El Niño and its relationship to changing background conditions in the tropical Pacific Ocean

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[1] This paper addresses the question of whether the increased occurrence of central Pacific (CP) versus Eastern Pacific (EP) El Niños is consistent with greenhouse gas forced changes in the background state of the tropical Pacific as inferred from global climate change models. Our analysis uses high-quality satellite and in situ ocean data combined with wind data from atmospheric reanalyses for the past 31 years (1980–2010). We find changes in background conditions that are opposite to those expected from greenhouse gas forcing in climate models and opposite to what is expected if changes in the background state are mediating more frequent occurrences of CP El Niños. A plausible interpretation of these results is that the character of El Niño over the past 31 years has varied naturally and that these variations projected onto changes in the background state because of the asymmetric spatial structures of CP and EP El Niños. **Citation:** McPhaden, M. J., T. Lee, and D. McClurg (2011), El Niño and its relationship to changing background conditions in the tropical Pacific Ocean, *Geophys. Res. Lett.*, *38*, L15709, doi:10.1029/2011GL048275.

1. Introduction

[2] The El Niño/Southern Oscillation (ENSO) cycle is the largest year-to-year variation of the Earth's climate. ENSO, the warm phase of which is referred to as El Niño and the cold phase La Niña, originates in the tropical Pacific through coupled interactions of the ocean and the atmosphere. Its effects are felt worldwide through atmospheric and oceanic teleconnections, with significant impacts on society and natural systems [*McPhaden et al.*, 2006].

[3] Recently, evidence has emerged for a new variant of El Niño, called either date line El Niño [*Larkin and Harrison*, 2005], warm pool El Niño [*Kug et al.*, 2009], central Pacific El Niño [*Kao and Yu*, 2009], or El Niño-Modoki [*Ashok et al.*, 2007]. This type of El Niño has its largest anomalous warming in the central equatorial Pacific in contrast to the more traditional type of El Niño which has its largest warming in the eastern equatorial Pacific. For the purposes of this study, we will refer to these variants of El Niños as central Pacific (CP) and eastern Pacific (EP) El Niños. There is a clear trend toward an increasing frequency of CP El Niños in the past 30 years [*Ashok et al.*, 2007; *Kao and Yu*, 2009; *Kug et al.*, 2009; *Lee and McPhaden*, 2010]. Moreover, compared to EP El Niños, CP El Niños result in different far-field teleconnection patterns and hence climatic impacts [e.g., *Wang and Hendon*, 2007; *Weng et al.*, 2007; *Kim et al.*, 2009].

[4] *Yeh et al.* [2009] have recently proposed that the increased frequency of CP El Niño occurrence is the result of anthropogenic greenhouse gas (GHG) forcing, based on an analysis of 11 global climate change models from the Coupled Model Intercomparison. Project phase 3 multimodel data set (CMIP-3). These authors compared 20th century control simulations to simulations in which CO_2 levels approximately doubled from current levels by the end of the 21st century. The ensemble of models they analyzed showed a greater tendency for more CP El Niños under doubled CO_2 conditions, leading the authors to hypothesize that "more frequent CP-El Niño occurrence during recent decades is associated with an anthropogenic climate change" [*Yeh et al.*, 2009, p. 513].

[5] *Yeh et al.* [2009] further proposed that the greater occurrence of CP El Niños under GHG forcing was mediated by changes in background conditions. In particular, various studies using CMIP-3 model output have shown that GHG forcing leads to a weakening of the Pacific trade winds and to a shoaling of the equatorial thermocline in the central and western Pacific [e.g., *Collins et al.*, 2010]. *Yeh et al.* [2009] argued that weakening of the trade winds weakens upwelling in the eastern Pacific, which would reduce the magnitude of sea surface temperature (SST) anomalies generated there. Conversely, they argued that a shallower thermocline in the central and western Pacific would strengthen the connection between surface and subsurface layers (i.e., the "thermocline feedback") allowing for development of larger SST anomalies near the date line. This thermocline feedback would act in concert with the "zonal advective feedback" which typically operates to generate SST anomalies in the central Pacific [*Wang and McPhaden*, 2000; *An and Jin*, 2001].

[6] The purpose of this paper is to address the question of whether the recent increased occurrence of CP versus EP El Niños is consistent with changes in the background state as proposed by *Yeh et al.* [2009]. Our analysis covers the past 31 years (1980–2010) for which numerous high-quality subsurface data exist to characterize thermocline depth variations in the tropical Pacific. This period also coincides with the satellite era of high-quality, high spatial resolution SST measurements, which allow for clear distinctions between differing El Niño SST patterns.

