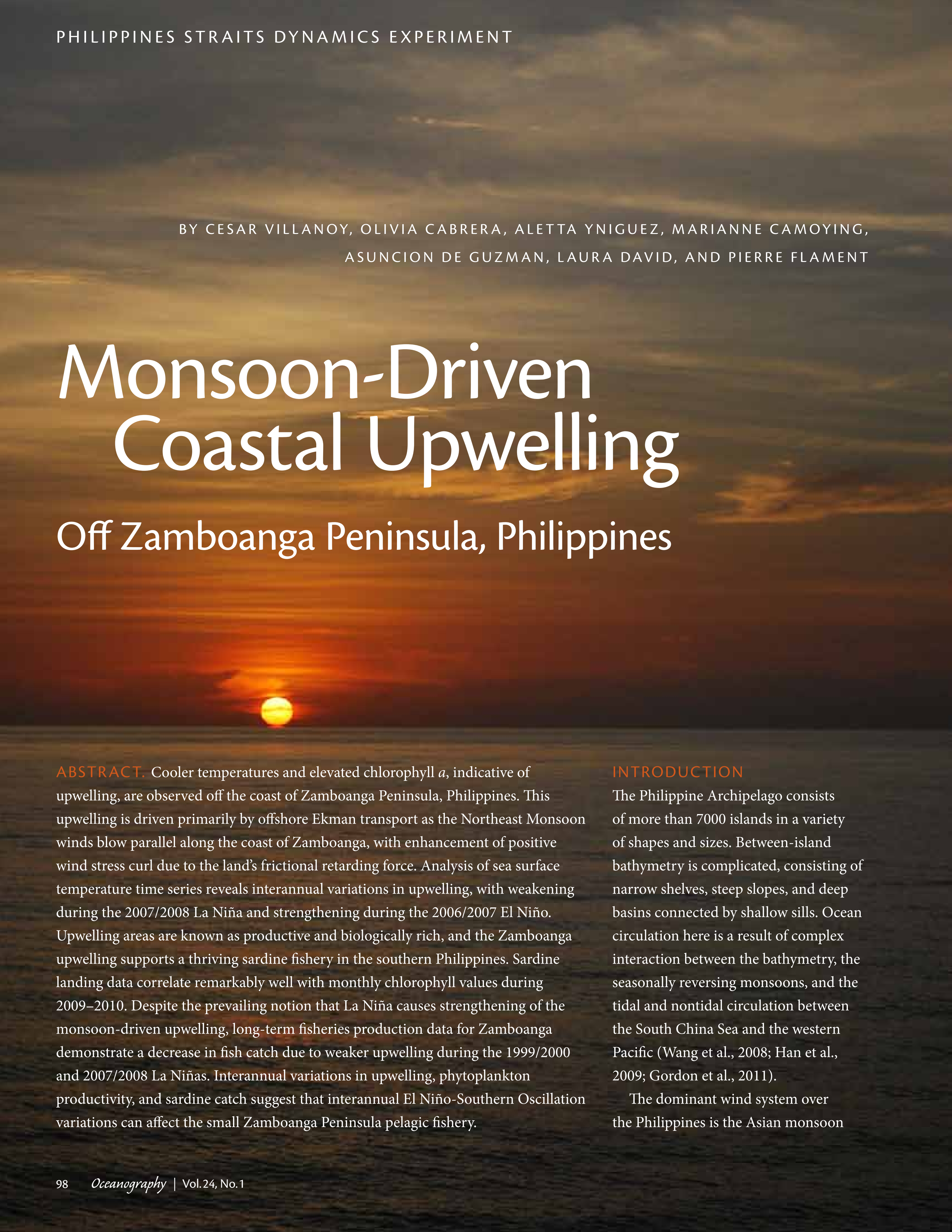

BY CESAR VILLANOY, OLIVIA CABRERA, ALETTA YNIGUEZ, MARIANNE CAMOYING,
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Monsoon-Driven Coastal Upwelling

Off Zamboanga Peninsula, Philippines

ABSTRACT. Cooler temperatures and elevated chlorophyll *a*, indicative of upwelling, are observed off the coast of Zamboanga Peninsula, Philippines. This upwelling is driven primarily by offshore Ekman transport as the Northeast Monsoon winds blow parallel along the coast of Zamboanga, with enhancement of positive wind stress curl due to the land's frictional retarding force. Analysis of sea surface temperature time series reveals interannual variations in upwelling, with weakening during the 2007/2008 La Niña and strengthening during the 2006/2007 El Niño. Upwelling areas are known as productive and biologically rich, and the Zamboanga upwelling supports a thriving sardine fishery in the southern Philippines. Sardine landing data correlate remarkably well with monthly chlorophyll values during 2009–2010. Despite the prevailing notion that La Niña causes strengthening of the monsoon-driven upwelling, long-term fisheries production data for Zamboanga demonstrate a decrease in fish catch due to weaker upwelling during the 1999/2000 and 2007/2008 La Niñas. Interannual variations in upwelling, phytoplankton productivity, and sardine catch suggest that interannual El Niño-Southern Oscillation variations can affect the small Zamboanga Peninsula pelagic fishery.

INTRODUCTION

The Philippine Archipelago consists of more than 7000 islands in a variety of shapes and sizes. Between-island bathymetry is complicated, consisting of narrow shelves, steep slopes, and deep basins connected by shallow sills. Ocean circulation here is a result of complex interaction between the bathymetry, the seasonally reversing monsoons, and the tidal and nontidal circulation between the South China Sea and the western Pacific (Wang et al., 2008; Han et al., 2009; Gordon et al., 2011).

The dominant wind system over the Philippines is the Asian monsoon that blows from the northeast between December and March and from the southwest between June and October (Wang et al., 2001). Monsoonal winds forced through the complicated topography can give rise to lee eddies and wind stress curl zones, particularly during monsoon surges (Pullen et al., 2008, 2011). Winds blowing through gaps between islands can induce upwelling and downwelling along the leeward sides of the islands (Chavanne et al., 2002). Interestingly, most of these features in the Philippines occur only during the Northeast Monsoon (NEM; Wang et al., 2006; Pullen et al, 2008), probably because warmer surface temperatures during the Southwest Monsoon increase near-surface stratification. The stronger winds and cooler temperatures during NEM can enhance convective mixing, resulting in elevated chlorophyll signals in many areas around the country, as seen from satellite ocean color data (Wang, et al., 2006; Peñaflor et al., 2007).

