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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

Jorgen S. Frederiksen and Roger J. Francey

jorgen.frederiksen@csiro.au

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

Jorgen S. Frederiksen and Roger J. Francey

CSIRO Oceans and Atmosphere, Aspendale, Victoria, AUSTRALIA Correspondence to: Jorgen S. Frederiksen (jorgen.frederiksen@csiro.au) Response Part 2 to Anonymous Referee 1 (RC1) review:

Response Part 2 to RC1. As noted in our first Response to RC1: "We thank the

Referee for the thoughtful comments which have led us to examine a large number of other trace gases and their relationships to our dynamical indices. We have carried out extra seasonal correlations between the Mauna Loa minus Cape Grim difference in trace gas species (CH4, CO, H2, N2O) routinely monitored by CSIRO with the our dynamical indices. We have also included corresponding correlations using NOAA SF6 data. In each case we have briefly examined biogeochemical factors that influence differences in inter-hemispheric fluxes from one species to the next. We believe that our findings detailed in the associated Supplement provide very strong evidence of the relationships between the Mauna Loa minus Cape Grim difference in trace gases (CO2 presented in the main paper) and dynamical indices of eddy and mean transport."

We have now restructured our manuscript and included the discussion of the other trace gases in the main paper. We have also added Section 2.1 where the role of surface fluxes is discussed in more detail. We summarize here these additional changes. The new Supplement still contains detailed evidence of the role of topographic Rossby waves during the 17 February 2015 episode of wave trains seen in the OCO-2 data and some extra material on the westerly ducts had been added.

Question 1 Comments from Referee: Pg2, Lines 10-13: I have some trouble to believe this interpretation. A lot of CO2 or XCO2 variations are flux driven, and land flux is governed by weather and climate. Author's response: We agree with the reviewer that changes in surface fluxes can be a very important component in the interhemispheric differences in these trace gases as is now discussed in 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 The interactions of fluxes and transport causes these XCO2 wave trains. Author's

response: As noted in our first Response to RC1: "We now provide in the Supplement detailed evidence of the role of topographic Rossby waves during the 17 February 2015 episode of wave trains seen in the OCO-2 data. We also discuss the role vertical uplift during that event. We consider the coincidence of timing, location, orientation and wave number of the Rossby waves observed by OCO-2 with dynamical theory as being compelling evidence for our interpretation." Additional material on the westerly ducts has also been added. Author's changes to manuscript: 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.

2 Topographic Rossby waves during February 2015 As noted in the Introduction, the NASA (2016) OCO-2 CO2 concentration in Figure 1(a) shows Rossby wave trains over the eastern Pacific and across South America on 17 February 2015. This episode is characteristic of other times of IH Rossby wave propagation during the boreal winter–spring, and particularly February, of 2015. The average 17 to 18 February 2015 streamfunction anomaly, from the thirty year 1981–2010 mean for the same period, is shown in Figure 3S(a) for the Western Hemisphere (0oW–180oW) between 60oS and 60oN and at the σ=0.2582 level. Here σ=pressure/(surface pressure) and the corresponding pressure level is circa 260 hPa. We note that the phase lines broadly run from SW to NE between the Southern and Northern Hemispheres but are modulated by some smaller scale features. Moreover the dominant zonal wavenumber m=4 . Indeed there are broad similarities between the streamfunction anomaly in Figure 3S(a) and the streamfunction for the purely topographic Rossby waves in Figures 3a and b of Frederiksen and O'Kane (2005). For both the observations considered here and the ensemble of nonlinear simulations and statistical closure calculations the phase lines in the Western Hemisphere run SW to NE and the dominant wavenumber is 4. The dominant wavenumber 4 is also clearly seen in the energy spectra in Figure 2 of Frederiksen and O'Kane (2005). The SW to NW phase lines of pure topographic Rossby waves are also seen in the linear calculations in Figure 6 of Frederiksen (1982). In both the linear and nonlinear calculations the topographic Rossby waves are generated by the interaction of westerly winds with a conical mountain located at 30o N (an idealized representation of the massive Himalayan orography) and for a situation where the near equatorial winds are westerly. For the observational results in Figure 3S(a), the near equatorial winds between 5oS and 5oN are westerly in the Western Hemisphere broadly above 400 hPa and easterly below (not shown). Figure 3S(b) shows the 300 hPa zonal wind anomaly corresponding to the average 17 to 18 February streamfunction anomaly in Figure 3S(a). Again the SW to NE phase lines are evident as is the dominant m=4 wavenumber although the presence of smaller scale features associated with disturbances in the storm tracks (typically m$\sim$8 – 12) is perhaps more

