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## Implications of changing El Niño patterns for biological dynamics in the equatorial Pacific Ocean

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[1] El Niño events are known to strongly affect biological production and ecosystem structure in the tropical Pacific. Understanding and predicting biological processes in this area are hampered because the existing *in situ* observing system focuses primarily on physical measurements and does not observe key biological parameters; the only high spatial and temporal resolution biology-related observations are from the global array of ocean color satellites which provide an estimate of surface chlorophyll concentrations only. Since the 1990s, an apparent shift of the El Niño maximum sea-surface temperature (SST) warm anomaly from the eastern to the central equatorial Pacific has frequently been observed. Satellite observations show significant changes in chlorophyll-a (Chl-a), new production (NP) and total primary production (PP) in the equatorial Pacific associated with these new central Pacific (CP) El Niño events (also called El Niño Modoki) relative to eastern Pacific El Niños. During CP-El Niños, NP, Chl-a and PP in the central basin are depressed relative to EP-El Niños and lower values of Chl-a and PP coincide spatially with higher SST in the central Pacific. While surface Chl-a, and integrated NP and PP over the entire equatorial band, decrease during both CP and EP-El Niños, the magnitude of this decrease seems to depend more on the intensity than type of event. The changing spatial patterns have significant implications for equatorial biological dynamics if, as has been suggested, CP-El Niños increase in frequency in the future. **Citation:** Turk, D., C. S. Meinen, D. Antoine, M. J. McPhaden, and M. R. Lewis (2011), Implications of changing El Niño patterns for biological dynamics in the equatorial Pacific Ocean, *Geophys. Res. Lett.*, 38, L23603, doi:10.1029/2011GL049674.

### 1. Introduction

[2] El Niño is known to result in interannual climate fluctuations over the Pacific Ocean, which in turn cause variability in biological production and ecosystem dynamics [e.g., Murtugudde *et al.*, 1999; Chavez *et al.*, 1999; McClain *et al.*, 2002; Wang *et al.*, 2005]. A significant decrease in biological production in the central and eastern tropical Pacific, and an increase in the western region, has been observed during

El Niño events as a result of changes in nutrient supply associated with the eastward expansion of the warm pool and the deepening/lifting of the thermocline/nutricline [Barber and Chavez, 1991; Strutton and Chavez, 2000; Turk *et al.*, 2001]. The resulting anomalies in equatorial surface chlorophyll over the past century are highly coherent with El Niño oscillation indices [Boyce *et al.*, 2010]. Recent studies also suggest a decadal change and possible regime shift in ecosystem structure [Wang *et al.*, 2010; Masotti *et al.*, 2011].

[3] One change to the physical system that may be contributing to changes in biological dynamics is the fact that since the 1990s there have been frequent occurrences of a new type of El Niño which involve a substantial longitudinal shift in both the maximum sea-surface temperature (SST) anomalies and the tropical–extra tropical teleconnections [Ashok *et al.*, 2007; Yeh *et al.*, 2009]. Central Pacific events (CP-El Niño, sometimes called El Niño Modoki) differ from the classical eastern Pacific El Niño events (EP-El Niño) in that EP-El Niños are associated with maximum warm SST anomalies in the eastern equatorial Pacific, while during the CP-El Niños, the maximum warm anomaly is observed in the central equatorial Pacific (CEP) [Lee and McPhaden, 2010; McPhaden *et al.*, 2011]. Studies have also shown that during CP-El Niños, higher than normal sea level is observed in the CEP sandwiched between lower than normal sea level on both sides of the basin [Behera and Yamagata, 2010]. Related anomalies in Walker circulation, winds, precipitation and salinity during CP-El Niño are also evident [Yeh *et al.*, 2009; Singh *et al.*, 2011]. It has been observed that the intensity of El Niños in the central equatorial Pacific has almost doubled in the past three decades, with the strongest warming occurring in 2009–10 [Lee and McPhaden, 2010]. CP-El Niños are predicted to occur more frequently under projected global warming scenarios [Yeh *et al.*, 2009] as a result of changes in background conditions such as shoaling of the thermocline in the CEP region that enhances vertical exchange processes. It is also possible that changes in the relative frequency of CP-El Niños result from natural variations in the climate system [Yeh *et al.*, 2011; McPhaden *et al.*, 2011]. Regardless of the ultimate causes for these changes, understanding the biological responses associated with CP-El Niños is necessary to fully account for the range of possible physical-biological interactions in the tropical Pacific.

