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LETTER

The carbon cycle response to two El Nino types: an observational study

Petr Chylek[1,2,5], Pieter Tans[3], John Christy[4] and Manvendra K Dubey[1]

1 Los Alamos National Laboratory, Earth and Environmental Sciences, Los Alamos, NM, United States of America
2 Department of Physics, New Mexico State University, Las Cruces, NM, United States of America
3 NOAA, Earth System Research Laboratory, Boulder, CO, United States of America
4 University of Alabama at Huntsville, AL, United States of America
5 Author to whom any correspondence should be addressed.

E-mail: chylek@lanl.gov

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Abstract

We analyze monthly tropical near surface air temperature and Mauna Loa Observatory carbon dioxide (CO_2) data within 1960–2016 to identify different carbon cycle responses for two El Nino types: El Ninos originating in the central tropical Pacific (CP El Nino) and El Ninos originating in the eastern tropical Pacific (EP El Nino). We find significant differences between the two types of El Nino events with respect to time delay of the CO_2 rise rate that follows the increase in tropical near surface air temperatures caused by El Nino events. The average time lag of the CP El Nino is 4.0 ± 1.7 months, while the mean time lag of EP El Nino is found to be 8.5 ± 2.3 months. The average lag of all considered 1960–2016 El Ninos is 5.2 ± 2.7 months. In contrast the sensitivity of the CO_2 growth rate to tropical near surface air temperature increase is determined to be about the same for both El Nino types equal to 2.8 ± 0.9 ppm $yr^{-1}K^{-1}$ (or 5.9 ± 1.9 GtC $yr^{-1}K^{-1}$). Our results should be useful for the understanding of the carbon cycle and constraining it in climate models.

1. Introduction

The El Nino-Southern Oscillation (ENSO) is one of the largest modes of climate variability, which is connected to a natural warming/cooling of the tropical Pacific Ocean that occurs about every three to seven years. Previous research has demonstrated that ENSO can arise from non-linear atmosphere–ocean interaction and that the ENSO has implications for temperature and rainfall in many parts of the globe (e.g. Yeh *et al* 2009, Jimenez-Munon *et al* 2016, Jacox *et al* 2016, Lee *et al* 2010, Lee and Julien 2016, Cobon *et al* 2016, Ng *et al* 2017). Furthermore, unforced control runs of climate models, which simulate the evolution of climate states due to internal ocean–air dynamics in the absence of external forcing, confirm that El Nino may arise spontaneously without the need for any change in external forcing (Choi *et al* 2011, Wittenberg *et al* 2014). However, it is conceivable that changes in global climate by greenhouse gas forcing may influence conditions favorable to El Nino generation and may also change its temporal and spatial characteristics. Although considerable effort has been devoted to identify the effects of anthropogenic emissions on El Nino characteristics, there are still uncertainties in ENSO projections under increased greenhouse gas scenario (e.g. Vecchi and Wittenberg 2010, Collins *et al* 2010, Christensen *et al* 2013, Cai *et al* 2015). There is no consensus on whether El Ninos will become more frequent under global warming (e.g. Taschetto *et al* 2014, Xu *et al* 2017).

The amount of atmospheric CO_2 increase due to El Nino events has been the subject of several investigations using observations and climate models with an incorporated carbon cycle, including expected El Nino changes, in some models, under an increasing atmospheric CO_2 (Keeling *et al* 1995, Meehl and Washington 1996, Jones *et al* 2001, Richards 2013, Christensen *et al* 2013, Cox *et al* 2013, Taschetto *et al* 2014, Kim *et al* 2016, Sterner and Johansson 2017). Most of these analyses assume a single El Nino type.

Recent publications point to the possibility of two basic types of El Nino, in contrast to a single El Nino phenomenon dependent on a continuum of changing parameters (Lee *et al* 2010, Yeh *et al* 2014, Capotondi *et al* 2015, Chen *et al* 2015, Xu *et al* 2017). The EP

