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BARRIER LAYER CONTROL OF ENTRAINMENT AND UPWELLING IN THE BOHOL SEA, PHILIPPINES

ABSTRACT. The Bohol Sea is a relatively unstudied marginal sea located in the southern part of the Philippines. Hydrographic data from the Philippine Straits Dynamics Experiment (PhilEx) cruises reveal a complex three-dimensional circulation composed of two overturning cells that may be referred to as “double-estuarine type.” This type of overturning circulation promotes upwelling of cold, nutrient-rich waters within the Bohol Sea associated with entrainment and eddy processes that promote phytoplankton blooms. Evidence from ocean color imagery supports entrainment in the eastern basin and eddy formation in the southwestern basin. However, PhilEx researchers found that the cyclonic Iligan Bay Eddy in the southwestern basin did not conform to the paradigm of cyclonic eddy upwelling. Although upwelling was evident through doming isotherms within the water column, the surface projection of this signal was suppressed by the presence of a thick barrier layer, particularly during cruises in December 2007 and January 2008, a known La Niña period. Long-term trends in chlorophyll data followed trends in rainfall and the ENSO 3.4 index, with elevated (reduced) chlorophyll during dry El Niño years (wet La Niña years). By promoting stability of surface layer stratification and preventing vertical transport of nutrients, the barrier layer is thus a mechanism by which the El Niño-Southern Oscillation influences phytoplankton biomass in the Bohol Sea.



INTRODUCTION

There are numerous Philippine marginal seas in addition to the relatively well-known Sulu Sea. One of them is the Bohol Sea, bounded by Negros, Cebu, Bohol, Leyte, and Mindanao islands in the southern Philippines (Figure 1). This sea receives waters from the Pacific Ocean and the Sulu Sea through two straits: Surigao Strait to the east with a sill depth of ~ 60 m, and Dipolog Strait to the west with a sill depth of ~ 500 m. These shallow sills, which connect the 1600-m-deep Bohol Sea with the neighboring basins, give rise to its unique

circulation and physicochemical properties (Gordon et al., 2011).

Four oceanographic cruises were conducted in various Philippine seas in connection with the Philippine Straits Dynamics Experiment (PhilEx): the exploratory cruise of June 2007, the Joint US/Philippines Cruise of November and December 2007, and the regional Intensive Observational Periods of January 2008 (IOP-08) and March 2009 (IOP-09). During the cruises, lowered acoustic Doppler current profiler (L-ADCP) casts as well as hull-ADCP along the cruise tracks provided data on