[4] While there has been significant research into the physical changes associated with CP-El Niños, there have been no studies to date to determine whether CP-El Niños induce a distinct biological response. There are not enough *in situ* biological observations currently being made to directly study the differences/similarities between CP and EP-El Niños; previous research has shown, however, that remote-sensing observations are well suited to estimate certain key

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biological parameters. This study uses time series of satellite estimates of Chlorophyll-a (Chl-a), total primary production (PP) estimated from SeaWiFS ocean color observations following Morel [1991], and new production (NP) estimated from altimeter measurements following Turk *et al.* [2001] to provide the first description of the biological response associated with CP-El Niño as observed from remote sensing observations during the years 1997–2010. This response is contrasted with that from satellite observations of classical EP-El Niños as well as neutral conditions.

## 2. Data and Methods

[5] The analysis period presented herein (December 1997 - October 2010) is constrained by the availability of the satellite products, in particular the SeaWiFS data (the satellite was launched in late 1997). All satellite data products are averaged over 1°N to 1°S for consistency with earlier research wherein relationships between *in situ* NP observations and satellite altimetry were first derived [Turk *et al.*, 2001].

[6] Monthly SST along the equator (1°N to 1°S, 140°E to 100°W) for 1997–2010 is derived by averaging the daily Advanced Very High Resolution Radiometer Optimal Interpolation SST product which has 1/4° resolution (v2) [Reynolds *et al.*, 2007]. Sea level anomalies (SLA) are derived from the AVISO satellite altimeter dataset, which merges all available altimeter observations. The 20°C isotherm depth (a proxy for the thermocline depth) is available from the direct measurements made by the Tropical Atmosphere Ocean (TAO) buoy array. The buoys have a fairly coarse 15° longitude spacing for these purposes; higher resolution estimates of 20°C isotherm depth were therefore determined from the measured SLA data and a relationship derived earlier between sea level anomaly and thermocline depth [e.g., Meinen, 2005]. Daily NP ( $\text{mmol N m}^{-2}$ ) is then calculated via a previously determined linear relationship between 20°C isotherm depth and integrated new production [Turk *et al.*, 2001].

[7] Daily PP ( $\text{gC m}^{-2}$ ) was estimated from SeaWiFS Chl-a, Reynolds SST [Reynolds *et al.*, 2007], and photosynthetically available radiation (PAR) [Frouin *et al.*, 2003] using the wavelength-, depth- and time-resolved light-photosynthesis model of Morel [1991]. This model uses the production vs irradiance (P vs E) formalism, with chlorophyll-specific wavelength-resolved absorption and quantum yield. Temperature dependence of PP is expressed through changes in the maximum chlorophyll-specific production rate ( $P_{\text{max}}^{\text{B}}$ ), following Eppley [1972]. More details are available in the work of Morel [1991], Morel *et al.* [1996], and Antoine and Morel [1996]. This model was among the best-performing algorithms that took part in an intercomparison exercise using *in situ*  $^{14}\text{C}$  data from the tropical Pacific [Friedrichs *et al.*, 2009]. Further discussion of the skill and limitations of such satellite PP models can be found in the work of Saba *et al.* [2011].

[8] The f-ratio [Eppley and Peterson, 1979] is defined as the ratio of new primary production (i.e. production that is supported by newly available nutrients in the euphotic zone) to total primary production (a sum of new and regenerated production). We calculated this quantity from a matchup of NP and PP data on a monthly scale with horizontal resolution in latitude and longitude of  $1^\circ \times 1^\circ$  as:  $\text{f-ratio} = \text{NP} * 6.6 / (\text{PP}/12) * 1000$ , where 6.6 represents the molar Redfield ratio, and the factor 1000/12 converts gC to mmol C.

