Improving Efforts to Measure and Monitor Greenhouse Gas Emissions

Estimating Carbon Dioxide and Methane Emissions from Space

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CEOS
Committee on
Earth Observation Satellites

Background

- Fossil fuel combustion, land use change and other human activities are now adding ~40 billion tons of carbon dioxide (CO_2) to the atmosphere each year
  - These emissions have increased the atmospheric CO_2 concentration by ~50% since the beginning of the industrial age, from ~277 to ~415 ppm and are currently increasing it by 2-3 ppm/year
  - These changes would have been much larger if natural "sinks" in the land biosphere and ocean had not absorbed over half of these anthropogenic CO_2 emissions
  - The identity & location of these natural sinks, and their response to climate change are uncertain
- Over this same period, human activities have increased atmospheric methane (CH_4) concentrations by ~160%, from ~0.72 ppm to more than 1.88 ppm.
  - Over the past decade, emissions have ~0.58 billion tons/year, ~60% of which is anthropogenic
  - While CH_4 concentrations are much lower than those of CO_2, it is a more potent greenhouse gas, with a greenhouse gas warming potential 28-36 times that of CO_2 on 100-year time scales
- CO_2 and CH_4 account for ~90% of the present-day global warming. Reducing these emissions is the major thrust of the Mitigation objectives of the Paris Agreement

You Can Only Manage What You Measure - Growing Capabilities in Atmospheric GHG Measurements

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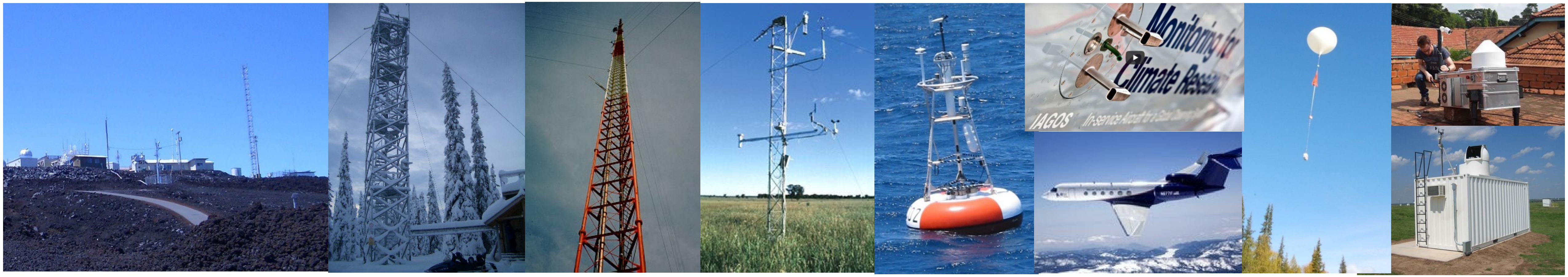
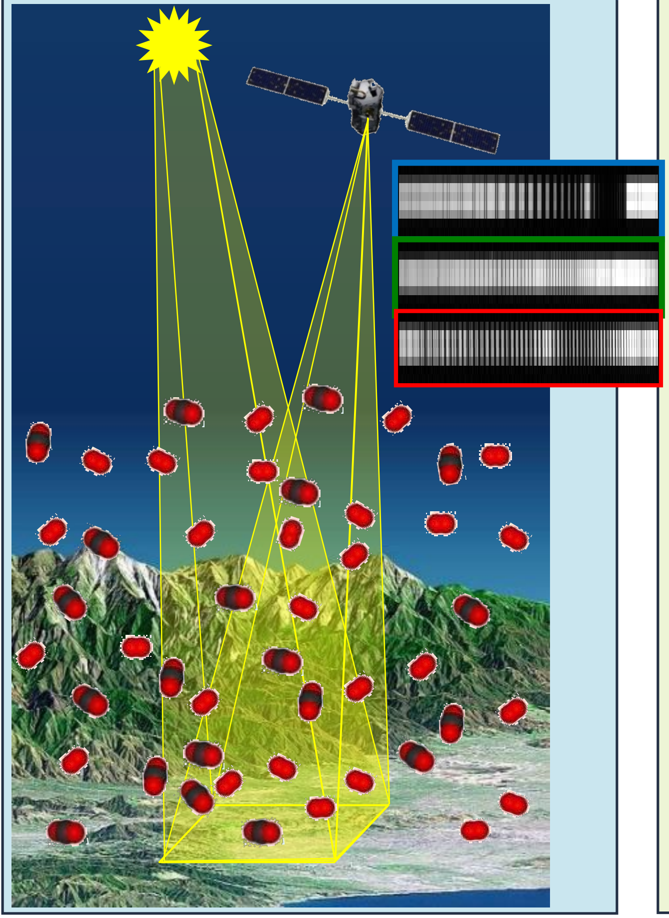
Space-based measurements of CO_2 and CH_4 from a growing fleet of satellites are less precise and accurate but provide high spatial and temporal resolution and greater coverage of the globe.