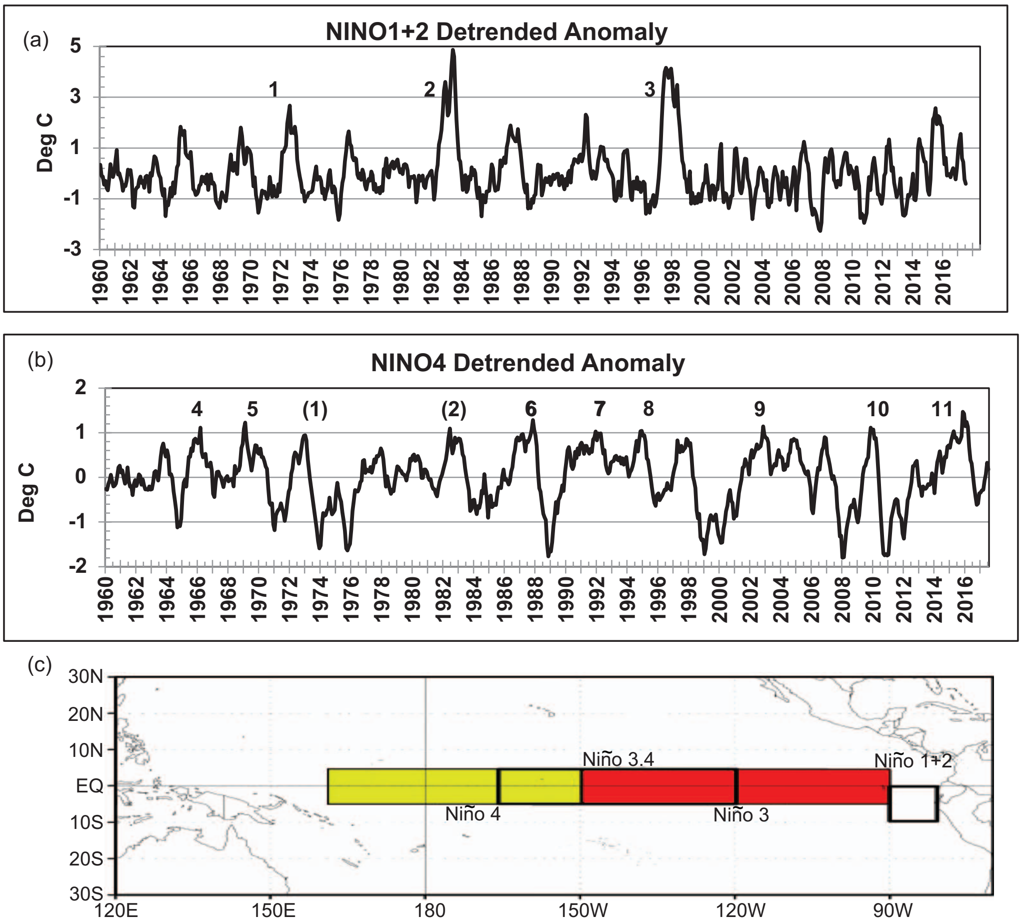

Figure 1. (*a*) The El Nino NINO1+2 index identifies three strong eastern Pacific El Nino events between 1960 and 2016. (*b*) El Nino index NINO4 characterizes the sea surface temperature of the central tropical Pacific with additional eight El Nino events. (*c*) Regions of temperature averaging for El Nino indices as defined by NOAA.

(Eastern Pacific) El Nino manifests with a warming in the eastern Pacific region characterized by a peak in El Nino index NINO1+2 (figure 1). The thermocline deepens there reducing upwelling of cold water to the surface. The CP (Central Pacific) El Nino starts with warming of the sea surface temperature in the central Pacific region, shown as a peak in NINO4 index, with the main feature being an advection of waters from the warm pool in the west. Different El Nino types have quite different teleconnections to different regions of the globe with different consequences for temperature and precipitation variability (Wang *et al* 2013, Kim *et al* 2016, Xu *et al* 2017). For example, the EP El Nino is connected with generally increased precipitation in the southwestern US, while the CP El Nino is not. Therefore it is of importance to understand the differences and similarity of different El Nino types.

In this report we investigate the atmospheric CO_2 response to strong El Nino events from 1960–2016, keeping in mind the possibility of different responses by the two different types of El Nino. From the NOAA NINO1+2 index (0–10°S and 90–80°W) available at the website www.cpc.ncep.noaa.gov/data/indices/sstoi.indices we select the three strongest El Nino events (figure 1(*a*)) of 1973, 1983, and 1998. The NOAA NINO4 (5°N–5°S and 160°E–150°W) index captures the CP El Nino events. Here we find eight additional identifiable peaks (denoted by numbers 4–11 in figure 1(*b*)), making a total of 11 El Nino events to be considered in the following analysis.

The 2016 El Nino is found to be of a mixture of both El Nino types. It is seen as the strongest El Nino in NINO4 index (figure 1(*b*)) and it also appears in a somehow weaker form in NINO1+2 index (figure 1(*a*)). The peak in NINO1+2 region occurs in June 2015, while the peak in NINO4 index occurs in November, which is the time of a year consistent with other El Nino peaks. In our analyses we classify the 2016 El Nino as predominantly of the CP character. Our classification of the 2016 El Nino is slightly different from that of Paek *et al* (2017) who also suggest the 2016 El Nino to be of a mixed character, however, with predominantly EP consequences.

