Questions & Answers Part 1

Please type your questions in the Question Box. We will try our best to answer all your questions. If we don't, feel free to email Erika Podest (erika.podest@jpl.nasa.gov) or Vivienne Payne (vivienne.h.payne@jpl.nasa.gov).

Question 1: How do OCO-2 results compare with TANSAT Satellite Data?
Answer 1: There have been comparisons done between them. The signal-to-noise for OCO-2 is somewhat higher than for Tansat, and so OCO-2 offers better precision. In general, their results have been in good agreement. Below are some references discussing comparisons between these two measurements:

Wang et al., 2020: Carbon dioxide retrievals from Tansat and validation with TCCON measurements, Remote Sensing, *12*, 2204; doi:10.3390/rs12142204

Yang et al., 2020; Toward High Precision XCO2 Retrievals From TanSat Observations: Retrieval Improvement and Validation Against TCCON Measurements, https://doi.org/10.1029/2020JD032794

Yang, D. X., Y. Liu, Z. N. Cai, X. Chen, L. Yao, and D. R. Lu, 2018: First global carbon dioxide maps produced from TanSat measurements. *Adv. Atmos. Sci.*, 35(6), 621–623, https://doi.org/10.1007/s00376-018-7312-6.

Question 2: Please clarify the point on slide 16 about how to convert the measured XCO2 column average volume in the atmosphere to pixel DN value. (The DN value is something you can scale based on how you want to project the XCO2 values)
Answer 2: The XCO2 values in the OCO-2 and OCO-3 files are not compressed and scaled to a digital number. The values are the actual units, which are parts per million (ppm). Hence, there is no scaling or conversion factor that needs to be applied to the values and you can use them directly as you read them off the file.

Question 3: What is meant by the averaging kernel (slide # 25)? Is this the band of measurement wavelength?
Answer 3: The averaging kernel is a number as a function of altitude. It is the sensitivity of the remote sensing measurement to the true atmosphere at any given altitude. It tells

us where in altitude the CO2 measurement is most sensitive. For example, on slide 25, there are two example averaging kernels. There is one for an OCO type measurement where you can see that the function is relatively constant with altitude and it drops off at higher altitude. That means that the OCO-2 and OCO-3 measurements are sensitive to variations in CO2 throughout that altitude range. If there was a measurement that was equally sensitive to CO2 at all altitude ranges then that averaging kernel would be 1 all the way from the surface to the top of the atmosphere. In the other extreme, if there was a measurement that was only sensitive to say CO2 at 900 hectopascals then that averaging kernel would be a delta function with a peak at 900 hectopascals.

In reality with remote sensing measurements we always have something in between. The OCO averaging kernels are not equal to 1 everywhere from the surface to the top of the atmosphere but are somewhere approximate to that. On slide 25 there is also an averaging kernel for AIRS, which is a thermal infrared measurement. These measurements have sensitivity that peaks in the mid-troposphere. You can see that the averaging kernel drops off as you near the surface, which means that those measurements are not really sensitive to variations in CO2 near the surface. In that case you are seeing CO2 in the region where the averaging kernel has the higher values.

For in-depth explanation of averaging kernels, see Rodgers, 2000, Inverse Methods for Atmospheric Sounding. Theory and Practice, World Scientific, https://doi.org/10.1142/3171

Question 4: Why are the high Solar Zenith Angle (SZA) measurements excluded from the OCO data sets?
Answer 4: We don’t have good confidence in the SZA measurements as there could be strong biases that cannot be corrected for.

Question 5: How are column averages of CO2 attributed to specific surface conditions (e.g., crops, fires, etc) when the column averages don't really correspond to point measurements on the surface? Also, how are the effects of atmospheric mixing accounted for in interpreting the results? Thank you!
Answer 5: There is a need to consider atmospheric mixing when interpreting a CO2 column average measurement. The column average measurement contains information about what is happening in the view of the satellite but it is also influenced by mixed air. The column average measurement does not correspond to a point measurement on the surface. Often when interpreting the results it is useful to have a transport model to look at what direction the wind is blowing and where the air is coming from on any

individual day. There is definitely some additional work needed to interpret the measurement.

Question 6: Are there any TCCON sites in South Asia, such as India, Bangladesh etc.?
Answer 6: Currently, no. All of the current TCCON sites were reflected in the presentation.

Question 7: What is meant by sounding?
Answer 7: Sounding refers to a remote measurement of the atmosphere. Atmospheric sounding is a vertical profile of the atmosphere at a given space and time. What is measured is dependent on the instrument.

Question 8: If the presenter could design her own CO2 monitoring satellite/program, what would she do differently than OCO-2 and 3? Improve the spatial resolution, change the orbit/revisit time? Are any new satellites coming up that will improve monitoring?
Answer 8: Ideally, there would be a measurement that would have a small footprint for and a wide swath coverage across the spatial domain. In terms of the orbit and the revisit time, given unlimited resources, it would be great to have a constellation to cover different times of the day.

