Atmos. Chem. Phys. Discuss.,
https://doi.org/10.5194/acp-2018-203-AC4, 2018

Atmospheric Chemistry and Physics
Discussions

Interactive comment on "Unprecedented strength of Hadley circulation in 2015–2016 impacts on CO_2 interhemispheric difference" *by* Jorgen S. Frederiksen and Roger J. Francey

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Received and published: 25 June 2018

Unprecedented strength of Hadley circulation in 2015-2016 impacts on CO2 interhemispheric difference

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CSIRO Oceans and Atmosphere, Aspendale, Victoria, AUSTRALIA Correspondence to: Jorgen S. Frederiksen (jorgen.frederiksen@csiro.au) Response to AC Chatterjee Referee 3 (RC3) review:

We are pleased to learn that the Referee thinks that the publication in ACP of this study,

connecting the large-scale dynamics to observed variations in atmospheric CO2 concentrations, would be timely. We thank the Referee for the insightful comments which have led us to clarify and improve the presentation of the results and to add more detailed discussion on surface flux variability. To be specific, we have responded to the Referee's suggestions as follows: Question 1 Comments from Referee: The observed interannual variability in Cmlo-cgo has to be a function of both the transport variability and the underlying surface flux variability. This latter part, especially the role of terrestrial ecosystems during the boreal summer-autumn is largely ignored. For example, in Section 4 (Lines 22-24) the authors talk about the impact of fossil fuel emissions over NH but do not counteract that with the strong biospheric uptake that happen at the same time. I would recommend that the authors have a discussion at the outset on how they are considering surface flux variability in their analyses. In the current version of the manuscript, this is not clear at all. Author's response: We agree with the Referee that interannual variability in Cmlo-cgo has to be a function of both transport variability and the underlying surface flux variability. Our focus has been to point out, in FF16 and in the current study, that transport variability may, at certain times, be an additional important contributor. We have followed the Referee's suggestion and added at the outset a new Subsection 2.1 on extratropical terrestrial flux variation. Author's changes to manuscript: 2.1 The influences of terrestrial fluxes and transport on interhemispheric CO2 differences The growth rate and concentration of atmospheric CO2 depend on many mechanisms including fossil fuel emissions, surface fluxes, such as associated with the growth and decay of vegetation, and atmospheric mean and eddy transport. The CO2 growth rate and IH gradients in CO2 vary on daily, monthly, yearly and multi-year time scales where there is a quasi-periodic variability associated with the influence of ENSO (e.g. Thoning et al. 1989). This reflects the response of tropical vegetation to rainfall variations and both hemispheres are also affected through dynamical coupling. A number of recent inversion studies have largely attributed growth anomalies in atmospheric CO2 concentrations to anomalous responses of the terrestrial biosphere. However, the variability in the responses within Dynamic Global Vegetation Models

