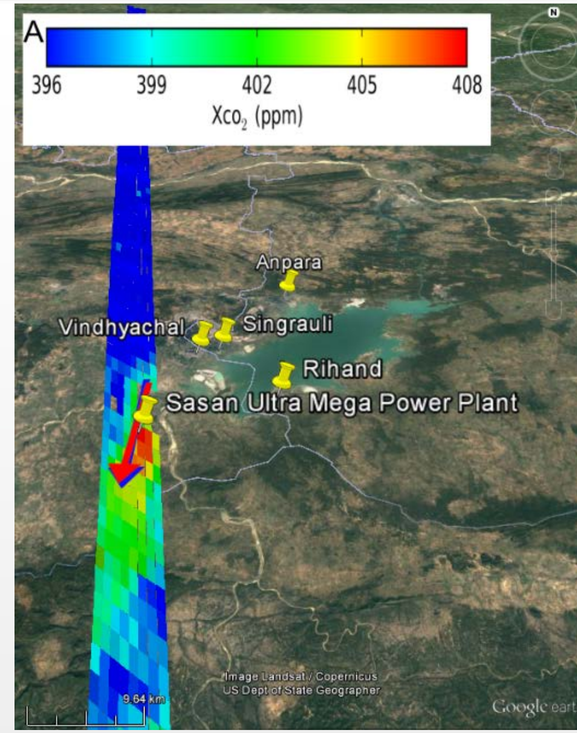


GEOS-5 XCO2 Weather

High precision and coverage needed to characterize compact sources



Winter and summer OCO-2 tracks across the Los Angeles basin and the Antelope Valley to the north of the San Gabriel mountains show X_{CO2} anomaly across the megacity [Schwandner et al, Submitted 2017] .

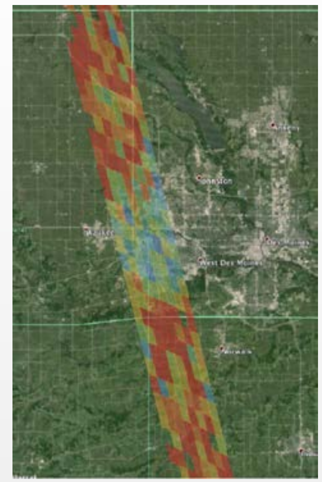


Direct OCO-2 overpasses or close flybys clearly detect emission plumes from individual, moderate sized power plants, yielding flux accuracies of 8 to 50% [Nassar et al. 2017].

Proxies and other Coincident measurements needed

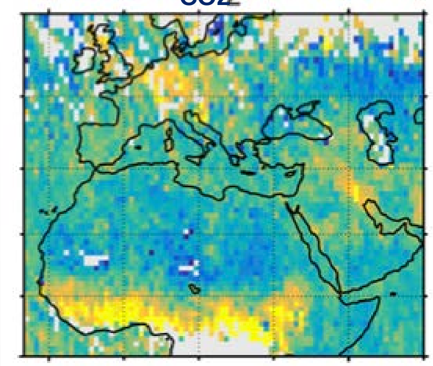
- Proxies useful for CO_2 emissions source attribution:
  - o CO traces both moderate (biomass burning) and high temperature (fossil fuel) combustion
  - o NO_2 traces high temperature (fossil fuel) combustion
  - o SIF traces spatial distribution of CO_2 uptake by the land biosphere

- What proxies are needed for discriminating CH_4 sources?

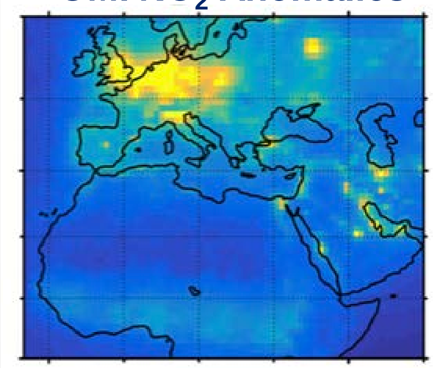


OCO-2 SIF is more intense over corn fields than over Des Moines, Iowa [Frankenberg et al., 2016]

OCO-2 X_{CO2} Anomalies



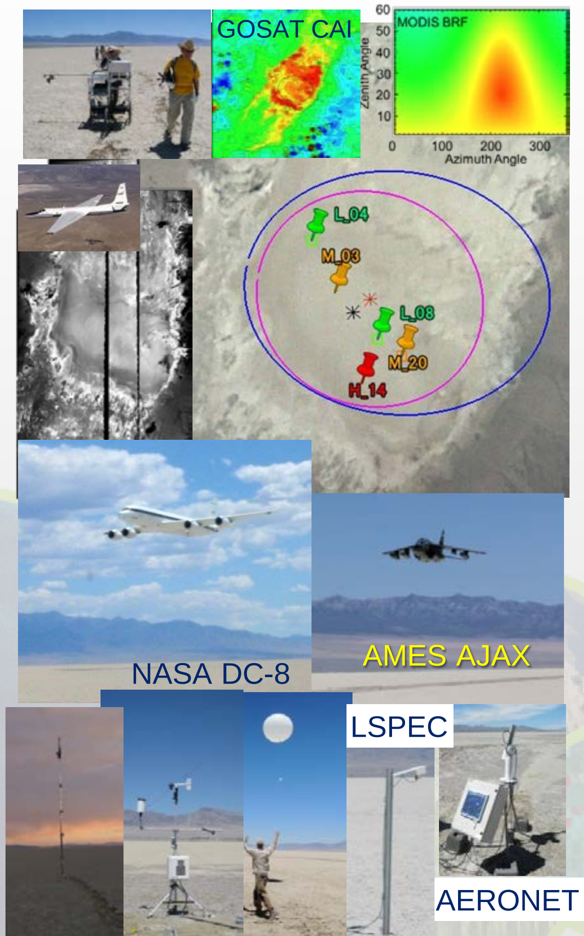
OMI NO_2 Anomalies



OCO-2 X_{CO2} and OMI NO_2 anomalies over Europe (fossil fuel combustion) but not over central Africa (biomass burning) [Hakkarainen et al., GRL 2016]

