Questions & Answers Part 1

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) or Sean McCartney (sean.mccartney@nasa.gov).

Question 1: What are the differences among BTR, NDC, and BUR?
Answer 1: These are 3 different types of reports to the UNFCCC. A Biennial Transparency Report (BTR) is the main reporting instrument under the Enhanced Transparency Framework of the Paris Agreement [see https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-paris-agreement]. This report is required from all parties, and replaces the earlier Biennial Update Reports (BURs) from non-Annex-1 countries and the Biennial Reports (BRs) from Annex-1 Countries. Like the BURs and BRs, the BTR includes a complete description of progress toward mitigation goals (i.e, emissions and removals of greenhouse gases), but also other reports on progress towards the adaptation, means of implementation and cross-cutting goals of the Paris Agreement.
NDC: The Nationally Determined Contributions (NDCs) are also required of each party and describe the efforts by each country to reduce national emissions and adapt to the impacts of climate change [see https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/nationally-determined-contributions-ndcs].

Question 2: What is the height level used to estimate the flux while one uses satellite data or other measurements (as most of the time, it may not provide good accuracy at ground-level)?
Answer 2: Fluxes between the Earth's surface and atmosphere are inferred from measurements collected by in situ sensors deployed under and on the surface of the ocean, at the surface on land, and in aircraft and remote sensing observations deployed at the surface and on orbiting satellites. The in situ sensors measure the CO_2 and CH_4 concentration in the immediate vicinity of the sensor. The ground-based and spacecraft remote sensing instruments measure the average concentration (or what scientists call the dry air mole fraction) in a column of air extending from the top of the atmosphere to the surface. While these are column averages, they are most sensitive to the CO_2 and CH_4 changes near the surface, where fluxes originate. To retrieve fluxes (emissions and removals) from these data, we assimilate them into an atmospheric

inverse model, using information about where the altitude or altitude range from which they were collected. In addition to fluxes, the inverse models compute vertical profiles of CO_2 and CH_4 that can then be compared directly to surface and aircraft measurements to assess the accuracy of the flux estimates.

Question 3: What is meant by the fugitive emissions from fuels on slide no. 18?
Answer 3: Fugitive Emissions (FE) are emissions that were not supposed to get away (e.g., gas leaks out from oil or natural gas pipelines). If a leak is detected via a ground-based, airborne or space-based sensor, the operator of the facility or pipeline can address these leaks. Fugitive methane leaks can occur during oil or natural gas extraction. These emissions are supposed to be burned in flares, but the flaring is sometimes extinguished, releasing fugitive methane. Fugitive emissions can also occur due to pipeline ruptures or equipment failures in storage facilities. Another source of fugitive emissions is waste management facilities (landfill, etc.). Landfill operators try to capture that gas to flare or use in a power plant, but sometimes that equipment malfunctions, releasing methane.

Question 4: In reference to the national inventories from the energy sector, and the need to track emissions from the transport sector, how are the emissions from the maritime transport sector accounted for (at the national level)?
Answer 4: The UNFCCC reporting guidelines on annual inventories require that emissions from international aviation and maritime transport be calculated as part of the national GHG inventories of Parties, but should be excluded from national totals and reported separately [see https://unfccc.int/topics/mitigation/workstreams/emissions-from-international-transport-bunker-fuels]. In practice, for international navigation routes, the emissions are reported either to the origin country, the destination country, or both. All maritime sector emissions are accounted for using methods specified in the Intergovernmental Panel on Climate Change (IPCC) Taskforce on Inventories and reported to the United Nation International Maritime Organization (IMO). The specific reporting methods depend on the fuel used (e.g., diesel, natural gas, biofuels), whether the transport is between domestic or international navigation and other factors. The actual emissions are derived using bottom-up methods that employ emission factors (amount of CO_2, CH_4, and N_2O generated per unit of fuel) and activity indices (amount of fuel used).

Question 5: Regarding slide 23, I'm curious to know why the latitude gradient of CH_4 is so much steeper than the latitude gradient of CO_2?

Answer 5: The two plots shown on Slide 23 have two different color scales for CO_2 and CH_4, respectively. For CO_2, the color scale ranges from 375–420 ppm (11%), while for CH_4 the color scale ranges from 1.65–2.00 ppm (19%. note: in the slide, this is reported in ppb). This is why the gradient in CH_4 looks much steeper than the gradient in CO_2. In general, for XCO_2 (total column CO_2), the Inter-Hemispheric (IH) gradient for CO_2 is approximately 5 ppm; while for XCH_4 (total column CH_4), this IH gradient is of the order of 0.05 ppm. These are annual maps compiled over a period of time. In addition, most CH_4 emissions originate from land rather than ocean sources. There is generally lower CH_4 in the Southern than in the North, when averaged over the year, because there is much more land in the Northern hemisphere than in the Southern hemisphere, and thus more sources.

Question 6: What is the required spatial resolution and the measurement frequency over time to quantify CO_2/CH_4? What is the required payload bandwidth range and spectral resolution?
Answer 6: This is actually a very complicated question because its answer depends on the spatial scale and temporal scale over which you wish to quantify CO_2 or CH_4 fluxes and other aspects of your chosen application.