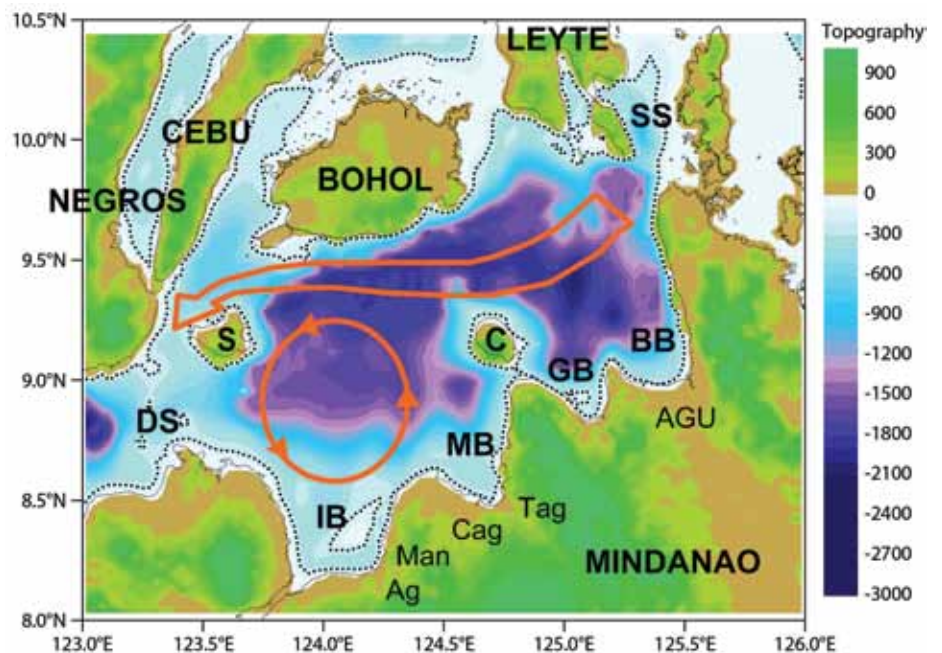


Figure 1. Basin topography and location of islands, sills, bays, and major rivers in the Bohol Sea. Orange arrows indicate the general location and flow direction of the Bohol Jet and the Iligan Bay Eddy, and dotted lines mark the 200-m bathymetric contour. S = Siquijor Island, C = Camiguin Island, DS = Dipolog Strait, SS = Surigao Strait, IB = Iligan Bay, MB = Macajalar Bay, GB = Gingoog Bay, BB = Butuan Bay, Ag = Agus River, Man = Mandulog River, Cag = Cagayan River, Tag = Tagaloan River, AGU = Agusan River. Topographic data are extracted from the two-minute resolution global topography of Smith and Sandwell (1997).

Bohol Sea currents. Consistent findings among these cruises are the observation of a strong southwestward-flowing surface current from the Pacific Ocean to the Sulu Sea along the northern Bohol Sea, and a cyclonic eddy at the southwestern basin of the Bohol Sea (Figure 1). Hereafter, we refer to the southwestward surface current as the Bohol Jet and the cyclonic eddy as the Iligan Bay Eddy (Gordon et al., 2011; Hurlburt et al., 2011).

DOUBLE-ESTUARINE-TYPE CIRCULATION

As Wyrтки (1961) describes, Bohol Sea surface waters flow westward from the Pacific, with the deep waters coming from the overflow of Sulu Sea waters through the Dipolog sill. ADCP data from three of the PhilEx cruises confirm these flows. However, the high vertical resolution provided by both the L-ADCP and the hull-ADCP shows that currents across Dipolog Strait are

composed of four layers instead of just two (Figure 2a). There is a strong westward flowing current from the surface to ~ 100 m, an undercurrent flowing eastward at ~ 100–200 m, a thicker layer flowing westward at 250–400 m, and an eastward-flowing layer below 400 m driving the Sulu overflow across Dipolog Strait.

Apparently, there are two systems exchanging water in the Bohol Sea through Dipolog Strait. Both the upper and lower cells are akin to estuarine circulation; thus, the Bohol Sea circulation is referred to as “double estuarine-type” (Figure 2b; Gordon et al., 2011). The shallow estuarine cell is composed of

surface outflow to the Sulu Sea, compensated with inflow into the Bohol Sea at 100–200-m depth. The surface outflow is driven mostly by the inflow of Pacific waters through Surigao Strait in the east, and this fast flow causes entrainment of deeper, colder, nutrient-rich waters from below. The deep estuarine cell is driven by the flow of dense water from the Sulu Sea spilling over the sill (> 400-m depth), displacing and causing upwelling of resident water that in turn exits back to the Sulu Sea in the 250–400-m layer. The two cells may be considered buoyancy-driven overturning circulation. A consequence of overturning circulation is upwelling and cyclonic

