Questions & Answers Part 3

Please type your questions in the Question Box. We will try our best to get to all your questions. If we don't, feel free to email David Crisp (dcrispjpl@gmail.com), Brendan Byrne (brendan.k.byrne@jpl.nasa.gov), Daniel Cusworth (dancusworth@gmail.com) or Sean McCartney (sean.mccartney@nasa.gov).

Question 1: Could you clarify whether the top-down method involves direct measurement of emissions in the atmosphere, or is it using modeling?
Answer 1: There is no method to directly measure a flux from anything larger than, for example, a smoke stack. Like most bottom-up methods, top-down methods use a combination of measurements and models to estimate emissions and removals of CO_2 and CH_4. The concentrations of atmospheric CO_2 and CH_4 can be measured directly by *in situ* sensors deployed at ground-based stations or on aircraft. Estimates of the column-averaged CO_2 and CH_4 dry air mole fractions, XCO_2 and XCH_4, can also be retrieved from high-resolution spectroscopic observations of reflected sunlight, collected by ground-based and satellite-based sensors. These XCO_2 and XCH_4 estimates are collected at high spatial and temporal resolution over the entire globe. They are then validated against accepted standards and assimilated into atmospheric inverse models to derive the emissions and removals (called "fluxes") needed to produce the observed atmospheric CO_2 and CH_4 distribution in the presence of the winds. When plumes of CO_2 or CH_4 from sources such as large power plants or pipeline leaks are imaged directly at high spatial resolution, these fluxes can be quantified using plume models. Both the atmospheric inverse modeling and plume modeling approaches were described in greater detail in Part 2 of this series.

Question 2: The lockdown has different limitations with respect to different levels of lockdown. Is the period chosen here during the time when road transport was restricted?
Answer 2: Yes, the specific examples of regional-scale emissions reductions shown here were taken during the first few months of the COVID-19 pandemic, when countries were implementing the strict lockdowns that restricted road transport. Top-down methods have also been used to estimate changes in anthropogenic emissions and compared with changes in traffic within cities during the lockdowns. Here is an example for San Francisco: https://doi.org/10.1029/2020GL090037
and here is an example for Toronto:

https://doi.org/10.3390/atmos12070848.

Question 3: What is the sampling frequency of space-based measurements adaptable for integration with a bottom-up inventory?
Answer 3: We are beginning to work with the bottom-up inventory community to determine how to best meet their sampling frequency requirements. Existing space-based measurements have a range of sampling frequencies that depend on the design of their sampling strategy and their orbit's ground track repeat cycle. The Copernicus Sentinel 5p TROPOMI instrument collects the measurements needed to estimate XCH_4 over all cloud-free parts of the sunlit hemisphere of the Earth each day. Japan's GOSAT and GOSAT-2 sample only a fraction of the sunlit hemisphere, but can repeat observations with the same viewing geometry at 3-day and 6-day intervals, respectively. Both of these spacecraft have agile pointing systems that allow them to observe a limited set of targets as often as one every two days. OCO-2 also routinely samples only a small fraction of the sunlit hemisphere, but can collect the measurements needed to estimate XCO_2 with a 32-day resampling interval. OCO-3 is in the International Space Station (ISS), which does not have a regularly repeating orbit, but like GOSAT and GOSAT-2, it has an agile pointing mechanism that allows it to collect observations over a limited set of targets at roughly weekly intervals. Thick clouds can limit space-based measurements over some regions, reducing these sampling frequencies. Future missions that are currently under development, such as the Copernicus CO2M constellation, will provide much higher spatial and temporal resolution. Their data can be assimilated into atmospheric inverse models to estimate emissions and removals at a range of intervals spanning days to years. This high spatial and temporal resolution should help to distinguish different types of anthropogenic and natural sources of CO_2 and CH_4.

Question 4: Are the current spatial resolutions and coverage adapted to quantify GHG only for medium/large countries, or is it suitable also for small countries (low latitude range)?
Answer 4: Both the density of GHG measurements from existing ground-based and space-based systems and the coarse spatial resolution of atmospheric inversion systems currently limit our ability to quantify emissions and removals for small countries. For the national-scale CO_2 Budget presented in this webinar series, we introduced the Z-statistic and the Influence Assimilated Data (IAD) to help users interpret how well a given country's CO_2 Budget is being informed by the atmospheric CO_2 measurements. We also provide CO_2 flux estimates for regional aggregates, such as the European Union, African Union, and the Association of Southeast Asian Nations,

which are generally better captured in the inversion analyses than many of the small countries within them. For the national-scale CH_4 estimates, degrees-of-freedom (DOF) is used to provide similar information.

