Developing a top-down carbon dioxide and methane inventory to aid the global stocktake

SUMMARY

Key Points

- Comprehensive, spatially-resolved global carbon dioxide and methane budgets are developed from space based atmospheric measurements to support Global Stocktake.
- These top-down carbon dioxide and methane budgets complement the bottom-up national inventories by providing an integrated constraint on net emissions from all sources and sinks at national and sub-national spatial scales.
- The primary objective of the pilot atmospheric budgets is to start a conversation to establish the utility and best practices for the use of top-down atmospheric budgets with bottom up inventories in future Global Stocktakes.

Service

- Mitigation
- Protocol monitoring

End users

- Government agencies
- Policymakers
- Researchers

Intermediate User(s)

- UNFCCC
- GCOS
- National inventory compilers

Application(s)

Provide the top-down CO_2 and CH_4 inventory to facilitate the development and verification of bottom-up national fossil fuel inventories for the global stocktake.

Essential Climate Variables

—Atmosphere

- Carbon dioxide, methane and other greenhouse gases
- Data record is in the ECV inventory, Record ID 11824

Models

- Orbiting Carbon Observatory Flux Multi-model Intercomparison Project (OCO Flux MIP; DOI: 10.5194/acp-19-9797-2019), and NASA Carbon Monitoring System Flux (CMS-Flux; DOI:10.1038/s41467-017-02246-0).

Agencies

- NASA (OCO-2 CO2
- JAXA/MOE/NIES (GOSAT CO2, CH4)

Satellite Observations

- NASA OCO-2
- JAXA/MOE/NIES GOSAT

Sustainability

- Demonstrational at the present and is in transition to be operational

DESCRIPTION

The objective of the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement is to reduce the risks and impacts of climate change. At global scales, these changes are driven primarily by anthropogenic emissions of carbon dioxide (CO_2) and methane (CH_4), potent greenhouse gases (GHGs), which now account for more than 92% of the observed global warming (IPCC 2014). Recognizing that global space-based observations of CO_2 and CH_4 could play a significant role in the success of the Paris Agreement, the Committee on Earth Observation Satellites (CEOS) and Coordination Group on Meteorological Satellites (CGMS) Joint Working Group on Climate (WGClimate) resolved to coordinate the development of comprehensive, spatially-resolved global atmospheric budgets of CO_2 and CH_4, and their changes over time. This Use Case describes this effort.

Parties to the Paris Agreement resolved to rapidly reduce emissions of GHGs. To track progress toward this goal, they are compiling national inventories of GHG emissions and removals, which will be evaluated at 5-year intervals in Global Stocktakes (GSTs). These inventories are compiled using best practices recommended in the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Inventories. These guidelines require reports of annual emissions by sources and removals by sinks in specific sectors and categories. The net emissions and removals in each category of each sector is approximated by multiplying the measured activity data (i.e. number of liters of oil or tons of coal burned) by an assumed emission factor (number of kilograms CO_2 emitted per liter of oil or ton of coal) and summing the results to yield totals.

These bottom-up methods can yield reliable results for categories within the Energy sector, such as fossil fuel combustion, where emissions can be accurately estimated from the amount and type of fuel burned because the carbon content of the fuel is well understood. However, these methods are often less reliable in other sectors and categories, such as Land Use category in the Agriculture, Forestry and Other Land Use (AFOLU) sector, where the emissions or removals associated with an observed change are more difficult to quantify.

CO_2 and CH_4 emissions and removals can also be estimated using measurements of their concentrations in the atmosphere. CO_2 or CH_4 emissions increase their downwind concentrations, while removals decrease their downwind concentrations. To infer net surface-atmosphere fluxes, CO_2 and CH_4 measurements are analyzed with atmospheric inverse models to derive the flux distribution needed to match the observed atmospheric concentrations in the presence of the wind field. The resulting top-down flux budgets are less source specific than bottom-up inventories, but complement those methods by providing an integrated constraint on net emissions from all sources and sinks on spatial scales spanning individual large power plants or urban areas to nations or the entire globe. In principle, it should be possible to combine bottom-up and top-down methods to provide a more complete and transparent account of GHG emissions and removals (Figure 1).