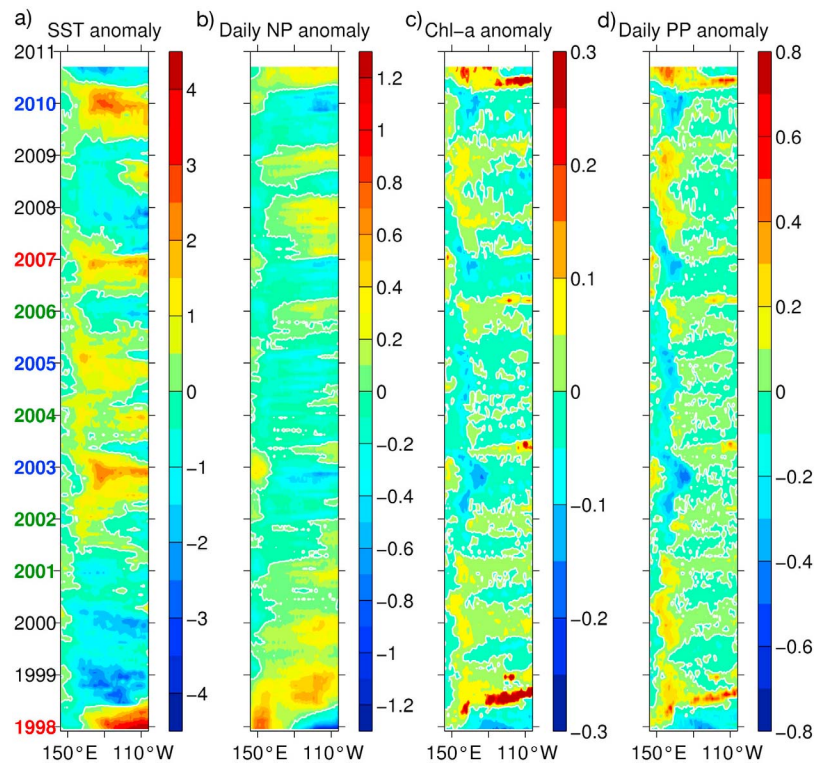
[9] Seasonal cycles were determined for each of the data sets by first calculating the monthly mean values, e.g. the mean of all January months from 1998–2006. These years were selected to exclude small time gaps in the data sets in 2007–2009. The monthly mean anomalies were then smoothed with a second-order Butterworth filter, passed forward and backward to avoid phase shifting, using a three month cutoff period to reduce residual noise. Differences between this mean seasonal cycle and the individual monthly means from 1997–2010 were computed to obtain monthly anomalies.

[10] A compositing technique is used based on the physical definitions of EP-El Niño and CP-El Niño from previous studies [Yeh *et al.*, 2009]. Within the time period presented here, Yeh *et al.* [2009] identified three CP-El Niño events (2002/03, 2004/05 and 2009/10) and two EP-El Niño events (1997/98 and 2006/07) based on detrended SST during the December-January-February (DJF) quarter. Neutral conditions refer to the DJF mean of the following years: 2000/01, 2001/02, 2003/04 and 2005/06. We calculate the winter (DJF) mean of SST, NP, Chl-a and PP over each of the three CP-El Niño events and the two EP-El Niño events as well as the neutral winters. Composites are created by averaging the DJF means to create a single DJF mean for CP-El Niño, EP-El Niño, and neutral conditions. As previous studies have shown that the CP-El Niño (El Niño Modoki) and canonical El Niño structures are also distinct in boreal summer [Ashok *et al.*, 2007], we also analyzed boreal summer data represented by June-July-August (JJA) for neutral conditions (2000, 2001, 2003, and 2005) and CP-El Niño events (2002, 2004 and 2009). Data for Chl-a and PP data during JJA in 1997 are not available, therefore no composite for summer EP-El Niño events was made.