Ground-based measurements from the WMO Global Atmospheric Watch (GAW) Network and its partners provide accurate estimates of atmospheric GHG concentrations and their trends on local and global scales.



Estimating CO_2 and CH_4 fluxes from Space

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



Retrieve estimates of column averaged dry air mole fraction (XCO_2/XCH_4)

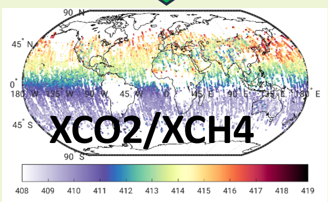
Prior Surface/ Atmosphere State

Radiative Transfer Model

Instrument Performance Model

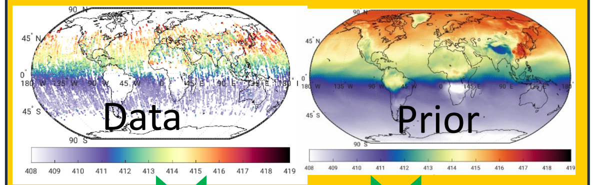
Inverse Model

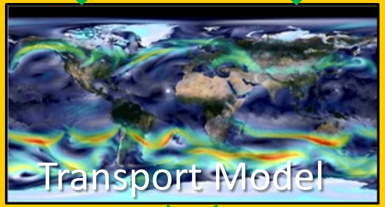
Revised Surface/ Atmosphere State



Validate XCO_2/XCH_4 estimates to ensure accuracy (0.25%)

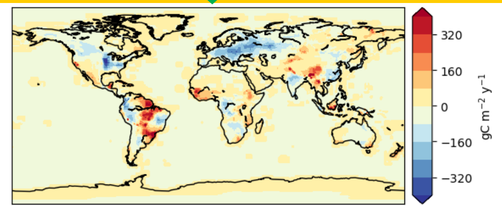
Assimilate into atmospheric inverse models to find fluxes





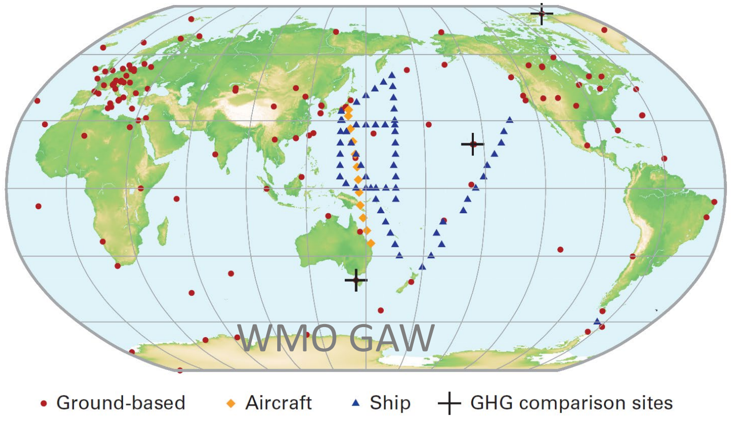
Inverse Model

$$\mathcal{J}(\mathbf{x}) = \frac{1}{2}||\mathbf{y} - \mathcal{H}(\mathbf{x})||^2_{\mathbf{R}^{-1}} + \frac{1}{2}||\mathbf{x} - \mathbf{x}_b||^2_{\mathbf{B}^{-1}}$$