As noted above, the spatial resolution and sampling repeat frequency of both the ground-based and space-based measurement networks are expected to increase substantially over the next decade. The spatial resolution of the atmospheric inverse models and emission plume models is also expected to increase. These improvements are expected to yield useful top-down budgets over progressively smaller nations.

Question 5: What are your thoughts on using drone technology to identify and measure Methane and CO_2 emissions. And do reference methods exist for this, or similar, such as those used on airplanes?
Answer 5: Drones are already being used to search for large methane leaks and to collect high altitude profiles of CO_2 and CH_4. As our colleagues develop miniaturized CO_2 and CH_4 sensors with increasing precision and accuracy, we expect that drones will be more widely used to quantify concentrations and fluxes.

So far, the best reference methods for these small payloads include conventional *in situ* sensors deployed on fixed-wing aircraft and the AirCore systems that are being deployed at increasing numbers of sites (see DOI: 10.1175/2010JTECHA1448.1). An AirCore is a long (~150 m), narrow (~0.6 cm) tube that is coiled up and launched by a balloon or drone. In typical applications, one end of the coiled tube is closed with a valve and the other is open. As the balloon ascends, the gas in the tube vents to the atmosphere. When the balloon reaches its maximum altitude (around 25 km), the AirCore is released from the balloon and falls back to the ground on parachute. As it falls, it is re-filled with atmospheric air, preserving its vertical stratification. When it reaches the ground, the AirCore is retrieved, the valve on the closed end is opened, and the air is drawn out through *in situ* analyzers, like those used for ground-based measurements, and the vertical profiles of CO_2, CH_4 and other gases are recorded. Here, the analyzer acts as the reference system.

Question 6: As of right now, what is the most accepted/utilized definition of "managed" and "unmanaged" land?
Answer 6: To the best of our knowledge, there is no internationally-accepted definition of managed and unmanaged lands. There are guidelines for defining the “managed land proxy” in the 2006 and 2019 IPCC Guidelines for National GHG Inventories. See:

https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

Members of the scientific community have attempted to develop and apply globally consistent definitions of managed and unmanaged land. See for example:

Ogle et al., https://doi.org/10.1186/s13021-018-0095-3
McGlynn et al., https://doi.org/10.1007/s10584-021-03254-2
Deng et al., https://doi.org/10.5194/essd-14-1639-2022-supplement
Ciais et al., https://doi.org/10.5194/gmd-15-1289-2022
Bastos et al., https://doi.org/10.5194/esd-12-745-2021

Question 7: Where can you find the 1-degree latitude by 1-degree longitude dataset? The link only provides the national dataset.
Answer 7: The CO_2 dataset has not yet been posted because the data are still being finalized. We anticipate that they will be posted in the coming weeks. We will also be submitting a manuscript with more details before the end of June. That manuscript will include links to the 1-degree by 1-degree CO_2 estimates.

The 1-degree by 1-degree CH_4 dataset is described here:
https://doi.org/10.5194/acp-22-6811-2022
The 1-degree by 1-degree CH_4 maps can be obtained from the NASA Carbon Monitoring System website:
https://cmsflux.jpl.nasa.gov/get-data/publication-data-sets
See the dataset called TopDownEmissions_GOSAT_GEOS_CHEM_2019.nc

Question 8: Could you please indicate the required setting of Excel in order to exploit the data (, ; : ...) ?
Answer 8: No special settings were used in Excel. The “;” and “:” symbols were added by accident in the original dataset that was posted. This error was corrected in the most recent version at the CEOS website (see https://ceos.org/gst/carbon-dioxide.html). Please try re-downloading and opening this version. If you are still having issues, please email Brendan Byrne (brendan.k.byrne@jpl.nasa.gov).

Question 9: In order to give an annual estimate of CH_4 flux, how many space-based measurements are required? What is the timeframe (number and

frequency)? For a given area of 100 km^2, what is the minimum measurement coverage?
Answer 9: In general, we need enough measurements to meet two goals. First, we must resolve the variability in the emission rates. Second, we need to reduce the uncertainty in individual measurements associated with XCH_4 measurement precision and uncertainties in environmental properties such as wind speed and direction and plume height. If the emission rate varies on hourly, daily, or monthly time scales, the sampling frequency must be high enough to resolve this variability, or temporal aliasing will bias the observations. If we are observing an isolated plume that has almost constant emission rates over a known period, we can estimate the total number of revisits needed to minimize other measurement uncertainties over that period using methods like those described in Jacob et al., (2022; see equation 8). If we wish to constrain a total flux in some area, such as a country, similar criteria apply, but here, both the spatial density and quality of satellite observations must be optimized to meet the measurement accuracy requirements. For example, see the recently published global budget paper (Appendix A; Worden et al., 2022): Here flux numbers are given per country using GOSAT satellite observations for 2019 with an important metric called "degrees of freedom for signal" (DOFS), which is a measure of the information content from the satellite XCH_4 estimates. If a country's DOFS estimate is greater than 1, there were enough satellite observations in 2019 to place a meaningful constraint on the emissions budget. If DOFS is less than 1, the satellite measurements do not inform the budget.

