The Carbon Cycle and the Climate, an evolving system?

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Abstract: An improved understanding of the natural carbon cycle is critical to our ability to predict rate of increase in the atmospheric carbon dioxide (CO₂) concentrations and their impact on the climate. Until recently, atmospheric CO₂ concentrations were measured in situ by instruments deployed at surface stations or on aircraft. These measurements provide the most accurate estimates of the CO₂ concentrations of their trends on global scales. However, their spatial coverage and resolution are limited, particularly in arctic, boreal or tropical land regions and over most of the ocean. With the launch of Japan’s Greenhouse gases Observing SATellite, GOSAT, in 2009, and NASA’s Orbiting Carbon Observatory-2 (OCO-2) in 2014, space based remote sensing measurements are complementing the ground-based and airborne CO₂ and CH₄ measurements with much greater spatial resolution and coverage. These space-based CO₂ estimates clearly reveal aspects of the atmospheric CO₂ cycle seen in the in situ measurements, such as the seasonal CO₂ drawdown in the northern hemisphere spring and large, positive CO₂ anomalies associated the anthropogenic emissions over East Asia, Western Europe and North America. Other features present in these space-based datasets were not anticipated. For example, since the beginning of the OCO-2 mission, tropical forests, once thought to be a significant CO₂ sink, show strong, persistent positive CO₂ anomalies, suggesting that they are now sources. Efforts are ongoing to determine whether these and other features of the space-based datasets indicate biases in the space-based CO₂ estimates, misinterpretations of the ground-based measurements due to limitations in their resolution or coverage, evidence for evolution of the carbon cycle in response to climate change.

Space-based CO₂ Estimates from GOSAT and OCO-2

Monthly mean estimates of the column-average CO₂ dry air mole fraction, XCO₂, from GOSAT (left) and OCO-2 (right) are shown for May 2016. GOSAT collects 300-1000 full-column XCO₂ measurements each day. OCO-2 collects about 80,000 XCO₂ measurements each day. Clouds preclude observations in some regions, but these measurements still provide a high spatial resolution description of the atmospheric CO₂ concentration field.

Persistent Spatial Anomalies in XCO₂

OCO-2 XCO₂ estimates (above) indicate that some regions have high (positive) and low (negative) XCO₂ anomalies that persist from season to season (left panel) and from year to year (right panel).
- Tropical forests exhibit 1-2 ppm positive XCO₂ anomalies, indicating that they are now a net source of CO₂, rather than a sink.
- Tropical oceans have weak negative XCO₂ anomalies, indicating a net CO₂ sink.
- Mid- and high latitudes show larger seasonal variations than expected, as well as large positive XCO₂ anomalies in regions with intense fossil fuel use (i.e. East Asia).

Possible Explanations for Regional Scale Differences

The large differences between the space-based results and those derived from earlier in situ measurements and models suggest:
1. Models constrained by in situ measurements tell an incomplete story.
   - While ground-based and airborne data are more precise and accurate than the space based measurements, their spatial resolution and coverage is very sparse, especially in regions where the largest XCO₂ anomalies are seen by the space-based sensors. Flux inversion models yield unreliable results where there are no measurements.
2. The space-based XCO₂ estimates still include regional biases.
   - OCO-2 measurements have been validated against TCCON and other standards, but there are few validation sites in regions with the largest XCO₂ anomalies.
   - While the tropical land results appear to be robust to updates in retrieval algorithms, recent results suggest that the tropical ocean anomaly may be much weaker.
3. The natural carbon cycle is evolving in response to climate change.
   - There is increasing evidence from atmospheric CO₂ measurements and modeling studies that the carbon cycle is evolving rapidly in response to human activities (deforestation, biomass burning, land use change) and climate change. Measurements and models based on earlier data may no longer describe this system.

Reconciling the in situ and Space-based Results

When in situ CO₂ measurements are assimilated into flux inversion models, like the 11 used by Peylin et al. (2013) (above), the resulting CO₂ flux distributions show the most variability over northern hemisphere continents, where most of the measurements sites are located. Elsewhere, the CO₂ fields produced by these models are spatially smooth on annual time scales. For the year considered here (2003), most models find that tropical forests in Africa and South America were either neutral or weak net sinks for atmospheric CO₂ (blue shades). They also indicate that the tropical ocean is a weak net source of CO₂. However, neither of these areas are well constrained by in situ measurements.

Additional ground-based and aircraft measurements are essential.
- New stations are needed to cover tropical land, topical ocean and Asia to identify mechanisms governing sources and sinks and to validate space based products.
- Advances in space-based measurements and analysis methods are needed to further improve coverage and to identify and correct biases.
- Data quality, retrieval algorithms and flux inversion tools are improving rapidly.
- Enhanced measurement and modeling capabilities are needed to detect and characterize the carbon cycle response to climate change.