A dense network of surface stations is needed to sample a plume from a power plant or large urban area as it is transported away from the source by the winds. For example, if you need to quantify fluxes over a specific city (e.g., Los Angeles Megacities Project), you might deploy a network of towers, instrumented with precise and continuous GHG sensors. With this system city- or basin-wide fluxes can be quantified on weekly scales. As you go to national and global scales, the existing ground-based monitoring network is too sparse, and thousands of additional stations would be needed. Alternatively, satellites could be used to fill in the gaps between existing stations. Here, coverage and spatial resolution are the primary drivers. Current satellite observations have been used to demonstrate this approach, but require weeks to months to fill in the gaps, so the measurement frequency is reduced.

From space, we can measure the entire plume from a power plant or large urban area in a single overpass, but the measurement sensitivity decreases with decreasing footprint size. Sensors like Japan's GOSAT, NASA's OCO-2 and the Copernicus S5p TROPOMI measure CO_2 and CH_4 variations as small as 0.125 to 0.5% over their footprints. These sensors can therefore detect CO_2 and CH_4 plumes many kilometers (km) from their sources. In contrast, high spatial resolution hyperspectral sensors, such as PRISMA, have relatively low sensitivity, but high spatial resolution, and can therefore

only detect intense plumes very close to their sources. Both types of sensors are useful, but have different applications. GOSAT/OCO-2/TROPOMI are best for quantifying weak, spatially extensive sources and sinks, such as those over the ocean or over a forest, while the hyperspectral sensors are best for pinpointing super-emitters.

For sensors with similar precision, the sensitivity to a given flux of CO_2 or CH_4 is inversely proportional to both the area of their surface "footprint" and the wind speed. The flux detection sensitivity depends on footprint size because it takes a much larger quantity of CO_2 or CH_4 to change the concentration in the air column over a large surface footprint by a fixed amount (e.g., 1%) than it takes to change the concentration in the air column over a smaller surface footprint. The wind speed matters because the "residence time" of the CO_2 or CH_4 over the footprint depends on the wind speed and dimension of the footprint in the direction of the wind. If it takes only seconds or minutes for the wind to blow across the footprint, a detectable mass of CO_2 or CH_4 has to be replaced in that footprint on that time scale.

Measurement network designers and spacecraft designers use these and other criteria along with an understanding of their measurement technologies to optimize their systems for specific applications. For example, satellite system designers might optimize for global coverage and high frequency repeat observations. Those constraints, combined with sensor technology constraints, usually yields larger surface footprint sizes. For example, the surface footprint of a GOSAT or GOSAT-2 sounding is a circle about 10 km in diameter (about 85 km area). It takes 4 seconds to collect each observation, so the observations are separated by about 250 km across the day side of the Earth over a 3-6 day orbit ground track repeat cycle. OCO-2 can collect 24 soundings per second continuously along a narrow (< 10 km wide) ground track, so its surface footprint is < 1 by 2.3 km. However, adjacent measurement tracks are separated by about 25 degrees of longitude (2500 km at the equator) on a given day. The spacecraft's orbit fills in these large gaps during its 16-day ground track repeat cycle, yielding a track-to-track spacing of 1.5 degrees of longitude. This was the best we could do in the 2014 time frame. Future spacecraft instruments, such as the Copernicus CO2M constellation, will obtain measurements with 2 km by 2 km footprints of a very wide (about 400 km) swath, so that they can yield both high resolution and global coverage at 1 to 2 week time scales.

The sensitivity and accuracy of space-based remote sensing measurements is critically dependent on the spectral resolving power and spectral range chosen. Different

solutions are needed to optimize the sensitivity for different measurement technologies that incorporate different detector architectures and different spectrometer or telescope designs. For CO_2, we typically use channels that are a few nanometers (nm) wide, covering the molecular oxygen band as 765nm and the CO_2 bands near 1610 and 2060 nm. For CH_4, narrow bands near 1670 or 2300 nm are used. Sensors such as those on GOSAT/GOSAT-2 and OCO-2/OCO-3 divide these narrow bands into about 1000 pieces, yielding a spectral resolving power of about 20000. Others like CO2M use the same spectral bands but have about half that resolving power, but much higher signal-to-noise ratios to exploit their detector technologies.

The spatial resolution requirements also apply to the models used to retrieve fluxes from the observations. Current generation global atmospheric inverse models have a spatial resolution of around 100 km. Much higher resolution models with more limited domains are used to infer fluxes from localized sources such as power plants and large urban areas. Higher spatial resolution global models and more capable limited-area models will be needed to analyze future ground-based, airborne, and space-based measurements of CO_2 and CH_4 flux.

These and other design activities and this overall design approach have benefited greatly through the development of the first generation of space-based sensors. This experience is now being exploited to support the next generation of purpose-built operational, global greenhouse gas monitoring systems.