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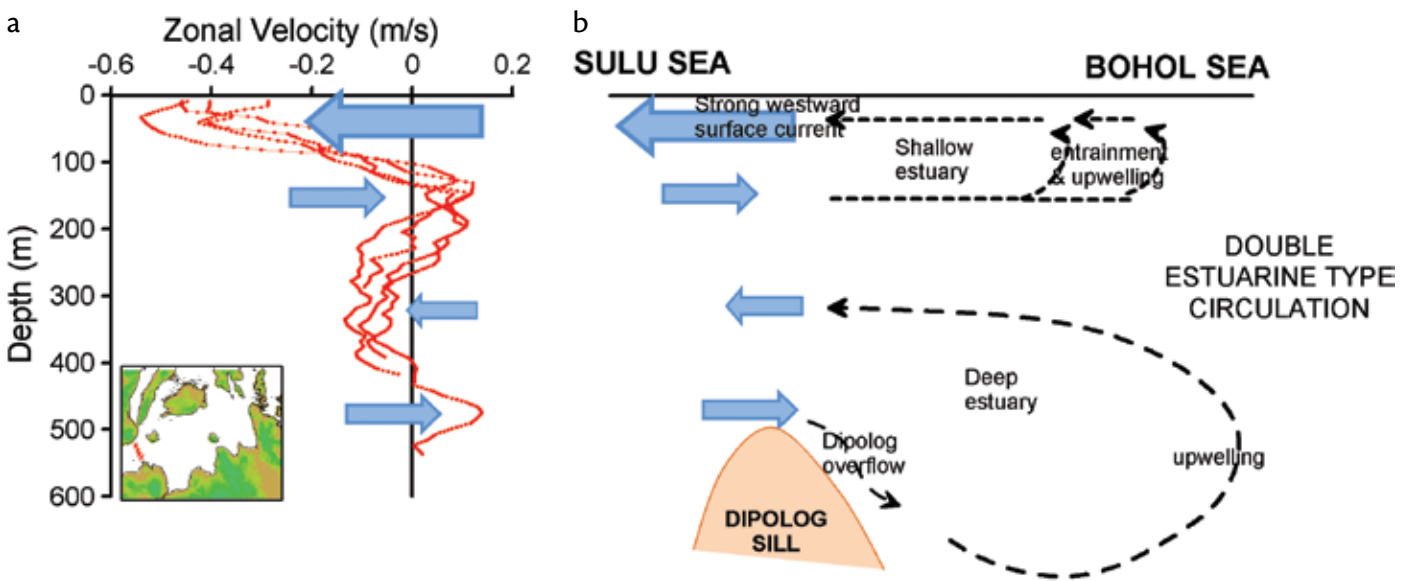


Figure 2. (a) Zonal velocities in units of $m\ s^{-1}$ from lowered acoustic Doppler current profiler (L-ADCP) data collected at stations in Dipolog Strait. (b) Schematics of Bohol Sea double-estuarine type circulation. Inset map in (a) shows station locations in Dipolog Strait, and blue arrows in both (a) and (b) denote the direction of velocities: westward for negative values and eastward for positive values.

rotation due to conservation of potential vorticity (Stewart, 2005). A layer of water becomes “stretched” as it upwells, and to conserve angular momentum, it tends to rotate counterclockwise (Northern Hemisphere) or clockwise (Southern Hemisphere).

This cyclonic rotation is evident in the zonal velocities of a section across the western Bohol Sea (Figure 3). At the surface, there is an eastward-flowing branch south of 9°N and a westward-flowing branch north of 9°N that comprise the edges of the Iligan Bay Eddy. The westward arm of the eddy appears to be contiguous with the westward Bohol Jet, whose intensity and thickness vary with the season. It is interesting to note that the surface eddy appears to be sitting on top of another cyclonic eddy found below 400-m depth, with a layer of discontinuity found at ~ 200-m depth. The 200-m layer is best characterized as a countercurrent, or eastward-flowing current, that circulates beneath the strong westward Bohol Jet. Countercurrent intensity and location also appear to vary with the season, most probably related to the strength of the Bohol Jet. The upper eddy has more positive vorticity than the lower eddy, a

feature that may result from frictional coupling with the Bohol Jet to the north. The lower eddy has a weaker positive vorticity but is much thicker, spanning from 400-m depth down to the seafloor.

spectrum, turning the water “green,” while colored dissolved organic matter (CDOM) absorbs highly in the blue part of the spectrum, making the ocean appear yellow or brown. Algorithms that

“ HYDROGRAPHIC DATA FROM THE PHILIPPINE STRAITS DYNAMICS EXPERIMENT (PHILEX) CRUISES REVEAL A COMPLEX THREE-DIMENSIONAL CIRCULATION COMPOSED OF TWO OVERTURNING CELLS THAT MAY BE REFERRED TO AS ‘DOUBLE-ESTUARINE TYPE.’ ”

The discontinuity of the two eddies can be taken as further evidence supporting the double-estuarine type of circulation proposed for the Bohol Sea.

EVIDENCE FROM OCEAN COLOR

Particulates and dissolved constituents in the ocean tend to change the color of the water from its normal deep blue hue. The pigment chlorophyll *a* found in phytoplankton absorbs highly in the blue and red part of the wavelength

use simple band-ratio techniques for select channels of satellite ocean color sensors enable estimates of chlorophyll *a* concentration (O’Reilly et al., 1998) and CDOM (Morel and Gentili, 2009), and allow production of large-scale, long-term maps of variability of these two constituents. These maps, in turn, provide insights into the circulation patterns of different water masses that have significantly different color signatures (Arnone et al., 2004).