2. Temperature and carbon dioxide data

To perform our study we start with monthly temperature and CO_2 data. We use the UK

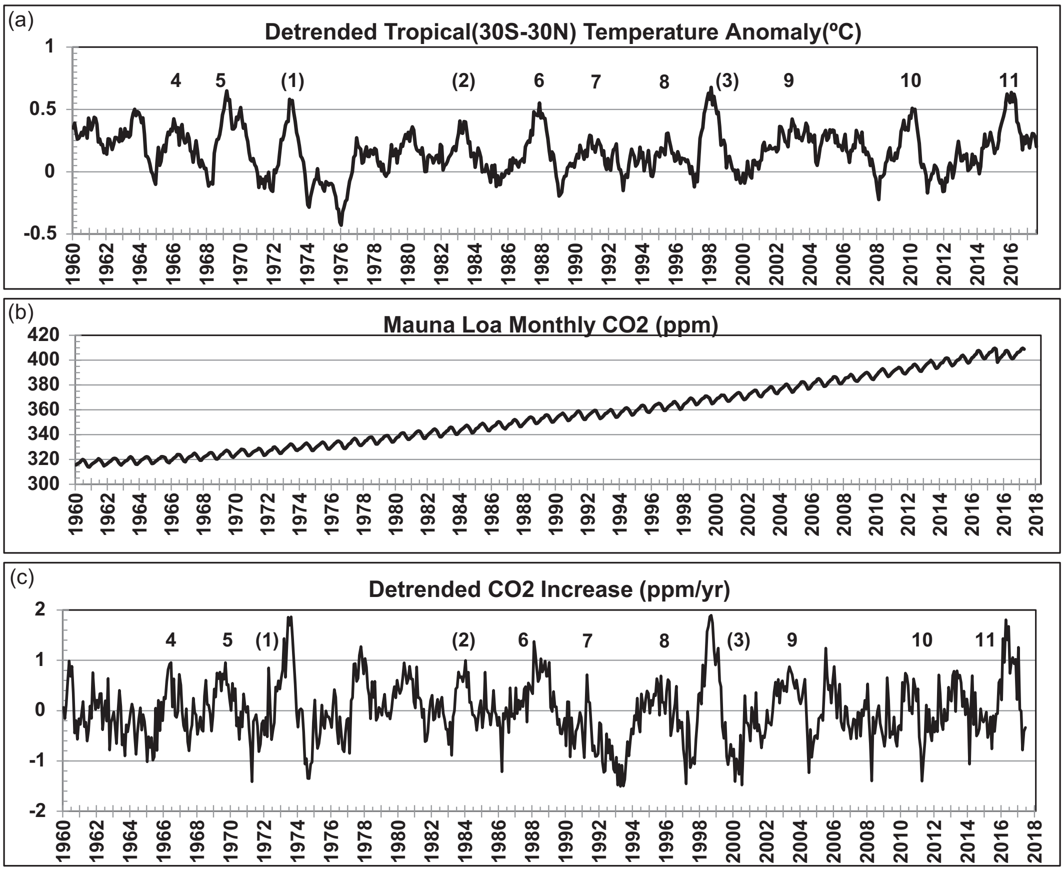

Figure 2. (*a*) Monthly tropical (30°S–30°N) temperature anomaly using the HadCRUT4 data. Numbers indicate the CP El Ninos and numbers in parenthesis the EP El Ninos. (*b*) Monthly atmospheric CO_2 concentration record from Mauna Loa Observatory. (*c*) Differentiated CO_2 anomaly record from Mauna Loa Observatory. All anomalies are with respect to the 1960–2016 mean. The time series are de-trended with the mean set to zero.

Meteorological Office HadCRUT4.5.0.0 monthly temperature data integrated over tropics (30°S to 30°N) available at the website www.metoffice.gov.uk/hadobs/hadcrut4/data/current/download.html.

The de-trended tropical temperature anomaly (with respect to 1960–2015 mean) shows peaks (figure 2(*a*)) near selected eleven El Nino events.

As a proxy for global mean CO_2 concentration (Thoning *et al* 1989) we use the monthly CO_2 averages at Mauna Loa Observatory available at the NOAA website ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt. The CO_2 record (figure 2(*b*)) is dominated by the anthropogenic contribution and the seasonal CO_2 cycle. They need to be removed to isolate the CO_2 contribution allocated to individual El Nino events. The seasonal cycle is removed as described on the NOAA website. The anthropogenic contribution can be removed by subtracting a definite fraction of estimated industrial CO_2 production (Keeling *et al* 1995, Jones *et al* 2001). To avoid uncertainty introduced by estimate of the amount of industrial produced CO_2 and the fraction thereof remaining in the atmosphere, we use an alternate procedure similar to that of Humlum *et al* (Humlum *et al* 2013, Richards 2013) in which we subtract from a given monthly CO_2 value the values that occurred in the same month a year earlier. In this case the peaks in resulting time series (figure 2(*c*)) are not maxima in CO_2 concentration (which are dominated by a seasonal cycle), but the annual increases in monthly CO_2 concentration. This procedure removes the anthropogenic CO_2 increase and preserves the CO_2 variability due to short term El Nino events. Such de-trended annual increase in CO_2 values (ppm yr^{-1}) with the 1960–2015 mean set to zero is shown in figure 2(*c*).