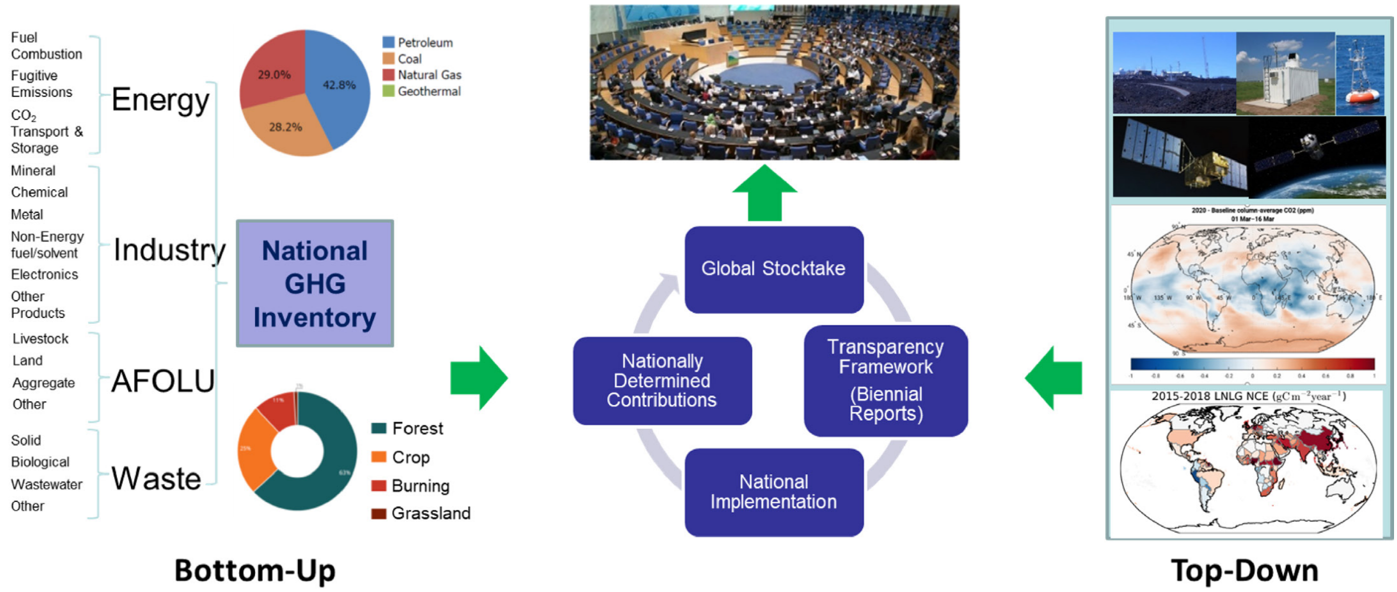

Figure 1. The Global Stocktake Process – (Left) Conventional GHG inventories are compiled using a bottom-up process that compiles estimate emissions and removals from specific sectors and categories. (Right). Top-down atmospheric GHG fluxes are derived from direct measurements of atmospheric GHGs. These two methods are complementary. The bottom-up methods are more source specific, while the top-down atmospheric methods provide an integral constraint on the net emissions by all sources and sinks. In principle, it should be possible to combine these two methods to provide a more complete and transparent account of GHG emissions and removals.

Recent advances in ground-based, airborne, and space-based measurements of CO_2 and CH_4, combined with progress in atmospheric inverse methods are yielding substantial improvements of the precision, accuracy, resolution and coverage provided by these top-down atmospheric flux products. Currently Japan's GOSAT and GOSAT-2, NASA's Orbiting Carbon Observatories (OCO) 2 and 3, and the European Copernicus Sentinel 5 Precursor TROPOMI spectrometers are returning CO_2 and CH_4 measurements. The growing fleet of satellite sensors operated by CEOS and CGMS agencies are committed to measuring CO_2 and CH_4 from space over the next decade (Figure 2).