The Bohol Jet and the Iligan Bay Eddy

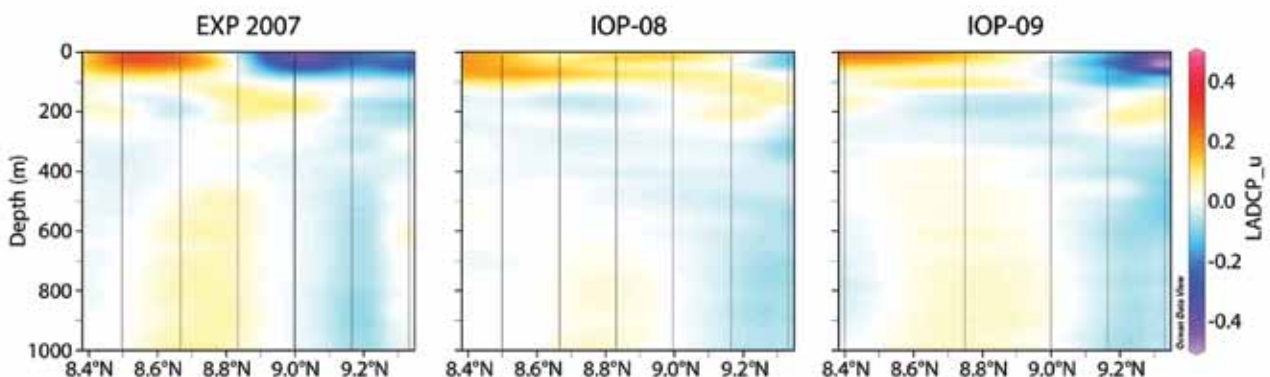


Figure 3. LADCP-derived zonal velocities in $m\ s^{-1}$ across $124^{\circ}E$ in the Bohol Sea. Positive values are eastward and negative values are westward.

are manifested in maps of remotely sensed CDOM and chlorophyll *a* for the Bohol Sea¹ (Figure 4). River-sourced waters are generally high in CDOM, so the mixing and dispersal of river plumes can be traced fairly well in CDOM maps (Coble et al., 2004). Numerous rivers discharge into the Bohol Sea, delivering buoyant plumes of relatively low-salinity surface waters that interact with inflowing high-salinity, low-CDOM Pacific surface waters. River influence is evident in small embayments found in northern Mindanao as the result of plumes that originate at the mouths of the Agusan, Tagaloan, Cagayan, Mandulog, and Agus rivers, which collectively discharge 37,198 million cubic meters of freshwater annually (Alejandrino et al., 1976; see Figure 1

for location of these rivers). There is a seasonal variability, with a peak in CDOM concentrations during the north-east monsoon months from December to February (DJF). The Bohol Jet is clearly delineated as a tongue of low-CDOM waters in the northern portion extending from Surigao Strait to Negros Island, while the Iligan Bay Eddy appears at 8°30'–9°15'N, 124°E as a ring of CDOM-rich waters enclosing relatively CDOM-low waters. The eddy is about 100 km in diameter and appears to be a mechanism for dispersal of CDOM-rich plumes of waters coming from Iligan and Macajalar bays, similar to the eddy dispersal of the Orinoco River plume in the eastern Caribbean (Corredor et al., 2004; Hu et al., 2004). Composite CDOM images also show that the main

route of the Bohol Jet is north of Siquijor Island, as observed in ADCP data during PhilEx cruises.

Aside from CDOM, phytoplankton's marker pigment chlorophyll *a* has been used in various studies to track eddies and pinpoint upwelling areas. For instance, the high chlorophyll concentration off the coasts of Java and Sumatra, Indonesia, was taken as evidence for the existence of upwelling in the region even though the upwelling signature was not seen in sea surface temperatures (Qu et al., 2005).