Question 7: How do you specify the space mission and its payloads in accordance with the national needs (surface, number of zones of interest, facility/regional level)?
Answer 7: This is a work in progress. It is important to note that the first generation of CO_2 and CH_4 sensors were not designed to address specific national needs. They were designed as scientific experiments to determine how well we could measure these greenhouse gases from space-based sensors. They were a proof of concept, not an operational system designed to meet specific user's needs.

As illustrated by the products described in this webinar series, we found that these systems could support some of the Paris Agreement's mitigation goals. A primary objective of this pilot product development activity was to start a conversation with the bottom-up inventory community, policy makers and other stakeholders to refine the requirements for future top-down CO_2 and CH_4 budgets. During their development, we identified improvements in precision, accuracy, spatial and temporal resolution,

coverage and continuity are needed to build a system that serves the quality assurance / quality control (QA/QC) objectives described in the 2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories. Based on experience with these first-generation systems and the rapid evolution of user requirements, we are refining the requirements of future ground-based, airborne and space-based sensors and modeling systems. We are also soliciting input from the UNFCCC inventory development and assessment communities for other requirements on the top-down budgets, including their content, documentation, and capacity building needs.

Question 8: What is it about OCO-2 and OCO-3 that makes them able to be added together? Can you talk a little bit more about why that addition can be done? And, does it mean that each dataset from OCO-2 and OCO-3 is less accurate on their own? Thanks!

Answer 8: One can use OCO-2 and OCO-3 data individually on their own to estimate column-averaged atmospheric CO_2 dry air mole fractions or CO_2 fluxes. OCO-2 data spans 7.5+ years (data beginning from Sep 2014 – current) while OCO-3 data spans 2.5+ years (data beginning from Aug 2019). Both the datasets are independently calibrated and validated against ground-based data to ensure their accuracy and stability when used alone. To combine their data, the OCO-2 and OCO-3 measurements must be cross-calibrated against common radiometric, spectroscopic and geometric measurement standards. Their retrieved XCO_2 estimates must also be cross-validated against common accuracy standards. This is relatively straightforward because even though these two spectrometers are flying on independent platforms, OCO-2 and OCO-3 use a common instrument design and the same retrieval algorithms to generate similar data products. To cross-calibrate these instruments, they regularly acquire observations of the moon and near-simultaneous observations of surface targets. The surface targets include well characterized vicarious calibration targets, such as the Railroad Valley Playa in Nevada, USA, which is visited by field campaigns 4-5 times each year to quantify its reflectance properties. To cross validate the products, both instruments regularly acquire observations over Total Carbon Column Observing Network (TCCON) stations, which provide the transfer standard between space-based measurements and the World Meteorological Organization's in situ CO_2 standards.

These same methods are being used to cross-calibrate and cross validate OCO-2 and OCO-3 measurements with those collected by Japan's GOSAT and GOSAT-2 sensors and Europe's Copernicus S5P TROPOMI sensors. However, in those cases, additional

effort is needed to accommodate the larger differences in instrument design and performance.

Question 9: There are organizations that claim that they can take OCO-2 and OCO-3 CO_2 measurements and down sample those measurements to a crop field (e.g., about a hectare), to understand the flux from the crop field. I have also seen groups disaggregate OCO CO_2 measurements and associate the OCO measurements with specific land cover classes via an emissions factor. What are your thoughts on these approaches and are OCO-2 and -3 measurements meant for this?
Answer 9: I am not aware of these efforts. In general, in areas that are homogeneous on the spatial scale of two or more OCO-2 or OCO-3 footprints, these approaches might work well. For example, in such regions, if the CO_2 sources and sinks and their relationships within the OCO-2/OCO-3 pixels are well understood, this approach might be useful for scaling the net effect of these sub-pixels processes. In regions characterized by significant surface albedo or topographic variability, or spatial variations in clouds or aerosols, this approach might be much less reliable.

Question 10: Do the NCE maps also exist in even higher resolutions?
Answer 10: The global inversion analyses presented here are best able to provide NCE estimates on large regional scales, such as country totals. Even though we produce 1x1 degree maps, we do not trust the individual grid cell fluxes because there are insufficient observational constraints, and suggest aggregating to 1,000 km x 1,000 km scales or larger. There are separate studies that are designed to look at higher resolution emissions. In particular, the OCO-3 mission is designed to map XCO_2 over cities and these data are being used to estimate urban emissions (e.g., https://doi.org/10.1016/j.rse.2021.112314).

Question 11: Regarding net CO_2 measurements for 2020, are the cumulative measurements for the complete year (e.g., added up for all the days in the year)?
Answer 11: Yes, the OCO-2 and GOSAT data used in these pilot products were continuous throughout 2020, and extend from 1 January 2020 through 31 December 2020. The only gaps are those for routine instrument calibration and decontamination activities, which typically require about one week of downtime.

Question 12: An open-ended question: Would love to hear more of an explanation on the technical differences between a GHG 'inventory' and a 'budget'. Are the

different terms just used to distinguish between bottom-up and top-down methods respectively? Or is there more nuance?

