Questions & Answers Part 2

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 Brendan Byrne (brendan.k.byrne@jpl.nasa.gov), Daniel Cusworth (dancusworth@gmail.com), David Crisp (dcrispjpl@gmail.com), or Sean McCartney (sean.mccartney@nasa.gov).

Question 1: (Referring to Slide 11): What are the estimated uncertainties on the flux values listed? How are these uncertainties estimated?
Answer 1: Fossil fuel emissions are estimated using bottom-up methods and, when integrated over the globe, have uncertainties on annual fluxes of about 10% [38.0 +/- 3.1 PgCO2; see https://doi.org/10.5194/essd-14-1917-2022]. The one-way fluxes between the biosphere and atmosphere are estimated using a few different methods, such as models, remote sensing and scaling-up site measurements. Uncertainties can be large, similar to magnitude of estimate [see https://doi.org/10.1002/2015RG000483]. For example, for land use and land use change, the global emissions for 2020 were 4.1 +/- 2.6 PgCO2, a 60% uncertainty. For the ocean, fluxes are estimated from models of ocean chemistry and circulation constrained by measurements of differences between the ocean and atmosphere CO_2 partial pressure, called pCO_2. As seawater absorbs CO_2, it produces carbonic acid. The ocean pCO_2 measurements are derived from measurements of the acidity of seawater. This approach yields global uncertainties of about 13% [for 2011-2020, the flux was 11 +/- 1.5 PgCO2, see https://essd.copernicus.org/preprints/essd-2021-386/essd-2021-386.pdf].

Question 2: (Referring to Slide 21): What kinds of observation stations are shown as a swath of "pixels" in the Pacific ocean?
Answer 2: The measurements over the Pacific Ocean are collected by ships participating in dedicated measurement campaigns and from ships of opportunity on their regular routes between Asia, Australia, and North America. Other measurements are acquired by CO2 instruments carried by commercial aircraft by programs such as Japan's CONTRAIL.

Question 3: What are some causes of the possible biases from the information that LNLGOGIS provides, and are there currently works of reducing them to have more accurate information?

Answer 3: Biases in the XCO2 retrievals can have a number of sources, including factors like spectroscopic errors and aerosols in the atmosphere. Because the CO_2 fluxes over the ocean are small, regional-scale errors as small as 0.1% in XCO2 can produce large flux errors. There is an intense effort to reduce these biases and major progress has been made since OCO-2's launch. The sparsity of in situ CO_2 measurements over the ocean have limited the rate of progress in these efforts. We expect that technical improvements will continue and the impact of biases will continue to decrease.

Question 4: When you aggregate the 1x1 degree net carbon exchange grid squares by country, are you taking a simple sum of all the grids that fall within each country? Or is there a more complex aggregation method to arrive at the country totals?

Answer 4: Yes, we multiply the flux by the area for each grid cell and sum across the grid cells. An important point is that we do this for each ensemble member first and then calculate the median and standard deviation. This is because there can be correlations between individual grid cells for each inversion, so performing the aggregation before calculating the statistics is a better method.

Question 5: In some places, the net carbon exchange calculated median and uncertainty are in equal range, any reason for it (as, we may need to expect that the uncertainty to be less)?

Answer 5: The uncertainties can be comparable to the net flux, especially when the net carbon exchange is relatively small. This is particularly true for small countries where it is hard to distinguish one country from another. These are pilot national flux budgets. First generation effort and will not be the last. Spatial and temporal resolutions and coverage will improve.

Question 6: No emissions from Russia with results per country?

Answer 6: There appears to be a large natural sink in the northern extratropics. This is seen across Russia and Canada, where sequestration by the biosphere roughly equals the magnitude of anthropogenic emissions. This uptake is not thought to be related to anything that these countries are doing policy wise. Both Canada and Russia have relatively large per capita emissions. Instead, this uptake is likely due to increased CO2 uptake by the plants (boreal forests) associated with a combination of CO2 fertilization and warming in these regions that is causing the biosphere to be more active. Large sequestration.

Question 7: Why are the flux estimates more uncertain in smaller countries?
Answer 7: This is due to a combination of gaps in the observational coverage. For example, we have many more measurements over Russia than we do over Cambodia. The other factor is that it is easy to capture large fluxes because they change in measured CO2 by a larger amount. So fluxes over a large country can build up the impact on atmospheric CO2 and it is easier to distinguish which country the emissions came from.