3. El Nino and near surface air tropical temperature

We define the El Nino induced warming as the height of the near surface air temperature peak above the 1960–2015 mean. The warming due to individual El Nino events is shown in figure 3(*a*). The super El Nino of 1998 produced the largest warming from all considered El Nino events. The average warming produced by the EP El Nino was about 50% higher (0.6 °C compared to 0.4 °C) than the average of the CP El Nino events.

The 2016 El Nino was among the three strongest CP El Ninos as far as the raise of tropical temperature is concerned (figure 2(*a*)). A special feature of this El Nino

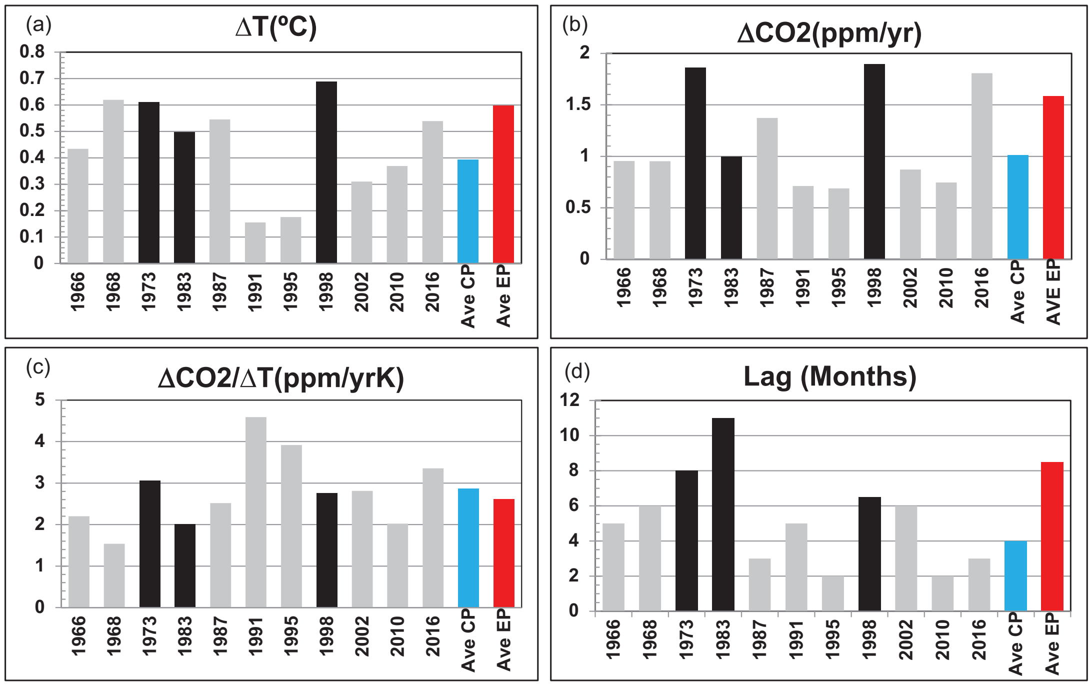

Figure 3. (*a*) The tropical temperature increase (ΔT) during the individual El Nino events. Gray columns denote the CP and the black columns EP El Ninos. The red and blue columns are corresponding averages over all EP and CP El Ninos. (*b*) The corresponding increases in CO_2 growth rate. (*c*) The temperature/CO_2 feedback, $\Delta CO_2/\Delta T$, for individual El Ninos and their averages. (*d*) Time lags for individual El Nino events and their averages.

is also the fact that the tropical temperature remained close to its peak value for several months, considerably longer than in the case of other El Ninos with a high tropical temperature peak.

4. Carbon dioxide response to El Nino warming

The atmospheric CO_2 concentration at Mauna Loa Observatory contains the generally increasing CO_2 background due to anthropogenic emission (it has been estimated that about 50% of the CO_2 emitted from fossil fuel burning and cement production remains in the atmosphere (Keeling *et al* 1995)). We are interested in the temperature increase that is due to a naturally occurring El Nino event, and the accompanying climate system CO_2 response. After removal of the low frequency variability (anthropogenic contribution and seasonal variability) we use the differentiated CO_2 time series (figure 2(*c*)) to calculate the CO_2 increase as the difference between the maximum value during the considered El Nino event and the 1960–2015 mean. The resulting increases for individual El Nino events are shown in figure 3(*b*). Again, the average height of the EP El Ninos is about 50% higher than the average of the CP El Ninos.