Answer 12: This difference in terminology attempts to reflect the differences in both data product production methods and product information content. We can think of an inventory of greenhouse gases like an inventory of a supermarket. The supermarket shelves might include one or more examples of hundreds of different types of food. For example, it might include 5 cans of one kind of beans and 10 cans of another type of beans, etc. The manager needs to know how many of each item they have in stock to know when they need to order more of each. Similarly, a greenhouse ga Inventory from a given country, might track emission factors and activities for a 1,000 specific emission sources and removal mechanisms. The policy makers need to know how each source or removal mechanism is emitting or removing CO_2 and CH_4 so that they can manage that category of that sector of emissions. They can then add all of these emissions and removals to determine how they are meeting their overall objectives.

We can't do that with the atmosphere. Measurements of atmospheric concentrations can be analyzed to yield a direct constraint on the net effect of emissions by sources and removals by sinks above a specific area, but, at the national or regional level, these measurements provide much less information on the performance of specific sources or sinks within this domain. The space-based measurements are therefore more like the bottom line on your checking account, which tells you how much money you have in the bank and perhaps how fast that number is changing, but not what specific actions are driving those changes. This information is therefore more like a top-level budget than an inventory of activities. To gain insight into the processes driving the budget, we need additional information. For example, if we have a good estimate of the fossil fuel emissions, and know that most of the remaining activity is associated with land use change, we can subtract the fossil fuel emissions from the net value to estimate the net land use emissions or removals. That is what we have done in the pilot top-down CO_2 products described here.

Directly imaged emissions from compact sources are a partial exception to this general rule. Occasionally, the satellite flies directly over a large power plant or pipeline leak, and its sensor directly measures the plume originating from that source. Here, if we know what type of source is there (from something like Google Maps), we can attribute the observed atmospheric enhancement to that source. This information could then be used to inform bottom-up inventories of emissions from that source.

Question 13: Did the lockdowns affect the accuracy of the GHG measurements as aircrafts were grounded, or did this event have no impact whatsoever?
Answer 13: The lockdowns did not directly affect the collection, analysis or quality of the data from the space-based sensors. The teams had to quickly learn how to operate these systems remotely, but we were able to maintain the data pipelines without interruption. The ground-based calibration and validation activities were initially disrupted as a few sites went off line and lock-down restrictions delayed repairs, but our teams soon found ways to work around those obstacles. The reductions in air travel did temporarily disrupt data streams from some airborne sensors, but these data were primarily being used for validation and their interruption produced no measurable effect on the data products described here. A longer shutdown of these datasteams would eventually erode the quality of the space-based data validation.

The lockdowns due to the COVID pandemic did have a very small impact on concentrations of greenhouse gases and a larger, more easily detectable impact on air quality across the globe. At the height of the global lockdowns (between April - June/July 2020), studies have shown that small, regional-scale changes in CO_2 concentrations (< 0.5 ppm) that were well correlated with the timing of the lockdowns were detected, but these changes did not have a significant impact on the annual growth rate of CO_2 concentrations. Please see the following study using the OCO-2 data - https://www.science.org/doi/10.1126/sciadv.abf9415

Other studies have focused on abrupt reductions in emissions during the lockdown periods that led to clearly observable changes in atmospheric composition. Please see - https://www.pnas.org/doi/10.1073/pnas.2109481118

Question 14: Plants in land or water absorb CO_2 during daytime and release during nighttime. Then how do they (plants/ocean) act as a sink for CO_2? What is the difference between the absorbed and released CO_2 levels for plants? Is this difference uniform and always a sink for all the plant species, their age, seasons and growth period?
Answer 14: This is a very good question. These processes are not uniform in space or time. As you have noted, the rate at which plants absorb and release CO_2 varies during the day. It also varies during the year and over the lifetime of the plant. Plants absorb CO_2 through photosynthesis during the day. Some of the carbon from the carbon dioxide is used for energy and some is used to create new leaves, stems, and roots during the growing season. Much of the fraction of this carbon that is used for energy is re-released through respiration. The relative rates of photosynthetic uptake and

respiration depends on a number of factors, including the amount of sunlight, temperature and the availability of water and other critical nutrients, such as nitrogen and phosphorus. Sometimes respiration is more efficient than photosynthesis, releasing more CO_2 to the atmosphere than the plant absorbs through photosynthesis and the plant loses carbon. Sometimes photosynthesis is more efficient than respiration and the plant gains carbon. The carbon that is fixed as wood can either be re-released to the atmosphere if that wood dies and rots, or it can be "sequestered" for long periods of time. For example, some of the wood that forms the roots of the plant can decay but remain in the soil as soil carbon. Some of the wood could be harvested and used to make homes or furniture, which can last for many years or even centuries before being re-emitted to the atmosphere. All of these processes combined determine whether a given blade of grass, tree or forest is a net source or net sink of CO_2. Our measurements show that some regions, such as tropical forests, are transitioning from net sinks to net sources. Meanwhile, they show that mid- and high-latitude forests are becoming better sinks of CO_2.