Question 8: The Negative (i.e., land carbon gain) across northern high latitudes. Does this gain account for wildfires?
Answer 8: Yes, that is right. We include net ecosystem exchange and wildfires in net biosphere exchange.

Question 9: Are ocean glint data from OCO-2 particularly suspect, or are ocean glint data generally of questionable quality across lots of different CO2/CH4 satellites? Would love to hear more about what makes ocean glint data useful/high quality or not.
Answer 9: The ocean glint measurements actually have higher precision than the land measurements. Their accuracy is difficult to assess because there are very few in situ measurements to validate their accuracy. Existing data suggest that their accuracy is similar to that of the land measurements, around 1 ppm on regional scales. The problem is that the fluxes over the ocean are much weaker than those over land. Because of this, much higher accuracy is needed over the ocean to quantify these fluxes.

Question 10: Does the LNLGOGIS inverse modeling experiment include emissions from the maritime transport sector (i.e., vessels)?
Answer 10: We prescribe these fossil fuel emissions in our simulation, however, our inversions are not set-up to improve upon these estimates. The inversions best capture large-scales, such as country total emissions.

Question 11: The NCE results are counterintuitive, as the tropical countries with forest are the ones with highest carbon stock loss. Am I understanding right?
Answer 11: Yes, you are understanding this correctly. Tropical countries have both the largest carbon stocks and the largest carbon stock losses. One reason why this may be counterintuitive is that the carbon stock loss estimates include land use change. In the tropics, there is quite a lot of deforestation, which would be included in the stock loss estimate. Finally, this 2015-2020 period included one of the largest El Ninos on

record, which is associated with increased carbon loss in the tropics, so the tropical carbon loss might not be so large outside of this period.

Question 12: Are OCO-2 estimates of NCE will be provided for 2020-2025?
Answer 12: Yes! We hope to continue providing regular updates (hopefully annually). So as long as OCO-2 keeps measuring we will continue producing. There are also a number of new space-based CO2 missions that are planned that can also be folded into this analysis.

Question 13: Slide 40 CH4 emissions plot shows hardly any emissions from China. What is the reason for this? In fact hardly any data is observed for China.
Answer 13: Slide 40 shows models of strictly wetland emissions (excluding rice paddies), so not representative of emissions from all sectors.

Question 14: Could we say that CO2 space-based measurements (with medium spectral resolution/large swath) are adapted for long-term CO2 monitoring, and CH4 space-based measurements (with High spectral resolution/narrow swath) are adapted for short-term monitoring and alarm detection?
Answer 14: I think you could say that under certain observing conditions, space-based measurements can do both for CO2 and CH4. Global mapping satellites whose measurements are very precise can be used for long-term monitoring and global budgets. Point source imagers are more adapted for alarm detection, assuming they meet satisfactory spatial and temporal coverage. However, we also need high precision, medium

Question 15: How do we solve the problem of resolution to sensitivity for methane emitters that are not essentially ultra-emitters but not very small either, say for instance coal mines or landfills and manufacturing industries?
Answer 15: On slide 48, we show a list of current satellite missions and planned missions. These satellites cover a range of spatial coverage, temporal coverage, and emission sensitivity. Many of the “Point source imagers” that are slated to launch in the coming decade will address exactly this - large single point source emissions that are large but aren’t “ultra-emitters.” Each of these satellites will have differing spatial coverage and revisit time, so it is important to understand these details when assessing their efficacy in observing a large set of potential sources.

Question 16: In inverse modeling is CO_2 a passive tracer? Can you say something more about how chemistry is included for CH_4?
Answer 16: Yes, CO_2 is being treated as a passive tracer. The lifetime of CH_4 in the atmosphere is much shorter than CO_2, but still long-lived (~10 years) for a chemical transport model. Some transport models, especially regional scale models therefore consider CH_4 a passive tracer. Other chemical transport models include the reaction with OH.

Question 17: So when considering the strong impacts of CH_4 on Greenhouse gases, what are the proper management approaches to dealing with those leakages... What do you think of integrated monitoring from satellites and prompt management systems?
Answer 17: Yes! On slide 50 we start to poke at this. A satellite observing system gets you part of the way there. But these systems need to be integrated into management or actionable systems to prompt action.