In the Bohol Sea, the eastern basin has generally higher chlorophyll *a* concentrations than the western basin (Figure 4b), evidence that the process of entrainment of colder, deeper, nutrient-rich water occurs in the Bohol Sea with

¹ The simple band-ratio algorithms are known to miscalculate both chlorophyll and CDOM concentrations for optically complex waters of coastal and marginal seas. It is not the aim of this paper to provide accurate estimates of neither chlorophyll nor CDOM but only to use maps of the two constituents to infer circulation of the Bohol Sea (i.e., patterns of mixing and dispersal, and evidence of upwelling). Relative accuracy and error estimates for satellite-derived inherent optical properties will be dealt with in another paper still in preparation, using underway data of chlorophyll fluorescence, CDOM fluorescence, absorbance, scatter, and attenuation of dissolved and particulate fraction of the waters along the IOP-09 cruise track.

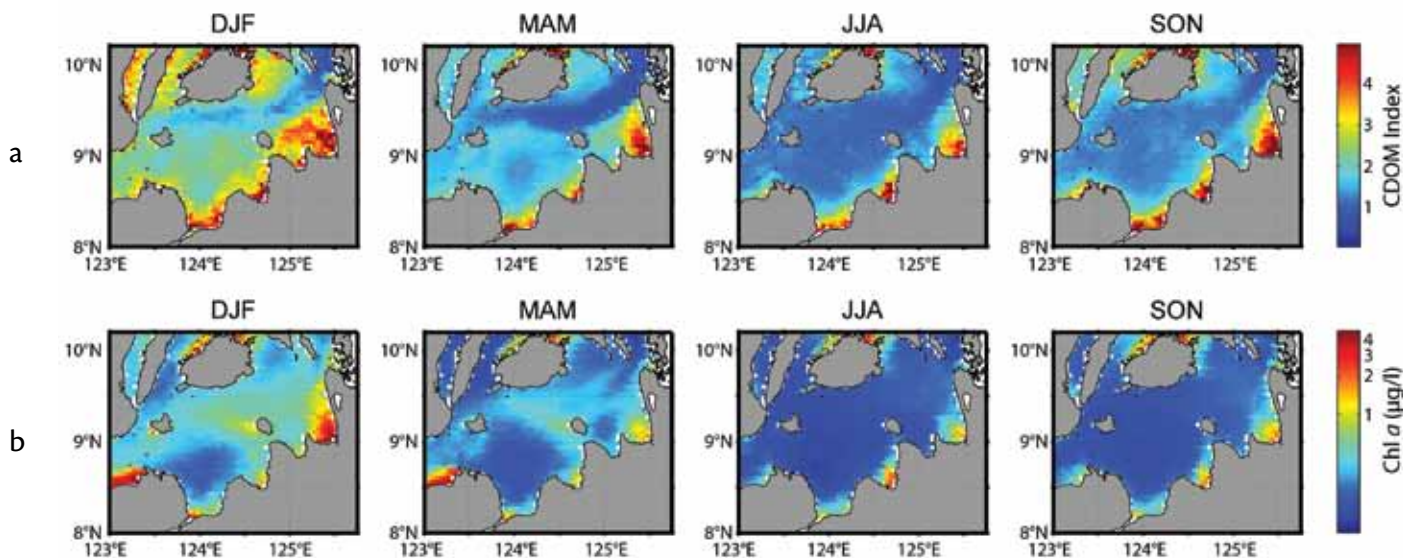


Figure 4. Seasonal averages of (a) colored dissolved organic matter (CDOM) and (b) chlorophyll *a* using January 2002 to June 2010 data from MODIS. (DJF = December, January, February. MAM = March, April, May. JJA = June, July, August. SON = September, October, November). CDOM and chlorophyll *a* data were extracted from global, monthly 4-km level 3 standard mapped images of colored dissolved organic matter index and chlorophyll *a* from the 2009 reprocessing of MODIS satellite data (<http://oceandata.sci.gsfc.nasa.gov>).

a greater magnitude in the eastern basin than the western basin. Influence of riverine inflow cannot be discounted, however, as the Agusan River, the second largest river in the Philippines, discharges into the eastern basin. Higher chlorophyll *a* concentration during the northeast monsoon period may be due to Bohol Jet intensification, with the northeasterly winds causing increasing shear between the westward flowing jet and the countercurrent beneath. It is interesting to note that the region of the Iligan Bay Eddy has consistently low chlorophyll *a* across seasons, with the eddy becoming more obvious from December to March as a circle of low-chlorophyll waters in the southwestern basin of the Bohol Sea.