Zamboanga Peninsula forms the northwest coast of the island of Mindanao (Figure 1). The coast is oriented northeast-southwest, similar to the axis of the monsoon winds. Thus, when the Northeast Monsoon blows, conditions become favorable for Ekman transport directed away from the shoreline. In addition, upwelling along this shelf can be enhanced by wind stress curl induced by the frictional retarding force of the land. Both types of processes contribute to upwelling in most shelf systems, even along a relatively straight coast such as California (Pickett and Paduan, 2003; Capet et al., 2004). In fact, off the central and southern California coast, wind stress curl is believed to account for 60–80% of total annual upwelling transport (Rykaczewski and Checkley, 2008).

The objective of this paper is to describe upwelling off Zamboanga Peninsula and to make use of satellite sea surface temperature (SST) and chlorophyll *a* distributions as proxies to determine interannual upwelling variability. We also briefly discuss the relationship of upwelling and recent local sardine fishery trends, as well as upwelling variability.

UPWELLING MECHANISM AND VARIABILITY

Dipolog Strait is 42-km wide and is located between Mindanao and Negros islands. The sill lies at ~ 470 m (Gordon et al., 2011) and serves as the boundary between the Sulu and Bohol seas (Figure 1). The northern coast of Zamboanga Peninsula is west of this strait. The coastline is oriented northeast/southwest, with sharp coastline bends at about 122°E and 123°E. The shelf is generally narrow, with the 200-m isobath located about 4–10 km from the coast. The shelf's widest part is to the west of a small cape at 122°40'E that protrudes about 2 km offshore.

During the Northeast Monsoon, the wind vector is directed toward the southwest, approximately parallel to the shelf (Figure 2), promoting offshore Ekman transport (Pond and Pickard, 1983) and coastal upwelling to replace the displaced surface water. Coastal upwelling is evident from the SST field along the Zamboanga coast during the upwelling-favorable NEM season (Figure 2). The seasonal SST variation is large (4–5°C) compared to the cross-shelf temperature gradient (nearshore SST is about 1°C cooler than offshore SST). This cross-shelf gradient is consistent throughout the NEM months, indicating that the

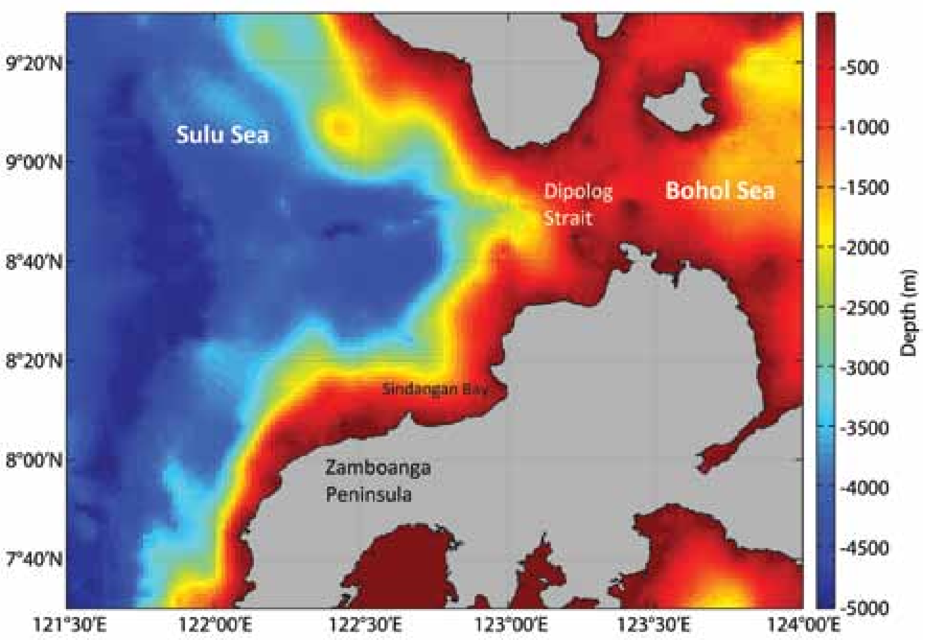

Figure 1. Map of the Zamboanga Peninsula shelf area showing bathymetry. *Data from Smith and Sandwell (1997)*

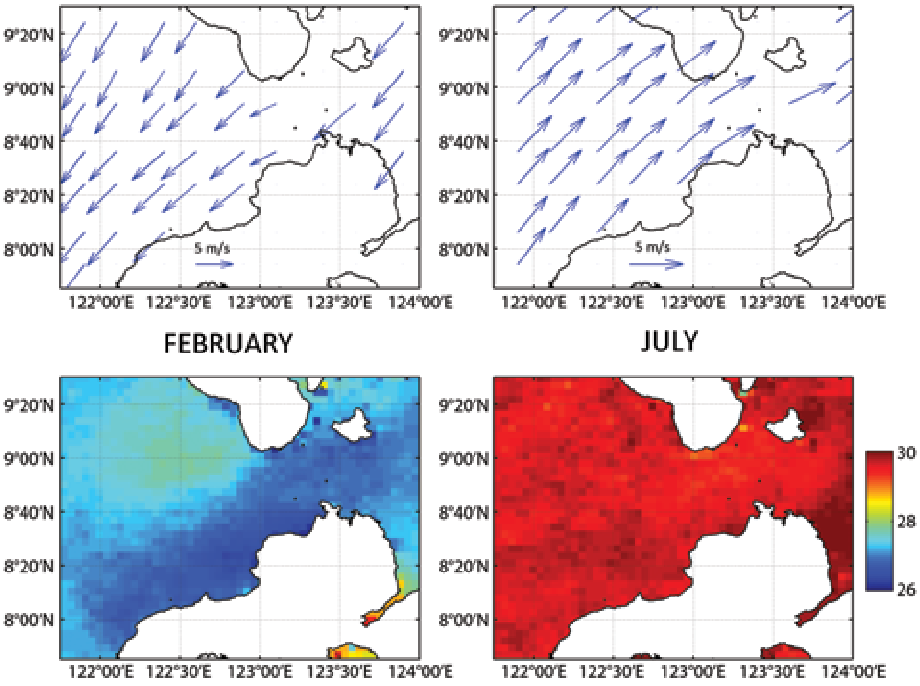

Figure 2. QuikSCAT monthly mean wind stress (in N m^{-2}) and mean sea surface temperature (SST; in °C) for January/Northeast Monsoon (left) and August/Southwest Monsoon (right). Monthly SST was calculated from Pathfinder SST for the period 1985–2009.

lower nearshore SST is not due to seasonal variation in surface heat flux alone. The negative temperature anomalies adjacent to the coast extend about 30 km from the coast.

