

Shifts in Chlorophyll α Associated with the North Equatorial Current Bifurcation Latitude off Eastern Luzon, Philippines

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ABSTRACT

The circulation pattern off the east coast of Luzon, Philippines, as observed during two oceanographic cruises conducted in May/June 2011 and April/May 2012, features a northward-flowing current (the nascent Kuroshio) bracketed by an anticyclonic eddy to its northeast and a cyclonic eddy to its southwest. A previous study showed that a more northerly location of the North Equatorial Current (NEC) bifurcation during the 2011 cruise resulted in entrainment of more subtropical water from the Kuroshio into upper thermocline waters, while a more southerly bifurcation location during the 2012 cruise injected more tropical NEC water into upper thermocline waters offshore of eastern Luzon. Here, we show that the change in source of upper thermocline waters in this region can also be recognized in the distribution pattern of chlorophyll *a*. Horizontally averaged chlorophyll *a* profiles showed higher concentrations in the upper 125 m of the water column during the 2011 cruise when the bifurcation latitude was 13°N–14°N than during the 2012 cruise when the bifurcation latitude was observed at 10°–11°N. Chlorophyll *a* data overlain on regional currents show that the 2011 nascent Kuroshio had a higher chlorophyll *a* content, supplied by its flanking cyclonic recirculation gyre, while the increased NEC content of the 2012 nascent Kuroshio was accompanied by reduced chlorophyll *a* within the upper thermocline, supporting the notion that horizontal advection plays an important role in chlorophyll variability off eastern Luzon. Using sea surface height anomalies as a proxy for upper ocean heat content, we show that warmer waters from the NEC supply the nascent Kuroshio when the location of the NEC bifurcation is more southerly. Empirical orthogonal function analysis of Moderate Resolution Imaging Spectroradiometer chlorophyll *a* data from 2003 to 2013 shows that the primary mode of chlorophyll *a* variability offshore of eastern Luzon was positively correlated with the NEC bifurcation latitude, further establishing that warmer, oligotrophic waters from the NEC supply the nascent Kuroshio when NEC bifurcation is southerly.

INTRODUCTION

The westward-flowing North Equatorial Current (NEC) in the western Pacific bifurcates just before encountering the Philippine coast and feeds both the northward-flowing Kuroshio and the southward-flowing Mindanao Current (Qu and Lukas, 2003). The NEC plays a vital role in North Pacific circulation as it partitions the flow to the subtropical gyre to the north and the tropical gyre to the south. The partitioning is primarily a function of the latitude where the NEC bifurcates. More NEC water flows to the north when the bifurcation latitude is southerly and to the south when the bifurcation latitude is northerly (Kim et al., 2004; Kashino et al., 2009).

At the surface, the NEC bifurcates at about 12°N, but the bifurcation latitude shifts to the north with increasing depth (Xie et al., 2009). The surface bifurcation latitude also shifts seasonally. Qu and Lukas (2003) used hydrographic data to

show that the bifurcation latitude is at its southernmost position in July and at its northernmost position in December.

In describing longer-term variability of the NEC bifurcation latitude based on satellite altimeter data, Qiu and Chen (2010a, 2012), found a clear interannual signal that appears to vary with the El Niño–Southern Oscillation (ENSO); it is northerly during El Niño and southerly during La Niña years. Also, the NEC bifurcation latitude has clearly trended southward over the past 18 years (Qiu and Chen, 2012; Wang, 2006).

The shifts in NEC bifurcation latitude not only affect the partitioning of NEC transport to the subtropical or tropical gyres (Qu and Lukas, 2003) but also changes the thermocline stratification of the waters off eastern Luzon. Underway acoustic Doppler current profiles (ADCP) and conductivity-temperature-depth (CTD) data from cruises in 2011 and 2012 (Gordon et al., 2014) show that in

May 2012 when the NEC bifurcation latitude was further to the south, the waters off eastern Luzon were enriched with NEC tropical waters, which are characterized by a saltier upper salinity maximum and a lower salinity minimum. However, in May 2011, the bifurcation latitude was further north, and the thermocline in the area mostly consisted of subtropical water supplied by the cyclonic and anticyclonic Kuroshio recirculation gyres that bound the nascent Kuroshio (Figure 1). Aside from temperature-salinity (T-S) characteristics, mean chlorophyll profiles also show a significant difference between the time of the two cruises (Figure 2), suggesting that this difference is most probably due to advection of low-productivity tropical waters when the bifurcation latitude is to the south and more productive western subtropical waters when the bifurcation latitude is to the north.

In this paper, we discuss chlorophyll distribution using data gathered during cruises in May/June 2011 and April/May 2012 described in Gordon et al. (2014), and relate these data to the changes in source waters of the eastern Luzon thermocline associated with a shift in the NEC bifurcation latitude. We trace the NEC transport feeding into the nascent Kuroshio using altimeter-derived sea surface height anomalies as a proxy for the upper ocean heat content anomaly. Lastly, empirical orthogonal function (EOF) analysis of the satellite-derived chlorophyll data set was conducted to determine if the long-term pattern of chlorophyll variability matched the changes in the amount of NEC tropical waters in the nascent Kuroshio.

