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The Carbon Cycle and the Climate, an evolving system?

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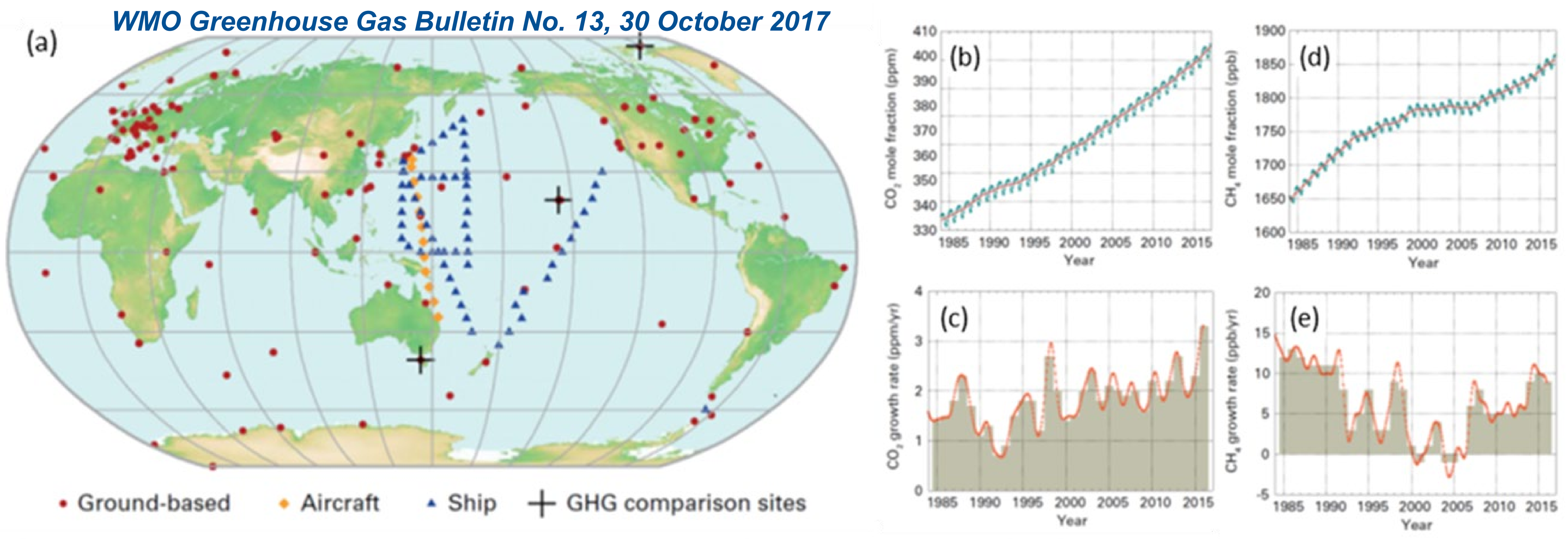
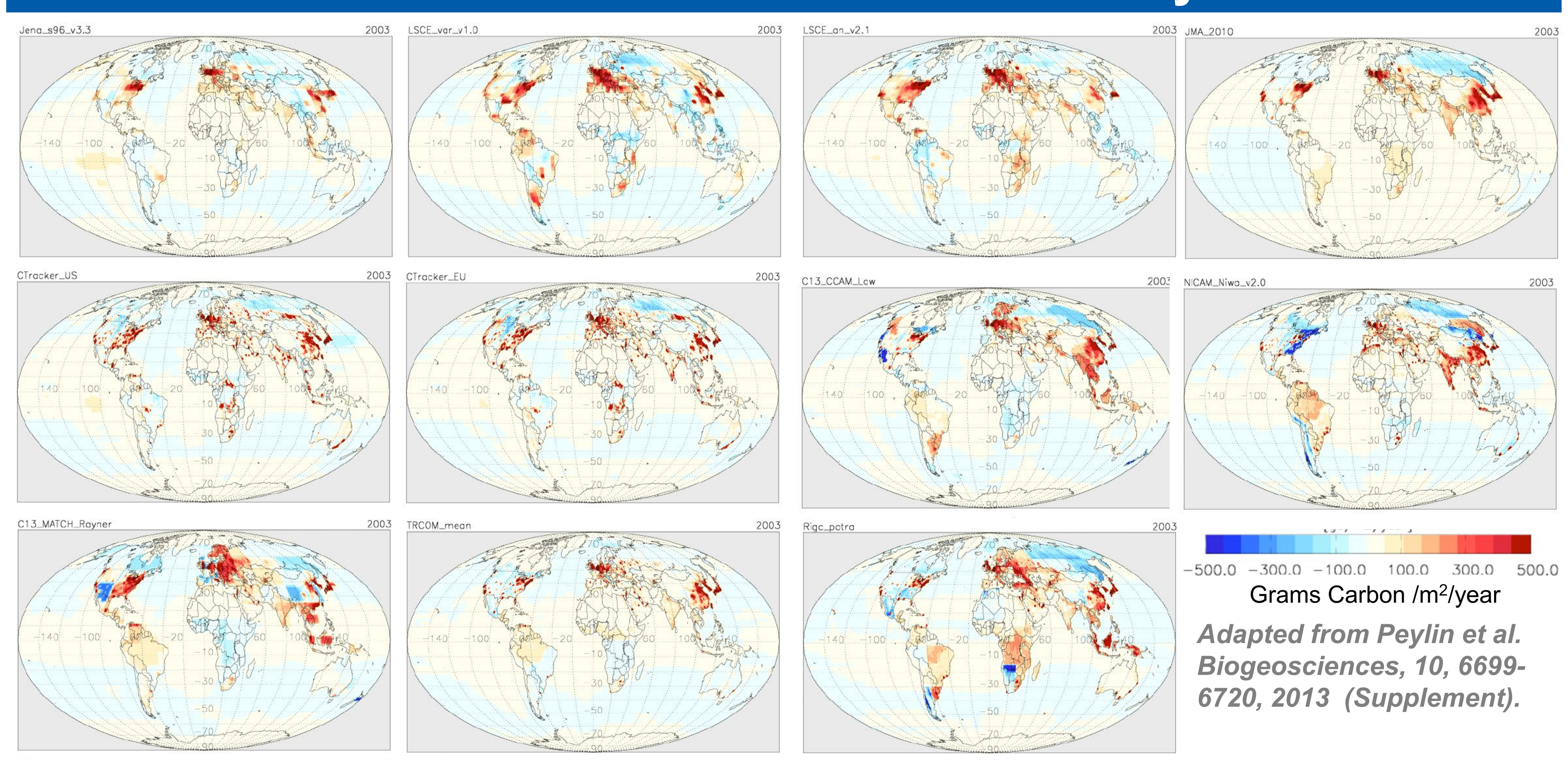
Abstract: The concentration of carbon dioxide (CO_2) in the atmosphere is controlled by natural processes, including plant photosynthesis and respiration and ocean solubility as well as human activities, such as fossil fuel combustion and land use practices. An improved understanding of these processes is critical to our ability to predict the rate of increase in the CO_2 in the atmosphere and its impact on the climate. Until recently, the concentrations atmospheric CO_2 and other greenhouse gases were measured *in situ* by instruments deployed at surface stations or on aircraft. *In situ* measurements still provide the most accurate estimates of the CO_2 concentrations and their trends on global scales. They also include chemical and isotopic tracers, such as carbon-14 (^{14}C), which help to discriminate fossil fuel from biogenic contributions to the observed CO_2 trends. However, the spatial coverage and resolution of these measurements are still far too limited to identify and quantify emission sources on regional scales, particularly in arctic, boreal and 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 estimates are complementing ground-based and airborne CO_2 measurements with much greater spatial resolution and coverage. Space-based CO_2 estimates clearly reveal the most robust aspects of the atmospheric CO_2 cycle seen in *in situ* measurements, such as the seasonal CO_2 drawdown in the northern hemisphere spring and the large, positive CO_2 anomalies associated the anthropogenic emissions over East Asia, Western Europe and eastern North America. Other features present in these space-based datasets were not anticipated. For example, since 2015, tropical forests, once thought to be net absorbers of CO_2, show strong, persistent positive CO_2 anomalies, suggesting that they are now net emitters. Efforts are ongoing to determine whether these and other features of the space-based products indicate biases in space-based CO_2 estimates, misinterpretations of the ground-based measurements due to limitations in their resolution or coverage, or evidence for evolution of the carbon cycle in response to climate change.