Cross-Calibration and Cross-Validation Essential to Combine Data Products

Vicarious Calibration



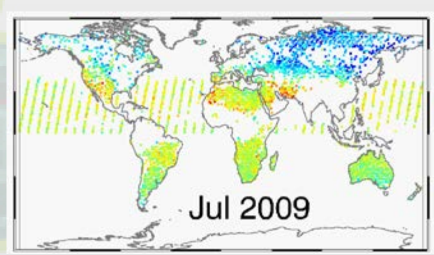
Retrieval Algorithm

Forward Radiative Transfer Model
Spectra + Jacobians

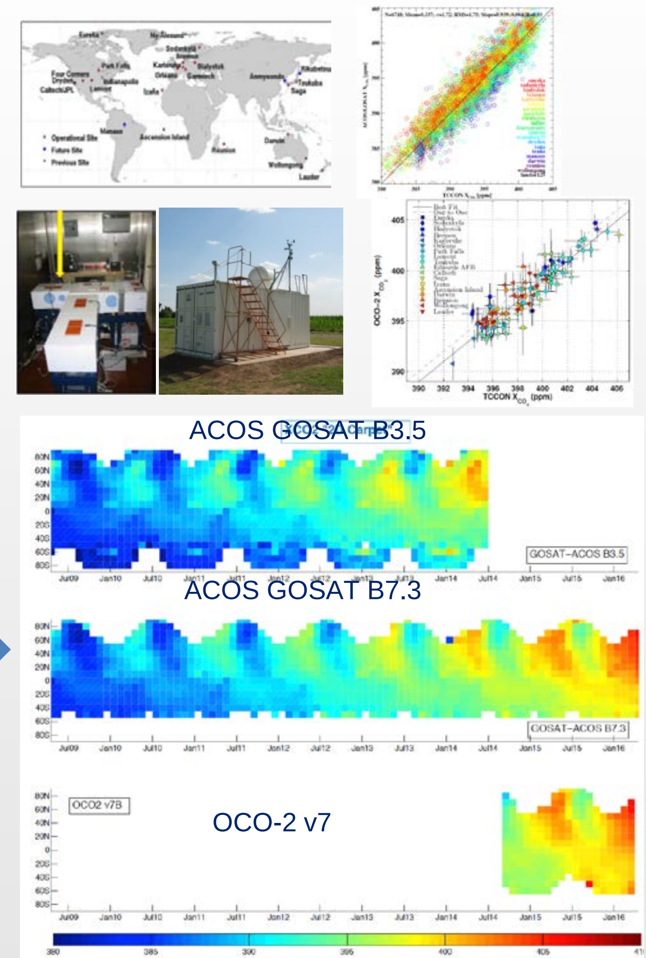
Instrument Model
Spectral+Polarization

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

?
not converged
converged

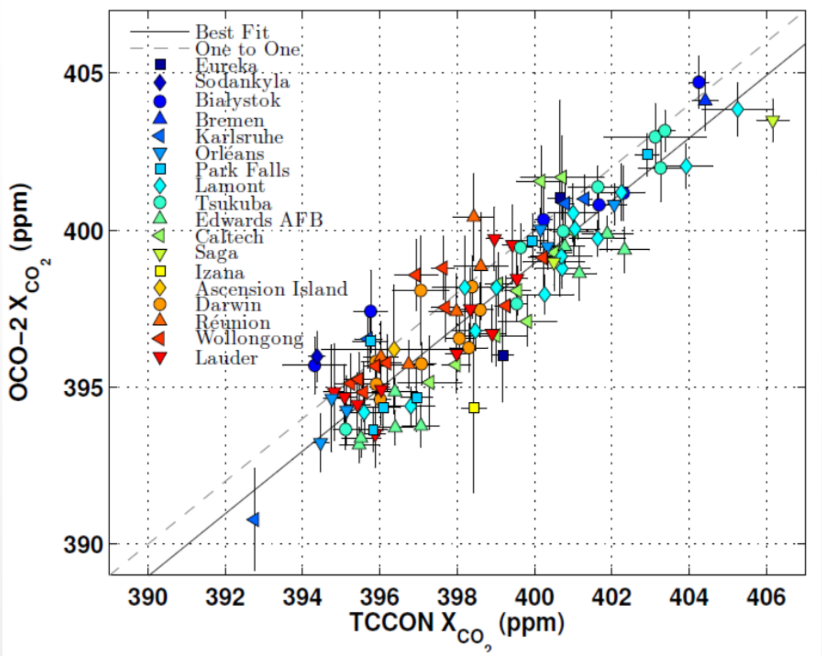


Cross Validation



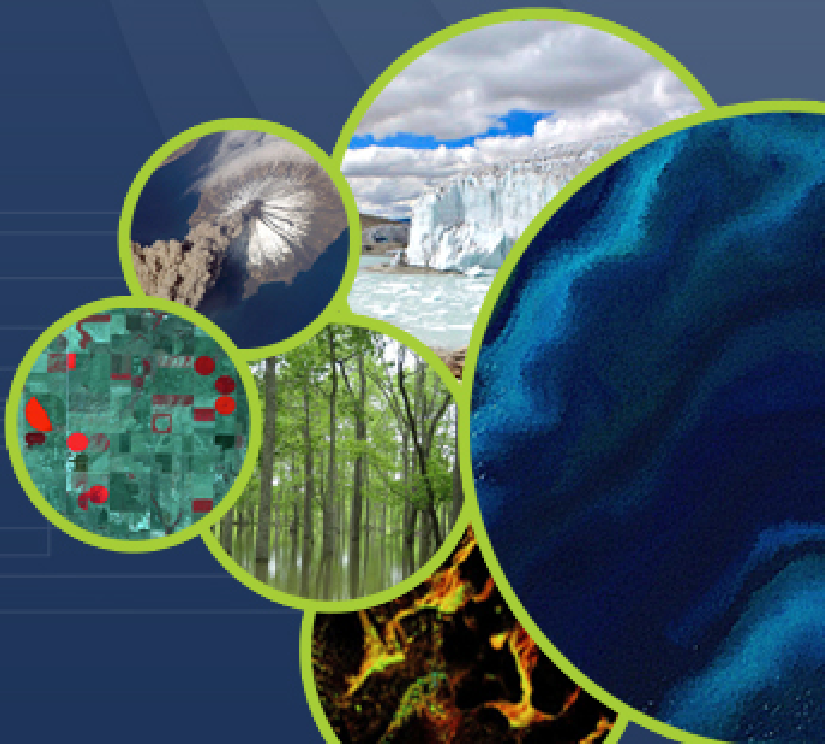
Validating space-based measurements against international standards