Question 18: How do we map out concentrations with satellite observations from say satellites which do not give column averages? I tried to map it out by simulating CH_4 concentrations in ppm using RTMs but the results were all over the place.
Answer 18: Currently, there are two types of satellite measurement of CH_4 (or CO_2). Measurements from satellite sensors that observe reflected short-wave-infrared (SWIR) sunlight can be analyzed to yield estimates of the total column CH_4. They essentially provide a surface-weighted average of the column density (molecules per cubic meter) of CH_4 molecules along the optical path traversed by the sunlight as it travels the top of the atmosphere to the surface, and back up to the satellite. In the language of remote sensing, these measurements have a Jacobian or "weighting function" that is quite broad (~10 km) and peaked at the surface, so that they provide little if any vertical resolution. We ratio these CH_4 measurements to simultaneous, bore-sighted measurements of molecular oxygen, which is used to estimate the dry air along that same path to yield estimates of the CH_4 dry air mole fraction, XCH_4. These are the measurements that we are using in the global flux inversion experiments.

The second type of estimate can be retrieved from measurements of thermal emission from the atmosphere and surface at longer infrared wavelengths. These measurements provide information about the CH_4 (or CO_2) in the middle troposphere (5-10 km), but very little information about the CH_4 (or CO_2) near the surface. They are therefore less useful for estimating emissions from surface sources. They also need very accurate estimates of the tropospheric temperature profile (errors no larger than 0.2 C) to yield accurate results. In principle, thermal IR estimates of the upper tropospheric CH_4 can be subtracted from the SWIR total column estimates of XCH_4 to estimate the lower tropospheric CH_4, but this is especially challenging because biases in either the thermal or SWIR estimates can compromise the result. Our Japanese colleagues on the GOSAT team have demonstrated this approach for CO_2 measurements, but have not yet applied this to CH_4, to the best of our knowledge. One could also imagine an active LIDAR system with range gates to provide some vertical resolution, but this has not yet been demonstrated.

In general, even with very accurate measurements, very accurate RTMs and very carefully designed remote sensing retrieval algorithms are needed to yield useful, quantitative estimates from either solar or thermal measurements, because we are looking for very small changes in XCH_4 (< 1%). A 1% difference in the column averaged CH_4 typically produces a 0.1% change in radiance for instruments with spectral resolving powers of 20000. Only a half dozen teams from the US, Europe, Japan and China have successfully demonstrated these capabilities so far, but the number of teams is growing rapidly as the space-based measurements have become available.

Question 19: Regarding the last study presented, since enteric fermentation represents a larger share of livestock emission than manure, why in the last study only manure was included? Is there a recognized method to inventory enteric emission?
Answer 19: Great question - and this gets back to what constitutes a “diffuse source” vs. a “point source”. For the study in Slide 51, the comparison between the middle and right panels were for sectors that emit like “point sources.” Wet manure management emissions are detectable by fine resolution imaging spectrometers because their emissions are point-source like - i.e., emissions are concentrated from manure ponds or digesters. Enteric fermentation, though likely a larger source in some regions, is more diffuse and not as easily detectable by a low precision instrument.

Question 20: How can we estimate the accuracy or uncertainty of atmospheric inversion models for top-down budgets?
Answer 20: This is an area of active research. The Bayesian formulation of the inverse problem lends itself to derive an explicit error budget. However, often this is too computationally expensive to calculate explicitly. In these cases, errors can be estimated by performing an ensemble of inverse simulations.

Question 21: What is the difference between CH4 plume emission estimation algorithms? What is the most used algorithm?
Answer 21: The most used algorithms are the Integrated Methane Enhancement (IME) and Cross-Sectional Flux (CSF) algorithms. IME quantifies the amount of excess mass created by a plume of gas, and then multiplies this quantity by a "plume lifetime" (wind speed divided by length of plume) to estimate an emission rate. The CSF algorithm integrates excess methane across the plume's main lateral axis.

Question 22: Is there any cloud computing platform like Google Earth Engine specified for climate change application?
Answer 22: We are not aware of any cloud computing platform for modeling climate change modeling and prediction because this usually requires large supercomputers and large dedicated teams of scientists to operate. Results from these efforts are compiled by the Intergovernmental Panel on Climate Change (IPCC) in large reports, like those here: https://www.ipcc.ch/assessment-report/ar6/. Cloud computing platforms such as Google Earth Engine can be used for tracking observed changes in the climate.