CHLOROPHYLL VARIABILITY IN 2011 AND 2012

Research expeditions LB01 (May 19 to June 4, 2011) and LBO2 (April 24 to May 11, 2012) were conducted aboard R/V *Roger Revelle*. Figure 2a shows the tracks and locations of underway ADCP and CTD stations that were collected during both cruises. The southeast tracks in LB01 indicate avoidance of a typhoon

that crossed the study area during the cruise. The current velocity profiles were measured using a hull-mounted 75kHz Teledyne RDI Ocean Surveyor™ ADCP, with 16 m bins from the surface to a maximum depth of 1,100 m. The CTD data, which included chlorophyll *a* fluorescence (calibrated with discrete measurements), dissolved oxygen, turbidity, transmissivity, pressure, temperature, and salinity were merged with the ADCP data by linearly interpolating the CTD data for each ADCP velocity location and depth. Gordon et al. (2014) provide a more detailed analysis of the changes in circulation and stratification.

Data recorded during the two cruises show surface waters very low in chlorophyll *a* and a deep chlorophyll maximum (DCM) between about 110 m and 120 m depth (Figure 2b), much deeper than that observed in the adjacent South China Sea between 50 m and 70 m depth (Liu et al., 2002). The LB01 mean chlorophyll *a* profile from the surface to 125 m was significantly higher ($p < 0.1$) compared to the LB02 profile. At the DCM, the chlorophyll *a* concentration difference between

LB01 and LB02 was 0.054 mg m^{-3} .

The along-track ADCP measurements and the chlorophyll *a* data from CTD casts for each cruise were interpolated on a rectangular grid using optimum interpolation (OI). The ADCP current vectors were then plotted with chlorophyll *a* color coded to show the patterns of advection near the surface (35 m) and at the depth of the DCM (110 m), as shown in Figures 3 and 4, respectively.

Circulation data taken at 35 m and at 110 m depths show similar patterns: dipole eddies bracketing a strong northwestward-moving current that is referred to as the nascent Kuroshio or the Kuroshio “feeder” current (Gordon et al., 2014). At the surface, chlorophyll variation is dominated by a cross-shelf gradient, with both LB01 and LB02 cruises showing high chlorophyll near the shelf and low chlorophyll offshore (Figure 3). The differences between LB01 and LB02 offshore chlorophyll *a* concentrations at 35 m depth are small but still significant ($p < 0.1$), discernible when chlorophyll *a* concentration is represented on a log scale, but still consistent with the

differences between cruises observed at deeper depths. At 110 m depth, the change in source water can be seen in the chlorophyll distribution (Figure 4). In LB01 data, the Kuroshio recirculation gyre extends as far south as 15°N , and there are high chlorophyll *a* concentrations along the path of this recirculating water. In LB02, the recirculation can be seen north of 17.5°N , and the high chlorophyll concentrations are limited to the north of 17.5°N (Figure 4). The Kuroshio recirculation gyre in LB01 appears to be supplying the nascent Kuroshio with waters higher in chlorophyll *a* content, while increased NEC input during LB02 results in reduced chlorophyll *a* within the upper thermocline.

It is also interesting to note that the maximum chlorophyll *a* concentrations are found at the core of the cyclonic eddy inshore of the nascent Kuroshio, while the lowest concentrations are found at the core of the anticyclonic eddy offshore of the nascent Kuroshio. This finding is consistent with the notion that upwelling (downwelling) occurs at the core of cyclonic (anticyclonic) eddies (McGillicuddy et al., 1998; Mizobata et al., 2002; Gaube et al., 2014).

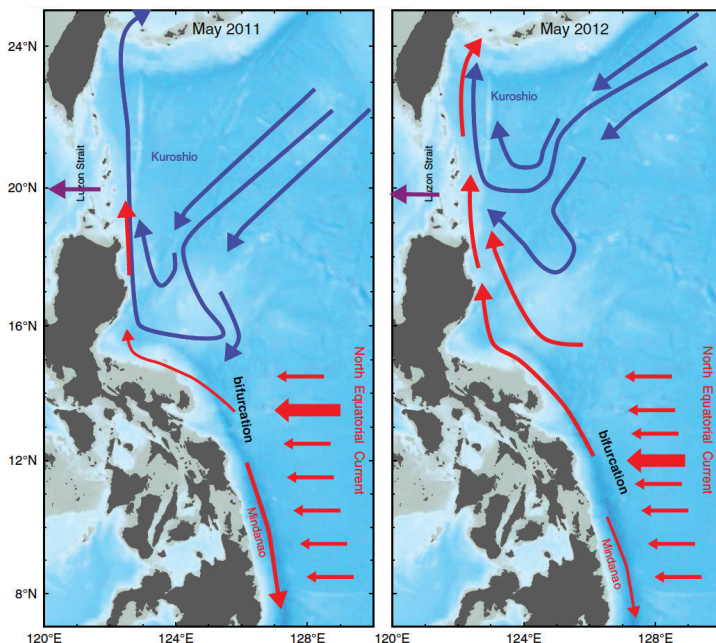


FIGURE 1. Schematic of the circulation pattern from Gordon et al. (2014) during two Lamón Bay research cruises when waters off eastern Luzon were dominated by subtropical thermocline waters (blue lines) in May/June 2011 and by tropical waters (red lines) of the North Equatorial Current (NEC) in April/May 2012.