The Atmospheric Carbon Cycle Constrained by Ground-based Greenhouse Gas Monitoring Network



Ground-based *in situ* measurements from the WMO Global Atmospheric Watch (GAW) Network and its partners provide the most accurate available estimates of atmospheric CO_2 and CH_4 concentrations and their trends on global scales, but the network's spatial coverage and resolution are limited.

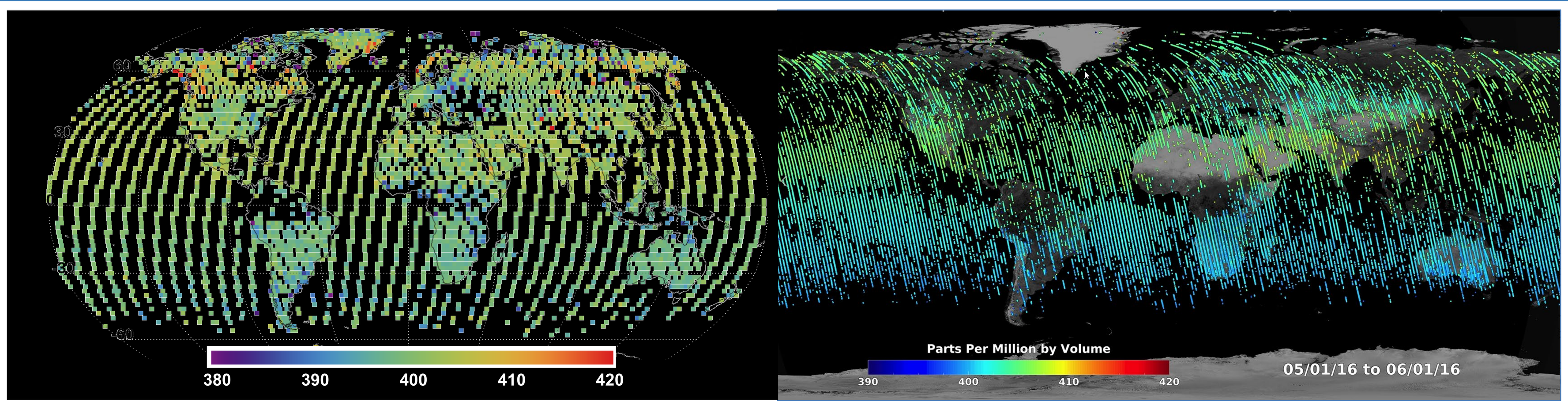
Global Flux Inversion Models Constrained by *in situ* Data



Adapted from Peylin et al. Biogeosciences, 10, 6699-6720, 2013 (Supplement).