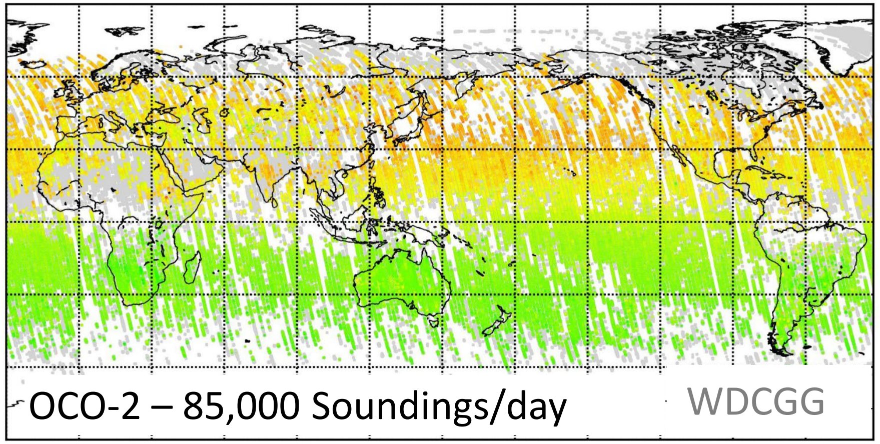


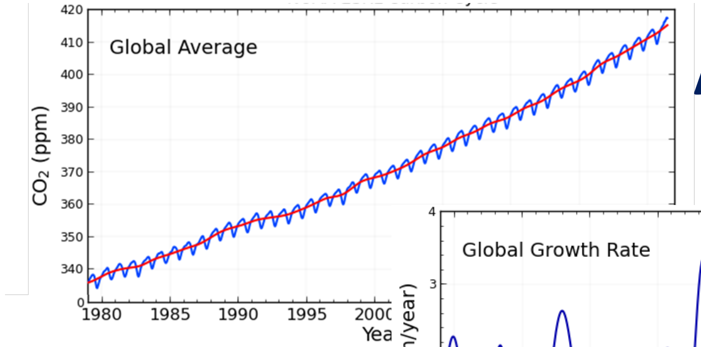
The Principal Roles of Surface, Airborne, and Space-based Measurements