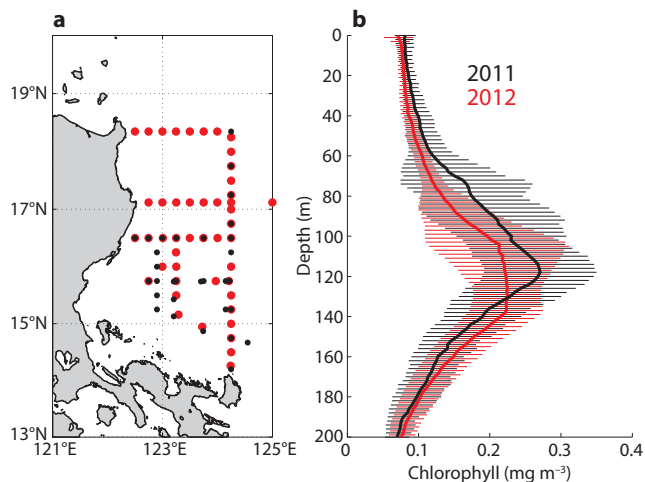


FIGURE 2. (a) Tracks and locations of underway acoustic Doppler current profiler (ADCP) and conductivity-temperature-depth (CTD) stations collected during the 2011 and 2012 cruises aboard R/V *Roger Revelle*. (b) Mean (solid lines) and standard deviation (error bars) of chlorophyll *a* profiles off eastern Luzon from CTD data obtained during the May/June 2011 LB01 cruise (black) and the April/May 2013 LB02 cruise (red). Mean profiles were computed using CTD stations shown in (a).

SEA SURFACE HEIGHT, UPPER OCEAN HEAT CONTENT ANOMALIES, AND THE NEC BIFURCATION

A more southerly NEC bifurcation brings warmer, more oligotrophic waters (low chlorophyll *a*) northward, similar to conditions at the end of 2011 and in early 2012 as seen in temperature data from a mooring located at Benham Bank (Figure 7a of Gordon et al., 2014). Here, temperature at 170 m depth oscillates at an amplitude of around 2°C with a period of about a month. These features prevailed over the second half of 2011. In November of that year, the temperature began to rise, and it increased from 20°C to about 25°C by May 2015, when the mooring was retrieved.

Daily delayed and near-real-time globally merged mapped sea level anomaly (MSLA) products used to derive the sea surface height anomaly (SSHa) at 0.25° resolution were downloaded from the Archiving Validation and Interpretation of Satellite Data (AVISO; <ftp://aviso.oceanobs.com>) covering the period January 1993 to December 2012. The SSHa at the mooring location for June 2011 to April 2012 is closely correlated

with temperature at 170 m ($R = 0.83$, $p < 0.001$), with positive SSHa anomalies coinciding with warmer waters. This relationship is expected, as the SSHa reflects the upper ocean heat content anomalies (Willis et al., 2004; Lyman and Johnson, 2008). Examination of the SSHa fields during this period show that monthly temperature variations during the second half of 2011 coincided with the passing of westward-propagating eddies just south of the Subtropical Countercurrent region (20°N–25°N; Qiu and Chen, 2010b; Chang and Oey, 2014; Figure 5a). The mooring data show that early 2012 warming temperatures coincided with an overall increase in positive SSHa at 15.75°N, where the mooring was deployed (location marked by a green dot of Figure 5c). These warm (positive SSHa) anomalies prevailed from January to September 2012 and extended east to 135°E. Relative to 2011, the westward-propagating eddies were also observed farther offshore, between 130°E and 140°E. At this time, the NEC bifurcation was further to the south (10°N–11°N in April 2012), and the nascent Kuroshio east of Luzon was supplied by NEC waters (Gordon et al., 2014).

We now examine the interannual

variability of the upper ocean heat content from SSHa data along 15.75°N and between 122°E and 180°E from 1993 to 2012 (Figure 5b), and relate the SSHa anomalies and upper ocean heat content anomalies east of Luzon to changes in the NEC bifurcation latitude. Increasing SSHa can be observed from 1993 to 2012. Prior to 2005, SSHa anomaly fields are dominated by westward-propagating positive and negative anomalies. From 2005 onward, the SSHa anomaly field appears to be dominated by positive anomalies.