Question 15: When using the top down approach, once we have identified the emitting sources using TROPOMI, what models are used to estimate the CO_2 and CH_4 concentrations? Are they publicly available?
Answer 15: Retrieved column-averaged concentrations of CH_4 are available from TROPOMI through various free and publicly available sources (e.g., https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-5p). Estimating fluxes requires an atmospheric transport model (we'll go into this in detail in Part 2 of this course). These models are also freely and publicly available (e.g., X-STILT; GEOS-Chem), but there is quite a bit of nuance and work required to reliably predict fluxes using these models.

Question 16: How do you account for the carbon estimates over oceans?
Answer 16: We use both in situ measurements from instruments deployed on ships, buoys, and autonomous platforms to measure the carbonic acid in seawater and the CO_2 We also use sensors on aircraft that can measure the vertical profile of CO_2 above the ocean. Space-based sensors also measure the XCO_2 over the ocean. These measurements are extrapolated to the whole ocean using a variety of different types of diagnostic and machine learning models or incorporated into ocean biogeochemical models and atmospheric inverse models to estimate the net emissions and uptake of CO_2 over the oceans. At this point, these estimates of emissions and removals are routinely reported by the scientific community, but are not yet accounted for in the inventories that nations prepare for the UNFCCC.

Question 17: What is the best way to access the OCO-2 and OCO-3 data products?
Answer 17: The OCO-2 and OCO-3 data are freely available at - https://disc.gsfc.nasa.gov/datasets?keywords=OCO2%20OCO3&page=1

There are a variety of data products that are available. However, the ones that are most relevant to the user community are -

(a) OCO-2 - https://disc.gsfc.nasa.gov/datasets/OCO2_L2_Lite_FP_10r/summary?keywords=OCO2%20L2%20Lite
(b) OCO-3 - https://disc.gsfc.nasa.gov/datasets/OCO3_L2_Lite_FP_10.4r/summary?keywords=OCO3%20L2%20Lite

Question 18: P. 40– what is the explanation for the disagreement of delta carbon of -1 for inventory and -2 for other methods? What improvements do we need to get better agreement?
Answer 18: This is the primary topic of part 3 of this webinar series. The differences might be due to:

1) The inventories and top-down budgets are not measuring the same area or time period. For example, the inventories only report carbon losses and gains on managed lands, while the top-down budgets include both managed and unmanaged lands. Errors are also introduced in the atmospheric budgets when the gridded values are interpolated into national boundaries.
2) There may be differences in the carbon pools included in the inventories and top-down budgets. The inventories assess carbon pools identified in the IPCC or UNFCCC guidelines for national inventories. The atmospheric budgets describe the net effects of all carbon pools.
3) There may be errors in either the activities or emission factors used for the inventories.
4) There may be errors or biases in either the atmospheric CO_2 measurements or inverse models used for the top-down budgets. Also, the top-down budgets describe the “Net Carbon Exchange (NCE)” due to all processes. To derive estimates of the land carbon changes, accurate estimates of the fossil fuel emissions and other processes such as crop wood exports, river runoff, etc. must be subtracted off. If the estimates of these properties include errors, they

will introduce errors in the estimated land carbon exchange. Reconciling these and other differences will require a substantial amount of collaboration between the inventory and atmospheric carbon communities.

Question 19: Can you talk a little about how using a 20-yr GWP (Like NYS requires) may look different in this work? I realize that certain sources may rise, like waste, but anything else to consider for using this work?
Answer 19: This is a very complex topic. Both the land and ocean carbon emissions and removals depend on the climate in intricate ways. Changes in the global warming potential (GWP) over the next two decades are expected to affect the land and ocean carbon sinks in different ways. For example, increased warming and drying are expected to increase emissions from tropical forests. Longer, warmer growing seasons are expected to continue increasing the uptake of CO_2 by mid- and high-latitude forests, at least for the next few years. The impact of increasing wildfire, insect infestations and human activity (deforestation, deforestation) are more difficult to predict. Meanwhile, the ocean sink is expected to respond to the changing rate of CO_2 emissions. If we cut back substantially on anthropogenic CO_2 emissions, the ocean sink is expected to become less efficient, absorbing a smaller fraction of those emissions. Many of these factors are described in the IPCC AR6 reports, which are just now becoming available.

Question 20: Is it possible to use space-based measurements of CO_2 and CH_4 to see the role of green urban spaces in reducing carbon emissions of cities or to validate models that estimate CO_2 or CH_4 from urban agriculture?
Answer 20: As the precision, accuracy, and spatial resolution of the atmospheric measurements improve, we expect them to play a key role in monitoring changes in net emissions from large urban areas. We will still need bottom-up inventories of activities, such as increased urban agriculture to accurately attribute the observed changes in net emissions to specific categories of specific emission sectors, such as urban agriculture.

Question 21: When sensing over cities and urban areas, how is the flux calculated? Some cities have very little tree cover or a depleting tree cover, how does it impact the flux calculations?
Answer 21: The atmospheric budgets describe the net impact of emissions and removals from all processes. These budgets will have to be analyzed in the context of known processes, derived from bottom-up inventories, to attribute changes to specific activities or sources and sinks.