Wind stress curl is another mechanism that can drive upwelling. Unfortunately, because no weather station data are available for this area, the only source of wind data are satellite measurements (e.g., the National Aeronautics and Space Administration's Quick Scatterometer [QuikSCAT] and the Advanced Scatterometer [ASCAT] instrument), which are too coarse to provide wind stress curl information within 50 km of the coast. Alternatively, we may use model winds from regional atmosphere models such as the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS)[1]. Model winds of the Philippine Archipelago using COAMPS show the same general features as QuikSCAT wind fields (Pullen et al., 2008).

With COAMPS, it is possible to compute both alongshore wind stress and wind stress curl close to the coast. Figure 3 shows a map of the February 2008 mean wind stress and wind stress curl fields. Note that all along the northern coast of Zamboanga Peninsula, the wind stress curl is positive, most likely due to frictional retardation by land. The maximum positive curl values are found off coastline bends (near 122°N and 123°N) and may contribute to upwelling transport in these areas. In the California and Benguela upwelling systems, bands of positive wind stress are believed to be important in shaping the upwelling systems (Fennel, 1999; Capet et al., 2004). The curl band also forces a downwind surface flow under the maximum wind axis and an inshore upwind countercurrent (Fennel, 1999). Similar offshore downwind and nearshore upwind flows were observed using underway acoustic Doppler current profiler (ADCP) data during the December 2007 Joint US/Philippines Cruise and the March 2009 Intense Observational Period (IOP) Cruise (IOP-09), but these flows were absent during IOP-08 in January.

Upwelling interannual variability was examined by using empirical orthogonal function (EOF) analysis of monthly 4-km resolution Pathfinder SST data

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[1] COAMPS or Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) is a regional weather prediction model used operationally by the US Navy and developed by the Marine Meteorology Division of the Naval Research Laboratory, Monterey, CA.

(http://data.nodc.noaa.gov/opendap/pathfinder). The seasonal SST range is about 4–5°C, while the surface SST signal associated with upwelling is only about 1°C cooler than offshore ambient temperatures. In order to highlight horizontal temperature gradients and at the same time remove the seasonal signal, the spatially averaged temperature was subtracted from the monthly SST data before EOF analysis. Figure 4 shows the result of the analysis. Only the first mode is described as it contributes 23% of the variance, while the contributions of the succeeding modes are too small to be significant. The spatial pattern of the first mode is associated with the cross-shelf temperature gradient off the coast of Zamboanga Peninsula (Figure 4, top panel). The temporal variation of this mode shows that upwelling conditions (negative values) prevail mostly during the NEM months and vary at interannual time scales (Figure 4, middle panel). The bottom panel in Figure 4 shows the time series of the Multivariate El Niño-Southern Oscillation (ENSO) Index (MEI; Wolter and Timlin, 1993, 1998) for the same time period. Negative MEI values represent the cold (La Niña) phase of ENSO, while positive values represent the warm phase (El Niño). The occurrences of negative values of the Mode 1 temporal variation, associated with stronger cross-shelf SST gradients and upwelling, coincide with El Niño events (e.g., the 1987/1988 El Niño, the series of weak El Niño events in the early 1990s, 1997/1998, 2002–2005, and 2007/2008). Comparison of the MEI time series with the temporal variation of the first EOF mode show an inverse relationship ($r = -0.43$) significant at $p < 0.05$.

The EOF analysis suggests that the general response to ENSO is lower SST (stronger upwelling) during El Niño and higher SST (weaker upwelling) during La Niña. This result appears to be counterintuitive because La Niña (El Niño) is often associated with stronger (weaker) winter monsoon winds (Webster et al., 1998; Wu and Chan, 2005). In the adjacent Bohol Sea, a similar pattern observed between the variability of chlorophyll *a* and ENSO is attributed by Cabrera et al. (2011) to the formation of a barrier layer due to the low-salinity surface layer produced by increased precipitation during La Niña. The same mechanism appears to modulate Zamboanga Peninsula upwelling. Rainfall anomalies derived from precipitation estimates using Tropical Rainfall Measuring Mission (TRMM) data from the area bounded by 8°–8°30'N and 122°15'–123°E are more positive during La Niña and more negative during El Niño (Figure 5). The rainfall anomalies were negatively correlated to MEI ($r = -0.73$ and statistically significant at $p < 0.05$). Field observations from the IOP-08 and IOP-09 cruises were consistent with these findings. Conductivity-temperature-depth (CTD) data off the Zamboanga coast show lower surface salinities, and consequently density, during January 2008 compared to March 2009 (Figure 6, top panel).

The upwelling was also evident from underway data for March 2009. The shelf area was cooler and had higher chlorophyll *a* concentration compared to offshore values (Figure 6, bottom panel). Because of higher salinity shoreward, the higher chlorophyll concentration is unlikely to be fed by nutrients coming from river runoff, but rather from upwelling of more nutrient-rich water from below the surface.