(DGVMs) is significant. Le Quéré et al. (2017) for example note that the “standard deviation of the annual CO2 sink across the DGVMs averages to ± 0.8 GtC yr-1 for the period 1959 to 2016”. This is significantly larger than the reported extratropical sink anomalies during for example the major 2009-2010 step in CO2 concentrations (Poulter et al., 2014; Trudinger et al., 2016). Francey and Frederiksen (2015) presented reasons supporting a dynamical contribution to the cause of the 2009-2010 Cmlo-cgo step. For the 2015-2016 period of particular relevance here there are two studies that stand out. Keenan et al. (2016) interpret slowing CO2 growth in 2016 as strong uptake by Northern Hemisphere terrestrial forests. Yue et al. (2018) examine the reasons for the strong positive anomalies in atmospheric CO2 growth rates during 2015. They present evidence of the Northern Hemisphere terrestrial response to El Niño events by way of satellite observations of vegetation greenness. To reconcile increased greenness with increased CO2 growth their inversion modelling requires the “largest ever observed” transition from sink to source in the tropical biosphere at the peak of the El Niño, “but the detailed mechanisms underlying such an extreme transition remain to be elucidated”. In this study, we find that the 2015-2016 El Niño also corresponds to unprecedented anomalies in both mean and eddy IH CO2 transport characterized by indices of these transfers that we introduce, affecting Northern Hemisphere CO2 growth. As for the anomalies in CO2 IH gradient during the 2009-2010 El Niño, studied in FF16, this again suggests a contributing role for anomalous IH transport during the 2015-2016 event. We examine this possibility in detail and study the relationships between the extremes in IH CO2 differences and transport anomalies for 1992 to 2016 and associated correlations between Cmlo-cgo (and other trace gases) and dynamical indices of transport. Question 2 Comments from Referee: Since the authors examine the IH CO2 annual difference from 1992 through to 2016, it is curious that the authors don’t attempt to put their findings for the 2015-2016 El Niño in context of the 1997-1998 El Niño. Figure 6 indicates that the eddy transport may have placed a larger role in the IH CO2 annual difference relative to the mean transport. This raises a bigger question - each El Niño has its own unique flavor, thus giving rise to its own individual teleconnection patterns (see Capotondi et al. [2015] BAMS, also available here - http://ocean.eas.gatech.edu/manu/papers/PDFs/Capotondi-2015-Understanding-ENSO-Diversity.pdf], it will be great to see a brief summary/discussion of how different El Niño flavors, and potentially a shift in El Niño type (EP – to – CP El Niños) may impact the two transport indices. Author’s response: We thank the Referee for the reference to Capotondi et al. (2015) which is now referred to. We now also discuss the 1997-1998 El Niño, El Niño flavours and in particular the differences in the Hadley circulation and in global warming between 1997-1998 and 2015-2016. Author’s changes to manuscript: The somewhat different behaviours of Cmlo-cgo and the dynamical indices, particularly during the El Niños of 2009-2010 and 2015-2016 and of 1997-1998, may partly reflect the diversity of El Niños and whether the heating is focussed in the Eastern Pacific or in the Central Pacific (Capotondi et al. 2015; L’Heureux et al. 2017 and references therein). The strong 1997-1998 event, like the 1982-1983 event, was a classic Eastern Pacific El Niño with maximum temperature anomalies there of nearly +4o C (L’Heureux et al. 2017). The 2009-2010 event in contrast was a Central Pacific El Niño with record-breaking warming in the central Pacific (Kim et al. 2011). The 2015-2016 El Niño fell between these two canonical cases with less warming in the eastern Pacific Ocean than the 1997-1998 event but similar warming to the 2009-2010 event in the central Pacific (L’Heureux et al. 2017). The broadly increasing magnitude of the negative ω and v_ indices since 2012 is associated with both increasing global temperatures, breaking the record in 2016, and the large El Niño of 2015 and 2016. This has resulted in the increasing importance of the mean convective and advective CO2 transport by the Hadley circulation relative to the eddy transport including through the Pacific duct. Question 3 Comments from Referee: The authors heavily rely on the information from the Francey and Frederiksen [2016] paper, especially in the discussion about the Atlantic duct (Section 3.1). The authors may want to include the relevant figure in this paper or introduce the necessary concepts here as well. Currently, it is challenging to put this paper in context without going back and reading the 2016 paper (which is what I had to do). For example, in

Section 2, the authors talk about modeling that was done in FF16 – it is impossible to know what kind of modeling was done. It is possible to reduce the dependence on that paper by introducing the concepts about the Pacific, Atlantic duct early on and providing a short summary of the findings. In a lot of places, reference to FF16 is not necessary. Author's response: At the suggestion of the Referee, we have summarized some more of the dynamical discussion from FF16 to make the current article more self contained. Also as noted in relation to Question 1 a new subsection has been added that details the modelling. Author's changes to manuscript: On the basis of long-term (1949-2011) correlations of the upper-tropospheric zonal wind with the Southern Oscillation Index (SOI), Francey & Frederiksen (2016; hereafter FF16) defined an index for the Pacific westerly duct, u_duct, as a measure of IH eddy transport of CO2. This index is the average zonal wind in the region 5°N to 5°S, 140°W to 170°W at 300hPa, as summarized in Table 1. In this article the period of interest is 1992 to 2016 and the corresponding correlation is shown in Figure 1S of the Supplement. There the role of the changing Walker circulation with the cycle of the El Niño-Southern Oscillation (ENSO) in determining the properties of the Pacific and Atlantic westerly ducts is also documented. SUPPLEMENTARY INFORMATION 1 Pacific and Atlantic westerly ducts The interhemispheric response to mid-latitude forcing produced by Rossby dispersion through equatorial westerly ducts was documented by Webster and Holton (1982). The zonal winds in the equatorial troposphere are generally easterly but in the upper troposphere the winds may be westerly in the Pacfic duct (centred on 5°N-5°S, 140oW-170oW) or the Atlantic duct (centred on 5°N-5°S, 10oW-40oW) as shown in Figure 2 of Webster and Chang (1988). As discussed in Francey and Frederiksen (2016, denoted FF16), and shown in Figure 1S for the period 1992 to 2016 of interest here, the upper-tropospheric zonal wind is strongly correlated with the SOI in the Pacific duct region and anti-correlated in the Atlantic duct region. As the atmospheric circulation changes between La Niña and El Niño conditions the warm ocean temperatures move from the western to eastern Pacific. The upward branch of the Walker circulation follows the warm water and the associated upper-tropospheric westerlies to