AN ANOMALOUS CYCLONIC EDDY

A well-accepted paradigm is that cyclonic eddies cause upwelling of cold, nutrient-rich waters that in turn stimulate phytoplankton blooms (Falkowski et al., 1991; McGillicuddy et al., 2007). However, the Iligan Bay Eddy's core shows neither lowered temperatures nor elevated chlorophyll at the sea surface based on data from the PhilEx cruises as well as from satellite images.

According to McGillicuddy et al. (1998), a cyclonic eddy would generate upwelling as indicated by a shoaling or doming of the isotherms. Temperature sections across the western basin of the Bohol Sea show this doming of isotherms; it is most evident for the 2007 exploratory cruise and IOP-09 (Figure 5). However, cold waters upwelled at the eddy's core seem to be prevented from reaching the surface by the presence of a freshwater lens. Across

the four cruises, a strong halocline is very much evident, leading to shallow mixed-layer depths.

Bohol Sea mixed-layer depth (MLD), computed as a function of surface salinity and temperature (Sprintall and Tomczak, 1992), was generally shallow (Figure 6). Most stations occupied during the PhilEx cruises had MLDs less than 50 m except for stations in the vicinity of the straits. The deeper mixed layers for these stations suggest that tidal mixing and intrusion of the Bohol Jet generate turbulence in addition to wind mixing. On average, MLD is at 25 m, which is important to phytoplankton productivity,

as the steep density gradient prevents mixing and diffusion of nutrients from deeper waters. In the Bohol Sea, a subsurface chlorophyll maximum (SCM), if present, occurs at a depth of 20–50 m at or below the MLD, while the nutricline occurs at about 20–60 m but at or below the SCM (Figure 7).

BARRIER LAYER

There was no significant difference in the MLDs for the four cruises, though the presence and thickness of a barrier layer was significantly different (Table 1). A barrier layer is an intermediate layer positioned between the lower-salinity