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		●		●
MetOp Sentinel-5 series	EC Copernicus/Europe		●	●	
MethaneSAT	EDF/USA		●		●
MicroCarb	CNES/France	●		●	
Feng Yun 3G (CMA)	CMA-NMSC/China	●	●	●	
Carbon Mapper[1]	Carbon Mapper LLC/USA	●	●	●	●
GeoCarb	NASA/USA	●	●	●	
GOSAT-GW	JAXA-NIES-MOE/Japan	●	●	●	
MERLIN	DLR/Germany-CNES/France		●	●	
CO2M	EC Copernicus/Europe	●	●	●	

Timeline columns: 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2030

Legend: CO_2+CH_4 | CO_2 Only | CH_4 Only | Extended Mission | Planned | Phased Deployment

Figure 2. Timeline of Greenhouse Gas monitoring Satellites. Timelines for satellites that measure CO_2 only are shown in blue, those that measure CH_4 only are colored green, and those that measure both gases are shown in gold.

While these top-down methods are still evolving rapidly and are providing key insights into the emissions and removals of CO_2 and CH_4 by natural processes and human activities, they do not yet fully address the requirements of the first UNFCCC GST in 2023. However, they should be adequate for fostering the development of requirements with CEOS stakeholders (UNFCCC, GCOS) and interfaces with users in the national inventory communities to accelerate the acceptance and use of top-down results from the much more capable system that will be coming on line later this decade to support future GSTs.

To demonstrate these capabilities, pilot top-down CO_2 and CH_4 inventories were developed to support the 2023 GST. For CO_2, top-down national inventories are based on CO_2 flux estimates from the Orbiting Carbon Observatory Flux Multi-model Intercomparison Project (OCO Flux MIP). This international effort currently includes participation by ten modeling teams from the US, Europe, and Australia. These teams use a broad range of transport model architectures, meteorological inputs, and flux optimization methods to assess the impact of these choices on the estimated CO_2 fluxes and their uncertainties. Each team derives flux maps based on ground-based in situ CO_2 measurements alone, and combinations of these measurements with estimates of the column average CO_2 dry air mole fraction (XCO2) from NASA's OCO-2 mission.

CO_2 flux estimates derived from OCO-2 version 9 (v9) CO_2 products were used to develop and test tools for deriving inventory products from CO_2 Flux MIP results. Meanwhile, the Flux MIP team started deriving fluxes from the OCO-2 version 10 (v10) CO_2 products, which span the period from 2015 to 2020. The pilot top-down CO_2 inventories delivered for use in the GST will be derived from these v10 OCO-2 flux products. For these pilot CO_2 products, fossil fuel and fire CO_2 emissions are accounted for in the flux inversions by prescribing maps of those emissions, but these fluxes were not optimized in the inversions. The fossil fuel emissions were based on values from the Open-source Data Inventory for Anthropogenic CO_2 (ODIAC: https://odiac.org/index.html) database. Fire emissions were derived from the Global Fire Emission Database (GFED). With fixed fossil fuels and fires, these inversions optimize terrestrial carbon stock changes, ΔC, which originate mainly from the AFOLU sector. These reported changes in terrestrial carbon stocks reflect the combined impact of direct anthropogenic activities and changes to both managed and unmanaged ecosystems in response to rising CO_2, climate change, and disturbance. Results for 24 representative countries are presented in Figure 3.