We estimate the CO_2 increase $\Delta CO_2/\Delta T$ per degree of temperature increase (figure 3(*c*)). The $\Delta CO_2/\Delta T$ is effectively the same for both El Nino types, 2.8 ppm yr^{-1} K^{-1} for CP El Ninos and 2.6 ppm yr^{-1} K^{-1} for the EP ones. Combining both El Nino types we obtain the sensitivity of CO_2 growth rate to tropical temperature to be 2.8 ± 0.9 ppm $yr^{-1}K^{-1}$ (or 5.9 ± 1.9 GtC $yr^{-1}K^{-1}$). We note that this value is per 1 K increase of the tropical near surface air temperature, not global temperature. The CO_2 sensitivity to global temperature would be about a factor of two higher (due to smaller increases of global compared to tropical temperature during El Nino events).

Our sensitivity of CO_2 growth rate to tropical temperature deduced from observation 5.9 ± 1.9 GtC $yr^{-1}K^{-1}$ is consistent with an estimated 'best fit' by Cox *et al* (2013) of 5.1 ± 0.9 GtC yr^{-1} K^{-1}.

5. Time lag of the temperature–CO_2 feedback

The lag of CO_2 flux after the tropical temperature has been known for some time. Adams and Piovesan (2005) found peaks of CO_2 fluxes into the atmosphere approximately 6 months after maximum values in the El Nino MEI (Multivariate ENSO Index) index, and a lag of about 4 months (they called this 'almost no lag') after mean tropical annual temperature. Wang *et al* (2013) report a strong concurrent correlation (no lag) between the CO_2 flux and the 12 month concurrent running averages of tropical land temperature. Humlum *et al* (2013) found a lag of about 9.5–10 months between the peaks in CO_2 flux and global surface air temperature.

Using the monthly data we find maximum correlations between the surface air tropical temperature and the CO_2 flux rate at the lag of 7 to 8 months (figure 4). This approximate mean value does not take

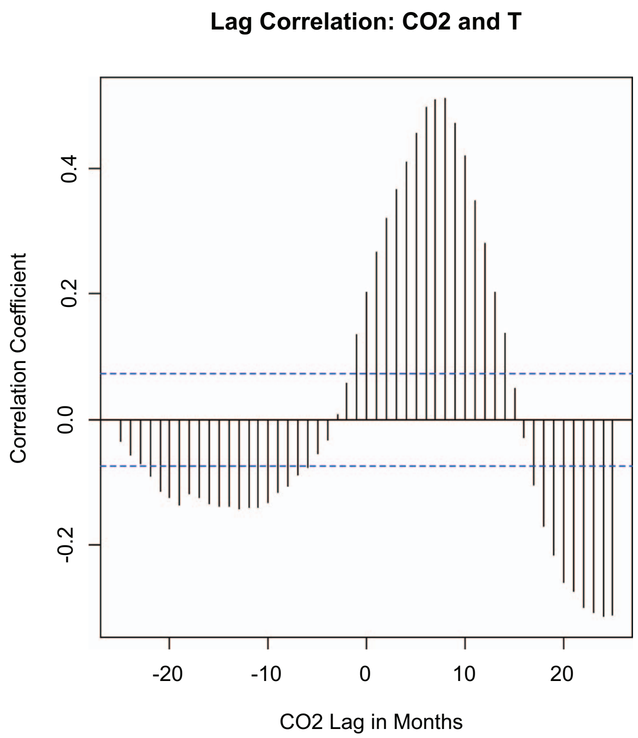

Figure 4. Lag correlations between monthly tropical temperature and the CO_2 atmospheric growth rate (1960–2016). The maximum correlation occurs at the lag between 7 and 8 months.

into account the differences between the two El Nino types. To obtain time lags for individual El Nino events we consider the tropical temperature anomaly (figure 2(*a*)) and the differential CO_2 anomaly as shown in figures 2(*a*) and (*c*). We determine the positions of the maxima of the temperature anomaly and the maxima in differential CO_2 for each considered El Nino event. We define the lag of the CO_2 behind the temperature by the difference in time between the maximum of temperature and the maximum of differentiated CO_2 record.

We find that the time lags of the CO_2 peaks behind the temperature peaks differ significantly for the two types of El Nino. The CP El Ninos (1966, 1969, 1987, 1991, 1995, 2002, 2010 and 2016) show the average lag of about 4.0 ± 1.7 months, while the group of EP El Ninos (1973, 1983 and 1998) shows the average delay of 8.5 ± 2.3 months (figure 3(*d*)). The difference is quite large with the average lag of the EP El Ninos larger by about a factor of two than the lag of the CP El Nino events.

The Welch two sample *t*-test for equal means leads to a *p*-value of $p = 0.04$ suggesting over 95% confidence level that the two means are not the same. This implies that there is less than 5% chance that the observed difference between the EP and CP El Nino lag means is produced by chance.

The earlier study (Humlum *et al* 2013) that did not distinguish between the two types of El Nino, found the maximum correlation at 9 months lag of CO_2 behind the differentiated global lower tropospheric temperature, which is close to our average lag between 7 and 8 months or our 8.5 months lag for the EP El Nino events. Other studies (Adams and Piovesan 2005, Kim *et al* 2016) suggested a shorter lag while Wang *et al* (2013) reported a lag of zero. We believe that this zero lag is an artifact of analysis procedures used. We found that the 12 month moving averages of monthly values (as used in Wang *et al* 2013) preserve positions of temperature peaks, but shifts the CO_2 peaks (due to a large asymmetry of values with respect to the peak) by about six months (so reported no lag is in reality a lag of about six months).

