TECHNICAL RESPONSE

CARBON CYCLE

Response to Comment on "Contrasting carbon cycle responses of the tropical continents to the 2015–2016 El Niño"

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Chevallier showed a column CO_2 (X_{CO_2}) anomaly of ±0.5 parts per million forced by a uniform net biosphere exchange (NBE) anomaly of 2.5 gigatonnes of carbon over the tropical continents within a year, so he claimed that the inferred NBE uncertainties should be larger than presented in Liu *et al*. We show that a much concentrated NBE anomaly led to much larger X_{CO_2} perturbations.

Chevallier has asserted that the uncertainties presented in Liu *et al.* (*1*) are too small, sufficiently so that the scientific conclusions are less robust than reported. Chevallier (*2*) showed that uniformly redistributing a net biosphere exchange (NBE) anomaly of 2.5 gigatonnes of carbon (Gt C) (*1*) over the tropical continents throughout a year could result in concentration signals of ±0.5 parts per million (ppm). He then speculated that systematic errors in retrievals and transport models may be similar in magnitude, and therefore argued that the uncertainties should be higher.

However, the uniformly distributed flux anomaly proposed by Chevallier is very different from the actual distribution of the biosphere flux anomaly during the 2015–2016 El Niño event. In fact, the NBE anomaly was highly concentrated in time and space, and so led to much larger column enhancements than Chevallier's simulation. Chevallier simulated a source of 0.27 g C m^{-2} day^{-1} to the atmosphere over the tropical continents, balanced by a regular sink of 0.01 g C m^{-2} day^{-1} elsewhere. However, the actual anomalous CO_2 release over the tropics primarily occurred over small areas that experienced extreme climate conditions [figure 4 of (*1*)] during the period September 2015–March 2016 [figure S1 of (*1*)]. For example, the flux anomaly was more than 2.0 g C m^{-2} day^{-1}, nearly 10 times Chevallier's value, over southwest Kalimantan Island, Indonesia in October and November, when the peak biomass burning occurred.

We carried out an experiment similar to that of Chevallier, using the inferred, spatiotemporally varying real NBE anomaly from the 2015–2016 El Niño as a boundary condition over all three tropical continents. We then sampled the X_{CO_2} perturbations using the sensitivity and locations of OCO-2 observations. Figure 1A shows the mean X_{CO_2} perturbations averaged between September 2015 and March 2016, corresponding to the peak of the 2015–2016 El Niño. Figure 1B shows the percentage of the number of simulated X_{CO_2} perturbations larger than 1.0 ppm at each 4° × 5° grid (the resolution of the transport model), and Fig. 1C is a histogram distribution of X_{CO_2} perturbations.

Figure 1A shows that the X_{CO_2} anomaly was typically much larger than 0.5 ppm during the peak of the 2015–2016 El Niño. About 90% and 70% of samples have enhancements larger than 0.5 ppm and 1.0 ppm, respectively (Fig. 1C), well above the threshold for OCO-2 X_{CO_2} systematic error. More than 60% of the samples at each 4° × 5° grid have perturbations larger than 1.0 ppm (Fig. 1B). This is in stark contrast to Chevallier's claim that "still only 1.5% of the sounding perturbations exceed 0.5 ppm in that case." Aside from using different transport models, the X_{CO_2} differences between the two experiments are due to the spatiotemporal distributions of the flux anomaly: concentrated versus uniformly distributed fluxes.