Question 23: Related to being on the cusp (and in 1st gen mode) with detection tech for mapping methane emissions, what new satellites are on the horizon beyond MethaneSat? How does this compare/complement with alternative tech innovation (e.g., handheld optical gas imaging cameras, remote sensing measurements taken from planes) into the future?
Answer 23: There are a series of space-based sensor platforms under development. The most recent summary was compiled by the World Geospatial Industry Council here:
https://wgicouncil.org/publication/reports/industry-reports/ghg-monitoring-from-space-report-satellites-public-private-hybrid-geo-climate-trace-wgic/ . A few examples of future missions are summarized here. Both MethaneSat and Carbon Mapper will be launched in late 2023. The Environmental Defence Fund (EDF) MethaneSat will gather high precision (~1%) data at 1 km by 1 km resolution over 200 km by 200 km regions of the globe. Carbon Mapper will collect measurements with somewhat lower precision, but at much higher spatial resolution (30m by 30 m) to pinpoint CH4 plumes. These dedicated methane satellites will be complemented by data from a wide range of public sector and private sector hyperspectral imaging satellites deployed over the next decade that provide low precision, but high spatial resolution observations that can detect large methane leaks.

While private sector satellites including MethaneSat and Carbon Mapper are focused on the detection of methane super-emitters, large public sector missions will continue to focus on global measurements of weak, spatially-extensive sources associated with wetlands and agriculture, which are the largest sources of emissions globally. The European Copernicus Sentinel 5 Precursor TROPOMI instrument will be followed by the Sentinel 5 series with similar global mapping capabilities in 2024 (7 km x 7 km, global daily maps). Japan's GOSAT-GW satellite will also launch in early 2024, and will measure CH_4 in two modes - a global mode at 10 km x 10 km resolution, and at point source mode with a resolution of 1 km x 3 km. Starting in 2025, the European Copernicus program will start deploying the CO2M constellation, which will deploy 2 or 3 satellites carrying sensors that will provide high precision, global coverage of XCO_2, XCH_4, and NO_2 a 2 km by 2 km resolution at weekly intervals.

These space-based capabilities will complement the more precise ground-based and airborne methane monitoring capabilities with much better spatial resolution and coverage of the globe. Alternative technologies, such as handheld greenhouse gas imaging cameras will be useful for pinpointing large leaks.

Question 24: In part 3 of this training will we see the demonstration of the estimation of emissions, sinks and the provision of specific information on resources used (e.g transport and inverse models)?

Answer 24: Part 3 will focus on the use of both the national-scale and local source estimates of CO_2 and CH_4 emissions and removals to support bottom-up inventory development and to assess collective progress toward the goals of Paris agreement. We will not have time to go into the details of the technical approach, such as the transport models or inverse methods in this webinar series. Those topics might require a series of graduate level courses to cover adequately. They are addressed in our publications. For example, see the following papers as a starting point:

Peiro et al. 2022: https://doi.org/10.5194/acp-22-1097-2022
Worden et al. 2022: https://doi.org/10.5194/acp-2021-955
Lauvaux et al. 2021: https://www.science.org/doi/10.1126/science.abj4351
Cusworth et al. 2021: https://doi.org/10.1021/acs.estlett.1c00173

Question 25: Can you give a short description about land use emission (LUE)?
Answer 25: Land use emissions refer to emissions (or removals) of CO_2 resulting from the way a parcel of land is being "used". An example of emissions would be from a change in land use, such as deforestation or reforestation. This can also include things like forest degradation from activities such as logging.

Question 26: Is there a difference in the rate of carbon uptake for vegetation types Trees and bushes herbs?
Answer 26: There are differences in carbon uptake between different ecosystems. These differences are primarily driven by how climate change is impacting these ecosystems, rather than the specific species that make up these ecosystems. For example, warming in the arctic is contributing to additional carbon uptake because photosynthesis is temperature limited in these ecosystems, but warming is not increasing the carbon uptake in the tropics because these ecosystems are not temperature limited. Similarly, in arid regions increasing CO_2 can increase water use efficiency, which can increase productivity in areas where growth is limited from water availability. Overall, it appears that the largest increases in terrestrial carbon stocks are occurring (increasing) in boreal forests. It is hard to generalize for vegetation types or plant species but changes in CO_2 and climate will definitely impact different species differently, and impose evolutionary pressure.

Question 27: Can the monitoring sites of carbon concentration located in the high areas give realistic values describing the concentration in that area? Note that the density of air and its components decreases with altitude.
Answer 27: Interpreting measurements of atmospheric CO_2 requires information about the altitude where the data were acquired as well as the concentration measurement. Atmospheric transport models can assimilate data acquired over a range of altitudes (i.e. different topographic elevations as well as airborne and space-based total-column), and relate observed CO_2 to the underlying fluxes. In general, in situ measurements made close to the Earth's surface will be most sensitive to nearby emissions and removals, while measurements collected at high altitude (aircraft) will be sensitive to emissions and removals at large scales because air undergoes a lot of mixing as it is transported from the surface to those altitudes.