6. Use of the daily data

To verify that our findings are not affected by a relatively coarse time resolution (monthly averages) of the records used, we repeated our analysis at much higher resolution, specifically using daily temperature and CO_2 data. The meteorological station temperature data are usually processed such that first the station monthly averages are obtained and after that the regional or global averages are produced by processes that include averaging, homogenization and smoothing. Thus station based daily temperature data are usually not available. For this reason we use satellite derived lower tropospheric temperatures that are available on a daily basis, starting in 1979, from the University of Alabama in Huntsville website http://vortex.nsstc.uah.edu/data/msu/t2lt/tltdayamz_5.6. We considered both the tropical and global lower tropospheric temperatures. We did not find any difference between

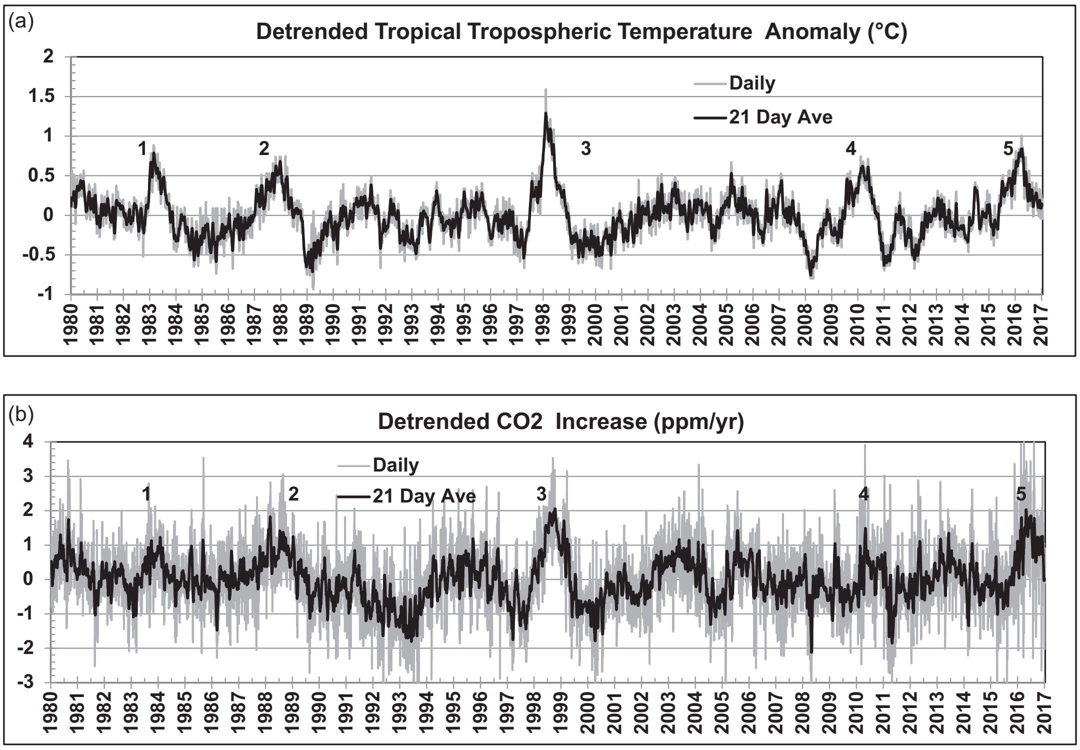

Figure 5. The daily and 21 day running averages of (*a*) the detrended tropical tropospheric temperature anomaly, and (*b*) detrended differential CO_2 data at Mauna Loa Observatory. The numbers 1 to 5 indicate strong El Ninos within the 1980–2016 years.

positions of peaks in the tropical and global temperatures (the lag correlation between the global and the tropical temperature has a maximum at the lag of zero days). The de-trended daily lower tropospheric tropical temperature anomaly (with respect to 1980–2015 mean) is shown in figure 5(*a*).

As a proxy for global mean CO_2 concentration we use the daily CO_2 measurements at Mauna Loa Observatory (Thoning *et al* 1989) that are available at ftp://aftp.cmdl.noaa.gov/data/greenhouse_gases/co2/in-situ/surface/.