the east of the uplift successively open the Pacific westerly duct and then the Atlantic westerly duct (Figure 1 of Webster and Chang 1988). This is the reason for the correlations in our Figure 1S. The strength (and sign) of the upper-tropospheric zonal velocity in the near-equatorial regions is correlated with corresponding levels in the turbulent kinetic energy which is generated by Rossby wave breaking (Figure 6 of Frederiksen and Webster 1988). The Pacific duct, u_duct of Table 1, is in general the dominant duct as shown in Figure 2S which depicts the boreal winter (Dec-Feb) upper tropospheric vector wind for 1992-2016. Question 4 Comments from Referee: Overall quality of the text and figures: A couple of figures need to be improved, especially Figures 1 and 5. Either the figure resolution is low or it is too hard to read the figures. For the NASA movie, the authors may want to check the appropriate procedure to reference a video animation. The authors also need to provide the necessary credits to NASA Goddard Space Flight Center and the production team, including the URL for the movie (see https://svs.gsfc.nasa.gov/12445). Author's response: We have improved the clarity of the labelling on several of the figures including Figures 1 and 5 (which has been split into the new Figures 5 and 6). We have also credited the NASA Goddard Space Flight Center and the production team and referenced the URL for the movie as suggested by the Referee. Author's changes to manuscript: Please see new Figures and Captions. We acknowledge NASA Goddard Flight Center and their Production Team for the movie 'Following Carbon Dioxide through the Atmosphere' available at the web site: https://svs.gsfc.nasa.gov/12445. Question 5 Comments from Referee: Minor/technical comments: a) Abstract – Line 15-16 – incomplete line b) Section 3.2, Lines 3 - 6 – it is not clear how Figure 4 captures the convective transport of CO2 emissions. Later the authors claim – "It demonstrates that when the Pacific duct is open there is also large-scale uplift slightly downstream of Asia, so. . .". It is not clear how all this information is derived from Figure 4. c) Throughout the manuscript, the authors introduce the different transport indices in line (i.e., in the text). Given that this paper will be of significant interest to the carbon cycle community (and several of whom may not be familiar with these notations), it may be useful to have a Table that introduces the notation, what it means/represents and how it is calculated. d) The overall text requires some careful and thorough editing. Several sentences are hard to read either due to a lack of punctuation or overuse of conjunctive adverbs. Author's response: We have attended to the minor – technical comments. We now note that the prominent correlations shown in Figure 4, within ±30°of the equator at longitudes 120°E to 170°W, in fact occur at all levels between the surface and 100 hPa. We have added a table summarizing the definitions of the transport indices. The text has been carefully edited and sentences split for clarity. Author's changes to manuscript: The most prominent correlations occur within ±30°of the equator at longitudes 120°E to 170°W, upstream and at the longitudes of the Pacific duct and this is in fact the case at all levels between the surface and 100 hPa (not shown). Broadly similar correlations are obtained between the 500 hPa ω and u_duct for Feb-Apr (and for 500 hPa ω and SOI for Jan-Dec). Table 1: Definitions of dynamical indices characterizing eddy and mean tracer transport. Dynamical index Definition u_duct Average 300 hPa zonal velocity in the region 5°N to 5°S, 140°W to 170°W. ω_H Average 300 hPa vertical velocity in pressure coordinates in the region 10°N to 15°N, 0 to 360E. v_P Average 200 hPa meridional velocity in the region 5°N to 10°N, 0 to 360E. ω_P Average 300 hPa vertical velocity in pressure coordinates in the region 10°N to 15°N, 120E to 240E. v_H Average 200 hPa meridional velocity in the region 10°N to 15°N, 120E to 240E.

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