CO2 Data Record Continuity Through Cross Calibration and Expansion

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What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

- Regional sources and sinks of carbon remain a large source of uncertainty in our understanding of the carbon cycle and limit predictive capability.
- Continuity of X_{CO2} data are critical to understanding the drivers of interannual variability in carbon sources and sinks.
- We describe a strategy that is centered on the cross calibration of international remote sensing instrument to achieve this continuity.

Fossil fuel combustion and other human activities have increased the atmospheric carbon dioxide (CO_2) concentration by over 40% since 1800. Over half of that increase has occurred over the past 30 years and the rate has accelerated recently as fossil fuel use has increased in the developing world. Interestingly, as CO_2 emissions have increased, natural “sinks” in the ocean and land biosphere have continued to absorb over half of the CO_2 emitted by human activities. The ground-based CO_2 monitoring network accurately tracks the CO_2 buildup on hemispheric to global scales and shows that the CO_2 uptake by natural sinks varies from year to year. However, this network does not have the resolution or coverage needed to quantify discrete emission sources or identify regional scale sinks or the processes that control their variability.

One way to improve the resolution and coverage of this network is to collect precise measurements of the column-averaged CO_2 dry air mole fraction, X_{CO2}, from satellites. This is a challenging remote sensing measurement, particularly for estimating surface CO_2 fluxes, as these must be inferred from the small perturbations that they produce in the background CO_2 distribution. Even the most intense sources and sinks rarely produce X_{CO2} variations larger than 2% (8 parts per million, ppm, out of the 400 ppm CO_2 background) and most produce variations no larger than 0.25% (1 ppm) on scales of 100 km^2 or more. High precision is therefore essential. Absolute accuracy and a connection to the World Meteorological Organization (WMO) CO_2 scale are also required so that these data can be integrated with ground-based in-situ measurements.

The Japanese Greenhouse gases Observing SATellite (GOSAT) and NASA Orbiting Carbon Observatory-2 (OCO-2) were the first two missions designed specifically to measure X_{CO2} with the precision, accuracy, and coverage needed to quantify CO_2 fluxes on regional scales (1000 km by 1000 km) over the globe. GOSAT has been operating since 2009, returning about 1000 X_{CO2} estimates each day with single sounding precisions near 0.5% (2 ppm). Since September 2014, OCO-2 has been returning hundreds of thousands of X_{CO2} estimates each day with single sounding precisions of 0.5 ppm. To validate the accuracy of the measurements and connect them to the WMO CO_2 scale, the GOSAT and OCO-2 X_{CO2} estimates have used those from the ground based Total Carbon Column Observing Network (TCCON).

Why are these challenges/questions timely to address now especially with respect to readiness?

At the time or writing, GOSAT is almost 2 years beyond its nominal, 5-year lifetime, and OCO-2 is more than half way through its nominal 2-year mission. A much longer, continuous record is needed to understand how CO_2 sources and sinks might evolve in response to climate drivers such as the El Nino Southern Oscillation, Pacific Decadal Oscillation, large-scale droughts and floods, and enhanced growing seasons in the rapidly warming boreal ecosystems. Meanwhile, policy makers are now urgently seeking new methods to monitor the efficacy of carbon reduction strategies. To address these needs, long-term, sustained X_{CO2} observations are highlighted in the pre-Decadal Survey Workshop on the Climate-Carbon System (U. Oklahoma, March 2015).

Continuity of an accurate, dense, global CO_2 data record can be achieved by deploying long-lived sensors, or by careful cross calibration of instruments with shorter lifetimes. In both cases, results from these sensors must be validated against international standards, such as the WMO CO_2 standard, so that they can be combined with in situ surface and aircraft CO_2 measurements and flux tower data. For GOSAT and OCO-2, TCCON is the transfer standard to meet this requirement. Future missions could use a similar approach if TCCON is maintained.

In spite of these needs and capabilities, NASA currently has no firm plans or funding for future CO_2 missions. NASA had planned to install the OCO-2 flight spare instrument on the International Space Station as the OCO-3 mission, but, there was no NASA funding for OCO-3 in FY15, and no budget is in place yet for FY16. If funding is restored, OCO-3 could still fly later this decade, but its 3-year mission would not extend through the time period addressed by this Decadal Survey.