- GOSAT and OCO-2 data were validated against the Total Column Carbon Observing Network (TCCON)
- TCCON is validated against the WMO standards profiles from in situ instruments on aircraft
- Other standards, including aircraft campaigns (HIPPO, ACT-America, Atom) also used
- These validation methods must be maintained and expanded to support future observations from LEO, GEO and HEO platforms



Example of comparisons between OCO-2 and a wide array of TCCON stations. After applying a bias corre ction, the global bias is reduced to < 0.5 ppm and the station-to-station biases reduced to ~1.5 ppm

Chapter 4: Integrating Near-term Missions into a Virtual Constellation



Moving Forward from "Science" to "Operational" GHG Missions

- With the exception of the Sentinels, all of the existing and planned GHG missions are "science" missions, designed to identify optimal methods for measuring CO_2 and CH_4, not "operational" missions designed to deliver policy relevant GHG products focused on anthropogenic emissions
- With the exception of SCIAMACHY, Sentinel 5p, and GeoCarb, these are "sampling" missions, rather than GHG "mapping" or "imaging" missions
- GHG imaging missions are needed to quantify emissions from compact sources including cities and large power plants
    - GOSAT and OCO-2 measurements clearly show that compact sources can be detected and quantified if they are captured within a footprint, but their plumes are more difficult to quantify downwind of the source
    - These two satellites sample < 10% of the surface area of the Earth each month, and only 10% of their samples are sufficiently cloud free to retrieve full-column estimates of X_{CO2} and X_{CH4}

Advantages of GHG Constellations

A multi-satellite GHG constellation could

- Exploit the benefits of observations from low Earth orbit (LEO), geostationary orbits (GEO), and Highly Elliptical Orbits (HEO) vantage points
- 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, and will limit sensitivity (spectral resolution, SNR, low scattered light …)
  - Introduce larger atmospheric path lengths at the edges the swath that are more likely to be contaminated by clouds
- Collect coincident observations of proxies (CO, NO_2, 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

Benefits of LEO Observations

High spatial resolution imaging observations from broad-swath instruments on LEO platforms

- Can collect measurements over nearly the entire globe at high spatial resolution at weekly to monthly intervals
- Use a single sensor, reducing sensor-to-sensor calibration biases
- Allows “glint” observations for adequate signal over ocean

Platforms in LEO orbits facilitate the combined use of passive spectrometers and active LIDAR measurements

- Passive sensors provide high spatial resolution and coverage across the sunlit hemisphere
- Active LIDAR sensors complement these passive measurements with sampling of high latitudes and the night side
- A combination of passive and active LEO sensors can reduce spatially-coherent biases, which affect the sensors differently

Principal limitation of individual LEO platforms is their relatively long repeat cycles (weeks)

Benefits of GEO Observations

Continuous imaging of X_{CO2} and X_{CH4} from GEO platforms

- Captures spatial and temporal context, resolving transport, boundary conditions and local sources and sinks
- Resolves emissions from localized sources in the context of CO_2/CH_4 “weather” and synoptic variability (clouds, fronts)
- Explicitly resolves variations in X_{CO2}, X_{CH4}, SIF from dawn to dusk
- Reduces temporal sampling bias – does not miss flux events

GEO platform limitations:

- Limited coverage at large viewing angles (> 50° from sub-satellite point)
  - Observations from satellites in Highly Elliptical Orbits (HEO) would provide high time resolution coverage of high latitudes
- Glint observations extremely limited, precluding observations over oceans
- Multiple satellites needed to cover major continents
  - Places additional demands calibration and validation capabilities

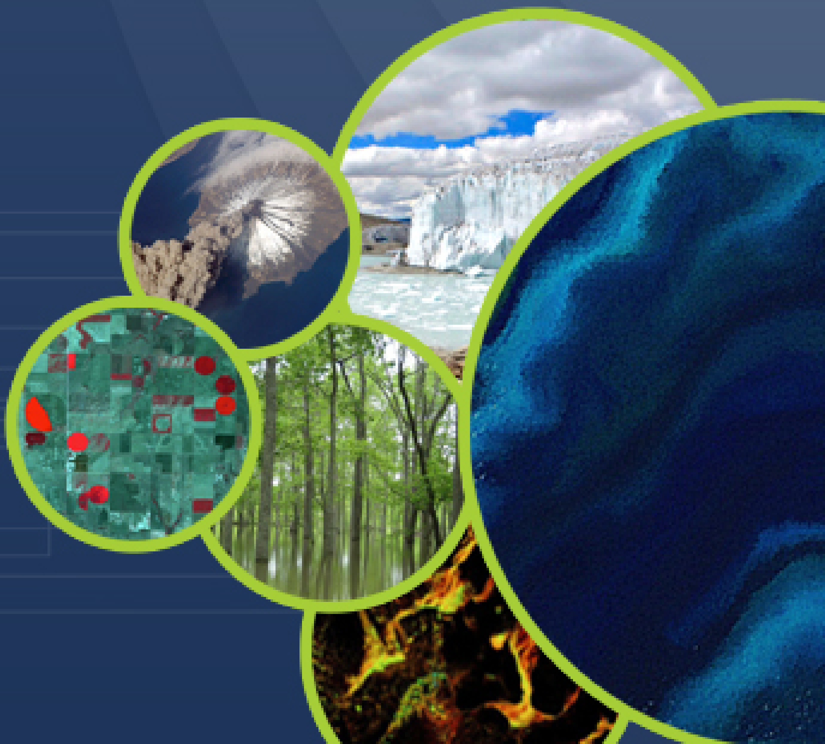
Benefits of integrating data across the evolving constellation

- Even for the existing GHG science missions, there are numerous benefits of integrating data across the constellation
  - Improving coverage in the presence of clouds
  - Covering more of the day-lit portion of the diurnal cycle
  - Maintaining data continuity if one satellite is lost
- Coordinating measurement capabilities during mission formulation
  - Trade-offs in precision, accuracy, resolution, coverage
  - Maximizing benefits of LEO, GEO, and HEO vantage points
- Cross calibration of measurements
  - Pre-launch calibration measurements using common standards
  - On orbit calibration (on-board, astronomical, and vicarious)
- Cross validation of retrieved CO_2 and CH_4 concentrations
  - Current role of TCCON, EM27/Sun and aircraft
  - Future needs

