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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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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 Anonymous Referee 2 (RC2) review:

We are pleased to learn that the Referee finds our article an interesting study and

would like to recommend publishing it in ACP. We thank the Referee for the helpful comments which have helped us in clarifying aspects of the paper and to make it more accessible to the carbon cycle readership. We have responded to the Referee's specific suggestions as follows:

Question 1 Comments from Referee: You may consider to repeat some more information from FF16. Currently the paper can only be understood when also having read FF16. Also some more background information would help, e.g.: - Can you add a general sentence about Rossby wave dispersion and the mechanism how it transports atmospheric tracers? - Is the interhemispheric "duct" a pre-established concept, or is FF16 the place where it was first introduced? Why is the duct located over oceans only? Is it obvious why Pacific and Atlantic ducts are anti-correlated? P1 L25: I did not understand the formulation "on the basis of long-term correlations". Why would eddy transport necessarily be expected to correlate with SOI? 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. We now discuss the Walker circulation, Rossby wave dispersion, Rossby wave breaking and the associated eddy transport and mixing of atmospheric tracers. We provide additional content on the historical understanding of the westerly ducts, on why the ducts are located over the oceans and why the Pacific and Atlantic ducts are generally anticorrelated. We now discuss the role of the SOI in eddy transport variability (original P1 L25).

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) vector wind for 1992-2016.

Question 2 Comments from Referee: Please specify somewhere where the wind data (used to calculate the indices) are taken from (NCEP?). If the winds are taken from re-analysis, a statement of the uncertainty in the upper-troposphere winds would be appropriate, because the study relies on them. How can they be validated? Author's response: The wind data is taken from the NCEP-NCAR reanalysis (NNR) data as stated on lines 13 to 15 of page 2 of the original manuscript. We now discuss the accuracy of the upper troposphere winds from NNR and compare our main results with ones based on NASA- MERRA reanalysis data set.

Author's changes to manuscript: The atmospheric circulation data and indices used throughout this article are obtained from the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis (NNR) data (Kalnay et al., 1996); in Section 6 we briefly consider the robustness of our results using another reanalysis data set. The dynamical indices that we have used for this study are based on the NCEP-NCAR reanalysis (NNR) data (Kalnay et al. 1996). There is generally close correspondence between the major global atmospheric circulation data sets that, like the NNR data, use full data assimilation throughout the atmosphere (Frederiksen & Frederiksen 2007; Frederiksen et al. 2017; Rikus 2018). We have confirmed this by recalculating our dynamical indices and main correlations with Cmlo-cgo based on the NASA Modern Era Retrospective-analysis for Research and Applications (MERRA) (Rienecker et al. 2011) data. For example, the 1992 to 2016 correlation between MERRA and NNR data for u_duct in Feb-Apr is r=0.974 , for ω_P in Jun-Aug is r=0.899 and for v_P in Jun-Aug is r=0.931 . The corresponding correlations between detrended anomalies of Cmlo-cgo and the MERRA based dynamical indices are also very similar. The correlations are r=-0.512 with u_duct for Feb-Apr (compared with r=-0.500 for the NNR index), r=0.504 with ω_P for Jun-Aug (compared with r=0.522 based on NNR) and r=0.538 with v_P for Jun-Aug (compared with r=0.539 based on NNR). Question 3 Comments from Referee: P2 L10: What does "uses the overlap" mean? This needs an explicit description. Same paragraph: Add the year (always 2015?) to all dates given. Author's response: The sentence referring to “uses the overlap” has been rewritten (original P2 L10). The year 2015 has been added to all the dates. Author's changes to manuscript: Requested changes implemented.

Question 4 Comments from Referee: P3 L8: "Modelling" is a very broad term, that could mean anything. Please add a brief description what has been done (e.g. saying "atmospheric transport simulation" with a description of the CO2 fluxes used). Reading FF16 did not actually clarify to me what you refer to here. Author's response: The sentence starting “Modelling” has been deleted and replaced by a much more detailed discussion also at the request of RC1 and RC3. 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 $\pm$ 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 5 Comments from Referee: P3 L25: It would help (here and at various other places) to split long sentences by commas, here e.g. after "15N", for a faster perception which parts belong together. (Also, e.g., P4 L8 after "wind" and "(140W-170W)", P8 L20 after "duct", P8 L26 after "open".) P5 L22-24: I found this sentence unclear. Maybe "with" in line 22 should be "which"? Author's response: Here (original P3 L21 to L24) and elsewhere long sentences have been split as suggested. This sentence (original P5 L22-24) has been rewritten. Author's changes to manuscript: Requested changes implemented.

Question 6 Comments from Referee: Sect 5: I would find it interesting to know which fraction of interannual variability in Cmlo−cgo can be explained by transport variability alone? Is it r2 = 25%? (In addition, I found the description of the correlation analysis not easy to follow, e.g. with respect to the two quantities C and C*.) Author's response: Yes, as the Referee notes, typically the correlations of MLO-CGO CO2 with our indices that explain transport have |r|=0.5 or slightly larger. The relationships between C and C* are further discussed and related to a new Figure. Author's changes to manuscript: In fact the FF-adjusted C*mlo-cgo has very similar behaviour to the detrended Cmlo-cgo, with pattern correlations of anomalies of r=0.931, r= 0.954 and r=0.981 for Jan-Dec, Jun-Aug and Feb-Apr respectively. The similarity can also be seen by comparing the top panel of Figure 7(b) with that of Figure 8. Question 7 Comments from Referee: P7 L7-8: Briefly say where the information on anomalously high/low NBP is coming from (biosphere model? eddy covariance data?).

Author's response: Reference is now given to Trudinger et al. (2016) where the details are given and that work is also discussed in Section 2.1 referred to in the response to Question 4. Author's changes to manuscript: Terrestrial Net Biosphere Production south of 30°S was also anomalously low in 2009 and anomalously high in 2010 (FF16; Trudinger et al. 2016; though by amounts not sufficient to impact on the Cape Grim baseline CO2 records). Question 8 Comments from Referee: P7 L11: Is "indicated" the right word here? Do you mean "connected"? P8 L28-31: De-compact the formulations, e.g. saying "vertical velocity w at 300hPa" (and again comma after 15N) Fig 1a: Unclear what the inset "OCO-2 Satellite" refers to in the graphics. Fig 5: The labelling is much too small to be readable. Also, it would be helpful to add row and column headings to the panels. Author's response: These sentences have been rephrased, "OCO-2 Satellite" has been explained and the Figures have been improved with row and column headings. Author's changes to manuscript: Rephrasing implemented. Figure 1: (a) OCO-2 image for 17 Feb 2015 showing Rossby wave dispersion (dashed red lines) in CO2 concentration across the equator (dotted black line); the box labeled 'OCO-2 Satellite' shows the time period of the associated movie, (b) seasonal cycle of Cmlo-cgo and u_duct, with area where both are positive shaded, for 1 Jan 2014 to 31 Dec 2016, and (c) 300 hPa wind vector directions and wind strength (ms-1) on 17 Feb 2015. Figures all updated.

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