Question 28: Are the 1x1 gridded NCE inverse modeling results available for download by the public?
Answer 28: Not yet. We are still refining this dataset but will release it when an accompanying manuscript is submitted for review. This should become available in June.

Question 29: What is Tg for the Gas unit?
Answer 29: A Teragram (Tg) is a unit of mass equal to 10^{12} grams or million tonnes. A TgCO2 therefore represents 10^{12} grams of CO2. Gases are also often measured as a mixing ratio (in units such as parts-per-million, ppm), which is the ratio of moles of the gas to moles of dry air. Therefore, to convert from mass to mixing ratio the amount of dry air needs to be specified. To relate a mass of CO_2 to a ppm difference across the entire atmosphere you can roughly use the relationship 1 ppm of CO_2 = 7800 $TgCO_2$.

Question 30: Which is the most effective plume emission algorithm you would suggest?
Answer 30: Both Integrated Methane Enhancement (IME) and Cross-Sectional Flux (CSF) approaches have been shown to give good results when compared to ground truths (i.e., controlled releases). However, the accuracy of these methods depends heavily on the quality of local wind speeds. In fact, uncertainty in wind speeds is the dominant driver of uncertainty in plume emission quantification methods. You will need to choose the best available wind speed data.

Question 31: With the growing concerns climate change, in the case of extreme conditions like rainfall that tend to reduce CO_2, in areas with increased development and impervious surfaces that may lead to increased flooding, are there any observations that are being done on the amount of CO_2 sink that is picked up by the biosphere compared to the amount that through flooding may end up in wetlands as CH4?
Answer 31: CO_2 does dissolve in rain, and rain is typically slightly acidic. Some scientists have tried to quantify the CO_2 sink associated with rainfall. They have found that when averaged over the globe, this is a relatively small sink compared to the biosphere - typically much smaller than 1%. However, heavy flooding can affect the amount of CO2 that is taken up by the biosphere. For example, airborne and space-based CO2 data collected during the intense flooding of the US midwest during 2019 delayed the planting of crops and reduced the CO_2 uptake by those crops by 0.37 $PgCO_2$ (0.1 PgC). For more on this, see
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019AV000140

Question 32: What is the significance of these different satellites, how is it different from each other? Won't it be a waste after some time in space?
Answer 32: For CH4, I'd like to point you in the direction of the following paper (in review) that discusses various current and future satellites (Jacob et al., https://acp.copernicus.org/preprints/acp-2022-246/acp-2022-246.pdf). Here they introduce a concept called "observing system completeness." Think of this as how much of the CH_4 that is emitted to the atmosphere can be measured by individual satellites and by constellations of satellites. Every satellite has different spatial coverage (i.e., how much of the earth it can cover in a day), temporal coverage (how often can revisit a target), and its detection limit to certain classes of emissions (low, medium, high). These all have to be considered when evaluating each instrument's individual capability for observing the global CH4 budget. The short answer is that even with all the exciting missions set to come online in the near future, we are still very likely to remain in a regime where we do not have "extra" measurements.

CO2 satellites are covering <1% over the surface in a month. Over the next decade, a series of satellite sensors will be deployed to dramatically improve this coverage and spatial resolution and measurement frequency. In addition to improved resolution and coverage, we need space-based sensors with improved precision and accuracy to produce estimates of CO_2 over the oceans that can provide accurate estimates of fluxes. None of the systems currently under development are focusing on this area. In short, while we have proven that top-down atmospheric budgets can be useful for quantifying CO_2 and CH_4 emissions and removals, we are a long way from having a system with the capabilities needed to fully address the needs of global stocktakes specified in the Paris Agreement.