## 3. Results and Discussion

[11] Monthly anomaly time series of SST, NP, Chl-a, and PP along the equatorial band (140°W to 100°E, averaged 1°N to 1°S) for 1997–2010 are presented in Figure 1. All variables show significant interannual variability associated with El Niño/La Niña events, with the strongest El Niño events in 1997/98 and 2009/10. In agreement with previous studies [Barber and Chavez, 1991; Strutton and Chavez, 2000; Turk *et al.*, 2001], during El Niño conditions NP, Chl-a, and PP increase in the western region (west of ~160°E) and decrease in the eastern region of the equatorial Pacific, consistent with changes in the nutrient supply associated with flattening of the thermocline. A significant decrease in Chl-a and PP is observed in the central Pacific during the CP-El Niño events coinciding with the maximum SST anomaly, while the lowest NP is shifted more toward the west. A similar decrease and shift is noted during the EP-El Niño event in 2006/07.

[12] Winter (DJF) composites during both types of El Niño events show that SST (Figure 2a) in the western region (140–160°E) is slightly lower (0.5°C) than in neutral conditions, while east of 160°E the SST is higher (1.5°C) than in neutral conditions. Consistent with previous studies, the maximum SST anomaly relative to neutral conditions (indicated in Figure 2a by the difference between the color and black curves) during CP-El Niño is observed in the central Pacific while the maximum anomaly during EP-El Niño is located in the eastern Pacific. None of the three CP-El Niño events



**Figure 1.** Monthly time/longitude sections of (a) SST ( $^{\circ}\text{C}$ ), (b) daily NP ( $\text{mmolN m}^{-2}$ ), (c) SeaWiFS Chl-a ( $\text{mgChl m}^{-3}$ ), and (d) daily PP ( $\text{gC m}^{-2}$ ) along the equator (from  $140^{\circ}\text{E}$  to  $100^{\circ}\text{W}$ ) for 1997 to 2010. All quantities have had a mean seasonal cycle removed and are anomalies relative to the record-length time mean at each longitude. Note that in order to illustrate smaller events in Chl-a as well as the extreme 1997 and 2010 events, the color map selected is artificially limited to  $0.3 \text{ mg m}^{-3}$ . The color of the year on the y-axis indicates whether the start of that year was during a CP-El Niño event (red), an EP-El Niño event (blue) or was during neutral conditions (green).

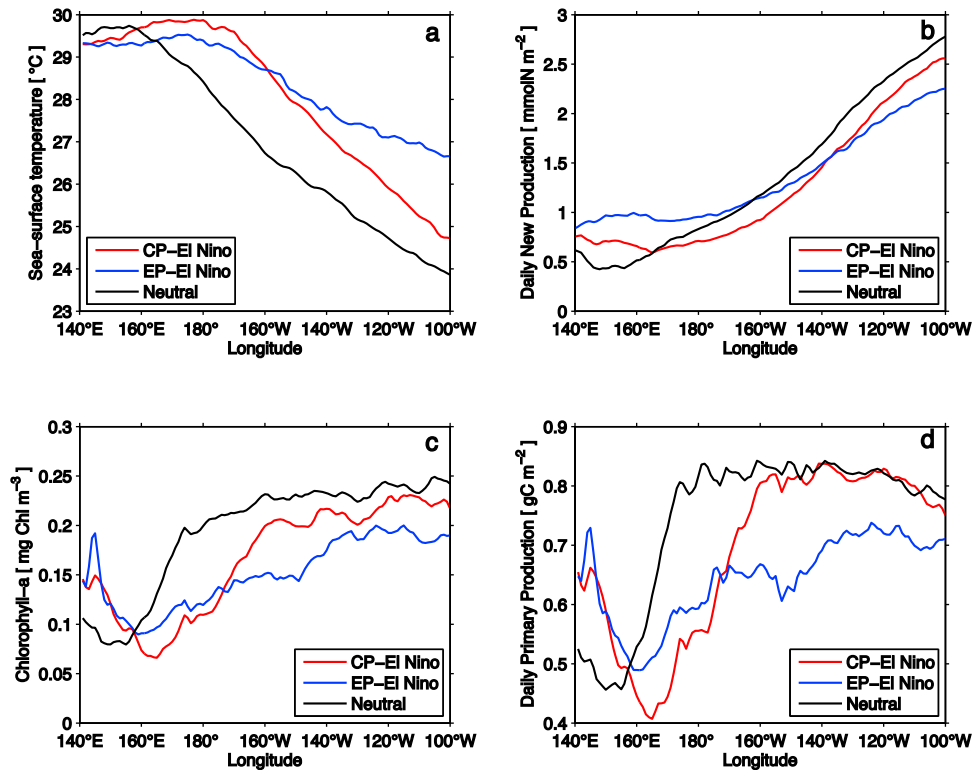
showed a distinct tripolar structure found by *Ashok et al.* [2007] with negative SST anomaly in the eastern Pacific, which is due to bounding our study domain at  $100^{\circ}\text{W}$  rather than the coast.