Collaborative CAL/VAL activities needed to integrate data sets across a constellation

- 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 databases
  - Retrieval algorithm development/intercomparison
  - Validation system development (TCCON, aircraft, models)
  - 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 (ROLO) standards
  - Cross validation: TCCON, EM27/Sun, and aircraft validation campaigns
  - Continued retrieval algorithm development/intercomparisons
  - Intercomparisons of flux inversions

Chapter 5: Defining GHG Constellation Requirements



The context of the GHG Constellation

- The GHG constellation architecture should recognize that space based GHG measurements are only one component of the GHG monitoring system
  - Other components include inventories, in-stack monitoring, atmospheric observations from ground-based and aircraft monitoring networks, and ground based remote sensing techniques (i.e. TCCON)
- To maximize its utility, the architecture should fully exploit the primary assets of space based remote sensing vantage point
  - Near global coverage of both continents and ocean
  - Adequate spatial resolution to resolve compact sources, such as cities
  - Adequate precision resolve resolve GHG plumes from the background
  - High revisit frequency to resolve temporal changes
- International standards must be defined to cross-calibrate the instruments, characterize the retrieval algorithms, and validate the products from each observatory to facilitate the integration of results across the constellation

Elements of a space based top-down GHG monitoring system

- Space based measurements from a constellation of satellites for
  - CO_2 and CH_4 with the accuracy, precision, spatial and temporal resolution, coverage, and continuity needed to detect and quantify emission sources and natural sinks on local (10 km x 10 km) to national (500 km x 500 km) scales over the globe
  - Proxy gases (CO, NO_2) and solar induced chlorophyll fluorescence (SIF) to facilitate attribution or sources and sinks
  - Clouds and aerosols and other meteorological sources of bias
- Precise, accurate, ground- and aircraft base measurements of atmospheric CO_2 and CH_4 for validating the space based concentrations and fluxes with respect to internationally recognized standards
- Ground-based measurements of key isotopes (i.e. ^{14}C) and proxy gases (CO, NO_2, ethane) for source attribution
- Modeling architecture for deriving CO_2 and CH_4 fluxes from the space based and ground based observations
- Methods to verify the GHG fluxes

Estimating fluxes from space based GHG measurements

Estimating surface fluxes of CO_2 or CH_4 from space-based remote sensing measurements of reflected sunlight is a 6-step process:

1. Acquire high spectral resolution, co-bore-sighted observations of reflected sunlight within near infrared GHG bands, and within the O_2 A-band at high spatial resolution over the sunlit hemisphere
2. Calibrate these measurements to yield spectral radiances
3. Use a remote sensing retrieval algorithm to estimate the column-averaged dry air mole fractions of the GHG, (X_{GHG}) and other relevant state properties (surface pressure and reflectance, atmospheric temperature, water vapor, clouds and aerosols) from each co-bore-sighted sounding
4. Validate the X_{GHG} measurements against available standards
5. Perform a flux inversion to estimate the surface GHG fluxes needed to maintain the observed X_{GHG} distribution in the presences of the prevailing winds
6. Validate the retrieved fluxes against available standards

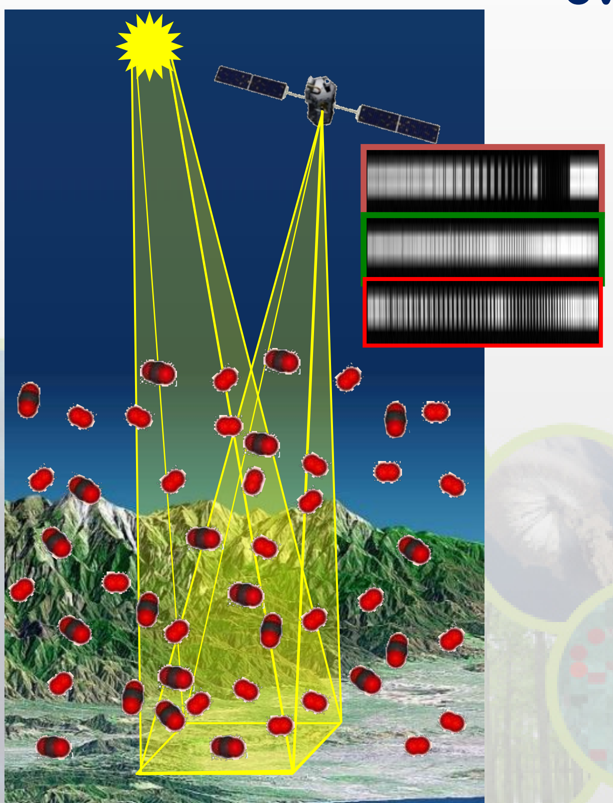
An end-to-end modeling framework is needed to trace flux requirements back to mission and instrument requirements

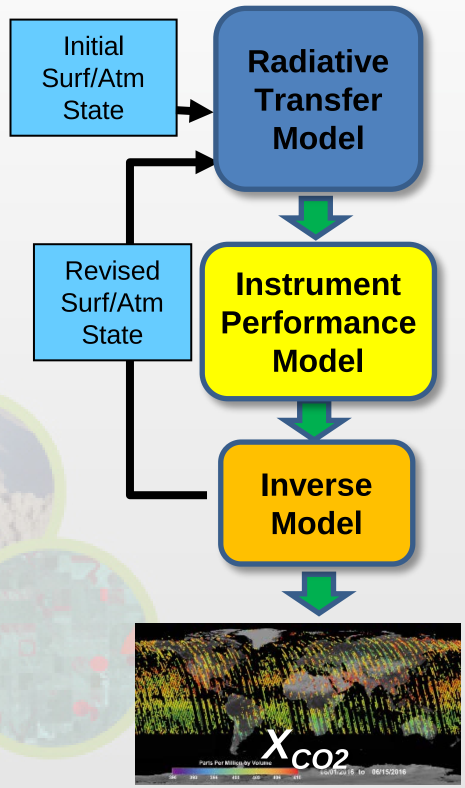
Deriving column-averaged CO_2 and CH_4 dry air mole fractions from measurements of reflected Sunlight