Analysis of the correlation between the monthly time series of NEC bifurcation latitude and SSHa at 15.75°N, 122.5°E (Figure 6a) from January 1993 to December 2012, smoothed using the robust local regression method with regression weights computed using a data span of 10% (two-year window), showed significant negative correlation ($R = -0.89$, $p < 0.001$). This result means that during the periods when the NEC bifurcation latitude was more to the south/north, this area was characterized by positive (warmer)/negative (colder) SSHa signals. When the NEC bifurcation is at a more southerly location, more warm, less-productive tropical NEC waters

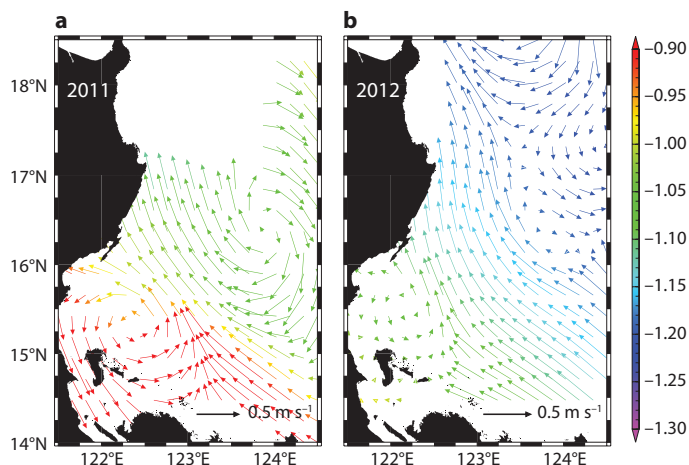


FIGURE 3. Optimum interpolated (OI) velocity vectors at 35 m depth from the hull-mounted ADCP during the 2011 LB01 (left) and 2012 LB02 (right) cruises aboard R/V *Roger Revelle*. The vector color is scaled to the log of the chlorophyll *a* concentration (mg m^{-3}) from CTD profiles linearly interpolated to depths and locations of ADCP vectors. A constant scale factor of 2.5 was applied to vectors $< 0.5 \text{ m s}^{-1}$ to accentuate the weaker cyclonic circulation off Lamon Bay.

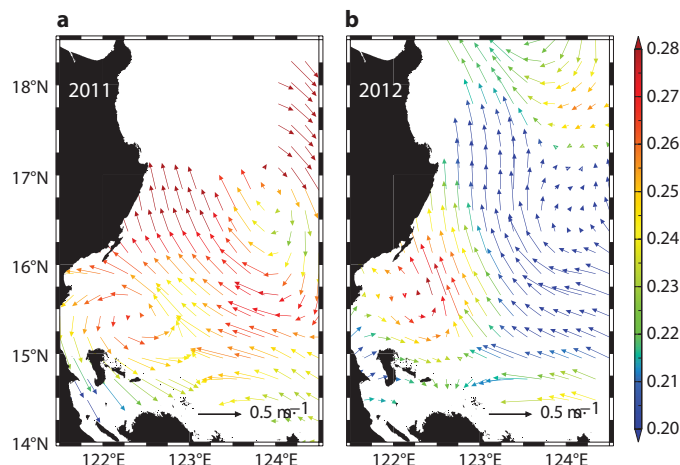


FIGURE 4. OI velocity vectors at 110 m depth from the hull-mounted ADCP during the 2011 LB01 (left) and 2012 LB02 (right) cruises. The vector color is scaled to a concentrations (in mg m^{-3}) from CTD profiles linearly interpolated to depths and location of ADCP vectors. A constant scale factor of 2.5 was applied to vectors $< 0.5 \text{ m s}^{-1}$ to accentuate the weaker cyclonic circulation off the Lamon Bay.