WMO GAW Ground-based/Airborne/Ship Network

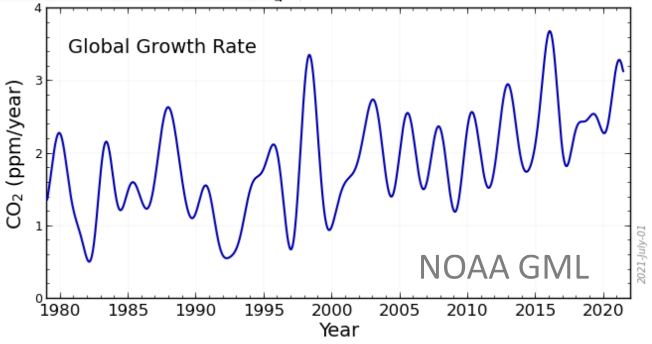


Space-based Measurements



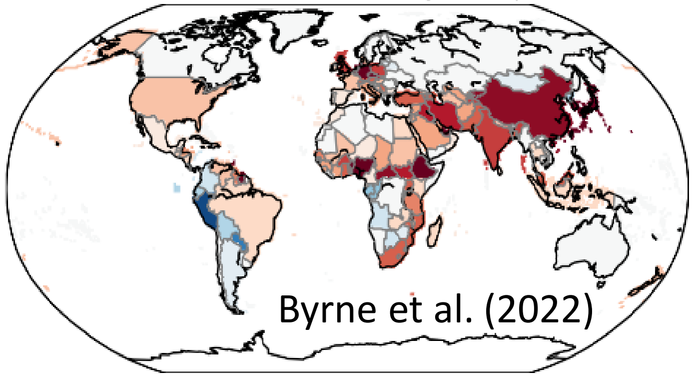


Global Totals



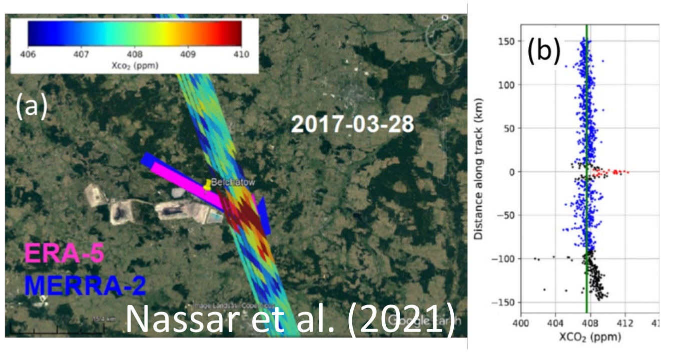
Global Growth Rates

Accuracy



Regional/National-scale Fluxes

Resolution/Coverage

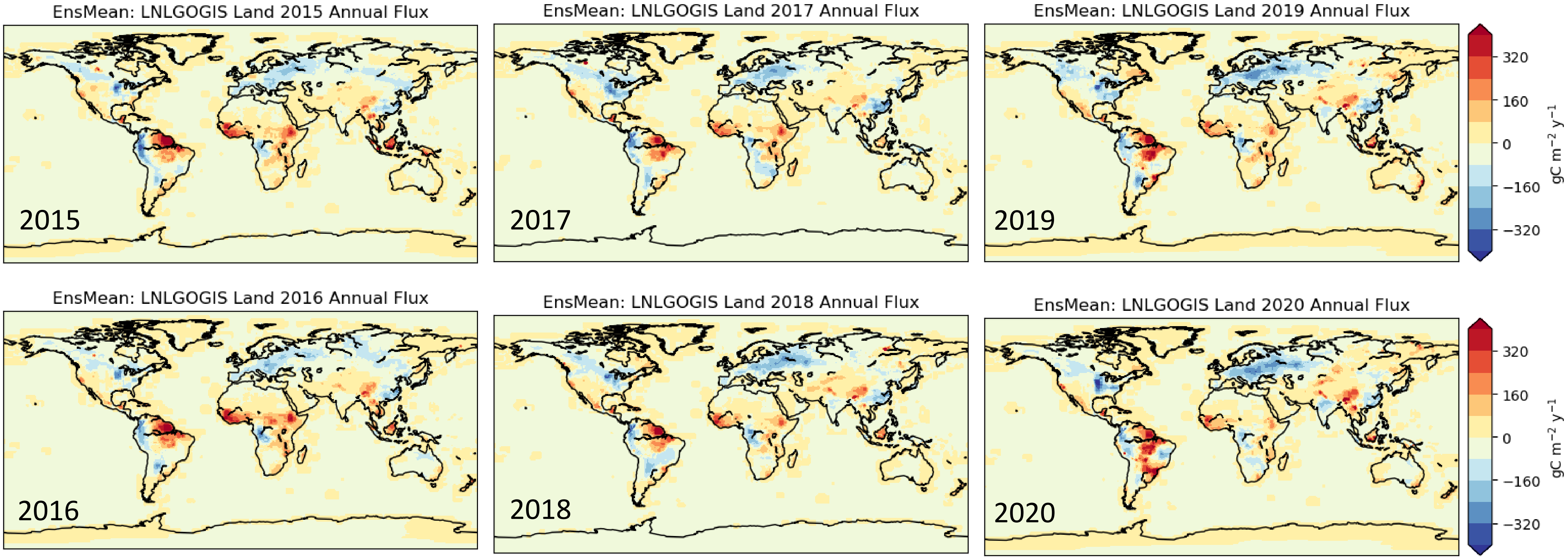


Emissions from Local Sources

Challenges for Estimating CO2 and CH4 Emissions from Atmospheric Measurements

- ❑ CO2 and CH4 can be retrieved from space using similar methods, but these two long-lived greenhouse gases pose unique challenges
  - Quantifying CO2 concentrations requires very high precision and accuracy, since only the largest sources produce XCO2 changes larger the 1 ppm out of the 415 ppm background (< 0.25%)
    - Currently, from orbit, only large, public sector high-resolution spectrometers meet these requirements
  - Anthropogenic CO2 emission sources of must be quantified in the context of natural sources and sinks that are often co-located with the source – high spatial resolution and coverage are essential
  - CH4 has a diverse range of sources, ranging from intense emission plumes from pipelines to large scale, weakly emitting wetlands and agricultural sources, which are the largest emitters
    - Private-sector hyperspectral imaging satellites are playing a role in detection of intense point sources
- ❑ Accurate estimates of the winds are essential for estimating fluxes from atmospheric measurements of CO2 and CH4
  - Currently, the transport algorithms in flux inversion models introduce errors comparable to the CO2 measurement uncertainties from space-based measurements

Atmospheric Inverse Models Constrain CO2 Emissions & Removals from Anthropogenic and Natural Sources



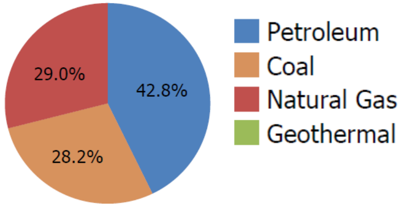
In situ data are being combined with OCO-2 observations to derive net annual CO2 fluxes. Here, prescribed fossil fuel emissions have been subtracted out to yield estimates of the net biospheric exchange (NBE). BLUE indicates net CO2 sinks while RED indicates CO2 sources.