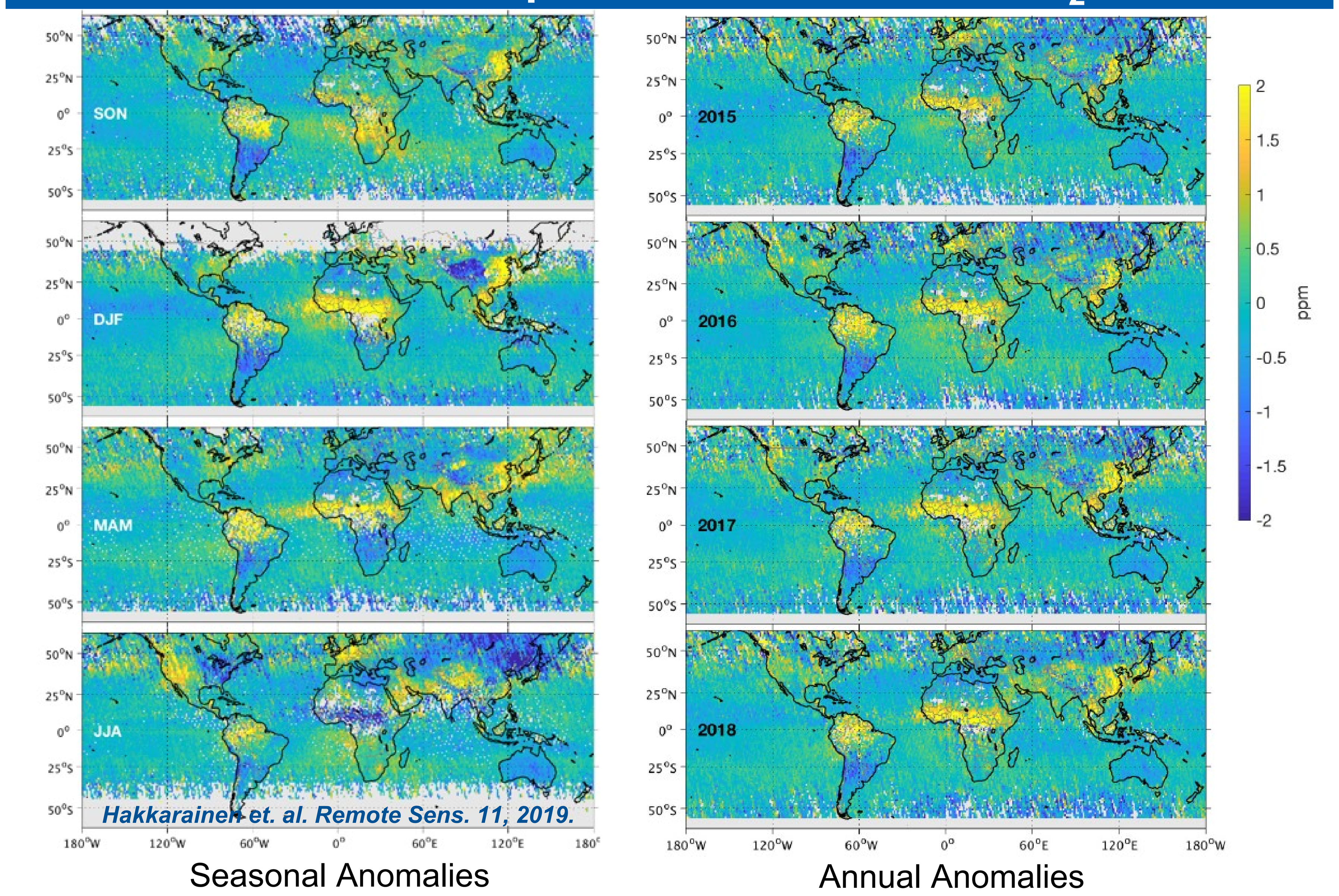
When *in situ* CO_2 measurements are assimilated into flux inversion models, like the 11 used by Peylin et al. (2013; above), the resulting CO_2 flux distributions show the most variability over northern hemisphere continents, where most of the measurements sites are located. Elsewhere, the CO_2 fields 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 CO_2 (blue shades). They also indicate that the tropical ocean is a weak net source of CO_2. However, these areas are well constrained by *in situ* measurements.

Space-based CO_2 Estimates from GOSAT and OCO-2



Monthly mean estimates of the column-average CO_2 dry air mole fraction, XCO_2, from GOSAT (left) and OCO-2 (right) are shown for May 2016. GOSAT collects 300-1000 full-column XCO_2 measurements each day. OCO-2 collects about 80,000 XCO_2 measurements each day. Clouds preclude observations in some regions, but these measurements still provide a high spatial resolution description of the atmospheric CO_2 concentration field.

Persistent Spatial Anomalies in XCO_2



With the seasonal cycle removed, OCO-2 XCO_2 estimates (above) indicate that some regions have high (positive) or low (negative) XCO_2 anomalies that persist from season to season (left) and from year to year (right).

- Tropical forests exhibit 1-2 ppm positive XCO_2 anomalies, indicating that they are net emitters of CO_2, rather than absorbers, in spite of their strong photosynthetic uptake.
- Tropical oceans have weak negative XCO_2 anomalies, indicating net CO_2 absorbers.
- Mid- and high latitudes show larger seasonal variations than expected, as well as large positive XCO_2 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 XCO_2 anomalies are seen by the space-based sensors. Flux inversion models yield unreliable results where there are no measurements.

2. The space-based XCO_2 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 XCO_2 anomalies.
- While tropical land anomalies 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 CO_2 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

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.
- Critical to the development of improved models for predicting the carbon cycle evolution.