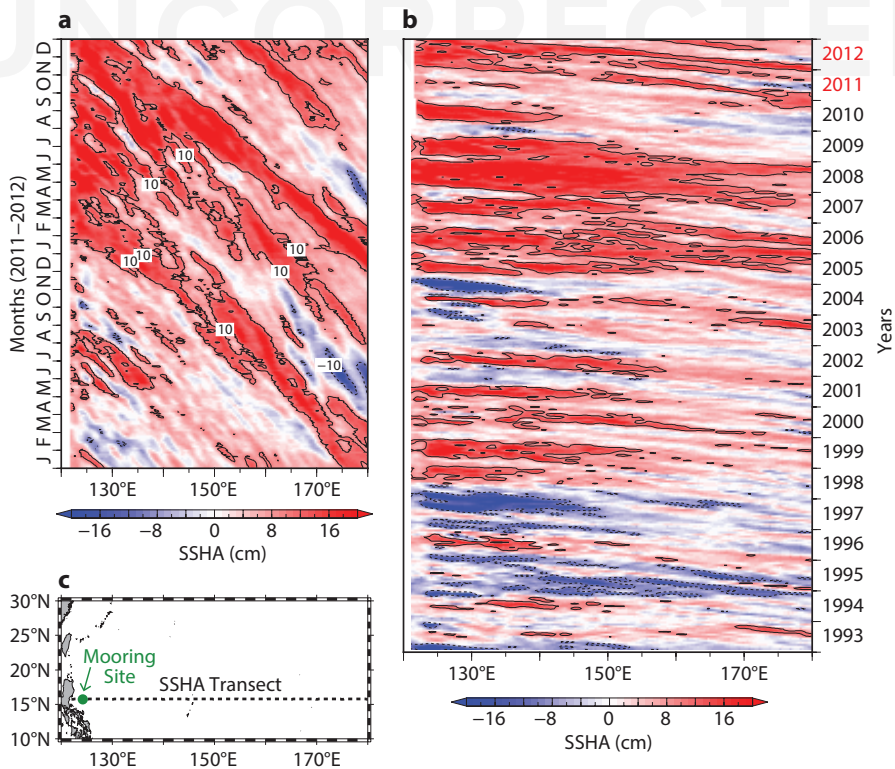


FIGURE 5. (a) Time-longitude slices of monthly sea surface height anomaly (SSHa) from January to December 1993 to 2012 and (b) daily SSHa from 2011 to 2012 corresponding to the survey periods, (c) subsequently extracted at 15.75°N and across 120°E to 180°E.

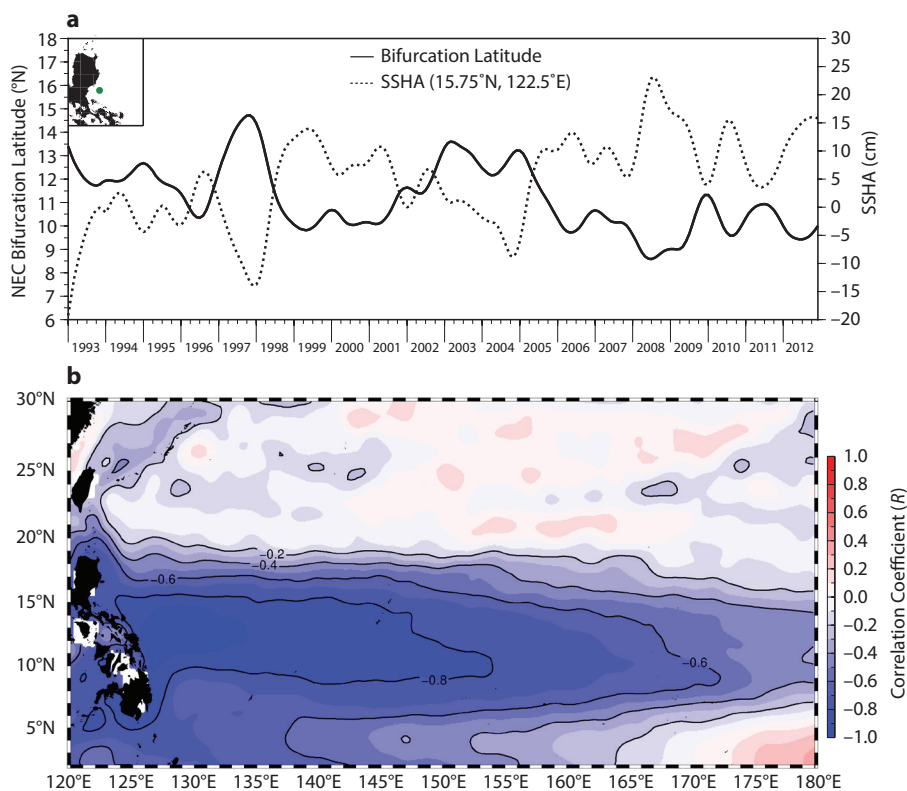


FIGURE 6. (a) Monthly smoothed time series of NEC bifurcation latitude (solid line) and SSHa (dashed line) extracted from 15.75°N, 122.5°E (inset map) and (b) pixel-wise correlations ($p < 0.05$) of NEC bifurcation latitude and SSHa from January to December 1993 to 2012

supply the nascent Kuroshio.

The pixel-wise correlation patterns between the SSHa and NEC bifurcation latitude from 1°N to 30°N and 120°E and 180°E (Figure 6b), also capture the spatial extents of the negative relationship observed between the two oceanographic variables. The highest significant negative correlations were located between 9°N and 15°N and between 126°E and 135°E, likely encompassing the region of the meridional shifts of the NEC bifurcation during the 20-year period. Moderately strong negative correlations ($R = -0.6$) expanded further north at roughly 20°N, with diminishing correlation magnitude past this point. The 20°N latitude corresponds to the southernmost boundary of the subtropical frontal zone dominated by the Subtropical Countercurrent at 20°N–25°N (Talley et al., 2011). The presence of open ocean eddies in this region is likely to modify the SSHa signals, potentially resulting in the lower spatial correlations with NEC bifurcation latitude.