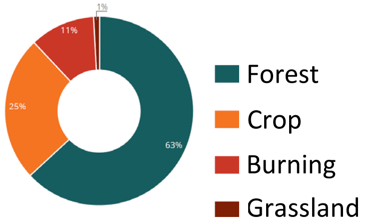
Images by Andy Jacobson and the OCO Flux MIP Team

Contributions to the First Global Stocktake

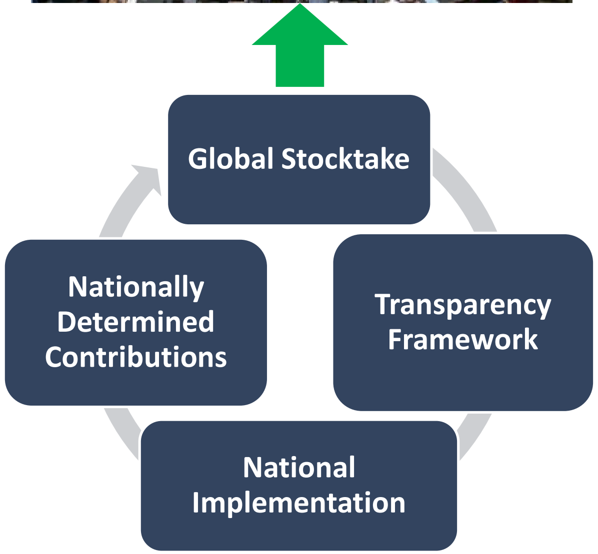
Bottom-up national GHG inventories can be combined with top-down atmospheric GHG budgets to produce a more complete and transparent input to Global Stocktake

- **Energy**: Fuel Combustion; Fugitive Emissions; CO_2 Transport & Storage
- **Industry**: Mineral; Chemical; Metal; Non-Energy fuel/solvent; Electronics; Other Products
- **AFOLU**: Livestock; Land; Aggregate; Other
- **Waste**: Solid; Biological; Wastewater; Other

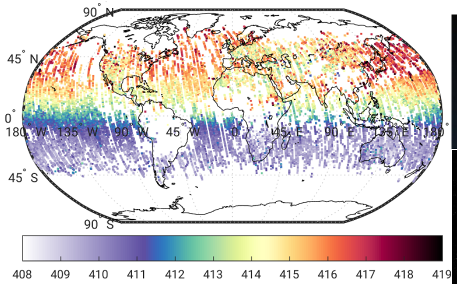


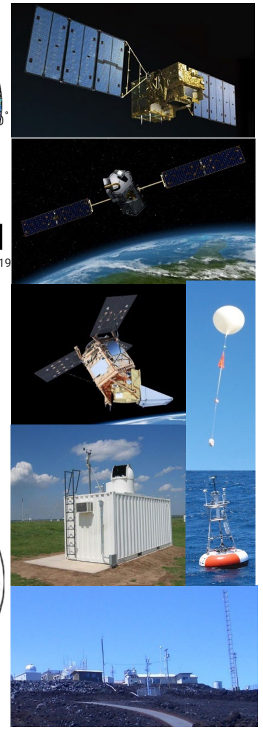


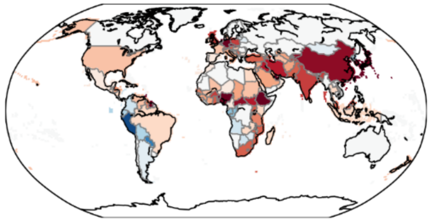
National GHG Inventory



National GHG Budgets







Bottom-up GHG Inventories

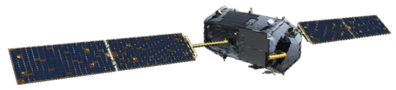
- Sector-specific estimates of emissions from known sources