[13] Also consistent with previous studies [*Turk et al.*, 2001], DJF new production rates (Figure 2b) in the western Pacific are higher than during neutral conditions and lower in the eastern Pacific for both types of El Niño events, primarily due to changes in nutrient supply associated with the changes in thermocline/nutricline depth. CP-El Niños show lower NP in the western and central region than EP-El Niños and slightly higher in the eastern Pacific (east of  $135^{\circ}\text{W}$ ). Lower NP in the central Pacific implies a deeper nutricline/thermocline during CP-El Niño as described by *Ashok and Yamagata* [2009]. *Behera and Yamagata* [2010] observed higher sea levels in the central Pacific during CP-El Niños compared to the EP-El Niño, which is also consistent with our observations.

[14] Chl-a and PP show similar patterns to NP, with elevated values in the western Pacific during both El Niño types and lower values in the central Pacific compared to neutral conditions (Figures 2c and 2d). In the eastern Pacific, both Chl-a and PP are also lower during EP-El Niño. Our observations during El Niño events agree with *Boyce et al.* [2010] who report that, after de-trending and removing seasonal variation, yearly Chl-a anomalies were strongly negatively correlated with the El Niño index in the equatorial Pacific. During CP-El Niño, PP east of  $160^{\circ}\text{W}$  is comparable to neutral conditions, probably due to compensating effects of

lower Chl-a (which implies a lower PP) and warmer waters (which implies a higher PP). The same compensation does not occur for EP-El Niños because Chl-a is further lowered by  $\sim 30\%$  as compared to CP-El Niños. Note that there are some limitations of the PP modeling used herein, which may not sufficiently account for modulating the efficiency of use of photosynthetic energy [*Behrenfeld*, 2011]. The model's so-called "photo-physiological" parameters are set to average values and the only parameter that changes as a function of the environment is  $P_{\text{max}}^{\text{B}}$ , which is a function of temperature. Possible influences of nutrient concentration, species composition or the average light level in the mixed layer are not accounted for, which is a current limitation of satellite primary production models more generally [*Taucher and Oeschlies*, 2011]. Phytoplankton populations during El Niño conditions might have a lower photosynthetic efficiency than those present during normal or La Niña conditions, which would reduce PP as compared to our calculations. Such uncertainties have been quantified and discussed elsewhere [*Antoine and Morel*, 1996; *Friedrichs et al.*, 2009; *Saba et al.*, 2011] and are not further discussed here because our focus is on the relative differences between CP and EP-El Niños.

[15] CP-El Niño events show lower Chl-a and PP in the western and central Pacific (west of  $170^{\circ}\text{W}$ ) and higher values to the east, as well as a shift of the high zonal gradient eastward compared to EP-El Niño events. Surprisingly, Chl-a and PP levels around  $160\text{--}175^{\circ}\text{E}$  are lower during CP-El



**Figure 2.** Mean (a) SST ( $^{\circ}\text{C}$ ), (b) daily NP ( $\text{mmolN m}^{-2}$ ), (c) SeaWiFS Chl-a ( $\text{mgChl m}^{-3}$ ), and (d) PP ( $\text{gC m}^{-2}$ ) for December-January-February (DJF) during CP-El Niño/ El Niño Modoki (red), EP-El Niño (blue) and neutral conditions (black).