The weaker upwelling during the

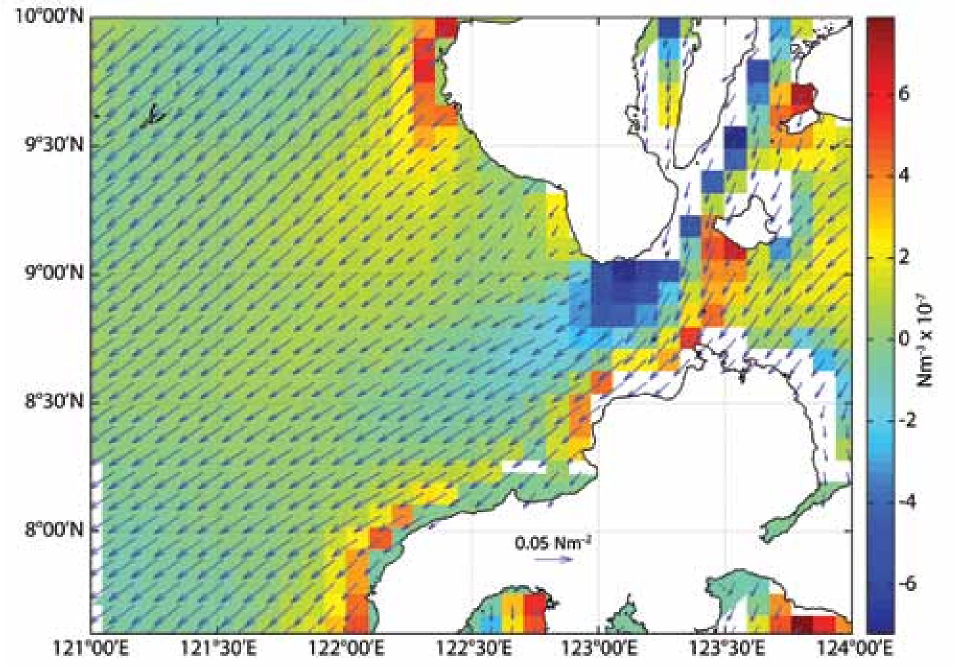


Figure 3. Mean wind stress (in N m^{-2}) and wind stress curl (in N m^{-3}) during February 2008 from the COAMPS model of the Philippine seas (Pullen et al., 2008).

2007/2008 La Niña may also be related to the weakening of the prevailing winds during the 2007/2008 NEM season. However, unlike rainfall, the seasonal QuikSCAT wind anomalies from January 2000 to October 2009 for the area off the Zamboanga shelf did not show a clear relationship with ENSO events.

CONSEQUENCES OF UPWELLING

Because algal blooms and an increase in primary production are some of the consequences of upwelling, chlorophyll *a* pigment concentrations measured from satellites are good tracers for upwelling, particularly in the tropics where the temperature differences between upwelled and ambient surface waters are small. Chlorophyll concentrations vary seasonally, with the highest surface concentrations occurring during the NEM months. EOF analysis of monthly chlorophyll images (2003–2009) with the spatially averaged concentration removed show the highest concentration at the shelf and a decrease offshore up to more than 50 km from the coast (Mode 1 accounting for 65% of the variability). The temporal pattern of the first EOF peaks during the first quarter of the year is consistent with upwelling induced by NEM winds. It is interesting to note that the results of the EOF analysis of chlorophyll yielded a more significant dominant mode than the EOF analysis of SST (65% variance explained for chlorophyll-a and only 23% for SST). This is an indication that the upwelling signal is much more evident in remotely sensed chlorophyll than in remotely sensed SST. Udarbe and Villanoy (2001) earlier reported the lack of manifestation of upwelling in the SST signal.

The most dramatic change in chlorophyll concentration since 2002 occurred during the NEM seasons of 2006/2007 and 2007/2008. The former was an El Niño year and surface chlorophyll concentrations were among the highest since 2002, while the latter was a La Niña year and chlorophyll concentrations off Zamboanga Peninsula were among the lowest (Figure 7).

