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To cite this article: Petr Chylek et al 2018 Environ. Res. Lett. 13 024001

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

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Keywords: El Nino, carbon dioxide, time lag, EP and CP El Ninos, near surface air tropical temperature, Mauna Loa Observatory

Abstract

We analyze monthly tropical near surface air temperature and Mauna Loa Observatory carbon dioxide (CO2) 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 CO2 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 CO2 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, Jach 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 CO2 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 CO2 (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
(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
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
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 CO₂ concentration at Mauna Loa Observatory contains the generally increasing CO₂ background due to anthropogenic emission (it has been estimated that about 50% of the CO₂ 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 CO₂ response. After removal of the low frequency variability (anthropogenic contribution and seasonal variability) we use the differentiated CO₂ time series (figure 2(c)) to calculate the CO₂ 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 CO₂ increase ΔCO₂/ΔT per degree of temperature increase (figure 3(c)). The ΔCO₂/ΔT 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 CO₂ 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 CO₂ 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 CO₂ 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–CO₂ feedback

The lag of CO₂ flux after the tropical temperature has been known for some time. Adams and Fioresean (2005) found peaks of CO₂ 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 CO₂ 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 CO₂ flux and global surface air temperature.

Using the monthly data we find maximum correlations between the surface air tropical temperature and the CO₂ flux rate at the lag of 7 to 8 months (figure 4). This approximate mean value does not take
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 CO₂ 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 has a maximum at the lag of zero 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 CO₂ concentration we use the daily CO₂ 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 CO₂ record (figure 5(b)) is noisy due to the large daily CO₂ variations. Consequently it is not easy to correlate the CO₂ peaks corresponding to peaks in temperature. Even with a 21 d averaging we were able to link the CO₂ peaks to temperature peaks only for the five major El Nino events (denoted by numbers 1–5 in figure 5) within the 1980–2016 time-span. 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 CO₂ 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 CO₂ 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 CO₂ 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 ± 0.9 ppm yr$^{-1}$K$^{-1}$ or in gigatons of carbon per year 5.9 ± 1.9 GtCyr$^{-1}$K$^{-1}$. This carbon growth rate sensitivity to tropical temperature derived from observations is consistent with the range of values from 2.9 ± 1.4 GtCyr$^{-1}$K$^{-1}$ to 9.7 ± 0.7 GtCyr$^{-1}$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 (sometimes 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.

Acknowledgments

The authors thank the editor, the IOP peer-review team, three anonymous reviewers, and Chris Jones for their effort to improve the submitted manuscript. MKD was supported by a grant from the US Department of Energy, Office of Science, Office of Biological and Environmental Research, Climate Change Research Directorate, Terrestrial Ecosystem Science Program. MKD thanks Michael Kuperberg for initiating the project and Daniel Stover for sustaining it. All data used in this research are available at the following websites: 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/

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