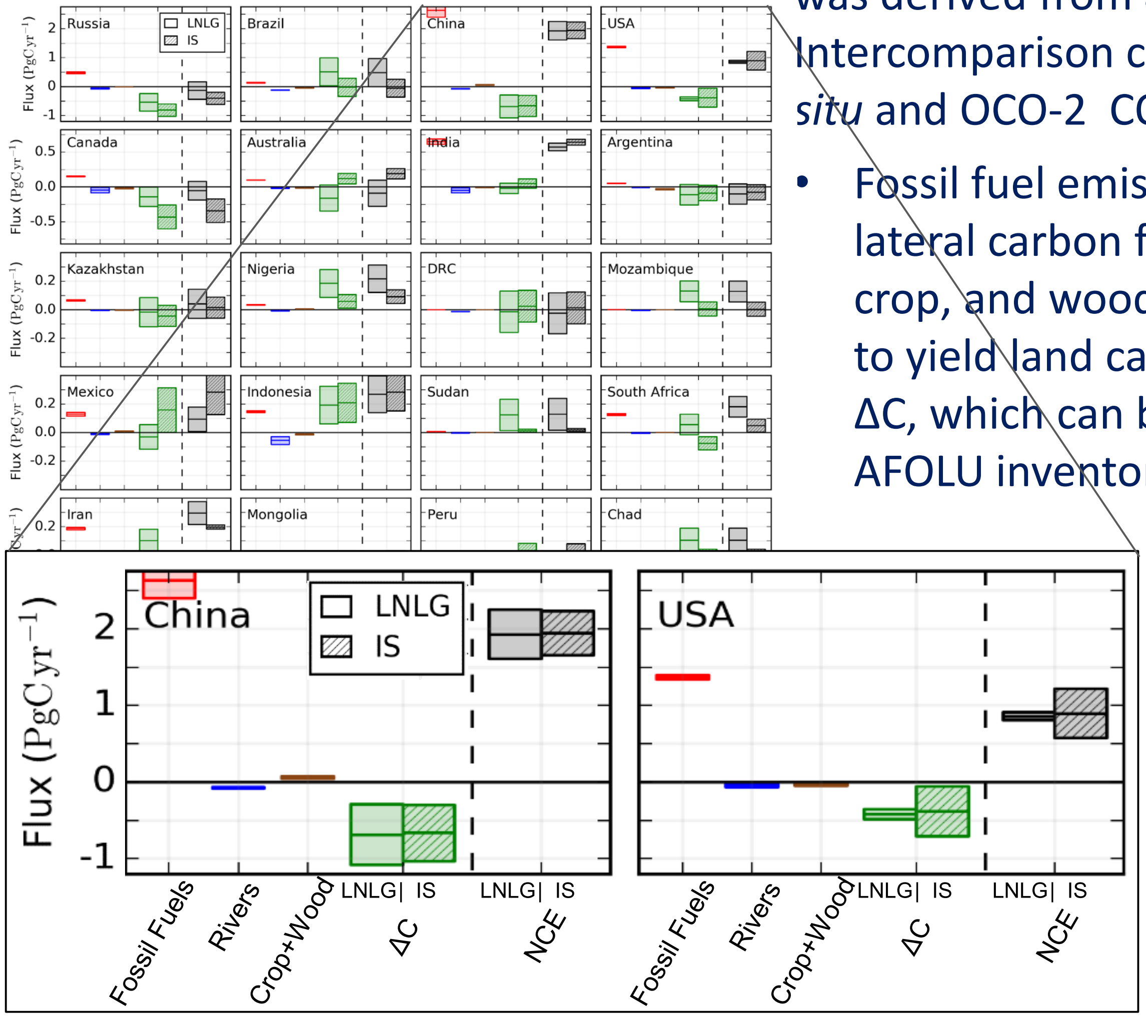
Top-down GHG Budgets

- integral constraint on emissions and removals from all processes

Objective – Start a conversation.

Pilot Top-down CO2 and CH4 Budgets





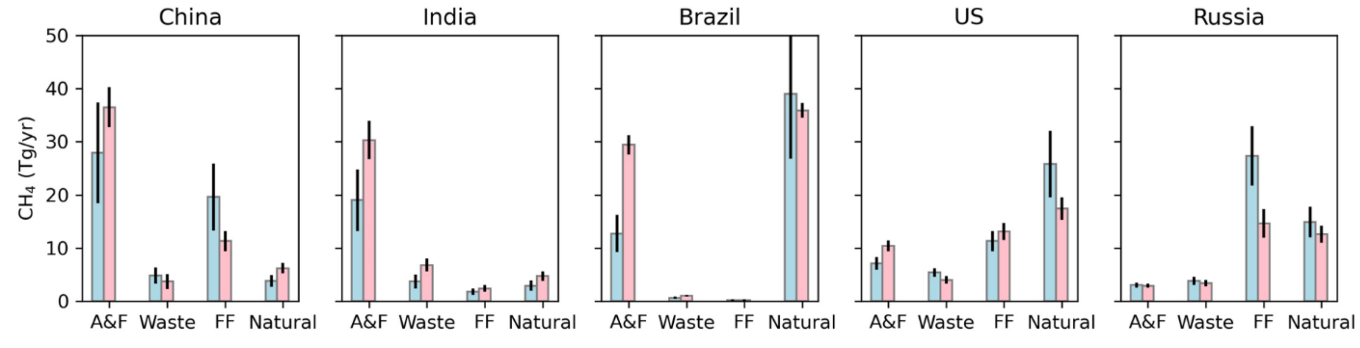
Plots by Brendan Byrne (NASA/JPL) and the OCO-2 Flux MIP