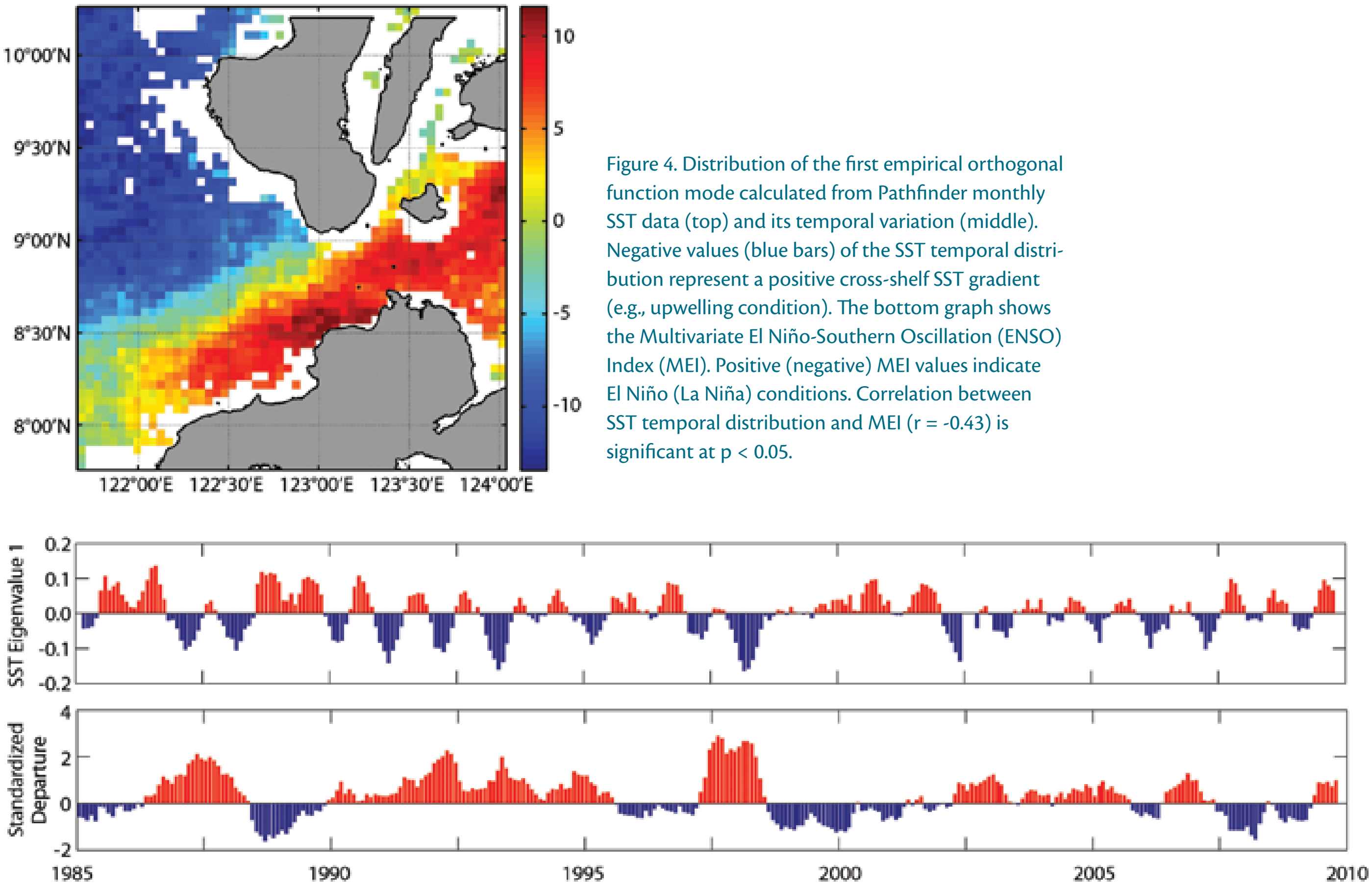


Figure 4. Distribution of the first empirical orthogonal function mode calculated from Pathfinder monthly SST data (top) and its temporal variation (middle). Negative values (blue bars) of the SST temporal distribution represent a positive cross-shelf SST gradient (e.g., upwelling condition). The bottom graph shows the Multivariate El Niño-Southern Oscillation (ENSO) Index (MEI). Positive (negative) MEI values indicate El Niño (La Niña) conditions. Correlation between SST temporal distribution and MEI (r = -0.43) is significant at $p < 0.05$.

IMPACTS ON THE SARDINE FISHERY

Despite their small size relative to the open ocean, coastal upwelling areas are the most biologically rich (Ryther, 1969; Botsford et al., 2006). In productive upwelling systems, the intermediate trophic level is often dominated by small pelagic plankton-feeding species that play a critical role in upwelling trophic dynamics (Cury et al., 2000; Santos et al., 2001). Common upwelling species include sardines and anchovies. In the Zamboanga upwelling, the dominant small pelagic species is the Indian oil sardine (*Sardinella longiceps*).

Monthly chlorophyll *a* time series for five zones from July 2002 to May 2010

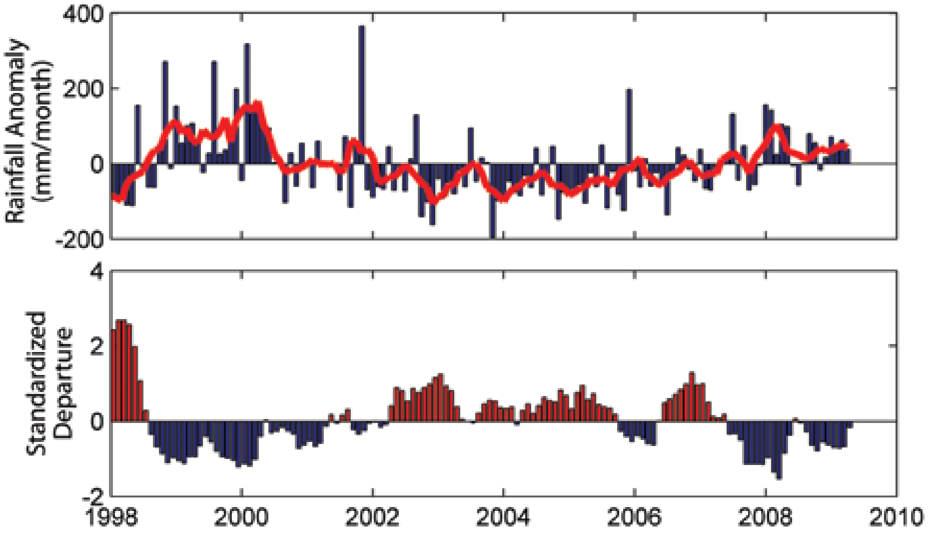
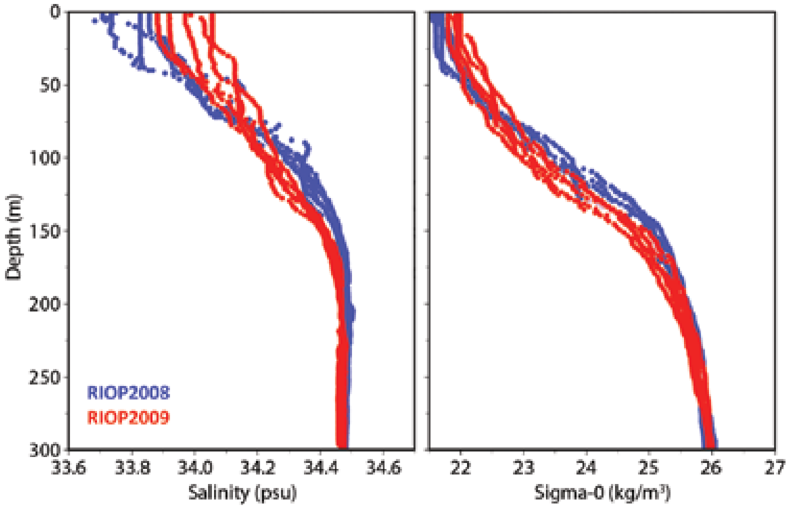


Figure 5. Monthly rainfall anomaly from the area bounded by 8–8°30′N, 122°15′–123°E (top) overlain with the five-month running mean (red solid line). Rainfall data are from the Tropical Rainfall Measuring Mission (http://trmm.gsfc.nasa.gov/data_dir/data.html). The bottom bar graph is the MEI.