One of the advantages about the afternoon orbit is that it is a good time to measure Solar Induced Fluorescence (SIF), which is also measured by OCO-2 and 3. It would be great to have measurements at different times of the day. There are new satellites coming up that will improve monitoring. One of the exciting missions in the horizon is CO2M from ESA Copernicus. There will be more than one satellite and they will have wide swath coverage. NASA also has plans to fly the GeoCarb instrument on a geostationary platform (see also Question 15 below).

For designing your own CO2 monitoring satellite, what you would want to specify would depend on what's your target measurement. In the case of OCO-2 and OCO-3 the regional science goals were to try to get to regional sources and sinks, which included anthropogenic and natural components. We have also been able to show with OCO-2 and OCO-3 that it is possible to look at point sources but the narrow swath coverage is not ideal for targeting point sources. The ideal specification and time of day could be different depending on whether you are targeting natural feedbacks of CO2 or anthropogenic point sources of CO2.

Question 9: Can you only compare equivalent observations between OCO-2 and OCO-3? That is, can you only compare nadir observations between the two, or could you compare (for example) a glint measurement on OCO-2 with a nadir measurement from OCO-3?

Answer 9: If you are looking over the ocean, you will want to use glint measurements from both. Over the ocean the nadir observations are not going to provide a great signal to noise. If you want to compare something on land with something on the ocean, there are some differences between the nadir and glint observations. For OCO-2 alone or for OCO-3 alone, it is possible to compare the nadir and glint observations but do so with caution.

Question 10: What is the main (technical?) reason for the difference in land coverage between OCO-2 and OCO-3?

Answer 10: One reason is when OCO-2 does an orbit, we have to do an orbit in either nadir mode or glint mode. In the case of OCO-3, the pointing mirror assembly and the additional capabilities that it provides allows us to switch from nadir to glint mode very quickly so we do not lose whole orbits of data over land when we are making glint observations over part of the orbit. In short it has to do with the ability to switch between nadir and glint observations quickly.

Question 11: I guess OCO-2 also provides CO2 concentrations at multiple (10) levels. How is that computed? Are those directly measured or derived from the column-averaged dry mole fraction of CO2?

Answer 11: In the algorithm to back out the CO2 from the radiance spectral measurements, we retrieve a profile and then calculate the column average from the profile retrieval. I do not recommend using the profile information. I instead recommend using the Lite files because the values reported are bias corrected column average CO2. There are altitude dependent biases in the profiles. The profiles are a stage in the processing but I do not recommend people to use it for science purposes.

Question 12: How accurate/reliable(%) is the method? because satellite data resolution is very low. Can this model estimate CO2 volume for each country? If yes, what is the accuracy/reliability (%)?

Answer 12: Bias corrected XCO2 measurements are accurate to better than 1ppm by volume. The latest validation studies suggested 0.7-0.8 ppm over land and 0.5 ppm over ocean. In terms of calculating country level emissions, there are efforts in that regard. Those efforts are in their infancy but showing promise.

There is a recent ARSET training on Global Stocktake efforts titled ”Atmospheric CO2 and CH4 Budgets to Support the Global Stocktake”, which can be found through the following link:
https://appliedsciences.nasa.gov/join-mission/training/english/arset-atmospheric-co2-and-ch4-budgets-support-global-stocktake

Question 13: In continuation to question #3, how are the averaging kernels determined given that atmospheric conditions vary widely from one place on the earth to another?
Answer 13: The averaging kernels are computed for every scene as part of the retrieval algorithm. For every scene we start with an estimate of the initial state of the atmosphere and the surface and we calculate a Jacobian using the forward model. Using the Jacobians and the retrieval constraint we can then calculate the averaging kernel. The averaging kernels are an output of the optimal estimation retrieval approach that we use in our algorithm. They are calculated for every scene and they are supplied in the product file for those interested in looking at them.

Question 14: Can you suggest a reference on validation over the tropical ocean areas or data assimilation modeling research? I noticed on slide 29 from TCCON Burgos and Izana?
Answer 14: Other TCCON stations that are relevant for tropical ocean areas include the Darwin site in northern Australia. Even though it is on land, it is a coastal site and is relevant for the tropical western Pacific. There is also TCCON data for some years for a site on Reunion Island.

Question 15: Why is there no geostationary satellite for CO2 monitoring?
Answer 15: NASA has plans to launch a geostationary CO2 satellite called GeoCarb within the next few years.

Question 16: Is there a difference in data quality between land nadir data and land glint data, such as a bias?
Answer 16: Not really. In the studies that we have done to look at validation of land nadir and land glint, they are very close and we are applying the same bias correction approach to the land nadir and the land glint. They are therefore not biased relative to each other.

Question 17: Knowing that it is not possible to compare CO_2 measurements at the surface level with those from OCO-2 and OCO-3, is there an algorithm or mathematical adjustment that relates these measurements? That is, for example, to estimate the surface CO_2 values with the OCO-2 and OCO-3 data?
Answer 17: You are able to relate the surface value with the column average by making an assumption about the shape of the profile. If you have a good estimate of the CO_2 profile shape over a given location you can scale that so that the column of that profile gas would match the column measured from the satellite and then infer what the surface would be. It is therefore possible, but there are always assumptions involved and uncertainties associated with those assumptions.