For CO2, Net Carbon Exchange (NCE) was derived from a Multi-model Intercomparison constrained by *in situ* and OCO-2 CO2 data.

- Fossil fuel emissions (FF) and lateral carbon fluxes due to rivers, crop, and wood, are subtracted off to yield land carbon stock change, ΔC, which can be compared to AFOLU inventories

For CH4, The NASA Carbon Monitoring System (CMS) Flux Team derived the CH4 budgets by analyzing remote sensing observations of CH4 from Japan's Greenhouse gases Observing SATellite (GOSAT), using an analytic Bayesian inversion approach and the GEOS-Chem global chemistry transport model.

- This approach constrains fluxes from 4 sectors in ~58 countries.
- The 5 largest emitters are responsible for 50% of the anthropogenic CH4



Plots by John Worden (NASA/JPL) and the CMS Flux Team

Summary of Progress, Promise, and Obstacles

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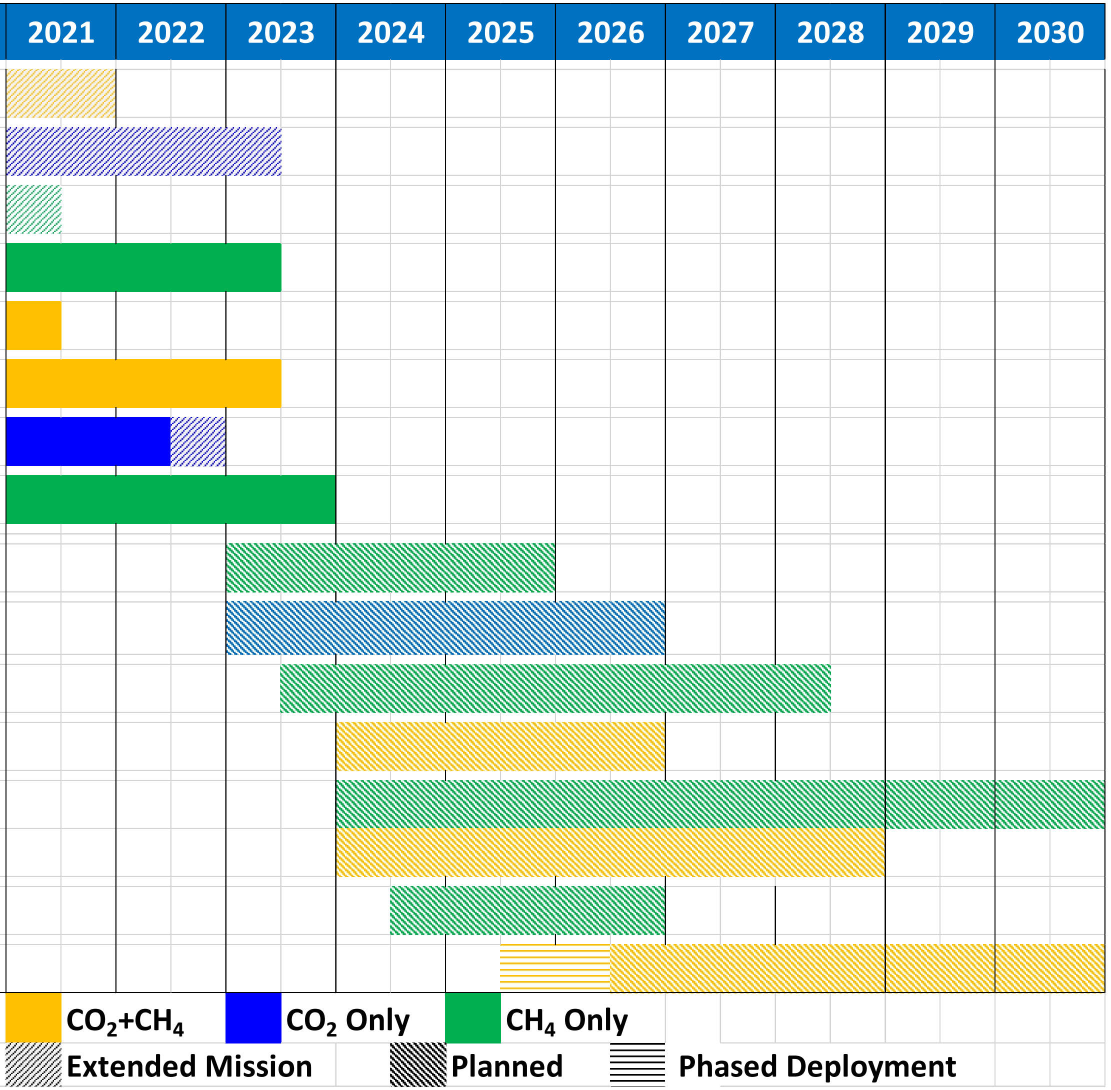
- ❑ OCO-2 and OCO-3 are returning policy-relevant CO2 results, but OCO-2 is well beyond its design life and OCO-3 is scheduled for removal from ISS early next year
- ❑ There are currently no US plans or resources to maintain or advance space-based or ground-based CO2 monitoring capabilities to meet future operational needs
  - GeoCarb will yield useful results over the Americas, but does not provide global coverage
  - Future missions by Japan (GOSAT-GW), the EU Copernicus Program (CO2M) and perhaps China (TanSat-2??) will provide continuity and improved global coverage, but offer limited redundancy and will not improve on the precision and accuracy demonstrated by OCO-2
  - Expanded ground/sea/airborne networks are needed to fully exploit the space-based data by
    - Augmenting the coverage in regions that are persistently cloudy or have too little sunlight, and
    - Providing a means for validating the space-based estimates to ensure their accuracy
- ❑ Only the US now has the technology needed to substantially improve over the precision, accuracy resolution and coverage provided by OCO-2 & OCO-3
  - If the US started today, it would take ~5 years to deploy new CO2/CH4 monitoring satellites