[7] The period of our study includes nine El Niños, with EP events clustering toward the beginning of the record and CP events toward the end. We recognize that there are not many El Niño realizations in this relatively short record. However, we will show that the patterns of variability over this 31 year period are robust based on dynamically consistent

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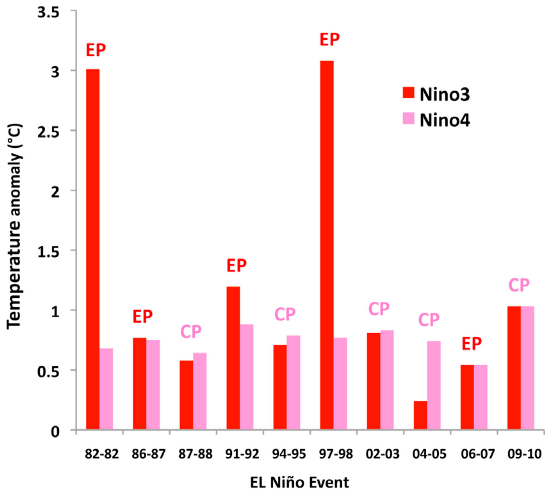

Figure 1. Nino3 (red) and Nino4 (pink) SST anomalies for El Niños between 1980 and 2010. Values are for the peak December to January season. Eastern Pacific (EP) and central Pacific (CP) events are labeled according to various indices described in the text.

relationships between fields of wind stress, SST, and thermocline depth variations that are completely independent of one another. Documentation of these consistent relationships among high-quality data products for the past three decades is valuable for both understanding current trends as well as for climate model evaluation.

2. Data

[8] We use three data sets, one for SST, one for the depth of the 20°C isotherm (Z20) which is a measure of thermocline depth in the tropical Pacific, and one for wind stress. Each covers the period January 1980 to December 2010. Monthly anomalies are computed around a mean seasonal cycle based on a 30 year (1981–2010) climatology.

[9] We obtain a gridded Z20 data set prepared by the Australian Bureau of Meteorology Research Centre (BMRC). The product [*Smith*, 1995] is based on data from moored buoys, expendable bathythermographs, and Argo floats. It is available with monthly resolution on a 1° latitude × 2° longitude horizontal grid.

[10] The SST data used in this study are derived from blended in situ and satellite analyses of *Reynolds et al.* [2002]. These data are available with weekly resolution on 1° latitude × 1° longitude horizontal grid. We processed these data to monthly averages for November 1981 to December 2010. To complete the record back to January 1980, we appended a gridded monthly in situ SST data product on a 2° latitude/longitude grid [*Smith et al.*, 2008].

[11] Daily wind data the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40) were downloaded from http://data.ecmwf.int/data/ for the period January 1980 to August 2002. We extended this record to December 2010 using daily interim ECMWF reanalysis winds. Daily wind stresses were computed using a constant drag coefficient of 1.2×10^{-3} and a constant air density of 1.2 kg m^{-3}. Monthly mean wind stresses were then computed from the daily data.

3. Results

[12] There are nine El Niños in the record, one of which (1986–1988) extends over 18 months with two peak (December to February) seasons. The tendency for increasing frequency of CP versus EP El Niños is evident in the trend (Figure 1) for SST anomalies in the central and western Pacific (characterized by the Nino4 index averaged over the region 5°N–5°S, 150°W–160°E) to equal or exceed SST anomalies in the eastern Pacific (characterized by the Nino3 index averaged over the region 5°N–5°S, 90°W–150°W). We identify specific CP events in the record based on various indices that have been developed using linear or nonlinear combinations of Nino3 and Nino4 time series, or other metrics, as summarized by *Ren and Jin* [2011] and *Singh et al.* [2011]. From these indices we can infer that three of four El Niños during the last decade (2000–2010) were CP El Niños (Figure 1). Conversely, four of six events in the first 20 years (1980–1999) were EP El Niños, two of which (1982–1983 and 1997–1998) were very strong. Thus, statistically 1980–1999 is characterized by a predominance of EP El Niño variability and 2000–2010 by CP El Niño variability.