evident. In Figures 4S(a) and 4S(b) we depict latitude pressure cross sections of the zonal wind anomalies for 17 to 18 February averaged between 120oW–140oW and 80oW–100oW respectively. We note that the anomaly is largely equivalent barotropic, as expected for topographic Rossby waves, and, by comparing the two panels, the SW to NW phase tilt is evident throughout the atmosphere. It can also be seen that the propagation across the equator into the Southern Hemisphere occurs primarily in the upper troposphere, particularly between 80oW–100oW where the mean westerly winds are weaker (not shown). We have also plotted latitude pressure cross sections of anomalies of the vertical velocity in pressure coordinates, ω=dp/dt where p is pressure, for 17 to 18 February averaged between 120oW–140oW and 80oW–100oW (not shown). These cross sections indicate that there is strong uplift in the Northern Hemisphere between 10oN and 30oN (negative ω) and general descent south of that band to 30oS. The topographic Rossby wave train generated by westerly winds impinging on the Himalayas may interact with a small region of uplift focused over the Andes in Peru (not shown) when it crosses into the Southern Hemisphere. However, in addition it should be noted that the wave train occurs at a time of seasonal minimum in Southern Hemisphere CO2.

Question 3 Comments from Referee: Pg2, Lines 31ff : I strongly believe, these features in C_mlo-cgo should also be shown using other tracers, e.g., SF6, CH4, N2O and halocarbons. The data are available at CSIRO, or NOAA. At the least I would like to see an anslysis using these species in the supplement. Author's response: As noted in our first Response to RC1: "We have carried out extra seasonal correlations between the Mauna Loa minus Cape Grim difference in trace gas species (CH4, CO, H2, N2O) routinely monitored by CSIRO with the our dynamical indices. We have also included corresponding correlations using NOAA SF6 data." This material has now been included as a new Section 6 of the manuscript. Author's changes to manuscript: 6 Interhemispheric exchange of other trace gases Next, we consider the eddy and mean IH exchange of other trace gas species and their correlations with CO2 and dynamical indices of transport. We focus on Feb-Apr for eddy transport and Jun-Aug for mean transport since these periods were the peaks for correlations of CO2 IH difference with eddy and mean transport indices respectively. However, there are differences in the seasonal variability of interhemispheric gradient in the different trace gas species that are reflected in their transport and for that reason we also briefly mention the results for other time periods. We begin by further examining Mauna Loa minus Cape Grim (mlo–cgo) differences, between 1992-2016, in the routinely monitored CSIRO species CH4, CO and H2 in addition to CO2 that were briefly considered in Frederiksen and Francey (FF16), as well as N2O (for 1993-2016). Thereafter we discuss mlo–cgo differences in SF6 data sourced from the NOAA Halocarbons and other Atmospheric Trace Species Group (HATS) program from 1998 (NOAA, 2018).

6.1 Pacific westerly duct and eddy IH transport of CSIRO monitored trace gases The IH exchange of the trace gas species CH4, CO and H2, in addition to CO2, and the role of the Pacific westerly wind duct was also considered in FF16. In particular, the covariance, of the mlo–cgo difference in these routinely monitored CSIRO species with u_duct, is shown in Figure 5 of FF16. We recall that the u_duct index is the average zonal wind in the region 5°N to 5°S, 140°W to 170°W at 300hPa. As noted in FF16, the extreme cases of Pacific westerly duct closure in 1997–98 and 2009–10 show up in the reduction of seasonal IH exchange for CH4 and CO as well as CO2. The similar behaviour of detrended anomalies of mlo–cgo difference in CH4, CO and CO2 and their correlations with u_duct is shown in Table 3 for Feb–Apr. We note the quite high correlations of CH4 and CO with CO2 (r=0.697 and r=0.645 respectively) and the significant anti–correlations of all these three species with u_(duct)(r=-0.448 , r=-0.605 and r=-0.500 respectively). In fact, for Mar-May the correlation between CH4 and CO2 is even larger at r=0.728 (and with u_(duct) it is r=-0.474) while between CO and CO2 it is r=0.611 (and with u_(duct) it is r=-0.507). These results are of course consistent with Figure 5 of FF16 and are further evidence of similarities of IH transient eddy transport of these three gases. Table 3 also shows that the Feb-Apr correlation of H2 with CO2 and anti–correlation with u_(duct) have smaller magnitudes (r=0.296 and r=-0.218 respectively) . These results for anomalies are probably related

to corresponding similarities and differences in the seasonal mean values (not shown) of these gases in Feb–Apr, as discussed below. Anomalies in mlo–cgo differences in CSIRO monitored N2O are generally poorly correlated with those in CO2 as shown for Feb-Apr and Jun-Aug in Tables 3 and 4 respectively (the maximum 3 month average correlation is r=0.274 for Mar-May) and this is mirrored in generally poor correlation with the dynamical indices shown in Tables 3 and 4. This reflects the fact that natural exchanges with equatorial agriculture and oceans are the main sources (Ishijima et al., 2009), and the seasonal range in mlo-cgo difference is only around 0.2% of the mean N2O level, more than 10 times less than is the case for the other species.