LONG-TERM TRENDS IN REMOTELY SENSED CHLOROPHYLL

Chlorophyll *a* concentrations measured during the cruises in 2011 and 2012 were shown to vary with shifts in the source waters of the nascent Kuroshio. The shifts coincide with the variation in the proportion of tropical NEC waters feeding the nascent Kuroshio, associated with the change in the NEC bifurcation latitude. To determine whether this relationship applies over longer time scales requires chlorophyll *a* data at temporal and spatial scales that can only be provided by satellite measurements. Our chlorophyll pattern is apparent from the surface to 125 m depth. In clear oligotrophic waters, the Moderate Resolution Imaging Spectroradiometer (MODIS) green band (550 nm wavelength) is estimated to have a penetration depth of 41 m (Li et al., 2003), more so for the blue bands, which are also used in the chlorophyll algorithms. Furthermore, strong empirical relationships have been established that

relate surface and remotely sensed chlorophyll data to vertically integrated (surface to beyond the depth of the DCM) phytoplankton biomass (Morel and Berthon, 1989; Uitz et al., 2006). We use this relationship to analyze satellite data for long-term trends.

MODIS images¹ from the LB01 and LB02 cruise periods show high (low) chlorophyll distributions inshore (offshore) of the nascent Kuroshio (Figure 7). Lower chlorophyll values offshore during the LB02 cruise are notable. Advective patterns in both the May 2011 and April 2012 images show the presence of a cyclonic eddy in Lamon Bay, inshore of the nascent Kuroshio. The eddy is more apparent in the 2011 image, as it advects both high-chlorophyll shelf waters from around 15°N, 123°E and low-chlorophyll offshore waters, increasing the contrast. In 2012, the eddy advects mostly high-chlorophyll shelf waters. This contrast is also clearly seen in the ADCP and CTD data plotted in Figure 3, where the size, shape, and chlorophyll values of the eddy are clearly different between the two years.

Monthly averaged chlorophyll data further show the difference between the LB01 and LB02 cruise periods, which may point to the importance of advection in creating this variability. A very wide oligotrophic zone (Figure 8a) east of the Philippines, centered around the Mariana Islands, is characterized by chlorophyll *a* concentrations of $0.034 \pm 0.003 \text{ mg m}^{-3}$ (Morel et al., 2010). This broad region is potentially the source of the oligotrophic NEC waters transported toward the western Pacific. In contrast, the subsurface chlorophyll *a* concentration is high north of 20°N in the western Pacific compared to subsurface concentrations at 10°N to 20°N. The DCM at about 31°N in

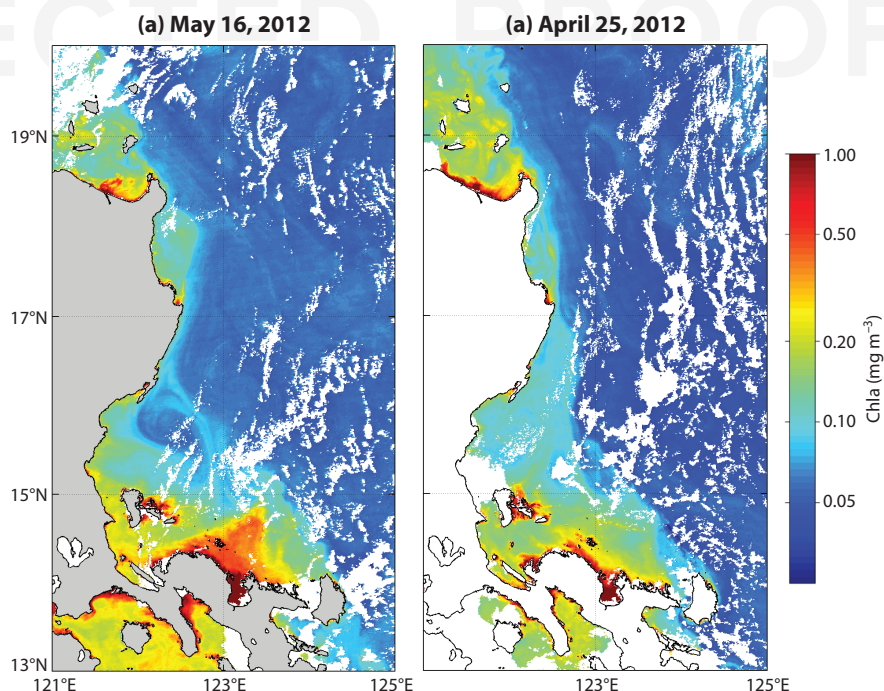


FIGURE 7. MODIS-derived chlorophyll *a* distribution during the (a) LB01 and (b) LB02 cruises, with dates selected to provide the most cloud-free images. Note the lower chlorophyll values offshore during the 2012 LB02 cruise.