Backup

- ❑Timeline for deployment of space-based CO2 and CH4 missions
- ❑Additional references to background information

CO2 and CH4 Deployment Timeline

Satellite, Instrument	Agency/Origin	CO_2	CH_4	Public	Private
GOSAT TANSO-FTS	JAXA-NIES-MOE/Japan	●	●	●	
OCO-2	NASA/USA	●		●	
GHGSat-D - Claire	GHGSat/Canada		●		●
Sentinel 5P TROPOMI	ESA/Europe		●	●	
GaoFen-5 GMI	CHEOS/China	●	●	●	
GOSAT-2 TANSO-FTS-2	JAXA-NIES-MOE/Japan	●	●	●	
OCO-3	NASA/USA	●			
GHGSat C1/C2 - Iris, Hugo	GHGSat/Canada		●		●
MethaneSAT	EDF/USA	● (grey)	●		●
MicroCarb	CNES/France	●		●	
Carbon Mapper[1]	Carbon Mapper LLC/USA	● (grey)	●	● (grey)	● (grey)
GeoCarb	NASA/USA	●	●	●	
MetOp Sentinel-5 series	EC Copernicus/Europe		●	●	
GOSAT-GW	JAXA-NIES-MOE/Japan	●	●	●	
MERLIN	DLR/Germany-CNES/France		●	●	
CO2M	EC Copernicus/Europe	●	●	●	



Additional Background Information

- A comprehensive description of a space-based architecture for measuring CO_2 and CH_4 is provided here:
  - https://ceos.org/document_management/Virtual_Constellations/ACC/Documents/CEOS_AC-VC_GHG_White_Paper_Version_1_20181009.pdf

- More information about the pilot, national-scale CO_2 and CH_4 budgets that CEOS is delivering to the UNFCCC to support the first global stocktake can be found here:
  - https://ceos.org/gst/ghg.html

- Greater insight into our current understanding of anthropogenic CO_2 and CH_4 emissions can be obtained from the annual reports of the Global Carbon Project
  - For CO_2: https://doi.org/10.5194/essd-12-3269-2020
  - For CH_4: https://doi.org/10.5194/essd-12-1561-2020