Question 22: When using the top down approach, once we have identified the emitting sources using TROPOMI, what models are used to estimate the CO_2 and CH_4 concentrations? Are they publicly available?
Answer 22: This is the topic of the second part of this webinar series. In general, these data are analyzed with global- or regional-scale atmospheric inverse models or one or more plume flux models to estimate the CO_2 or CH_4 fluxes consistent with the observed concentrations and winds. Many of these estimates are available in the published scientific literature and can be obtained from the data sources listed in these publications. The pilot, national-scale CEOS CO_2 and CH_4 estimates described in Part 2 of this webinar series can be accessed here:

https://ceos.org/gst/ghg.html

Question 23: We can divide the individual impacts of sources from the bottom up approach, but how do you transform it to the atmospheric measurement impacts? Do you apply the same contribution ratio for each source? For instance, TMDLs in the basin in South Korea have a physically based watershed model or geomorphological functions to explain the relationship between generated pollution and stream pollution which is a delivery coefficient.
Answer 23: The IPCC Taskforce on Inventories has defined a series of methods for cataloging activity data and selecting emission factors for different emission sources and natural sinks. Please see the reports here:
https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/
and
https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

There is additional guidance here:
https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/reporting-requirements

Question 24: What is the problem formulation solved by the inverse method?
Answer 24: We will go into this in detail in Part 2. The inverse problem estimates fluxes from atmospheric concentrations. Fluxes are related to concentrations through an atmospheric transport model - i.e., an atmospheric transport model simulates atmospheric concentrations based on prescribed flux values. The inverse problem then

optimizes the fluxes to provide the best fit to observations, given some prior information.

Question 25: Do atmospheric conditions affect the measurement of CO_2/CH_4, like the optical bands are affected in multispectral remote sensing?
Answer 25: Yes, the water vapor content (humidity) must be accounted for precisely for in situ measurements of CO_2 and CH4 concentrations measured from ground-based and airborne sensors. This atmospheric property as well as the scattering of sunlight clouds and airborne particles (aerosols) must be accounted for in estimates of column-averaged greenhouse gas dry air mole fractions obtained from space-based remote sensing observations. Scattering of sunlight by clouds and aerosols introduces uncertainties in the optical path length traveled by the sunlight, which introduces uncertainties in the number of molecules per cubic meter along that path. For the remote sensing measurements, we acquire simultaneous, bore-sighted observations of molecular oxygen along with the CO_2 and CH4 measurements to provide an independent estimate of the optical path length and number density of dry air along the optical path.

Question 26: How does the temporal resolution of satellite measurements affect estimates?
Answer 26: Satellite observations must be collected often enough to resolve substantial variations in the emissions by sources and sinks. Both natural processes and human activities can change CO_2 and CH_4 emissions on diurnal (daily) as well as season and interannual time scales. In principle, this would require that we resolve the diurnal cycles of CO_2 and CH_4 as well as the seasonal and year-to-year variations. Because this is not currently possible, we try to measure CO_2 and CH_4 everywhere at the same time of day, by placing our spacecraft in sun-synchronous orbits, and then use models to estimate the diurnal variability. This approach generally works well, but can introduce temporal aliasing errors in some cases. These errors can be reduced to some extent by taking repeated observations and combining the results.

Question 27: What accuracy is required to predict CH_4 and CO_2? Is the bottleneck the sensors we can deploy or the models we simulate on ground to map out the spectrum?
Answer 27: The accuracy required depends on the problem that we need to solve. For example, the emission plume from a typical medium to large coal fired power plant or a large urban area will increase the column-averaged CO_2 dry air mole fraction, XCO_2, by one to two parts per million (ppm) out of the background concentration of around 400

ppm. This is a 0.25 to 0.5% effect. To quantify these concentration differences to 50%, we need measurements of the plume and the background with an accuracy of about 0.125 to 0.25%. This places rigorous constraints on the measurements, their calibration, and the models used to estimate XCO_2 from the space-based measurements of reflected sunlight. Scientists are currently working to improve all aspects of these measurements and models.

Question 28: Is it possible to compare emissions in mass from a country (i.e., CO_2 in tonnes per year) with the readings obtained via satellite?
Answer 28: Yes. This is the topic of parts 2 and 3 of this webinar series. There, we show how space-based CO_2 and CH_4 estimates can be analyzed with atmospheric inverse models to yield estimates of CO_2 and CH_4 fluxes at high spatial resolution. These results can then be mapped into the boundaries of individual countries and integrated over a specified time period, such as a year, to estimate the net CO_2 or CH_4 emitted by or absorbed by each nation. These data can then be combined with insights from bottom-up inventories to estimate the emissions or removals from specific sectors, such as Agriculture, Forestry and Other Land Use (AFOLU). See more in parts 2 and 3 of this webinar series.

Question 29: How much does the diurnal variation of CO_2 or CH_4 in the boundary layer affect the total column?
Answer 29: For both CO_2 and CH_4, the concentration differences are typically largest at the surface and decay with height. For example, a large urban area changes the CO_2 concentrations by more than 10 ppm in the boundary layer. When averaged through the column, these differences may be reduced to less than 1 ppm.