With satellites like GOSAT, which collect samples at 250 intervals, it is impossible to derive robust annual flux estimates on areas as small as 100 km^2. However, this limitation should be mitigated in the near future, as satellite missions with much greater spatial resolution and coverage are deployed (e.g., MethaneSat, GOSAT-GW, GeoCarb and CO2M).

Question 10: Can you describe what methods are used to delineate the "edge" of plumes detected by satellites or airborne spectrometers? i.e. the figures on slide 41--what sort of non-manual, non-subjective methods are used to draw a line around a plume vs. background?
Answer 10: Great question. We have developed automated methods that define a set radius around each detected plume, then apply a concentration threshold to differentiate between methane-enhanced (plume) pixels and background pixels. These methane-enhanced pixels are then analyzed further to infer the total methane plume mass and emissions. Many groups are applying machine learning and image

processing algorithms to refine these plume boundaries, but those are works in progress.

Question 11: Deserts are reported as sinks. How can we make a balance to better estimate the effectiveness of deserts as sinks using regional modeling?
Answer 11: The pilot top-down CO_2 budgets indicate that large deserts are roughly neutral, except in regions where human activities including large urban areas or fossil fuel extraction activities introduce a net source. It should be possible to combine these top-down results with the bottom-up inventories to refine the activity data and emission factors over these areas.

Question 12: Are there currently efforts to create artificial sinks of CO2?
Answer 12: There are a variety of efforts ongoing to sequester CO_2. Some efforts focus on planting trees (see, for example: https://climate.nasa.gov/news/2927/examining-the-viability-of-planting-trees-to-help-mitigate-climate-change/)
Other efforts attempt to capture and sequester CO2 underground (see for example, https://pubs.usgs.gov/fs/2010/3122/pdf/FS2010-3122.pdf ; https://doi.org/10.3389/fclim.2019.00009) or in the ocean (see for example, https://www2.lbl.gov/Science-Articles/Archive/sea-carb-bish.html ; https://www.technologyreview.com/2006/08/08/228472/storing-carbon-dioxide-under-the-ocean/?utm_medium=search&utm_source=google&utm_campaign=BL-ACQ-DYN&utm_content=categories&gclid=CjwKCAjwp7eUBhBeEiwAZbHwkYTADhFjW9-2X8ul3NOuYnnDj7rNO0-6ktICFYxQEpeHj-Moa2vhPxoCVg4QAvD_BwE)

So far, these efforts have returned mixed results, and none has yet been demonstrated on the scale needed ro remove a substantial fraction of the 40 billion tonnes of CO_2 emitted by human activities each year. However, these methods are expected to improve over the next few decades as nations of the world attempt to manage their emissions. The recent IPCC report concludes that effective CO_2 sequestration may be an essential component of plans to meet the goal of net zero emissions by 2050.

Question 13: Can you elaborate on how to integrate the process values between ground, airborne, and satellite sensors' measured values of CO2 , CH4
Answer 13: The ground-based, airborne, and space-based CO_2 and CH_4 data products must first be cross validated against common standards before they can be combined. They can then be assimilated into atmospheric inverse models, along with information about their spatial sampling characteristics and uncertainties, to estimate fluxes. The

ground-based and airborne *in situ* sensors are cross validated against a standard maintained by the World Meteorological Organization (WMO). The methods are described here: https://gml.noaa.gov/ccl/co2_scale.html.

The ground-based remote sensing observations collected by the Total Carbon Column Observing Network (TCCON) stations then adopt the ground-based and airborne *in situ* measurements as their standard. The TCCON estimates of the column-integrated dry air mole fractions of CO_2 and CH_4 (XCO_2 and XCH_4), are validated through routine comparisons with measurements collected above the stations by high-altitude, fixed-wing aircraft and balloons that carry in situ sensors calibrated to the WMO standard. This process is described in detail here: https://royalsocietypublishing.org/doi/10.1098/rsta.2010.0240. The space-based groups then use TCCON measurements as their accuracy standard. Each spacecraft collects large numbers of observations as they fly over TCCON stations and these measurements are compared to the TCCON measurements to identify and correct biases. That process is described here https://doi.org/10.5194/amt-10-2209-2017 and https://doi.org/10.5194/amt-14-665-2021.