For CH_4, the NASA Carbon Monitoring System Flux group (CMS-Flux) team used column-average methane dry air mole fraction (XCH_4) estimates from Japan's GOSAT mission. They used an analytic Bayesian inversion approach and the GEOS-Chem global chemistry transport model to quantify emissions and their uncertainties at a spatial resolution of 1° by 1°. Unlike the pilot CO_2 inventories, these CH_4 budgets optimize emissions from fossil fuel extraction, transport and use as well as those from wetlands, agriculture, and waste. They then attributed these top-down emissions to known surface emission at national levels. This approach yielded estimates of total CH_4 emissions from 58 (of the 242) countries. Like the bottom-up inventories, they find that the top five emitting countries are responsible for about half (~170 Tg CH_4/yr) of the global anthropogenic CH_4 emissions (Figure 4). However, results are more difficult to reconcile with other inventories. First, the space-based estimates indicate that fossil fuel emissions account for less of the total CH_4 than earlier estimates based on in situ isotopic studies. Second, the space-based inversions indicate that agricultural emissions account for a larger fraction of the CH_4 emission budget than inversions that used only in situ CH_4 observations.

Both groups caution that these pilot product should be interpreted with caution. The primary objective of these pilot inventories is to start a conversation among the atmospheric GHG measurement and modeling communities and the national inventory agencies, the UNFCCC, and other relevant stakeholders (IG3IS, GCOS, IPCC) to establish the utility and best practices for the use of top-down atmospheric inventories in future Global Stocktakes. We also anticipate that they will foster the development and delivery of capacity building curricula to build a larger user community for the much more advanced top-down inventory products to be delivered for the 2028 global stocktake and beyond.