[13] To highlight the structural changes in El Niño over the past three decades, we form composites of wind stress, SST, and Z20 in the tropical Pacific for these two time periods (Figure 2). We focus on the peak of El Niño

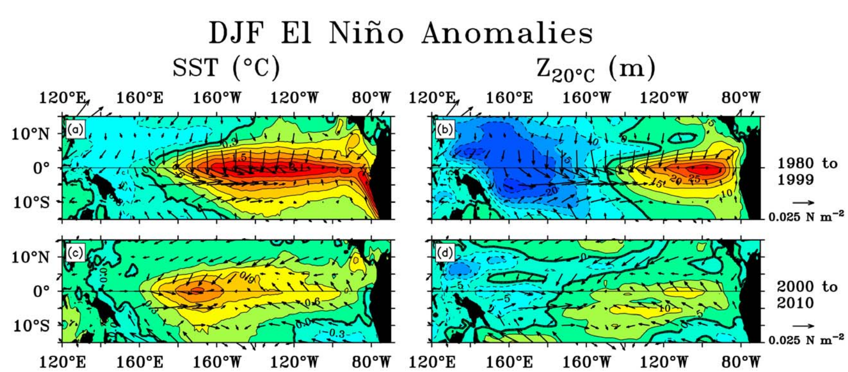

Figure 2. Composites of (a) SST (in °C) and (b) Z20 (in m) for December-February (DJF) of El Niño years during 1980–1999 with zonal wind stress (in N m^{-2}) overplotted on both. (c and d) Same as Figures 2a and 2b but for 2000–2010. Versions of these plots masking out values less than one standard error for the mean are shown in Figure S2.

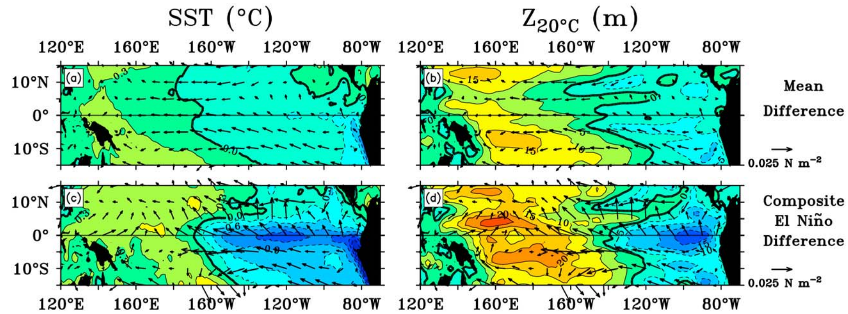

Figure 3. Decadal mean differences (2000–2010 minus 1980–1999) for (a) SST (in °C) and (b) Z20 (in m) with decadal mean wind stress differences (in N m^{-2}) overplotted on both. (c and d) Corresponding El Niño composite differences. Versions of these plots masking out values less than one standard error for the mean are shown in Figure S3.

development in December-February, though alternative choices of 3 month seasons from September through February would yield similar results. For 1980–1999, maximum SST anomalies were located east of 160°W, with westerly wind anomalies to the west and anomalous surface wind convergence over the warm SST anomalies (Figure 2a). Associated with the westerly wind anomalies, the thermocline along the equator flattened out, with deeper than normal Z20 in the east and shallower than normal Z20 in the west (Figure 2b). East of 140°W, SST anomalies were associated with large thermocline depth anomalies, indicating the efficacy of the thermocline feedback in the eastern Pacific. Conversely, substantial warm SST anomalies between 140°W and the date line, where thermocline depth did not change much or was shallower than normal, indicate the importance of the zonal advective feedback in this region.

[14] For the period 2000–2010, the maximum SST anomaly was located between the date line and 160°W (Figure 2c). The trade winds on average did not weaken as much as during El Niños of the previous 20 years, and there were even easterly anomalies evident along the equator in the eastern Pacific. The thermocline anomalously deepened in the eastern Pacific and shoaled in the west, but not as much as during 1980–1999 (Figure 2d). Weak SST and Z20 anomalies in the eastern Pacific suggest that the thermocline feedback was not very strong. On the other hand, the maximum SST anomaly coincided with a zero in Z20 anomaly near the date line, indicating that the zonal advective feedback was the primary source of anomalous warming during this time period.

[15] There have been systematic changes in background conditions over the past 31 years as well (Figure 3 and Figure S1 in the auxiliary material).[1] Compared to the last 2 decades of the 20th century, the trade winds were stronger, the thermocline was deeper in the west and shallow in the east, and SSTs were slightly cooler in east and warmer in the west during the first decade of the 21st century (Figures 3a and 3b). *Feng et al.* [2010] noted similar tendencies over the same time period for tropical Pacific surface wind stress, SST and sea level height differences (which mirror thermocline depth differences) across the Pacific basin. These tendencies are opposite to that expected for the response of the tropical Pacific to GHG forcing exhibited by most climate change models [*Collins et al.*, 2010]. We thus interpret the observed trends in background conditions to imply that natural climate variability has been more prominent than the effects of GHG forcing over the past three decades.