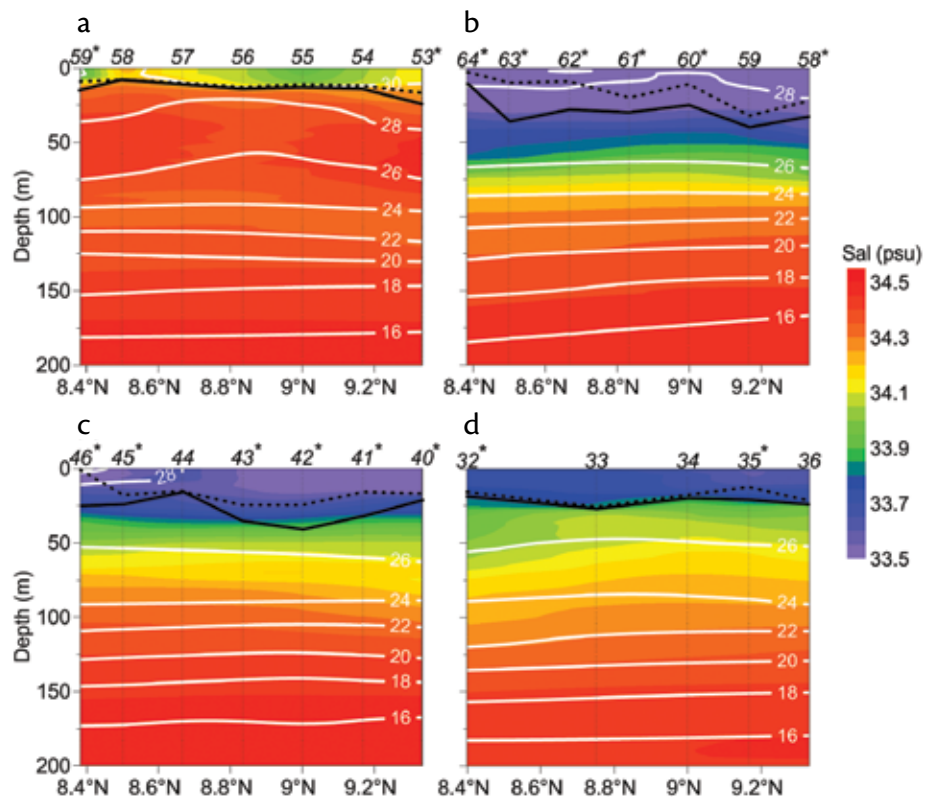


Figure 5. Temperature and salinity sections across 124°E in the Bohol Sea during the four PhilEx cruises. (a) The exploratory cruise of June 2007, (b) the Joint US/Philippines Cruise of November–December 2007, (c) the regional Intensive Observational Period of January 2008 (IOP-08), and (d) the regional Intensive Observational Period of January 2009 (IOP-09). White isolines plot temperature and colored contours indicate salinity. The black dashed lines mark mixed-layer depths (MLDs) and the black solid lines isothermal depths (IDs). Station numbers are shown along the tops of the sections. Asterisks denote stations with a barrier layer (ID-MLD) thicker than 3 m.

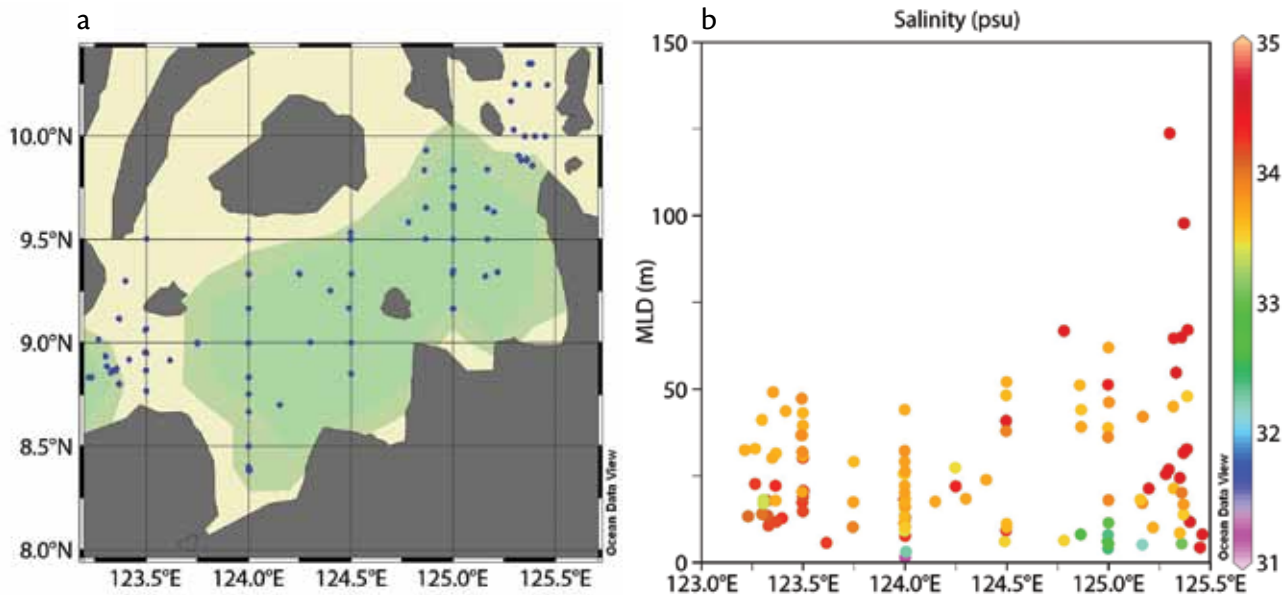


Figure 6. Mixed-layer depths (MLDs) at the Bohol Sea as a function of longitude and surface salinity. MLDs are less than 60 m except for stations within Surigao Strait where tidal mixing is strong and stratification is not solely due to surface buoyancy flux.