The differentiated CO_2 record (figure 5(*b*)) is noisy due to the large daily CO_2 variations. Consequently it is not easy to correlate the CO_2 peaks corresponding to peaks in temperature. Even with a 21 d averaging we were able to link the CO_2 peaks to temperature peaks only for the five major El Nino events (denoted by numbers 1−5 in figure 5) within the 1980–2016 timespan. The averaging over a longer (31 d) or a shorter (11 d) time (not shown) does not change the resulting time series in any significant way. We have only two EP and three CP El Nino events in this period. Although the averages over different El Nino types are now different from those using the monthly data (and eleven El Ninos), the main result concerning the different lags of two El Nino types remains are robust. We deduce the averaged lag for two EP El Ninos to be 292 d compared to a lag of 52 d for the three CP El Ninos.

We have also subjected the daily temperature time series to a similar differentiating procedure as CO_2 data (subtracting the values of temperature a year earlier) to confirm that the procedure does not change significantly the positions of temperature peaks and we found that the resulting time lags are not significantly different.

7. Summary, discussion, and conclusion

The main goal of our analysis was to determine the differences in lag, if any, between the tropical temperature and the resulting CO_2 increases during major El Nino events. We find that the 1966, 1969, 1987, 1991, 1995, 2002, 2010, and 2016 El Nino events (figure 1(*b*)) originating predominantly in the central tropical Pacific (a region of the NINO4 index) show an average time lag of 4.0 ± 1.7 months compared to the average time lag of 8.5 ± 2.3 months for the eastern Pacific (region of the NINO1+2 index) El Nino events. The differences between the time lags of the two El Nino groups are statistically significant at the 95% confidence level, as confirmed by the Welch two sample *t*-test for equal means. The observed differences are likely related to different telecommunications of the two El Nino types and dominated by vegetation response.

Recent analysis of OCO-2 satellite data (Liu *et al* 2017) found that during the 2016 El Nino the vegetation contributed to the CO_2 emission increase through both the fires and vegetation respiration changes. We conjecture that fire response to increasing temperature and decreasing precipitation can be fast relative to response in vegetation respiration. Thus our hypothesis is that the shorter time lag between the temperature rise and an increase in CO_2 emission rates (central Pacific CP El Ninos) is influenced predominantly by fire response, while the longer time lag (eastern Pacific EP El Ninos) is dominated by the vegetation respiration change. Future research will confirm or reject our hypothesis.

We also find that the CP El Nino has a lower rate of temperature (figure 3(*a*)) and CO_2 increase (figure 3(*b*)) than the EP El Nino events. However, the sensitivity of CO_2 growth rate to tropical temperature is the same for both El Nino types (figure 3(*d*)) around $2.8 \pm 0.9\,\mathrm{ppm\,yr^{-1}K^{-1}}$ or in gigatons of carbon per year $5.9 \pm 1.9\,\mathrm{GtC\,yr^{-1}\,K^{-1}}$. This carbon growth rate sensitivity to tropical temperature derived from observations is consistent with the range of values from $2.9 \pm 1.4\,\mathrm{GtC\,yr^{-1}\,K^{-1}}$ to $9.7 \pm 0.7\,\mathrm{GtC\,yr^{-1}K^{-1}}$ deduced earlier (Cox *et al* 2013) from simulations by the nine climate models.

The 2016 El Nino was unusual (Paek *et al* 2017) in that its warming was distinct in both regions, in the region of NINO1+2 characterizing the eastern Pacific El Ninos and in the NINO4 region of the central Pacific. In our treatment we considered the 2016 El Nino as a part of the central Pacific group since it produced the highest peak in the NINO4 records (figure 1(*b*)). We could have considered the 2016 El Nino as belonging to both the eastern Pacific and central Pacific group. The CO_2 record (figure 2(*c*)) shows two separate CO_2 peaks in response to the 2016 tropical Pacific warming (figure 2(*a*)). The first peak appears with a lag of about 3 months and the second with a lag of 11 months, consistent with our result of different lags between the CP and EP El Ninos.

Our analysis provides at least a partial support to the notion of two El Nino types (Yeh *et al* 2014, Capotondi *et al* 2015) with some distinct characteristics, rather than a single El Nino phenomenon with a continuum of changing parameters. The general time delay between the temperature and the CO_2 increases suggests that the CO_2 responds to temperature increase indirectly through other climate related processes (sometime acting in opposite directions) like vegetation (precipitation increase in one area and droughts and wildfires in another), and upwelling of CO_2 in the cold tongue of tropical Pacific (Keeling *et al* 1995, Jones *et al* 2001, Yeh *et al* 2014). It is our hope that our analysis that identifies and delineates the two types of El Nino will contribute towards further identification of relevant processes.