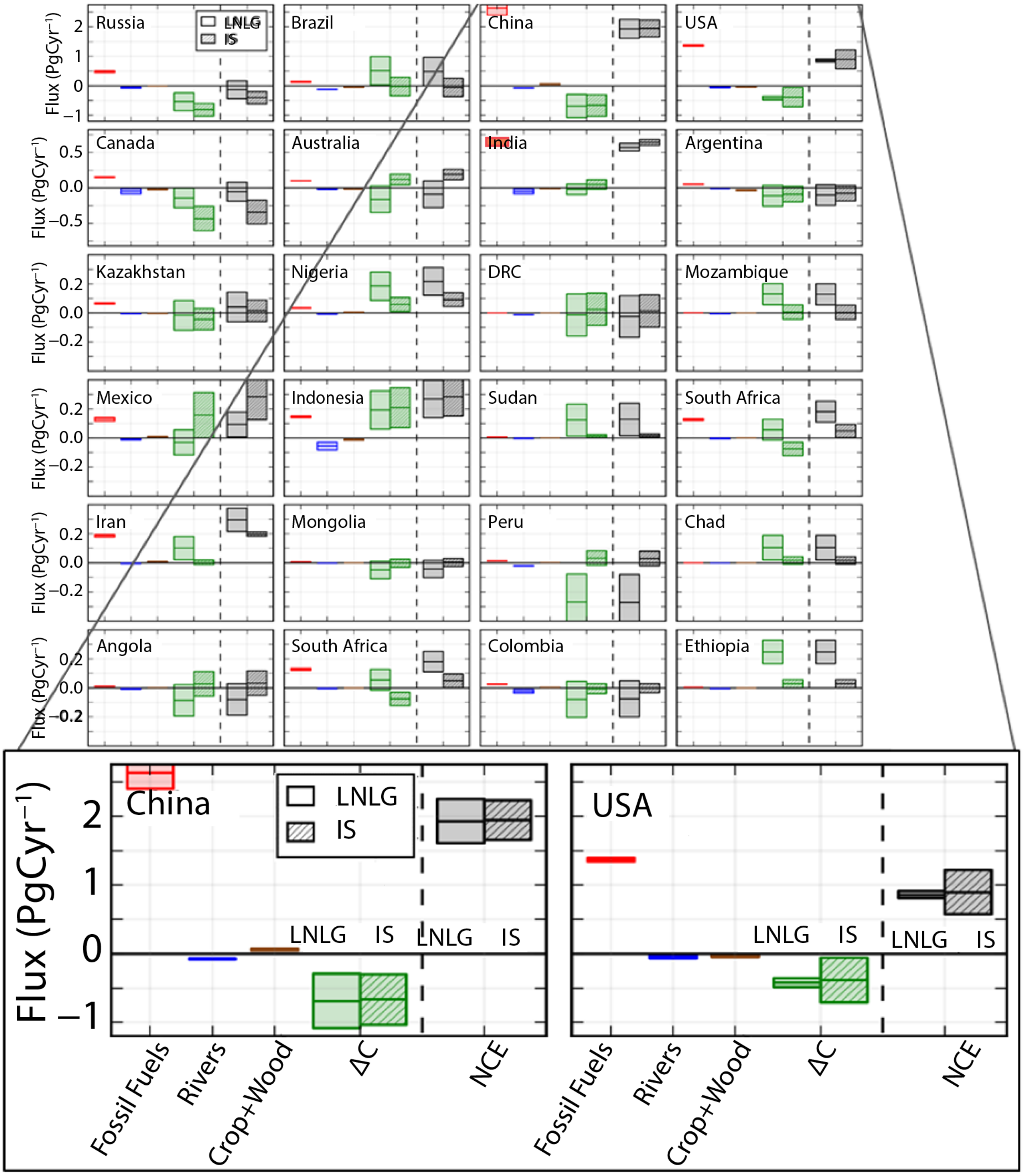

Figure 3. Examples of country level emissions for 2015 – 2018 from inverse model experiments using only in situ (IS) or OCO-2 Land Nadir and Land Glint (LNLG) estimates of CO_2. Contributions to the Net Carbon Exchange (NCE) is shown (grey) as well as its contributions from Fossil Fuels (red) and the land biosphere (ΔC; green). Land carbon losses associated with lateral exports by rivers (violet) and crops and wood harvest (brown) are shown for comparison. All fluxes are expressed in units of Petagrams (10^{15} grams = 10^{12} kg = 10^9 tons) of Carbon per year, expressed as $PgCyr^{-1}$. A Pg of carbon corresponds to 3.66 Pg of CO_2. Positive values indicate emissions into the atmosphere (sources) while negative values indicate removals (sinks). Uncertainties are expressed by the vertical dimension of the box.