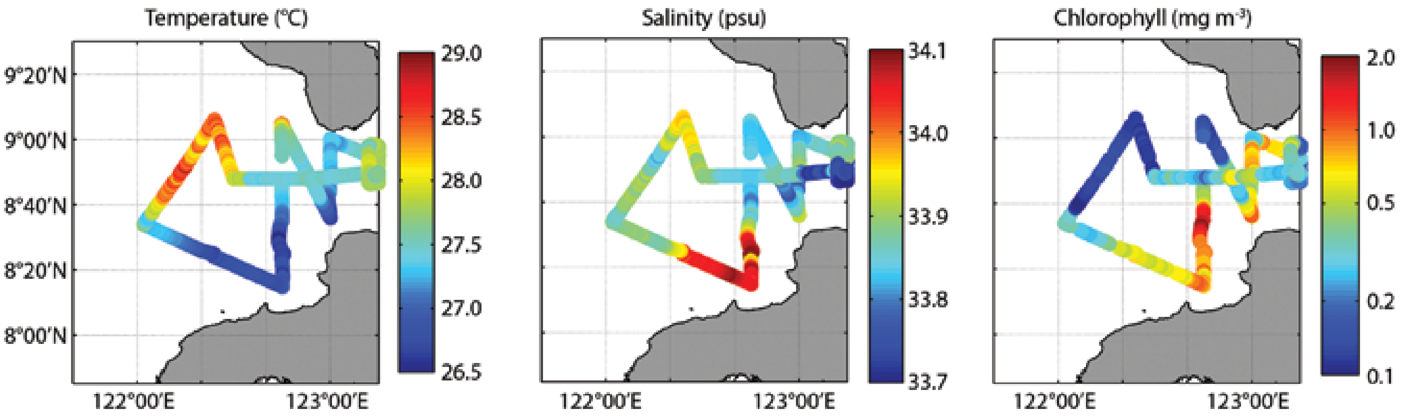


Figure 6. (top panels) Salinity and density profiles from conductivity-temperature-depth stations off the Zamboanga coast from the Intense Observational Period cruises of 2008 (blue) and 2009 (IOP-09; red) (bottom panels) Surface temperature, salinity, and chlorophyll *a* concentration from the ship underway system along the cruise track off Zamboanga Peninsula during IOP-09.

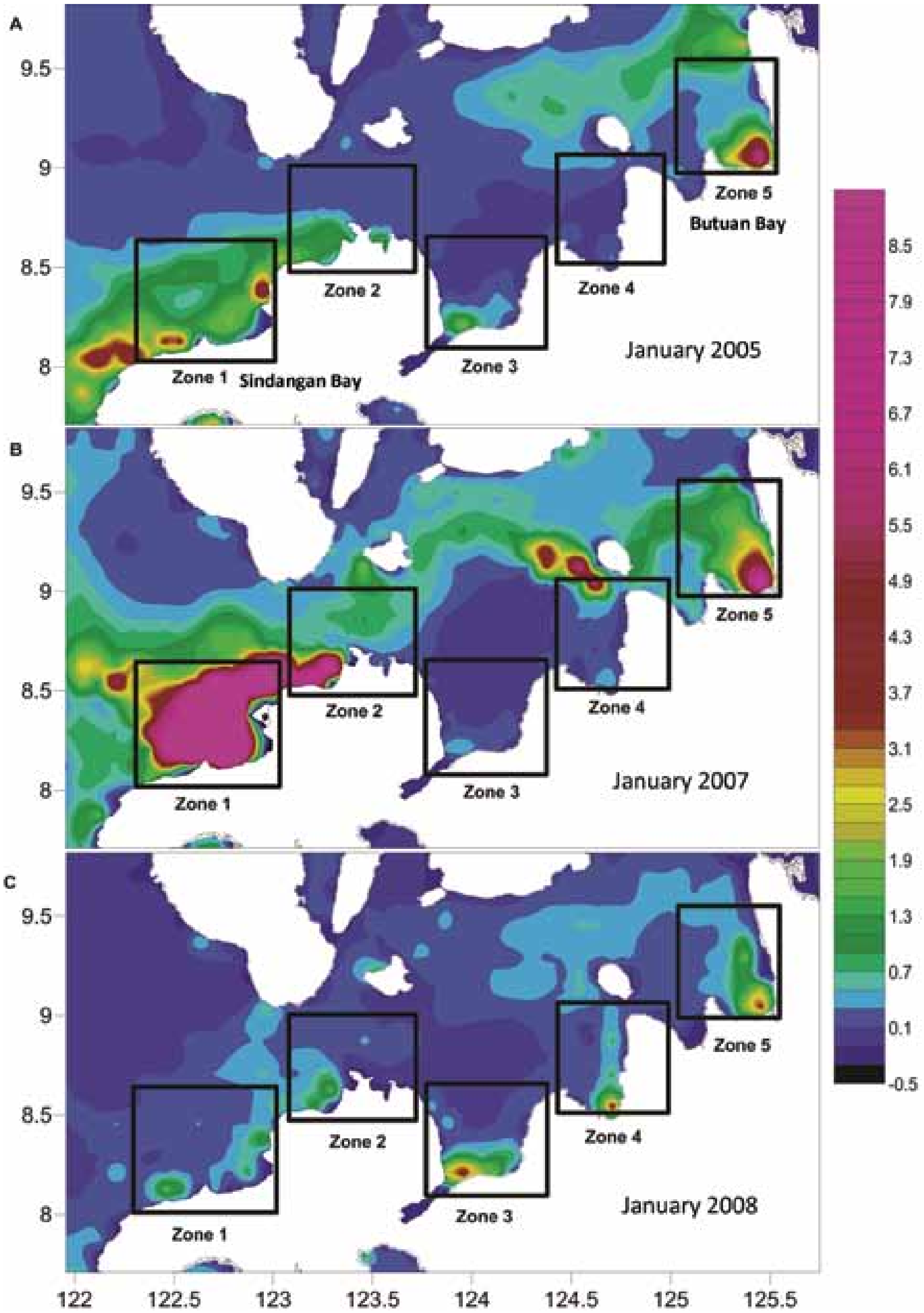


Figure 7. Spatial distribution of chlorophyll in mg m^{-3} off Zamboanga Peninsula and in the Bohol Sea during (A) January 2005, (B) January 2007, and (C) January 2008.

(Figure 8, upper panel) from Sindangan Bay (of Zamboanga Peninsula) and across the Bohol Sea to Butuan Bay were investigated to examine spatial and temporal changes in relation to the sardine fisheries. The data set used was derived from Level 3 MODIS-Aqua.R1.1 chlorophyll *a* data through the Goddard Earth Sciences Data and Information Services Center (GES DISC) Interactive Online Visualization And aNalysis Infrastructure, (GIOVANNI; http://disc.sci.gsfc.nasa.gov/giovanni) for the period July 2002–May 2010. Acker et al. (2009) used GIOVANNI for trend detection in river-influenced coastal regions and Thompson et al. (2009) used it for determining long-term changes in temperate Australian coastal waters. Monthly averaged chlorophyll *a* values were generated (Figure 8) for the five zones identified in Figure 7.