The perturbed X_{CO_2} signal over each of the three tropical continents arises primarily from flux anomalies in the respective continent [figure S1 of (*1*)]. Consistent with uncertainty quantification (*1*) and fundamental source-receptor relationships (*3*), this analysis supports that our inversion system can discriminate between the anomalies in the three tropical continents, enabling the main conclusion in (*1*) that diverse biogeochemical processes are responsible for the large NBE anomaly over three tropical continents,

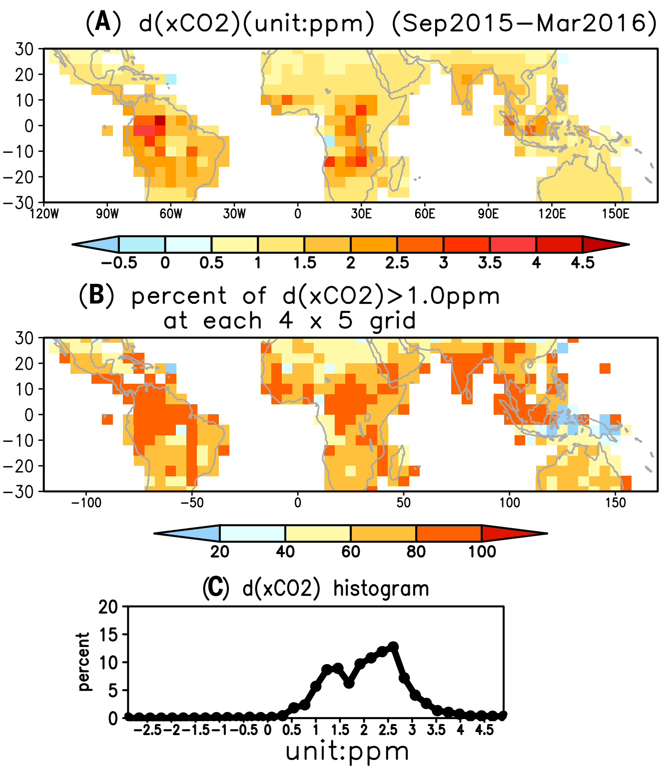

Fig. 1. X_{CO_2} perturbations due to net biosphere flux anomaly during the peak of 2015–2016 El Niño. (**A**) Mean X_{CO_2} perturbations over the period September 2015–March 2016. X_{CO_2} was sampled with OCO-2 sensitivity and locations of OCO-2 observations. (**B**) Percentage of X_{CO_2} perturbations larger than 1 ppm at each 4° × 5° grid. (**C**) Histogram of X_{CO_2} perturbations.

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which was also supported by two additional types of observations: carbon monoxide and solar-induced chlorophyll fluorescence used to constrain biomass burning and plant primary productivity, respectively.

The 2015–2016 El Niño was an extreme climate event, generating intense but localized climate and NBE anomalies (*1*, *4*) that were exploited by the inversion system in (*1*). Systematic errors in X_{CO_2} retrievals are one of the many factors contributing to the overall estimated net biosphere flux uncertainty. Quantification and mitigation of these errors is an active area of research and is likely to lead to improved data products and analyses of subtler phenomena, such as downwind enhancements from megacity fossil fuel emissions. Substantial advances have been demonstrated by the OCO-2 and GOSAT communities, and we expect continued progress toward the capability of quantifying fluxes by the emerging international constellation of satellites with a much higher confidence level than now. We agree with Chevallier that this advancement must remain a priority (*5*).

REFERENCES AND NOTES

1. J. Liu *et al*., *Science* **358**, eaam5690 (2017).
2. F. Chevallier, *Science* **362**, eaar5432 (2018).
3. J. Liu, K. W. Bowman, D. K. Henze, *J. Geophys. Res. Atmospheres* **120**, 5214–5236 (2015).
4. J. C. Jiménez-Muñoz *et al*., *Sci. Rep.* **6**, 33130 (2016).
5. P. J. Sellers, D. S. Schimel, B. Moore III, J. Liu, A. Eldering, *Proc. Natl. Acad. Sci. U.S.A.* **115**, 7860–7868 (2018).

ACKNOWLEDGMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. This work was in part supported by NASA Carbon Monitoring System program grant 14-CMS14-0054 and by NASA Orbiting Carbon Observatory Science team program grants 14-OCO2_14-0007 and 11-OCO211-0024. K.R.G. was supported by NSF CAREER award 0846358.

8 February 2018; accepted 4 October 2018
10.1126/science.aat1211

Science

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Science **362** (6418), eaat1211.
DOI: 10.1126/science.aat1211