- **Record** spectra of CO_2 , CH_4, and O_2 absorption in reflected sunlight

Retrieve variations in the **column averaged CO_2 and CH_4 dry air mole fractions [X_{CO2}, XCH_4]** over sunlit hemisphere

Validate measurements against available standards to ensure X_{CO2}, X_{CH4} accuracy





The promise and challenge for space-based GHG measurements

The primary assets of space based GHG measurements include

- Spatial coverage
  - Observations over both land and ocean
- Temporal resolution and sampling
  - Hourly sampling needed to resolve diurnal cycle and plumes
  - Daily to weekly sampling needed to resolve CO_2 weather
  - Monthly measurements required over multiple years to resolve seasonal and inter-annual variability in CO_2
- Spatial resolution and sampling
  - Sensitivity to point sources scales with area of footprint
  - Small measurement footprints enhance sensitivity to point sources and reduce data losses due to clouds

The primary challenge is precision and accuracy

- High precision required to resolve the small (< 1%) variations in CO_2 and CH_4 associated with sources and sinks
- High accuracy essential to avoid regional-scale biases

Tools for deriving constellation measurement requirements

- Efforts to trace requirements on the space based CO_2 and CH_4 concentration measurements to the desired improvements in natural fluxes and fossil fuel inventories use a range of numerical modeling approaches:
  - Signal detection experiments use carbon tracer transport models (CTTMs) to simulate atmospheric the impact of atmospheric transport on GHG concentration changes associated with specified changes in surface fluxes (i.e. doubled CO_2 emissions from East Asia or CH_4 injections from a broken pipeline or melting permafrost)
  - End-to-end Observational System Simulation Experiments (OSSEs) combine CTTMs with remote sensing retrieval models and instrument models to assess observing system and retrieval algorithm trade in "realistic" conditions
  - Flux inversion experiments using existing space-, aircraft-, and ground based data provide an end-to-end test of accuracy, precision, resolution, and coverage of existing observing systems for a wide range of conditions

Challenges in deriving constellation measurement requirements

- All 3 approaches need improvements to derive requirements for a constellation of satellites for anthropogenic GHG measurements
  - Signal Detection experiments provide insight into sensitivity, resolution, and coverage needs as a function of source/sink scale, but provide no information about correlated errors or systematic biases
  - OSSEs are good for identifying impact of random errors in concentration or transport or limitations of coverage, but are generally not adequate for assessing the impact of systematic biases in transport or measured concentration
  - Flux inversion experiments show that spatially-dense space based data pose special problems
    - Limitations in coverage and biases in transport and measured GHG concentration introduce significant uncertainties in fluxes
    - These sources of uncertainty play different roles in city (10 km x 10 km), national (500 km x 500 km), and global scale experiments
  - Few existing modeling systems span the full range of scales needed

A path forward for defining constellation requirements

- While existing studies have identified a number of challenges in defining traceable measurement requirements, they have also indicate that different approaches can be combined to define different requirements
  - Signal detection experiments provide insight into the amplitude of X_{CO2} and X_{CH4} anomalies associated with persistent flux changes and their dependence on wind speed at local to global scales
  - Realistic, end-to-end OSSEs are adequate for assessing flux uncertainties associated with sensor precision, resolution, and coverage in the presence of realistic transport and clouds
  - Flux inversion experiments combining data from in situ, TCCON, GOSAT and OCO-2 are being validated against “withheld data” (from aircraft or surface stations) to provide insight into the impact of biases in concentration measurements and transport
- All three methods must be used to derive instrument and measurement requirements from the flux requirements

Scale dependence of GHG measurement requirements

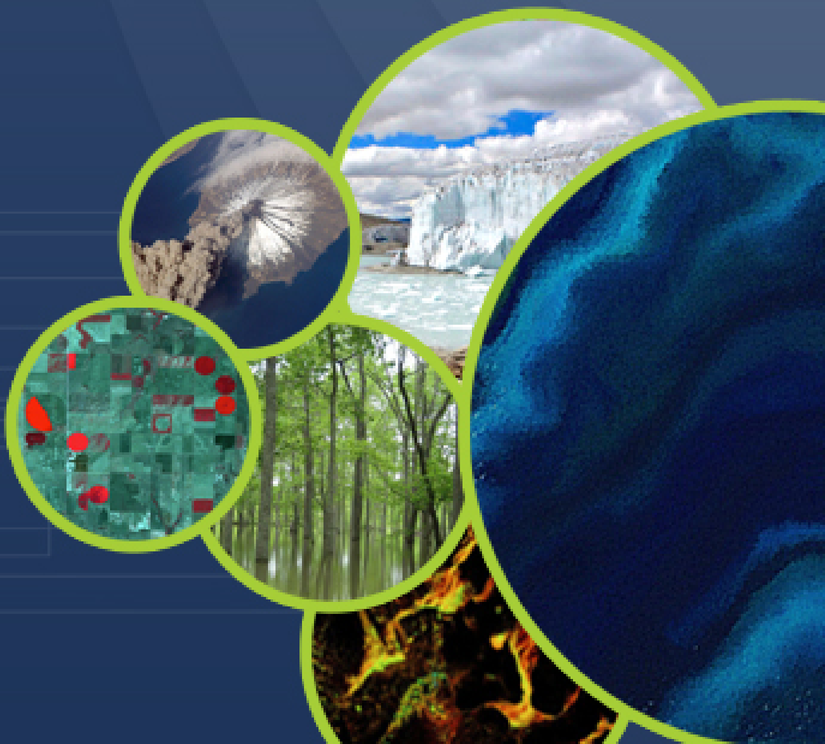
Efforts to estimate fluxes from existing measurements indicate that driving requirements vary with scale

- City scale: High precision and high spatial resolution (small footprint) and coverage are essential to resolve compact sources
  - The sensitivity (ppm) needed to quantify a given flux of CO_2 or CH_4 from a sub-footprint scale source is inversely proportional to the area of the footprint and the wind speed
  - Sources (plumes) not directly measured cannot be quantified
- National scale (500 km x 500 km): Precise, accurate measurements with complete coverage are needed at frequent intervals to
  - Discriminate contributions from distributed sources and natural sinks in the presence of synoptic-scale transport (e.g. CO_2 weather)
- Continental to hemispheric scale: Nearly bias free results are essential to quantify large scale greenhouse gas budgets
  - A 0.1 ppm north-south or land-sea bias in CO_2 can yield spurious sources/sinks exceeding a gigaton/year
  - These errors obscure the evolving roles of the natural carbon cycle