Niño than the mean neutral warm pool levels. As CP-El Niño NP in this area is higher than the mean neutral warm pool level, these low productivity levels cannot be fully described by decreased nutrient supply associated with lower thermocline/nutricline depth. The CEP is a region of relatively weak thermocline variability, and somewhat lower correlation between thermocline depth and new production [Turk *et al.*, 2001], which may be due to higher noise-to-signal ratio near the pivot point of the east-west thermocline tilt in this area and the role of lateral advection. However, east of  $175^{\circ}\text{E}$ , horizontal advection also cannot explain the Chl-a and PP decrease because surface current anomalies are negative [Singh *et al.*, 2011]. This suggests that currents are anomalously strong (still westward), which should increase Chl-a in this region (as Chl increases towards the east).

[16] The analysis of the boreal summer data for CP-El Niño events in 2002, 2004 and 2009 (not shown) indicates similar general patterns to boreal winter for all variables with a few small differences between the boreal winter and summer composites. The 2004 CP-El Niño event has a distinct tripolar structure with weak negative SST anomaly in the eastern Pacific as found by Ashok *et al.* [2007], while warmer than normal SST can be seen in the eastern Pacific during the 2009 CP-El Niño event. During the 2002 event, we observe positive anomalies in our study domain west of  $100^{\circ}\text{W}$ . However, during this event, our data also suggest negative anomaly between  $95^{\circ}\text{W}$  and  $85^{\circ}\text{W}$  and anomalously positive warming close to the coast (not shown). SST anomalies in the central Pacific are weaker during boreal summer. Lower NP is observed in the western Pacific and higher in the eastern Pacific. Chl-a and PP in the central

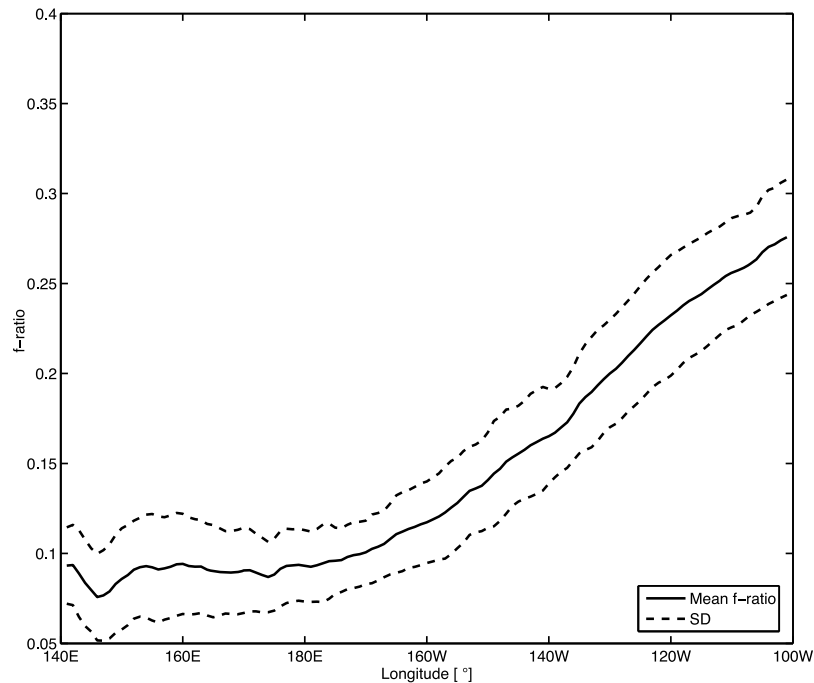
Pacific during boreal summer were comparable to warm pool values, while during the winter they were significantly lower. During CP-El Niño events, the sharp zonal increase in Chl-a and PP moved westward from the summer to the winter, which is consistent with previous studies that reported negative current anomalies (westward currents) during CP-El Niño [Singh *et al.*, 2011].