[16] In tandem with these changes in background conditions, CP El Niños have increased in frequency relative to EP El Niños. This relationship is opposite to what is expected if background conditions are mediating the greater frequency CP El Niños as proposed by *Yeh et al.* [2009]. In addition, because the thermocline is on average deeper in the central and western equatorial Pacific during 2000–2010 compared to 1980–1999, one would expect the thermocline feedback to be weaker there rather than stronger there, and thus less efficient at generating SST anomalies.

[17] It is interesting to note that the difference between the two El Niño composites in terms of zonal wind stress, Z20 and SST patterns (Figures 3c and 3d) is similar to that for the decade mean differences (Figures 3a and 3b). Both exhibit anomalously shallow thermocline and cold SST in the east, deep thermocline and warm SST in the west, and stronger trade winds during the first decade of the 21st century relative to the last two decades of the 20th century. The El Niño composite differences reflect the fact that during CP El Niños, the trade winds do not weaken as much, the thermocline does not flatten as much, and SST in the eastern Pacific cold tongue does not warm up as much. We interpret this similarity between mean and El Niño composite differences to indicate that decadal changes in the background state are the result of (rather than the cause of) a shift in El Niño statistics, which are varying naturally. Corresponding mean and El Niño composite difference patterns are not identical because the mean differences also include neutral and La Niña years not included in the El Niño composites.

4. Summary and Discussion

[18] We have shown that coincident with a systematic shift over the past 31 years to more frequent CP versus EP El Niños, the trade winds have strengthened and the thermocline has tilted more steeply down to the west in the tropical Pacific. These changes in background conditions are opposite to those expected from GHG forcing and opposite to what is expected if changes in the background state are mediating the more frequent occurrence of CP El Niños as proposed by *Yeh et al.* [2009]. A plausible interpretation of these results is that the character of El Niño over the past 31 years has varied naturally and that these variations have

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL048275.

projected onto changes in the background state because of the asymmetric spatial structures of CP and EP El Niños. *Yeh et al.* [2011] have also suggested based on a coupled model study that one cannot preclude the possibility of natural variability in causing the more frequent CP-El Niño observed in recent decades.

[19] Our interpretation of the relationship between background conditions and El Niño statistics is similar to that of *Rodgers et al.* [2004] who noted that in a coupled ocean-atmosphere model simulation, tropical Pacific decadal variability arose from the statistical residual of asymmetric anomaly patterns associated with model El Niño and La Niña events. *Sun and Yu* [2009] using historical and paleoclimate data also suggested that changes in ENSO statistics could project onto decadal changes in background conditions. The emphasis in our paper is on the contribution to this decadal variability associated with the asymmetry between EP and CP El Niños whose relative frequency and amplitude vary with time. *Lee and McPhaden* [2010] similarly pointed out that the recent SST warming trends in the western equatorial Pacific appeared to be the result of greater frequency and amplitude of CP El Niños. Likewise, *Choi et al.* [2011] have noted in coupled model simulations that residuals resulting from structural asymmetries in these two types of El Niño contribute to decadal background state variations in their model.

[20] Our interpretation of changes over the past 31 years in terms of natural variability is based on the lack of correspondence between the observations and the CMIP-3 simulations for combined mean and El Niño tendencies. It could be however that GHG forcing plays a role in the observed changes, on the premise that the climate models do yet not properly represent ENSO dynamics with sufficient fidelity to consistently produce realistic behavior in the tropical Pacific under various GHG forcing scenarios [*Collins et al.*, 2010]. Alternatively, it is possible that GHG forcing effects on El Niño as inferred by *Yeh et al.* [2009] are too weak at present to be discernible above the spectrum of natural variations; or that they are evident only on longer (e.g., centennial) time scales not considered in this study.

[21] We note that *Ashok et al.* [2007] analyzed the differences between the 1979–2004 and 1958–1978 periods and found a relationship between background state and CP versus EP El Niño variations more in keeping with that proposed by *Yeh et al.* [2009]. This relationship is opposite to that between 2000–2010 and 1980–1999 analyzed here. To the extent that the data used by *Ashok et al.* [2007] for 1958–1978 are sufficiently reliable, the differences between our two studies imply that these relationships may be non stationary due, for example, to decadal changes in background conditions that occur independent of changes in El Niño statistics. Resolving these issues will require more research on ENSO, decadal variability, climate change, and their interactions.

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