Using space based products to update inventories

- Ongoing measurements and modeling efforts show that space based products can provide the precision (~0.13%) and spatial resolution (< 3 km^2) needed to reduce uncertainties in inventories
- However, to produce meaningful improvements in inventories, future constellations must address the following issues:
  - systematic biases must be reduced
  - Spatial coverage and revisit frequency must be increased
- Even with their limitations, an ad-hoc constellation consisting of existing and near-term space-based GHG measurement and modeling systems can reduce uncertainties in inventories for:
  - Fossil fuel and biomass burning in the developing world
  - Fossil fuel emissions associated with extraction (flaring/leaks) and delivery (pipeline infrastructure)
  - Agricultural practices (slash/burn, livestock)

Chapter 6: Candidate Constellation Architectures



A Candidate GHG 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 (~200) km swath with a mean footprint size < 4 km^2
  - A single sounding random error near 0.5 ppm, and vanishing small regional scale bias (< 0.1 ppm) over > 80% of the sunlit hemisphere
  - One (or more) satellites carrying ancillary sensors (CO, NO_2, CO_2 and/or CH_4 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

Synergies with Air Quality Missions

- There are strong synergies between the requirements for air quality and GHGs measurements, since sources that emit GHGs also emit reactive gases and aerosols that affect air quality
- In many cases, reactive trace gases that compromise air quality (CO, NO_2) are more easily discriminated from the background than the associated GHGs, facilitating GHG detection
  - Can be used for plume detection and tracking
- Simultaneous observations of the reactive trace gases associated with GHG emissions can facilitate the attribution of GHG sources
  - Natural CO2 sources including respiration, ocean outgassing, and volcanos emit CO_2 but little CO or NO_2
  - Biomass burning produces CO_2, CO, and aerosols but little NO_2
  - Fossil fuel combustion produces NO_2 and CO as well as CO_2

Synergies with Meteorological Measurements

- There are strong synergies between the measurement requirements of GHG and Meteorological satellites
  - o GHG instruments also return high spatial resolution estimates of surface pressure (±1 hPa) and column water vapor (± 1 mm) over both land and ocean that could be assimilated into numerical weather prediction models
  - o Simultaneous observations of clouds by meteorological instruments could reduce cloud-related biases in GHG retrievals
  - o A combined assimilation of simultaneously-acquired meteorological measurements and GHG concentrations could reduce the impact of transport errors in the GHG flux inversions
    - ▪ Both meteorological properties (clouds, water vapor) and GHG are transported by the same wind field
- GHG missions require the same space-based LEO, GEO, and HEO vantage points currently used by Meteorological satellites

Calibration and Validation requirements

- Calibration and validation capabilities must be maintained and expanded to meet the demanding accuracy requirements of future GHG constellations
- The GOSAT and OCO-2 teams pioneered methods for cross-calibrating sensors and cross-validating results from LEO missions
  - Cross calibration of pre-flight calibration standards, and joint post launch vicarious calibration campaigns over Railroad Valley, NV U.S.A.
  - Cross validation of products using TCCON and AirCore
- GEO GHG missions stationed over different longitudes place additional demands on calibration and validation capabilities
  - Pre-launch and on-orbit calibration methods must be referenced to internationally recognized standards
    - Additional vicarious calibration sites and/or well calibrated astronomical targets may be needed
  - To validate GEO platforms, TCCON must be expanded to improve coverage of the tropics and southern hemisphere continents

Open Data Policy and Common Cal/Val Standards: Recommendations

1. **Apply best practices (lessons learned) for spectrometer calibration, characterization, and validation**
   - Share calibration/characterization plans and invite cross participation in reviews of such plans
   - Develop longer term recommendations for common post-launch cal/val strategies (e.g. cal/val instrumentation round-robins, joint vicarious calibration campaigns, joint airborne campaigns)
2. **Radiometric consistency**
   - Pre-launch: highest priority is per-instrument calibration/characterization as completely as possible (common absolute radiance calibration is secondary)
   - Post-launch: (e.g. LEO vicarious intercalibration, lunar calibration, solar calibration)
3. **Sharing and consistency of data products (format, content, metadata)**
   - Share specification documents
   - Share instrument characterization/calibration databases and Level 1-b data, in a common format, to allow wide application of algorithms to all datasets
   - Identify and produce common constellation data products (may differ from standard products)
4. **Consistency in retrieval algorithms**
   - Cross participation in ATBD reviews
   - Jointly improve retrieval algorithms by conducting inter-comparisons on common spectra
5. **Consistency of laboratory spectroscopy**
6. **Support scientific collaboration among teams**

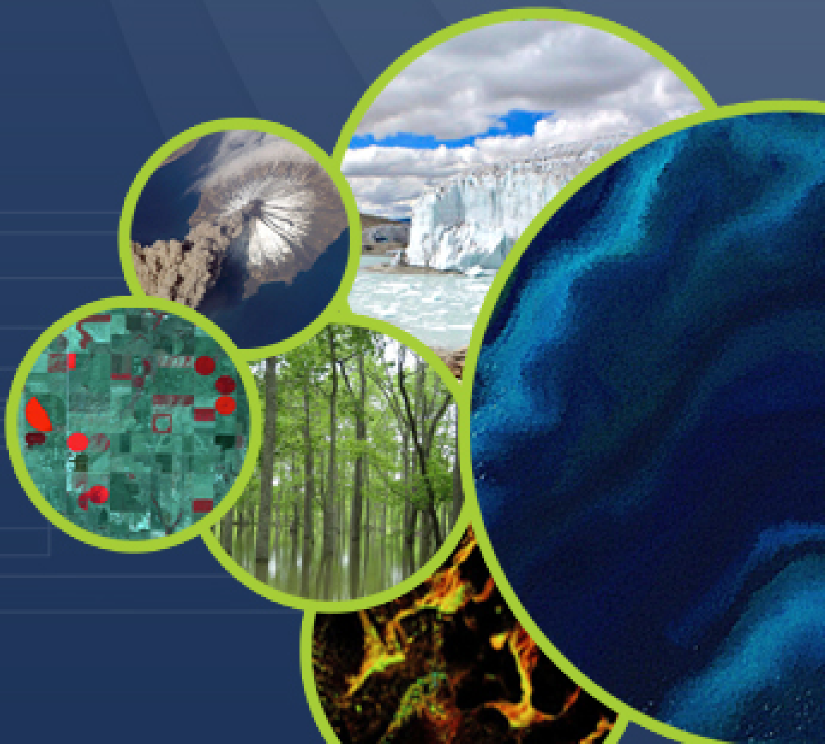
Adapted from Atmospheric Composition Constellation Meeting ACC-11, Frascati, Italy, 28-30 April 2015