Zone 1 (Sindangan Bay along the northern coast of Zamboanga Peninsula) exhibited the highest chlorophyll *a* concentration (Figure 8, upper panel) followed by Zone 2 (west of Dipolog Strait). Chlorophyll *a* concentrations in the Bohol Sea (Zones 3–5) were much lower. Zone 5 (Butuan Bay) exhibited the highest concentrations in the Bohol Sea, most likely due to the large riverine freshwater discharge it receives from the Agusan River, the second largest river in the Philippines (Alejandrino et al., 1976). The highest concentration occurred during the NEM season of 2006/2007 and more recently in 2009/2010. Both of these periods are El Niños. On the other hand, chlorophyll concentrations were lowest both off the Zamboanga Peninsula (Zone 1 and 2) and in the Bohol Sea during the 2007/2008 La Niña.

Butuan Bay, in the Bohol Sea, is also a sardine fishing area and is compared here to the Zamboanga upwelling to show the relationship of sardines to primary productivity. Both the Zamboanga upwelling and Butuan Bay are high-productivity areas, but the Butuan Bay primary production is probably fueled mainly by nutrients coming from the large Agusan River and possible entrainment of subsurface waters through the "double estuarine circulation" mentioned in Gordon et al. (2011) and Cabrera et al. (2011).

Sardine catch data in Sindangan Bay

(Zone 1, Zamboanga Peninsula shelf) from daily fish landing monitoring show a strong seasonality and are highly correlated to chlorophyll *a* (Figure 8, lower panel). Chlorophyll *a* values were highest during the NEM and upwelling period of December 2009 until February 2010. Sardine production in Sindangan Bay was also correspondingly strongly seasonal, with a pronounced peak from January to February (Figure 8).

High annual production from sardine fisheries motivated the rapid growth of the sardine postharvest industry in Sindangan Bay in the early 1980s. The collective memory of fishers and postharvest investors pointed to the greatest abundance of sardine in 2007, which coincided with the phenomenal spike in chlorophyll *a* concentration in the upwelling area (Figure 8). In 2008, fishers observed a remarkable decline in the abundance of Indian oil sardines (*S. longiceps)* in the Zamboanga upwelling. Many sardine postharvest operators noted that the decline in available fresh sardines started in 2008/2009. These anecdotal accounts seem to coincide with the decline in sea surface chlorophyll *a* concentration recorded around the upwelling zone from April 2007 to November 2009 (Figure 8). The causes for the decline are still not well understood but may be related either to shifts in the exploitation level and/or modulation of upwelling by either monsoon or rainfall variability associated with ENSO. In contrast, a relative increase in sardine catch has been noted in Butuan Bay, coinciding with a modest increase in chlorophyll concentration (Figure 8, bottom panel).

The variability in the upwelling-driven productivity of Zone 1, Sindangan Bay, and Zone 2, Butuan Bay, can exert a large influence on sardine fishery production and spatial distribution in these areas. Sindangan Bay in particular can be more vulnerable to interannual fluctuations in both primary production and availability of small pelagics as seen in other coastal upwelling systems (e.g., Rykaczewski and Checkley, 2008; Pérez et al., 2010). During the 2007/2008 NEM season, the significant decrease in sardine catch in Sindangan Bay coincided with a decline in chlorophyll *a*. Fishers shifted operations to the Bohol Sea (in particular, Butuan Bay) and during the 2009/2010 season, the sardine landed catch in Butuan increased to a peak of about 250 tons in December 2009 (Figure 8, lower panel). Chlorophyll concentrations in Butuan Bay also peaked during the same