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El Nino indices: www.cpc.ncep.noaa.gov/data/indices/sstoi.indices
Tropospheric temperature data: http://vortex.nsstc.uah.edu/data/msu/t2lt/tltdayamz_5.6. Mauna Loa CO_2 data: ftp://aftp.cmdl.noaa.gov/data/greenhouse_gases/co2/in-situ/surface/

ORCID iDs

Petr Chylek https://orcid.org/0000-0001-5916-1608

References

Adams J and Piovesan G 2005 Long series relationships between global interannual CO_2 increment and climate: evidence for stability and change in role of the tropical and boreal-temperate zones *Chemosphere* **59** 1595–612

Cai W *et al* 2015 ENSO and greenhouse gas warming *Nat. Clim. Change* **5** 849–59

Capotondi A *et al* 2015 Understanding ENSO diversity *Bull. Am. Meteorol. Soc.* **96** 921–38

Chen D *et al* 2015 Strong influence of westerly wind bursts on El Nino diversity *Nat. Geosci.* **8** 339–45

Choi J, An S-I, Kug J-S and Yeh S-W 2011 The role of mean state on changes in El Nino's flavor *Clim. Dyn.* **37** 1205–15

Christensen J H *et al* 2013 Climate phenomena and their relevance for future regional climate change *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker (Cambridge: Cambridge University Press)

Cobon D, Ewai M, Inape K and Bourke R 2016 Food shortages associated with droughts, floods, frosts and ENSO in Papua New Guinea *Agric. Syst.* **145** 150–64

Collins M *et al* 2010 The impact of global warming on the tropical Pacific Ocean and El Nino *Nat. Geosci.* **3** 391–7

Cox P *et al* 2013 Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability *Nature* **494** 341–4

Humlum O, Stordahl K and Solheim J-E 2013 The phase relation between atmospheric carbon dioxide and global temperature *Glob. Planet. Change* **100** 51–69

Jacox M *et al* 2016 Impacts of the 2015–2016 El Nino on the California current system: early assessment and comparison to past events *Geophys. Res. Lett.* **43** 7072–80

Jimenez-Munoz J *et al* 2016 Record-breaking warming and extreme drought in the Amazon rainforest during the course of El Nino 2015–2016 *Sci. Rep.* **6** 33130

Jones C, Collins M, Cox P and Spall S 2001 The carbon cycle response to ENSO: a coupled climate-carbon cycle model study *J. Clim.* **14** 4113–29

Keeling C, Whorf T, Whalen M and van der Plicht J 1995 Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980 *Nature* **375** 666–70

Kim J-S, Kug J-S, Hoon J-H and Jeong S-J 2016 Increased atmospheric CO_2 growth rate during El Nino driven reduced terrestrial productivity in the CMIP5 ESMs *J. Clim.* **29** 8783–805

Lee J and Julien P 2016 Teleconnections of the ENSO and South Korean precipitation patterns *J. Hydrol.* **534** 237–150

Lee T *et al* 2010 Record warming in the South Pacific and western Antarctica associated with the strong central-Pacific El Nino in 2009–2010 *Geophys. Res. Lett.* **37** L19704

Liu J *et al* 2017 Contrasting carbon cycle responses of the tropical continents to the 2015–2016 El Nino *Science* **358** eaam5690
Meehl G and Washington W 1996 El Nino-like climate change in a model with increased atmospheric CO_2 concentrations *Nature* **382** 56–60
Ng J, Turner S and Galelli S 2017 Influence of El Nino Southern Oscillation on global hydropower production *Environ Res. Lett.* **12** 034010
Paek H, Yu J-Y and Qian C 2017 Why were the 2015/2016 and 1997/1998 extreme El Ninos different *Geophys. Res. Lett.* **44** 1848–56
Richards M 2013 Comment on the phase relation between atmospheric carbon dioxide and global temperature *Glob. Planet. Change* **107** 226–8
Sterner E and Johansson D 2017 The effect of climate-carbon cycle feedbacks on emission metrics *Environ. Res. Lett.* **12** 034019
Taschetto A *et al* 2014 Cold tongue and warm pool ENSO events in CMIP5: mean state and future projections *J. Clim.* **27** 2861–85
Thoning K, Tans P and Komhyr W 1989 Atmospheric carbon dioxide at Mauna Loa Observatory 2. Analysis of the NOAA GMCC data *J. Geophys. Res.* **94** 1974–85
Vecchi G and Wittenberg A 2010 El Nino and our future climate: where do we stand? WIREs *Clim. Change* **1** 260–70
Wang W *et al* 2013 Variations in atmospheric CO_2 growth rates coupled with tropical temperature *Proc. Natl Acad. Sci. USA* **110** 13061–6
Wittenberg A, Rosati A, Delworth T, Vecchi G and Zeng F 2014 ENSO Modulation: is it decadally predictable? *J. Clim.* **27** 2667–81
Xu K *et al* 2017 CMIP5 projections of two types of El Nino and their related tropical precipitation in the twenty-first century *J. Clim.* **30** 849–64
Yeh S-W, Kug J-S, Dewitte B, Kwon M-H, Kirtman B and Jin F 2009 El Nino in a changing climate *Nature* **461** 511–4
Yeh S-W, Kug J-S and An S-I 2014 Recent progress on two types of El Nino: observations, dynamics, and future changes *Asia-Pac. J. Atmos. Sci.* **50** 69–81