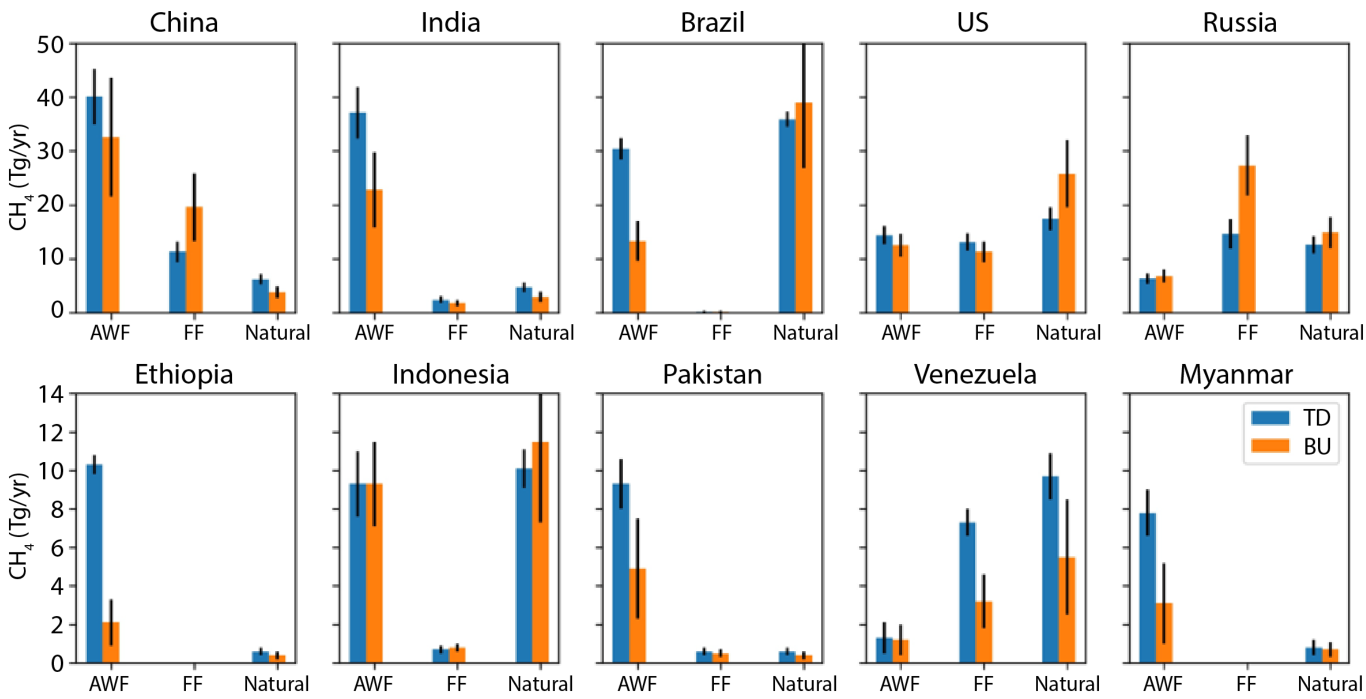

Figure 4. Top-down (TD, blue) and bottom-up (BU, orange) methane emissions by sector from the top five emitting countries are compared. The sectors shown include Agriculture, Waste and Fires (AWF), Fossil Fuels (FF), and Natural sources, such as wetlands and seeps.

INFORMATION FLOW

Sense

- OCO-2 XCO_2 estimates are combined with in situ CO_2 measurements from the NOAA Global Monitoring Division ObsPack product
- GOSAT XCH_4 estimates

Climate data

- Wind direction and speed
- Prior atmospheric temperature and humidity profiles
- Aerosol types from NASA's Global Monitoring and Assimilation Office Goddard Earth Observing System Model Forward Product for Instrument Teams (GEOS FP IT)

Apply

- Atmospheric inverse models are used to derive the CO_2 and CH_4 fluxes needed to match the observed CO_2 and CH_4 distributions in the presence of the wind field

Decision making

- The UNFCCC and its partners can use the top-down inventories to assess how well the combined efforts by all nations are meeting the overall greenhouse gas emission reduction goals

Use additional data

- Prior estimates of CO_2 and CH_4 concentrations and fluxes, which are optimized by atmospheric inverse models

FUTURE IMPROVEMENTS

This case study combines in situ CO_2 and CH_4 measurements from the WMO GAW network with space-based XCO2 estimates from the NASA Orbiting Carbon Observatory and XCH4 estimates from Japan's GOSAT to yield top-down estimates of emissions and removals of CO_2 and CH_4 by the land biosphere at the scale of medium size countries. In these experiments, a priori estimates of CO_2 and CH_4 fluxes from the land biosphere are optimized to fit the observed distributions of these gases, assuming that their emissions derived from fossil fuel combustion specified in national inventory data are correct. The current observation network and analysis tools do not yet provide the accuracy, precision, resolution and coverage needed to simultaneously optimize the emissions and uptake of CO_2 and CH_4 by both fossil fuel use and the land processes. This limitation is expected to be relaxed in the future as the ground-based and airborne greenhouse gas network is expanded and new greenhouse gas monitoring satellites including Japan's GOSAT-GW satellite, and the Copernicus CO_2M, and China's TanSat-2 constellations are deployed later in the 2020s. Once those systems are deployed, updated top-down estimates of the emissions and removals of CO_2 and CH_4 by both fossil land sources will be attempted.