[17] Our composites include three CP and two EP-El Niño events. There are, however, some notable differences between the individual events, and it is legitimate to question whether our composites are truly representative of the two different types of El Niño events. To test the sensitivity of the results to the fact that some events are stronger than others and may dominate the composites (e.g., 1997–98 for the EP composite and 2009–10 for the CP composite), we tested normalizing the events prior to creating the composites by dividing each event by the maximum anomaly in each quantity as a function of longitude. The “normalized” version of the SST, NP, Chl-a, and PP composite spatial patterns are very similar to those shown on Figure 2, which demonstrates that the observed spatial patterns are robust and are not controlled solely by the two large events.

[18] Integrated values of NP and PP over the entire study domain ( $1^{\circ}\text{N}$  to  $1^{\circ}\text{S}$ ,  $140^{\circ}\text{W}$  to  $100^{\circ}\text{E}$ ) for all El Niños are lower compared to neutral conditions. The magnitude of this decrease seems to depend more on the intensity than on the type of event, with the lowest values during the strongest events, irrespective of the type of event (EP-El Niño 1997/98 and CP-El Niño 2009/10).

[19] The range of f-ratio values observed was 0.02–0.37 (with a mean of 0.15 and a standard error of 0.07), in





**Figure 3.** Mean f-ratio ( $\pm$  one SD) from 140°E to 100°W for 1997 to 2010.

agreement with shipboard observations in the tropical Pacific which found f-ratio values of 0.01–0.46 (with mean of  $0.16 \pm 0.08$  SE,  $n=114$ ) [Dugdale *et al.*, 1992; McCarthy *et al.*, 1996; Rodier and Le Borgne, 1997; Raimbault *et al.*, 1999; Aufdenkampe *et al.*, 2001]. The observed east-west gradient in f-ratio with values increasing toward the east (Figure 3) is also consistent with previous shipboard observations [Aufdenkampe *et al.*, 2001]. As f-ratio is estimated herein solely from two independent remotely sensed observations, this agreement is encouraging. Based on a comparison of composites during CP and EP-El Niño events (not shown), the satellite observations also suggest that f-ratio during CP-El Niño events may be lower than during EP-El Niño events, particularly in the 140°E–140°W region.

#### 4. Conclusions

[20] The results of this preliminary study indicate that CP-El Niños (sometimes called El Niño Modoki) cause a significantly different pattern of decreases in Chl-a, NP and PP in the central equatorial Pacific in comparison to classical EP-El Niños. During CP-El Niños, NP, Chl-a and PP in the central basin are lower than those observed during EP-El Niños and the zonal increase in Chl-a and PP in the central basin is shifted eastward. Lower values of Chl-a and PP coincide spatially with higher SST in the central Pacific. In boreal winter, they reach values below the mean neutral warm pool values, while NP stays above the warm pool values. Although the deeper thermocline/nutricline in the central Pacific during CP-El Niños contributes to decreases in Chl-a and PP, neither a change of the nutricline depth nor westward horizontal advection can fully explain such low values. While surface Chl-a, and integrated NP and PP over the entire equatorial band decrease during both CP and EP-El Niños, the magnitude of this decrease seems to depend more on the intensity than type of event. The influence of CP-El Niño

events on physical climate can be detected in the tropical Pacific as well as in the extra-tropics through atmospheric teleconnections; CP-El Niños may have biological consequences over a wider area as well. If CP-El Niños occur more frequently as suggested under projected global warming scenarios [Yeh *et al.*, 2009], then the central Pacific may experience lower biological productivity, which may be partly offset by an increase in the eastern basin. Our observations are consistent with the hypothesis that increasing ocean warming is contributing to a restructuring of marine ecosystems [Boyce *et al.*, 2010] with implications for biogeochemical cycling and ecosystem dynamics. Further improvements of the NP and PP estimation techniques and an enhancement of the ocean observing system to include biological sensor data (especially from fluorometers, radiometers,  $p\text{CO}_2$  and nutrient sensors) assimilated into advanced biogeochemical models will be required to confirm these results.

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