Question 30: Warming is a function of the number of CO_2 or CH_4 molecules and inventories are mass fluxes. Why is there such importance given to measuring air mass O_2?
Answer 30: If we measure a particular column abundance of CO_2 (i.e., number of CO_2 molecules per square meter, integrated over the column) over one location and a different column abundance over another place, it may just be that optical path lengths might have been different. One measurement might be over a mountain and the other might be over a valley. So, from that measurement, the differences might result from differences in the CO_2 concentration of CO_2 in the atmosphere or just the topographic altitude. We know the concentration of oxygen to very high accuracy. The measure of dry air mass therefore provides a useful constraint on the optical path length traveled by the photons as well as the total atmospheric mass.

Question 31: Do you have any methane budget slide for Australia, similar to the plots on slide no. 34, considering the coal production in this country?
Answer 31: See the plots presented in Part 2.

Question 32: What is the percentage difference between space-based measurements of CO_2 and CH_4 and ground-based measurements?
Answer 32 Currently the space-based measurements for CO_2 are within about 0.25% of the ground-based measurements, when averaged over the globe. For CH_4, this number is about 0.5%.

Question 33: How are the measurements of CO_2 and CH_4 validated?
Answer 33: This is very important. Ground-based measurements have been taken for over 60 years. Precise space-based measurements have only been available for about 12 years. The space-based measurements are validated against the ground based measurements using data from the Total Carbon Column Observing Network (TCCON) stations, which are used as a transfer standard. We take simultaneous space-based measurements and ground-based measurements over the TCCON stations frequently. thousands of space-based measurements can be collected in a single pass to compare with the more precise TCCON measurements. To validate the TCCON stations against the ground-based in situ measurements, we periodically take vertical profiles of in situ measurements using in situ sensors deployed on high altitude aircraft or balloons, using the same measurement technique as ground-based measurements. This is how we are able to calculate the errors cited in the previous question.

Question 34: Can you please provide an explanation of IPCC reporting on anthropogenic emissions vs all emissions (including all sources and sinks, inc natural)?
Answer 34: The IPCC guidelines for national inventories require bottom-up estimates of emissions and removals of certain greenhouse gases (i.e., CO_2, CH_4, nitrous oxide, fluorinated gases) in specific sectors of human activities, including Energy, Industrial Production and Product Use (IPPU), Agriculture, Forestry and Other Land Use (AFOLU) and Waste. Each sector is subdivided into categories (e.g., ground transportation, electricity generation) and emissions are reported in each, typically by multiplying a measure of “activity” in that category (i.e. the number of tonnes of coal burned or number of kiloJoules of electricity generated) by an “emission factor”, which specifies the number of tonnes of each greenhouse gas emitted per activity unit. See the following report for a more complete description:

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

These reports summarize the largest direct emissions and removals associated with human activities, but only include emissions and removals from managed lands. The IPCC guidelines do not require reports of emissions and removals of greenhouse gases from natural processes on unmanaged lands or from the ocean. The basic assumption is that these emissions and removals will balance out over time. This assumption may no longer be correct as these systems continue to respond to human activities and climate change.

Question 35: How do we calculate the amount of CO_2 emitted to the atmosphere?
Answer 35: The best way to estimate the net amount of CO_2 emitted to the atmosphere is to monitor changes in the atmospheric concentrations over time. For example, measurements of atmospheric CO_2 acquired during one month are compared to measurements acquired in subsequent months and calculate the difference. Both space-based and ground-based measurements of atmospheric CO_2 indicate that global average CO_2 is increasing at a rate of 1-3 ppm per year..

Question 36: How can we calculate the agriculture sector emissions? May we have some papers to read?
Answer 36: Both bottom-up and top-down methods can be used to track agriculture sector emissions. For example, bottom-up methods from ground-based and space based data provide the most reliable information about the number of hectares planted and harvested. Ground-based bottom-up methods provide the most reliable information about the mass of crops (tonnes) harvested. Measurements of changes in soil carbon are very difficult to accurately estimate directly, but can be estimated from the ratio of the top-down atmospheric CO_2 budget with the activity data. Top-down atmospheric budgets can also be used to assess the impact of severe weather on agricultural carbon emissions. See for example:
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019AV000140

Question 37: Will there be a practical session of this course? Maybe we could apply a programming language to obtain some of the plots displayed. I think this would help us to retain the knowledge better.
Answer 37: Yes, we will demonstrate data access and show how we use the top-down budgets to assess year-to-year changes in CO_2 emissions in Part 3 of this series.

Question 38: Can top-down inversions produce sector-based emission estimates over a region with mixed sources?