Other space agencies are planning to launch a few CO_2 missions. The Chinese Academy of Sciences (CAS) and Ministry of Science and Technology (MOST) plan to launch the TanSat satellite into the 705 km Afternoon Constellation (A-Train) in July of 2016. During its 3-year nominal mission, TanSat will acquire X_{CO2} measurements at 2 x 2 km resolution along a 20 km wide swath with a precision of 1 to 4 ppm. However, TanSat team members still do not have permission from the Chinese government to share data or to participate in international efforts to cross calibrate measurements or to validate their CO_2 products. There are also significant legal barriers to direct collaboration between NASA and TanSat team.

The GOSAT partners at the Japanese Aerospace Exploration Agency (JAXA), National Institute for Environmental Studies (NIES) and Ministry of the Environment of Japan (MoE) plan to launch GOSAT-2 in 2018. During its 5-year mission, GOSAT-2 will measure carbon monoxide (CO) as well as CO_2 and methane. It will collect about twice as many useful soundings as GOSAT and each sounding will have roughly 4 times the precision (0.5 ppm for CO_2). The GOSAT partners have also started formulating the

GOSAT-3 mission for a launch around 2023, but the requirements for that mission have not yet been finalized.

The French Space Agency, CNES, is formulating a mission called MicroCarb, which could be selected for development in the near future. MicroCarb could be deployed in the A-Train as early as 2020, providing an excellent opportunity to extend the OCO-2 CO_2 data record. It will collect soundings at 1 Hz along a narrow path, yielding 30 km^2 footprints (~10 times the area as OCO-2 footprint) with a single sounding precision of 0.6 ppm. MicroCarb will have a data density about 10 times larger than GOSAT or GOSAT-2, but 1/10 as large as OCO-2 or OCO-3.

Two other CO_2 missions have been studied for deployment beyond 2023. The European Space Agency (ESA) selected CarbonSat as a candidate for the 8th ESA Earth Explorer (EE8). CarbonSat was to launch around 2023 and measure both X_{CO2} and X_{CH4} at high spatial resolution (6 km^2/footprint) over a broad (~200 km) swath to cover the entire Earth's surface each month. Unfortunately, in September 2015, the ESA Science Advisory Committee (ESAC) did not recommend CarbonSat for the EE8 opportunity, so its future is uncertain.

The previous NASA decadal survey selected the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission as a Tier 2 option. Unlike the sensors listed above, ASCENDS uses a lidar to measure X_{CO2}. The spatial coverage and precision of this approach is lower than that of passive spectrometers, like OCO-2 over the sunlit hemisphere, but it provides the only method that can measure X_{CO2} at night or over high latitudes in winter. While the specific instrument and mission architecture are not yet known, studies are targeting a measurement precision of ~1 ppm over 10-second integrations along the orbit path in cloud-free conditions. The priority of this class of instruments in the next Decadal Survey is unknown.

The value of this suite of missions could be substantially improved if their data can be combined to yield a uniform, continuous, CO_2 climate data record spanning more than a decade. To do this, their measurements must be cross-calibrated, and their X_{CO2} estimates must be cross-validated against internationally-accepted standards (e.g. WMO, TCCON). This approach has been demonstrated for the GOSAT and OCO-2 missions. Based on the success of this activity, NASA and the GOSAT partners have extended this arrangement to GOSAT-3 (and 2?), with a formal Memorandum of Understanding, signed in March 2015. Preliminary agreements to facilitate this type of collaboration were also executed between the OCO-2, OCO-3 and the CNES MicroCarb and ESA CarbonSat missions. In spite of their potential value, there is no funding targeted to maintain the OCO/GOSAT cross-calibration, to maintain TCCON, or to extend these programs to future missions. We strongly recommend that these activities be included as an integral part of the next Decadal Survey.

Why are space-based observations fundamental to addressing these challenges/questions?

Only the vantage point of space can provide the spatial coverage and density of measurements needed for global flux inversion of CO_2. The GOSAT/OCO-2 data record is being analyzed by a growing, interdisciplinary community of scientists, whose results are beginning to yield important insights into regional scale CO_2 sources and sinks. To continue this progress, the existing data record must be extended well beyond the lifetimes of these two pioneering missions.

A flight of the OCO-2 spare instrument, OCO-3, is in NASA's planning documents for the allocation of space on the International Space Station Japanese External Module (JEM-EF). But, there was no NASA funding for OCO-3 in FY15, and no budget is in place yet for FY16. Several other space agencies are planning to launch X_{CO2} satellites over the next half decade. Given these resources, linking together multiple measurement sets is the most feasible approach for developing a sustained time series of X_{CO2}. This approach will not satisfy the growing need for a more capable, dedicated, constellation of CO_2 monitoring satellites, but it will provide the data needed to answer critical questions about the sensitivity of CO_2 sources and sinks to climate change on regional scales.