Other Infrastructure Needed to support a Space-based GHG Constellation

- Laboratory Measurements of gas absorption cross sections
  - Significant progress has been made in laboratory spectroscopy, but uncertainties in gas absorption coefficients continue to be a leading source of bias in X_{CO2} and X_{CH4} retrievals.
  - A robust program of laboratory measurements and analysis is critical element of any future space based GHG measurement network

- Modeling infrastructure needs
  - Development of more advanced retrieval algorithms and flux inversion models must be a continued focus of any space based GHG constellation program
  - The need to retrieve accurate results over the globe at high spatial resolution will place unprecedented demands on high performance computing

Chapter 7: The EC/ESA CO_2 Sentinels: an example of an operational greenhou se gas monitoring constellation



CO_2 Monitoring Mission Objectives

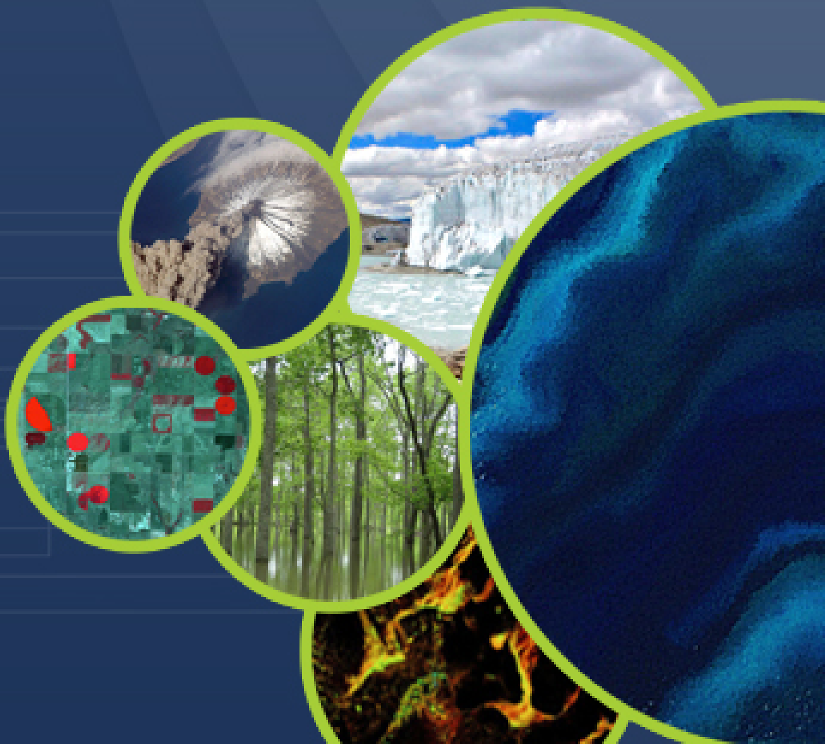
The high-level **monitoring system** objectives are

1. to provide policy-relevant information (trends, impacts of measures),
2. to support national emission inventories,
3. to observe strong point & area sources (e.g., power plants and cities).
   - *As part of an integrated system comprising: satellite - in-situ – modelling - emission inventory components, for provision of timely input to policymakers*

In view of the above system objectives, the following mission objective of the space component has been tentatively formulated:

The CO_2 mission shall monitor anthropogenic CO_2 emissions using high spatial resolution imaging of total column CO_2

Chapter 8: The Transition from Science to Operations

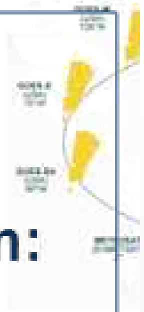


Moving Forward from “Science” to “Operational” GHG Missions

- With the exception of the Sentinels, all of the existing and planned GHG missions are “science” missions, designed to identify optimal methods for measuring CO_2 and CH_4, not “operational” missions designed to deliver policy relevant GHG products focused on anthropogenic emissions
- With the exception of SCIAMACHY, Sentinel 5p, and GeoCarb, these are “sampling” missions, rather than GHG “mapping” or “imaging” missions
- GHG imaging missions are needed to quantify emissions from compact sources including cities and large power plants
    - GOSAT and OCO-2 measurements clearly show that compact sources can be detected and quantified if they are captured within a footprint, but their plumes are more difficult to quantify downwind of the source
    - These two satellites sample < 10% of the surface area of the Earth each month, and only 10% of their samples are sufficiently cloud free to retrieve full-column estimates of X_{CO2} and X_{CH4}

CEOS

To be considered by CGMS:



Anticipated CGMS contribution to developing the space component of a carbon monitoring system:

- Orbit/mission coordination of Carbon monitoring satellites
- Enhance capabilities of meteorological satellites
- Data distribution
- Data exchange
- Formats
- Training/outreach

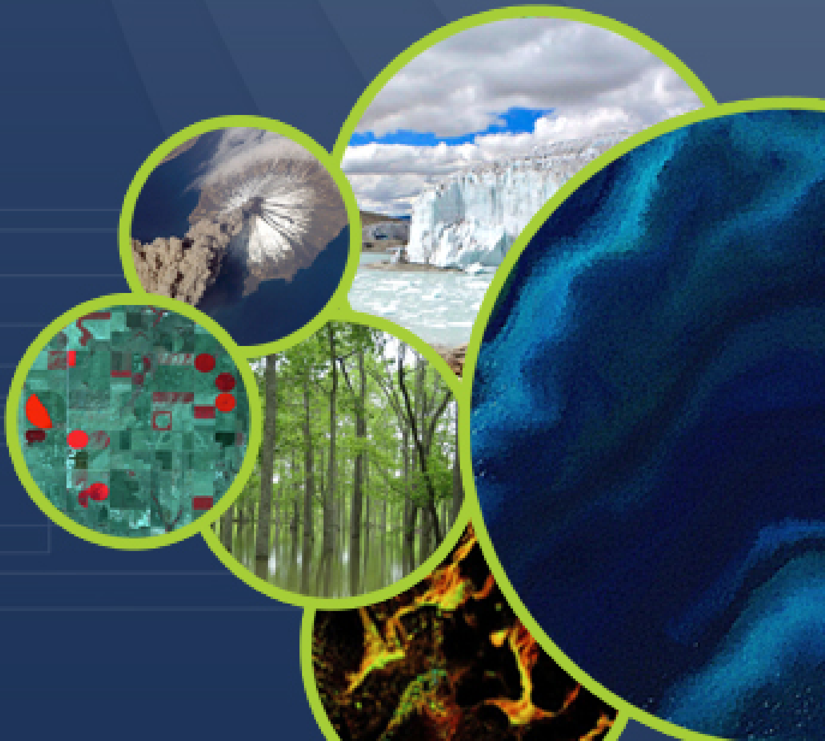
To be considered by CGMS:

- **New item for HLPP**

The planning for

Provide a coordinated contribution to a future satellite-based carbon constellation and to related activities on mission coordination, data distribution, exchange, formatting, and on training and outreach.

Chapter 9: Conclusions



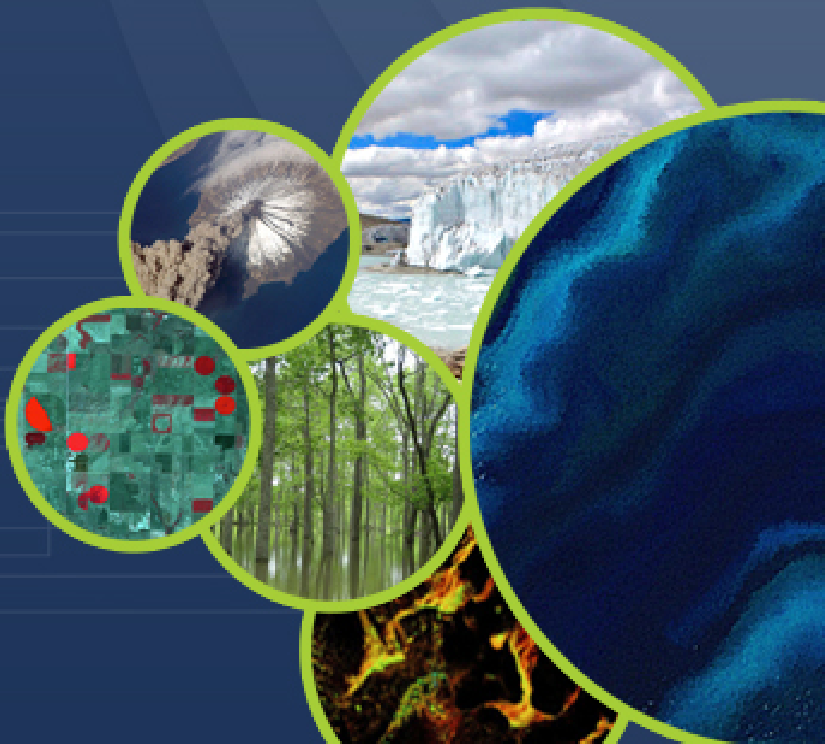
Conclusions (1)

- Space-based remote sensing observations hold substantial promise for future long-term monitoring of greenhouse gases
  - These measurements will complement existing ground-based and aircraft based in situ data with increased spatial coverage and sampling density
- Over the next decade, a succession of missions with a range of CO_2 and CH_4 measurement capabilities will be deployed
  - Most of these are scientific satellites designed to test GHG measurement techniques, not monitor GHG inventories
  - Because there is little overlap between the missions, each one is a critical link in a chain that must be successfully deployed to ensure a continuous climate data record.
  - Much greater benefits could be realized if these missions could be coordinated and their data products can be combined

Conclusions (2)

- Data from a future, coordinated GHG constellation that combines LEO, GEO, and HEO vantage points could meet the measurement accuracy, precision, resolution, and coverage requirements
- To provide reliable, verifiable constraints on GHG inventories as well as the response of the natural carbon cycle to climate change, advances are needed in:
  - Laboratory measurements of gas absorption cross sections
  - pre-launch and on-orbit calibration capabilities,
  - GHG retrieval algorithms
  - flux inversion algorithms
  - GHG concentration and flux validation techniques
- Open data policies that encourage the cross-calibration of sensors, the cross validation and free exchange of space based data products will accelerate the development of these capabilities and the acceptance of their results by scientists and policy makers

Backup



Requirements from *GEO Carbon Strategy Report (2010)*

- The next generation of GHG satellite measurements needs to provide high accuracy measurements of CO_2 and CH_4 with high spatial resolution (1-2 km) to observe and attribute surface fluxes and, to minimize cloud contamination.
- A daily repeat-frequency is required.
  - Lower repeat cycles are valuable but clearly lose information on the variability of surface fluxes, whether natural or anthropogenic in origin.
- Continuity of the time series of space-based planetary boundary layer CO_2 and CH_4 measurements, ideally in a GHG-satellite constellation.
  - managed within the international system of operational meteorological satellites or by a dedicated organization.
- A strategy for easy access to GHG satellite observations should be developed.
- A coordinated planning effort towards the next generation of a constellation of GHG satellite observations is also required.

Requirements from *CEOS Strategy for Carbon Observations from Space*

- A coordinated constellation of passive and active X_{CO2} and X_{CH4} remote sensing instruments in Low Earth Orbit (LEO), with
  - retrieved, single-sounding measurement accuracy of 0.1 to 0.2% for X_{CO2} and X_{CH4}
  - Spatial resolution of 1-2 km
  - Temporal sampling yielding daily coverage of the entire globe.
- A coordinated constellation of passive X_{CO2} and X_{CH4} remote sensing instruments in geostationary orbit (GEO)
  - To cover all longitudes at a spatial resolution of 1-2 km
  - Retrieved, single sounding measurement accuracy of 0.1 to 0.2% for X_{CO2} and X_{CH4} over continents
  - Temporal sampling interval of 20 minutes to 1 hour.
- These missions should be considered in the context of the added value to be derived from coordinated mission planning and associated data compilation activities (spaceborne and in situ/aircraft) both in the future and by exploiting archive data.

GCOS

EC CO_2 Report (Ciais et al. 2015)