6.2 Hadley circulation and mean IH transport of CSIRO monitored trace gases We examine the role of the Hadley circulation on the mean transport of trace gases focusing on the boreal summer period of Jun–Aug. Table 4 shows the correlations between the detrended anomalies of mlo–cgo difference in CH4, CO and H2 with CO2 and with the dynamical indices ω_P and v_(P) (Table 1). We note that the largest Jun-Aug correlation is between H2 and CO2 (r=0.680) and the correlations between CH4 and CO with CO2 are considerably smaller (r=0.246 and r=0.108 respectively) while for Apr-Jun the latter correlations are more comparable at r=0.583 and r=0.496 respectively. These correlations with CO2 are also reflected in the respective correlations of the other trace gases with ω_P and v_(P). We note from Table 4 that the Jun-Aug correlations of H2 with ω_P and v_(P) are r=0.427 and r=0.442 respectively which is slightly less than the corresponding correlations between CO2 and the dynamical indices (r=0.522 and r=0.539 respectively) but considerably larger than for CH4 and CO. For May-Jul the correlation of H2 with ω_P is slightly larger with r=0.526 . Again, the different behaviour of the trace gas anomalies may be related to their different seasonal mean values; the seasonal mean IH difference for H2 peaks in boreal summer while for CH4 and CO it is relatively low with a minimum in August. The distribution and variability of surface exchange is different for each of the trace gases and there is potential for this to interact with the restricted extent and seasonal meandering of the regions of uplift to influence IH exchange of a species. For example, 70% of the global total CH4 emissions are from mainly equatorial biogenic sources that include wetlands, rice agriculture, livestock, landfills, forests, oceans and termites (Denman et al., 2007) and CO emissions contain a significant contribution from CH4 oxidation and from tropical biomass burning. A more detailed examination of the inter–annual variation of the mlo–cgo difference in H2 during boreal summer is presented in Figure 8. It shows the detrended H2 data in comparison with the corresponding CO2 data and with the ω_P and v_(P) indices. First we note that the detrended CO2 data in the top panel has very similar inter–annual variation to the FF–adjusted C*mlo-cgo in Figure 7(b). We also see that the qualitative behaviour of H2 mirrors many aspects of CO2, as expected from the correlations in Table 4. In particular, the increase in the IH difference of H2 in 2010 is even more pronounced than for CO2. For CO2 and for H2 there is a steady reduction in the IH difference from around 2013 leading to a local minimum in 2016. In both of these respects these gases broadly follow the changes in the Hadley circulation including the strengthening during 2015–2016. Vertical lines in Figure 8 indicate other times between 1992 and 2016 when transitions occur in both these trace gases and in the Hadley circulation characterized by ω_P and v_P. Surface exchanges of H2 have similarities to those of CO2 in that they occur mostly at mid–northern latitudes and are mainly due to emissions from Fossil Fuel combustion. However H2 also has mid–northern latitude photochemical sources peaking in August (Price et al., 2007). These boreal summer sources are almost offset by a combined soil and hydroxyl sink, but the overall interhemispheric partial pressure difference is boosted by a significant reduction in the Southern Hemisphere photochemical source at that time. For both species, the most northern excursions of the inter–tropical convergence zone that occurs at Pacific latitudes encounter increasing concentrations of both gases. As noted above, anomalies in mlo–cgo differences in N2O are poorly correlated with those in CO2 and in dynamical indices (Tables 3 and 4). Indeed the 3 month average anticorrelation with u_(duct) that has the largest magnitude is r=-0.133 for Mar-May and the largest correlations with ω_P is r=0.359 for Apr-Jun and with v_(P) is r=0.350 for May-Jul.

6.3 Interhemispheric exchange of SF6 In the case of SF6 we have analysed the mlo–cgo difference in available NOAA HATS data from 1998 to 2012 when cgo HATS measurements ceased. Correlations (Tables 3 and 4) of detrended anomalies in IH differences in SF6 with those in CO2 are as follows: the Feb–Apr correlation is r=0.619 , the Mar-May correlation is r=0.722 , the Apr-Jun correlation is r=0.595, the May–Jul correlation is r=0.303 and the Jun–Aug correlation is r=0.223 . The corresponding correlations with dynamical indices are as follows: for Feb–Apr the correlation with u_duct is r=-0.617 , the May–Jul correlations with ω_P is r=0.465 , the Jun–Aug correlation with ω_P is r=0.433 , the May–Jul correlation with v_(P) is r=0.517 and the Jun–Aug correlation with v_(P) is r=0.385 . We note that SF6 has an anti-correlation with u_duct for Feb-Apr that has larger magnitude than for CO2 and even CO. Thus, there is again a significant influence of the Pacific westerly duct, in late boreal winter and spring, and of the Hadley circulation, in boreal summer and late spring, as measured by these indices, on the mlo–cgo differences of SF6; these SF6 differences exhibit a similar step change in 2009-2010 as shown for CO2 in Figures 2 and 7.

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