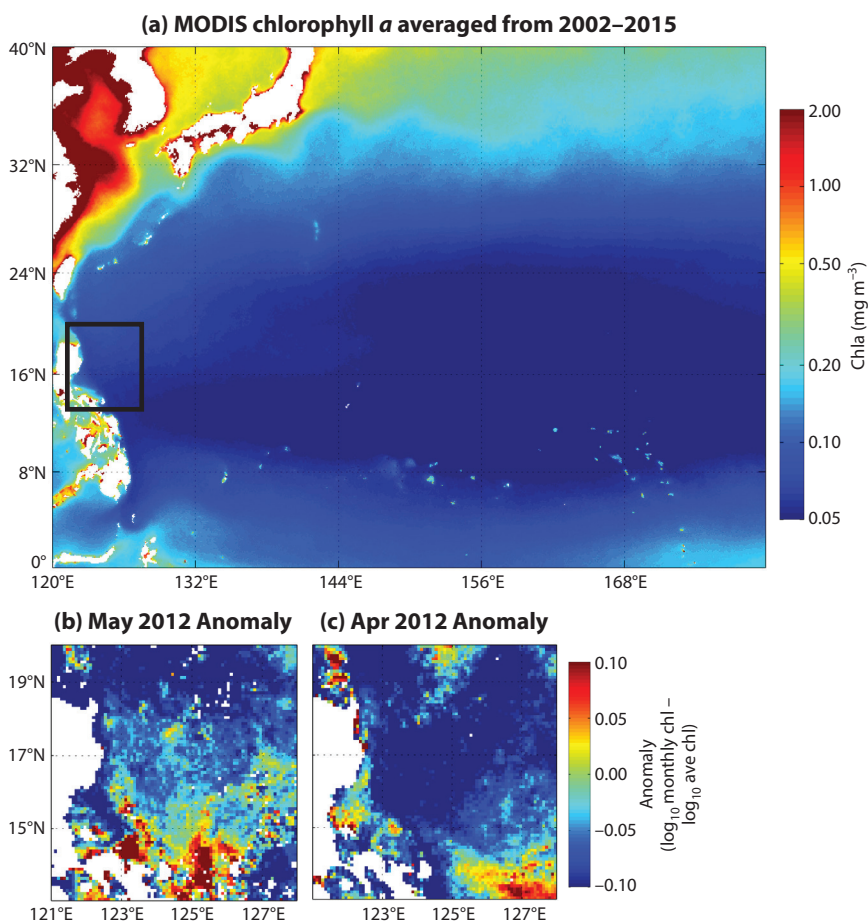


FIGURE 8. (a) Long-term average calculated from 13-year-long monthly MODIS standard mapped images. Monthly mean chlorophyll *a* concentration anomalies for (b) May 2011 and (c) April 2012, roughly coinciding with the period of the 2011 LB01 and 2012 LB02 cruises, respectively.

¹ NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. 2014. MODIS-Aqua Ocean Color Data; NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. http://dx.doi.org/10.5067/AQUA/MODIS_OC.2014.0.

the western Pacific is at 65 m depth and deepens to the south to about 120–130 m between 5°N and 20°N. The southward deepening of the DCM is also characterized by a southward decrease in DCM chlorophyll *a* concentration (Furuya, 1990).

During May 2011, the month of the LB01 cruise, surface chlorophyll was higher than the long-term mean both offshore and at the Bicol shelf (14°N–15°N, 122°E–123°E), as seen in Figure 8b. The Kuroshio recirculation gyre, with higher chlorophyll content, reaches south to 14°N–15°N. In April 2012, the month of the LB02 cruise, chlorophyll levels measured east of Luzon were generally lower, and the Kuroshio-recirculated high-chlorophyll waters reached south only to 19°N (Figure 8c).

To further resolve the spatial and temporal variability in chlorophyll, we conducted an EOF analysis on chlorophyll *a* following the method of Garcia and Garcia (2008) using the monthly standard mapped images from MODIS. Pre-processing included log-transformation, double-pass smoothing by computing a running average of 12 and two months,

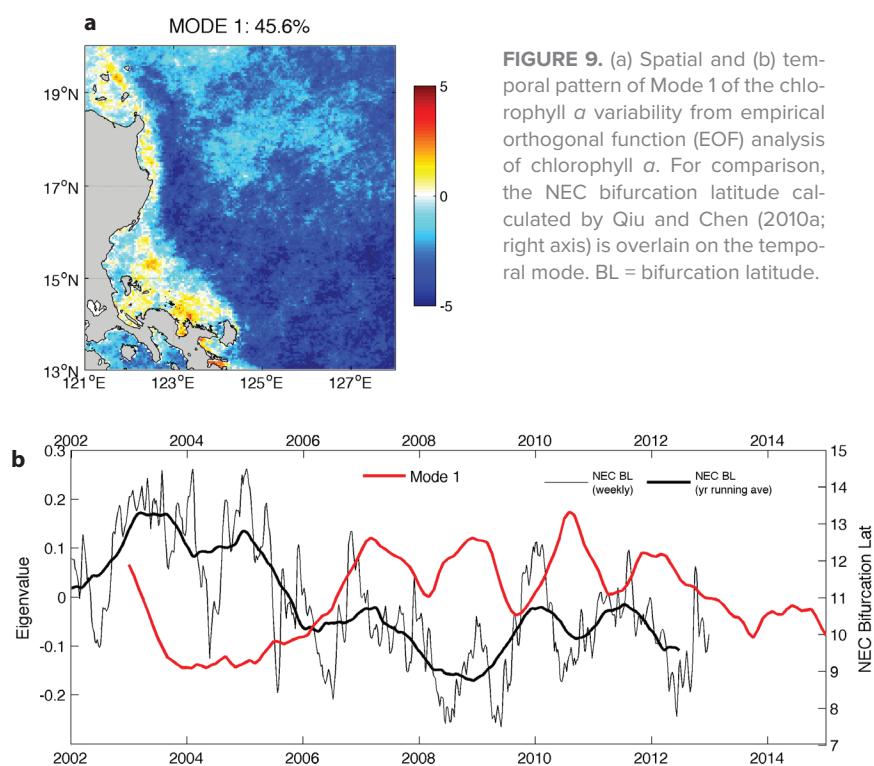
and Z-normalization.