Once the data from the ground-based, airborne and space-based sources are cross validated, they can be assimilated into atmospheric inverse models, which were discussed in Part 2 of this webinar series. These models incorporate atmospheric transport models and data assimilation systems similar to those used in numerical weather prediction models. In this application, individual measurements, along with their vertical and horizontal sampling information and estimates of their uncertainties, are typically used as constraints on a Bayesian inverse modeling framework. These models are designed to optimize surface fluxes to minimize a “cost function,” which describes the mismatch between the observed and simulated CO_2 or CH_4 field. Atmospheric inverse modeling systems are described in several publications, including:
https://doi.org/10.1017/CBO9780511535741,
https://doi.org/10.1029/2010JD013887,
https://doi.org/10.5194/acp-22-6811-2022 and
https://doi.org/10.5194/acp-22-1097-2022.
These methods have evolved rapidly in recent years to more fully exploit the growing availability of in situ and remote sensing estimates of CO_2 and CH_4.

Question 14: Since the bottom-up emission inventories are used as prior information for top down inversion modeling, my concern is, to what extent does the top-down inversion modeling rely on the prior information?
Answer 14: The top-down budget estimates combine the prior information with the information provided by the atmospheric GHG measurements. In general, for regions where the measurement density and uncertainties are small, the prior has a limited impact on the retrieved fluxes. The prior can have a much larger influence in regions where there are few measurements or where measurement uncertainties are high.The extent to which the top-down estimates refine the prior information is reflected in their uncertainty estimates. For the pilot top-down CO_2 budget, we provide the metric "Influence of Assimilated Data" or IAD (see pg. 32), which indicates how much the top-down CO_2 fluxes are impacted by the assimilated data. For the pilot CH_4 budgets, the Degrees of Freedom for Signal (DOFS) similar information.

Question 15: Is this available as a raster format? And if so, at what resolution?
Answer 15: The top-down CO_2 and CH_4 budgets are currently available as national totals in files that are formatted as comma-separated values (CSV) file and Microsoft Excel worksheet file. In coming weeks, a Network Common Data Form (NetCDF) file will also be released. The national budgets were derived from 2-dimensional maps of fluxes that are resolved on a regular, 1-degree latitude by 1-degree longitude spatial grid. The gridded flux maps will be provided as a Network Common Data Form (NetCDF) file within the next few weeks, at the CEOS website (https://ceos.org/gst/carbon-dioxide.html). Feel free to email Brendan Byrne if you cannot locate the file.

Question 16: Thanks for the amazing presentation. Do you see some opportunity here to use AI (e.g., in identifying emissions of CH_4 events or some other similar cases)?
Answer 16: Artificial Intelligence (AI) and other Machine Learning techniques are currently being used in several greenhouse gas applications. For example, they are being used to fill gaps between the available measurements of ocean fluxes (See Fay et

al., 2021, https://doi.org/10.5194/essd-13-4693-2021 or Gloege et al., 2021, https://doi.org/10.1029/2020GB006788 for specific examples). They are also being used to combine plot-scale ecosystem flux tower data with satellite observations from MODIS to upscale these fluxes to continental scales (see Yang et al., https://doi.org/10.1016/j.rse.2007.02.016).

For CH_4, a considerable amount of work is going into image recognition of CH_4 plumes. Future satellites are going to capture an enormous amount of data at high spatial resolution, so analyzing the data to identify individual plumes with quick turnaround will be a key element to informing mitigation. In these efforts, AI and other machine learning techniques are expected to be important especially at the localized plume scale (health concerns).

Question 17: What problem/topic would you like to see resolved in the next few years?
Answer 17: One thing we would like to see is an expanded network of ground-based and airborne CO_2 measurements to fill in the data gaps in developing countries across the tropics and across the arctic and boreal zones. These measurements are needed to better investigate some of the differences that we see in the flux estimates from *in situ* CO_2 measurements and space-based XCO_2 estimates. We would also benefit from more situ pCO_2 measurements over the ocean to foster the development and validation of more precise and accurate space-based estimates of CO_2 fluxes over that critical domain.

We also need to expand our collaboration with the national inventory development and policy communities to refine the requirements for top-down atmospheric budgets for supporting the stocktakes. Many of the planned interaction opportunities were interrupted by the COVID-19 pandemic. Hopefully this training will help to restart these efforts.

Question 18: We know that the availability of the satellite observations is seasonally varied, i.e., less valid observations in winter from TROPOMI over some regions. Would this be an important factor that may bias the atmospheric inversion analysis (e.g., more observations during the period with more emissions may lead to overestimation of the annual emission)?
Answer 18: Data gaps remain a major challenge to accuracy of atmospheric inverse methods. They can introduce biases, obscure sources and sinks and introduce other artifacts that should be accounted for in uncertainty estimates. However, it is important

to note that space-based observations are only one source of data on CO_2 and CH_4. The presence of persistent gaps in the space-based data reinforces the need for expanded ground-based and airborne networks, especially in tropical regions, which are often obscured by clouds and at high latitudes, which have both low light levels and clouds during the winter.