Question 33: Do you know which satellite instrument could be the most efficient to measure atmospheric CO2 and CH4 over the tropical forests?
Answer 33: The best way to measure the tropics is still a bit of an open question. One planned satellite, GeoCarb, will be in geostationary orbit above the Americas (meaning that it will sit above the same location on Earth). Tentative Launch date, 2024.
In the tropics there are not many ground based measurements. Space based measurements offer greater coverage than ground based. Clouds still remain an issue in the tropics, so more airborne and ground measurements will be needed. High latitudes are also

Question 34: How accurate can one discriminate among different CH4 sources using top-down techniques? For example, emissions coming from oil & gas facilities vs. emissions coming from livestock in very close locations.
Answer 34: Great question - and this is often difficult to do. For top-down inversion techniques that constrain fluxes on spatial scales of several latitude/longitude degrees, we usually have to rely on prior inventories to partition total fluxes we estimate to individual emission sectors. Isotopic information can also be used where available. In contrast, for high spatial resolution imaging of plumes, it is much easier to do source attribution with georegistered visible imagery (e.g., Google Earth).

Question 35: Are there limitations on the geographies (i.e., latitudes) that can be monitored with TROPOMI?
Answer 35: TROPOMI collects measurements covering the entire sunlit hemisphere. In the spring and fall, these measurements extend almost from pole to pole. However, observations collected at high latitudes (greater than 60 degrees) or in topographically-rough, mountainous terrain are difficult to analyze, regardless of satellite. High latitude observations are precluded during the winter because there is too little sunlight or because the surface is obscured by clouds.

The Copernicus CO2m constellation, which will be launched in 2025/26 will have better spatial resolution and greater sensitivity than TROPOMI and should increase the latitude range of useful measurements. Its smaller measurement footprint (2 km by 2 km for CO2M vs 7 km by 7 km for TROPOMI) is expected to yield more cloud-free pixels in partially cloudy regions and more useful soundings in regions with rough topography. CO2M also includes dedicated cloud and aerosol instruments that should reduce errors associated with uncertainties in the amount of cloud and aerosol. We hope this will extend measurements in the high latitudes, with greater accuracy.

Question 36: Hi Dan, as you mentioned that many places don't have good coverage by satellites such as TROPOMI (almost all polar-orbiting sun-synchronized LEO satellites). With the launch of more advanced satellites, how will observations from multiple satellites be coordinated in the future to make methane observations more useful/ Increase the synergy between satellites?
Answer 36: A number of mechanisms are being used to coordinate observations among different satellite systems. International organizations including the Committee on Earth Observation Satellites (CEOS) and the Coordination Group on Meteorological Satellites (CGMS) are working with space agencies to coordinate the operational

strategies of future satellites to maximize the synergy among their measurements and minimize measurement gaps. Other international organizations, such as the UN Environmental Program (UNEP) International Methane Emissions Observatory (IMEO) and the World Meteorological Organization (WMO) Integrated Global Greenhouse Gas Information System (IG3IS) are coordinating these space-based data with bottom-up inventories from the fossil fuel industry and ground-based and airborne measurement communities, respectively.

To combine observations from multiple satellites, their measurements must be cross-calibrated and their retrieved data products must be cross-validated against international reference standards so that they can be combined in atmospheric inverse models to estimate fluxes. The first generation of greenhouse gas measurement satellites, GOSAT, GOSAT-2, OCO-2, OCO-3 and S5p TROPOMI have been pioneering methods in both areas. For example, all five of these systems are cross calibrated in annual vicarious calibration campaigns over a dry lakebed in Nevada, USA, called Railroad Valley. All five sensors are also being cross validated against the ground-base Total Carbon Column Observing Network, which now include about two dozen stations between Lauder, New Zealand and Eureka, Canada. These cross-calibration and cross validation efforts are being supported by international organizations such as CEOS and CGMS. As more advanced CO2 and CH4 satellites are added to the constellation, these coordinated ground-based calibration and validation efforts will be extended to them as well.

Finally, in a bilateral context, individual mission teams, such as the TROPOMI and GHGSat teams have pioneered “tip and cue” methods, as described in the presentation, where TROPOMI identifies a region with anomalous emissions and then GHGSat data are used to zoom in to pinpoint the source. This approach will be expanded to more fully exploit future satellites such as MethaneSat, CO2M and Carbon Mapper.

Question 37: Are there any publicly available products that combine retrievals from several satellites? Either in the form of coarser time averages or coarser spatial averages to improve confidence in the retrieval or combining to result in a finer spatial or temporal resolution (but without improving margin of error)? If not, is that something that is in the works or being done by private parties?
Answer 37: At this point, most of these efforts have been conducted as science experiments rather than operational activities. Their products can be obtained directly from the science teams. For example, see:

Varon et al., 2019
(https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019GL083798)
Maasakkers et al., 2021 (https://doi.org/10.31223/X5N33G)
Cusworth et al., 2021 (https://doi.org/10.1021/acs.estlett.1c00173)