Results highlighted three prominent regions defined by first EOF mode: (1) the shelf and coastal waters inshore of the nascent Kuroshio, and the offshore (2) north and (3) south waters, separated at 16°N (Figure 9, upper panel). The first EOF mode explained almost half of the total chlorophyll *a* variance of the inshore and offshore sides of the nascent Kuroshio, which have opposite signs in the spatial EOF. The temporal function of the first mode, shown in the lower panel of Figure 9, varies inversely with the NEC bifurcation latitude variations ($R = -0.73$, $p < 0.01$). A higher correlation coefficient of -0.81 is obtained if the chlorophyll EOF Mode 1 is lagged by five months. Thus, when the NEC bifurcation latitude is to the south, the temporal EOF function is positive, but because the spatial EOF is negative, the chlorophyll concentration offshore of the nascent Kuroshio is lower. The lowest concentrations are found along the path of the NEC waters feeding into the nascent Kuroshio (upper panel of Figure 9 where spatial EOF values < -0.25). Correlations of both the chlorophyll EOF Mode 1 and the SSHa


fields off eastern Luzon with the NEC bifurcation latitude show that long-term chlorophyll variability is likely driven by the warm, low-chlorophyll NEC component that feeds the nascent Kuroshio, whose magnitude varies with the NEC bifurcation latitude.

Gordon et al. (2014) show that waters offshore of eastern Luzon exhibit marked enrichment in NEC tropical thermocline water in 2012 relative to 2011, based on temperature and salinity, which are conservative tracers of water mass. Chlorophyll *a* is not considered a conservative tracer because of biological processes within the water column. However, in this region off eastern Luzon characterized by very low chlorophyll concentrations, horizontal advective processes can dominate such that long-term chlorophyll signals may be attributed to changes in thermocline source waters that occur with shifts in the NEC bifurcation latitude. Aside from the Kuroshio recirculation, meridional advection of chlorophyll *a* may also be eddy-induced as shown by Chelton et al. (2011) and Gaube et al. (2014) for the tropical Pacific, linking the temporal scales of variability in chlorophyll *a* from short term (eddy time scales) to interannual scales.

Shiozaki et al. (2013) show that southward transport of nitrogen-fixing phytoplankton can play an important role in stimulating productivity in the normally oligotrophic western Pacific warm pool. This southward advection by the Kuroshio recirculation gyre is also seen in our 2011 cruise data set; hence, we cannot discount southward advection as an important process in causing the observed chlorophyll *a* variability. To establish this relationship, it is necessary to link the southward penetration of the Kuroshio recirculation with the NEC bifurcation latitude; however, we have no concrete data to support this link, only observations on the change in dominance of the NEC source water. The influence of Kuroshio recirculation will be examined in future studies.



SUMMARY AND CONCLUSIONS

A combination of cruise data, satellite ocean color data, and sea surface height anomalies are used to investigate changes in chlorophyll *a* distributions associated with shifts in the NEC bifurcation latitude. Two cruises conducted in May/June 2011 and April/May 2012 coincided with more northerly and more southerly NEC bifurcation latitudes, respectively. We associate the changes in chlorophyll *a* concentrations off eastern Luzon with shifts in the water masses that supply the nascent Kuroshio, from a more subtropical, chlorophyll-rich Kuroshio recirculation from the north in 2011 to more tropical, warm, low-chlorophyll NEC waters from the east in 2012. MODIS satellite-derived chlorophyll *a* data from 2002 to the present, together with SSHa anomalies as proxies for the upper ocean heat content anomaly, were used to examine longer-term variability in conjunction with NEC bifurcation latitude. Correlation analysis and EOF analysis both show a similar pattern—when the bifurcation latitude is to the south, more warm, oligotrophic NEC waters supply the nascent Kuroshio and less chlorophyll *a* is present offshore eastern Luzon. 

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