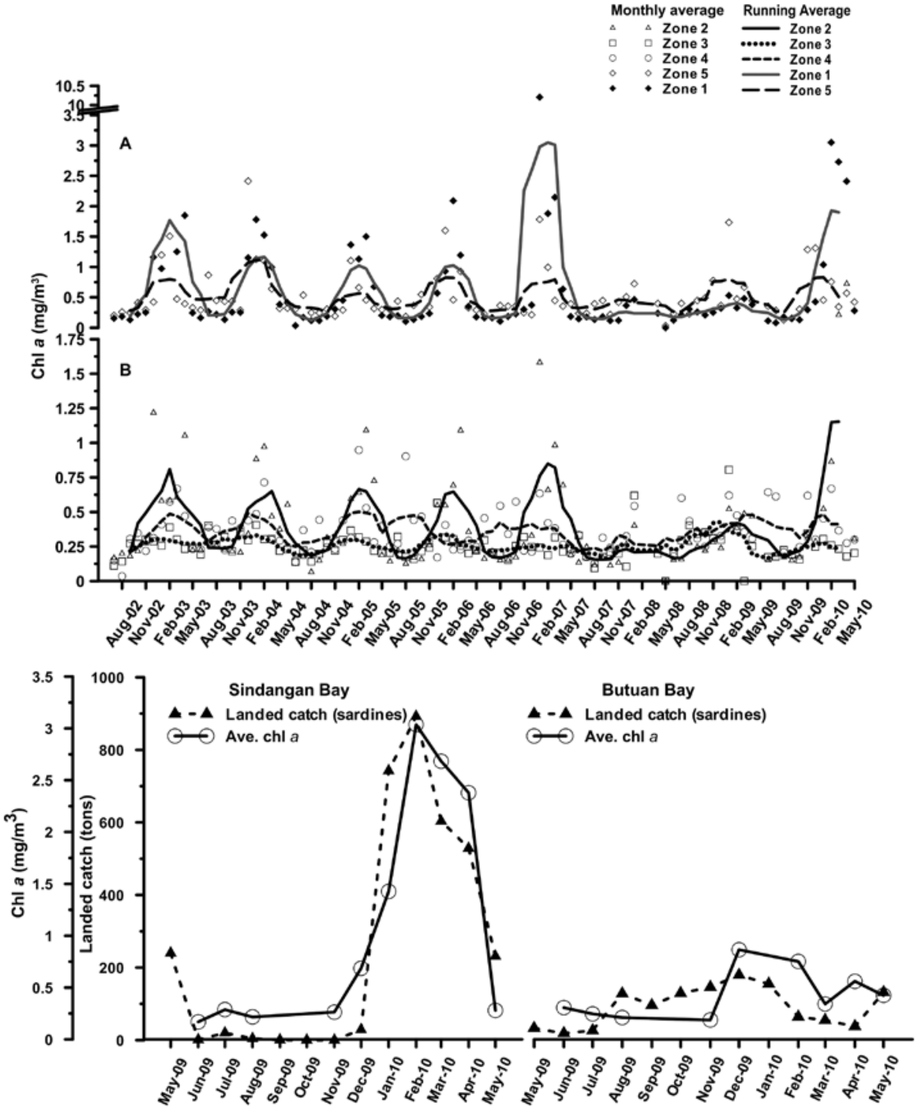


Figure 8. Chlorophyll time series for five zones from July 2002 to January 2010. Panel A (top) represents Zone 1 (Sindangan Bay) and Zone 5 (Butuan Bay); Panel B (middle) consists of Zones 2, 3, and 4. The bottom panel shows chlorophyll values (in mg m^{-3}) and landed sardine catch (in metric tons) in Sindangan Bay and Butuan Bay from May 2009 to May 2010.

month. In the meantime, the Zamboanga sardine catch (in Sindangan Bay during the 2009/2010 season also increased to more than four times the landed catch in Butuan and peaked at the same time the chlorophyll *a* concentrations were highest.

Except for tuna, long-term fishery data in the Philippines for specific fish groups are not available. To determine interannual variations, especially in relation to the upwelling off the coast of Zamboanga, we make use of first quarter (JFM) municipal fisheries production for Zamboanga del Norte province from 1998–2009 (http://www.bas.gov.ph). The assumption here is that the majority of the fish catch landed in Zamboanga del Norte ports from January to March is sardines, and is based on one-year fish catch landing monitoring data (recent work of author de Guzman). By definition, the municipal fishery involves the use of small fishing vessels (< 3 gross tons) within 15 km of the coast. Limiting the data presented here to the first quarter municipal fish production (accounting for 75% of the total Zamboanga del Norte fishery) will most likely reflect the variation in landed sardine catch from the upwelling area (Figure 9). Although the small number of data points in the time series does not make the relationship between ENSO and catch data statistically significant, it is interesting to note that the sardine fishing seasons with the two highest landed fish catches occurred during El Niño years (2004/2005 and 2006/2007) while the two lowest fish catches occurred during La Niña years (1999/2000 and 2007/2008). Thus, there appears to be a connection between fish catch and ENSO wherein landed fish catch is low during La Niña years and high during El Niño years. A much more robust data set is needed to show this relationship with confidence. Other data sets, such as sardine production data from sardine canning factories in the area, will be obtained and analyzed.

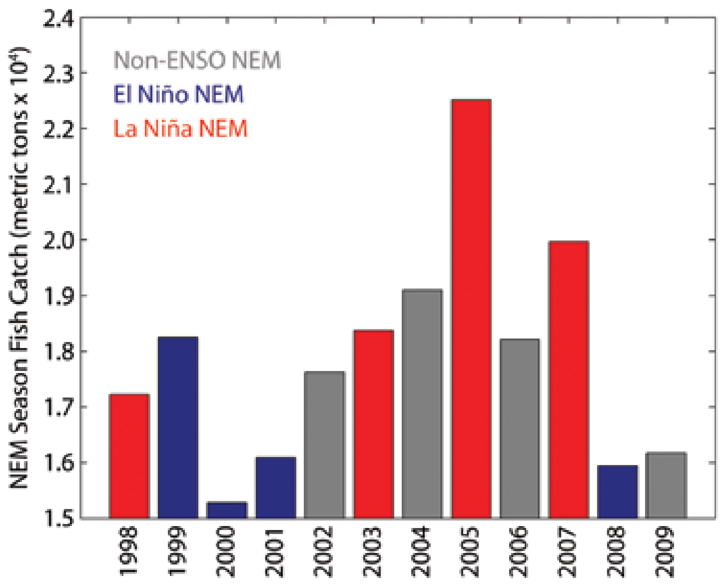


Figure 9. Historical data on the marine municipal fisheries production for Zamboanga del Norte province ports during the Northeast Monsoon (NEM). Data are from the Philippine Bureau of Agricultural Statistics (http://www.bas.gov.ph/, fishery production database accessed in August 2010). The assumption that sardines comprise the majority of fish catch during NEM is based on fish catch monitoring data along the northern coast of Zamboanga Peninsula. Bar colors represent ENSO phases during the NEM season (red is El Niño, blue is La Niña, and gray is a non-ENSO event).

SUMMARY AND CONCLUSIONS

A major upwelling regime exists off the northern coast of Zamboanga Peninsula in the Philippine Archipelago. Upwelling is driven by NEM winds, which are directed toward the southwest from December to March. The NEM winds blow alongshore roughly parallel to the northern coast of Zamboanga; thus, the upwelling is driven mainly by offshore Ekman transport and possibly enhanced Ekman pumping from topographic positive wind stress curl, particularly where the coasts have sharp bends. Upwelling intensity seems to be modulated by ENSO, as shown by the negative correlation between SST and MEI, and is likely influenced by rainfall anomalies. Excessive rainfall during La Niña freshens the surface layer and increases near-surface stratification, hampering upwelling. Satellite measurements of chlorophyll *a* and SST reveal upwelling weakening during the 2007/2008 La Niña and strengthening during the 2006/2007 El Niño, and more recently in 2009–2010, despite the notion of strong (weak) monsoons driving a stronger (weaker) upwelling during La Niña (El Niño).

An important consequence of the upwelling along Zamboanga Peninsula is the relatively large sardine fishery. Monitored sardine landing data from 2009–2010 show a remarkable correlation with average monthly chlorophyll. A reported drop in sardine catch in early 2008 was consistent with SST, chlorophyll *a*, and rainfall data. While recent data for 2009–2010 show signs of increasing catch levels. Improved understanding of the relationship between sardine catch and ENSO variability will help develop a sustainable management plan for this important resource.

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