Answer 38: Sometimes, but not always. The primary advantage of bottom-up inventories is that the sources of emissions and removals reported there can be identified and managed. The primary limitation of these bottom-up methods is that they sometimes miss critical sources and sinks. Top-down atmospheric budgets can produce sector-specific estimates when the plumes from individual sources can be directly imaged and their fluxes quantified. In other cases, we can combine the top-down budgets with other data from bottom-up inventories or atmospheric measurements to attribute emissions to a particular sector. For example, if the fossil fuel emissions are well understood in a region, these emissions can be subtracted from the total net carbon exchange estimates derived from top-down atmospheric methods to provide information about the Agriculture, Forestry and Other Land Use (AFOLU) sector. This approach is illustrated in Parts 2 and 3 of this webinar series. Top-down budgets for CO_2 can also be combined with measurements of atmospheric "proxies" such as carbon monoxide (CO) and nitrogen dioxide (NO_2) to distinguish sources. For example, sources such as wildfires or biomass burning typically emit more CO, whale high-temperature fossil fuel combustion generates more NO_2. Finally, measurements of the relative abundances of isotopes, such as Carbon-14 (^{14}C) in the CO2 can be used to assess relative contributions of fossil fuel combustion (which has almost no ^{14}C) and AFOLU emissions.

Question 39: Thanks for the wonderful training. Is fossil fuel combustion also the main source of CH_4 emissions? For CO_2, 60% of emissions come from fossil fuel combustion, is that correct? How much would that be for CH_4?

Answer 39: The extraction and transport of methane for use as a fossil fuel is a major source of CH_4 emissions, but the combustion is not a significant source of CH_4 emissions. In general, fossil fuel combustion accounts for almost 85% of all CO_2 emissions.

Question 40: How is soil respiration factored inverse modeling for CO_2 fluxes? Are priors focused on process-based models and bottom up measurements?

Answer 40: Soil respiration is one of the most difficult sources to quantify from bottom or top down methods. A recent review of bottom-up methods is given here:

https://www.sciencedirect.com/science/article/abs/pii/S0341816220301247
And
https://www.sciencedirect.com/science/article/pii/S0301479717305613

Generally, these studies use empirical relationships, derived from a limited number of field measurements, to estimate soil carbon respiration associated with carbon losses from the decomposition of litter detritus and soil organic matter by microorganisms. Space-based measurements of soil temperature and land use are playing an increasing role in these estimates.

Top-down atmospheric methods provide complementary information. These measurements constraint the total net carbon emissions from a biome. If the above-ground biomass stock changes and or gross primary production can be constrained by other measurements, these data can be combined to estimate the soil carbon change as a residual. One approach for doing this is suggested in Part 3 of this webinar series.

Question 41: I have a question about retrieval algorithms used to extract GOSAT XCO2 and XCH4 concentrations. Which is the best one?
Answer 41: Several teams have developed algorithms for estimating XCO_2 from GOSAT, GOSAT-2, OCO-2 and OCO-3. Other teams have developed algorithms for estimating XCH_4 from GOSAT and Sentinel 5 precursors for XCH_4. The algorithms for XCO_2 are performing slightly better than those for XCH_4, largely because more effort has been put into the XCO_2 algorithms. As noted in earlier questions, several groups are now estimating XCO2 with accuracies of 0.25%, while the best results for XCH_4 are typically around 0.5%, when compared to measurements from the Total Carbon Column Observing Network (TCCON) and other standards. Different algorithms perform better in different conditions, so it is difficult to identify a “best” one. As new groups update algorithms, these get better.

Question 42: Do TROPOMI and GOSAT have the same remote sensing retrieval algorithm?
Answer 42: Several teams have developed retrieval algorithms to analyze both the TROPOMI and GOSAT data to estimate XCH_4. Examples include the teams from the University of Leicester, the University of Bremen, and the Netherlands Space Agency, SRON.

Question 43: Can you speak to how these CO_2 measures may be used in tandem with other satellite products for terrestrial CO_2 (i.e., net primary production). Can we simply subtract terrestrial CO_2 from total CO_2 (i.e., OCO-2 minus MOD17A)?

Answer 43: A variety of methods are being developed and combined with estimates of atmospheric CO_2 to study the terrestrial biospheric emissions and removals of CO_2. For example, XCO2 data are being combined with estimates of gross primary production (GPP) derived from observations of solar induced chlorophyll fluorescence (SIF), or vegetation indices, such as NIRv. These data are providing new insights into biospheric health and productivity. For example, top-down estimates of the net carbon gain or loss by the biome (see Part 2 of this webinar series) can be combined with GPP estimates to estimate the total biome autotrophic and heterotrophic respiration.

Question 44: I tried to work with Sentinel 5p products for CO_2 monitoring using Python. Now if I want to combine in situ data within my process 1) where I can find the data and 2) how do you combine the data practically to derive a stable and solid temporal measurements?
Answer 44: The TROPOMI instrument on Sentinel 5p provides the data needed to estimate XCH_4, but does not provide any information about CO_2. The best source of in situ CO_2 data is the Observation Package (ObsPack) Data Products, which can be downloaded here:

https://gml.noaa.gov/ccgg/obspack/

Question 45: Could we determine the loss of forest by analyzing changes in the fluxes?
Answer 45: The best way to monitor forest loss is to monitor above-ground biomass and imaging observations of land use change. Top-down CO_2 budgets can be combined with these biomass and land use observations to produce regionally-specific estimates of the CO_2 or CH_4 emission factors associated with observed gains and losses of forested area.