IOP-09

a) Stn 32, no BL (BLT < 3 m)

b) Stn 32, BLT = 11 m

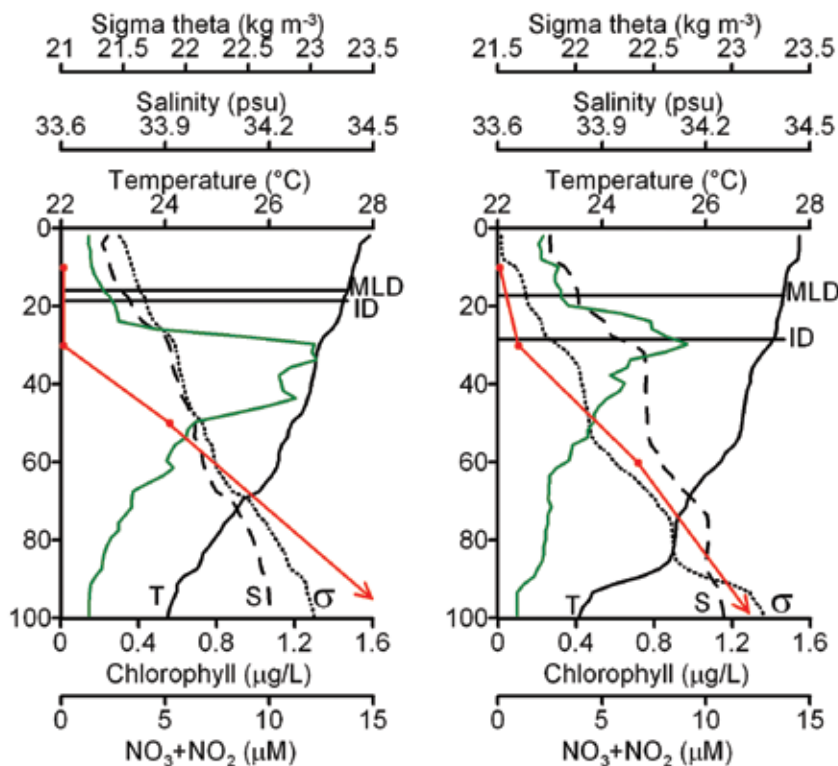


Figure 7. Sample profiles showing stations (a) without a barrier layer and (b) with a barrier layer. Profiles of temperature (solid), salinity (dashed), density (dotted), chlorophyll (green), and nutrient (red) are from CTD casts in the Bohol Sea during the IOP-09 cruise.

upper mixed layer and the top of the thermocline (Lukas and Lindstrom, 1991). Defined operationally as the difference of the isothermal depths (ID) and MLDs, the presence of a barrier layer indicates a strong halocline above the thermocline (Sprintall and Tomczak, 1992). In this study, ID is computed as the interpolated depth where temperature is 0.5°C less than the value at the surface (0–2-m depth).

Presence of the barrier layer has been documented for the South China, Sulu, and Celebes seas, all marginal seas around the Philippines (Chu et al., 2002; Du et al., 2004; Pan et al., 2006; Zeng et al., 2009). This is the first report that a barrier layer is also present in the Bohol Sea. Occurrence rate and thickness of the barrier layer appear to be correlated with rainfall; the barrier layer was found to be thicker and occurred more frequently during the Joint US/Philippines Cruise of 2007 and IOP-08, as shown by mean and median barrier layer thickness and

Table 1. General statistics of the barrier layer in the Bohol Sea

Cruise	Duration	Number of CTD Stations	% Occurrence (BLT > 3 m)	Mean Thickness (m)
Exploratory	Jun 6–Jul 2, 2007	45	42	4
Joint US/Philippines	Nov 3, 2007–Jan 3, 2008	24	88	10
Intensive Observational Period 2008	Jan 10–29, 2008	37	89	12
Intensive Observational Period 2009	Feb 28–Mar 10, 2009	21	52	10

One-way analysis of variance showed that barrier layer thickness (BLT) is significantly different between cruises ($p = 0.0003$)

percent occurrence of a barrier layer thicker than 3 m for the four PhilEx cruises (Figure 8, Table 1). It is highly likely that monsoon rainfall and river runoff are responsible for barrier layer formation in this small basin, similar to the formation mechanism invoked for the other marginal seas in the previously mentioned papers.

Many barrier layer studies focus on the layer's effect on the ocean heat budget. The term “barrier” is used to signify that the layer prevents transfer of heat from the mixed layer to the isothermal waters below (Sprintall and Tomczak, 1992). Another way of looking at it is that the barrier prevents the transport of cold, nutrient-rich waters from below to the surface (Qu and Meyers, 2005). With its steep gradient in density, the barrier layer enhances stratification so that upwelling and entrainment must be more intense to overcome the barrier layer's stability. This barrier may very well be important to the primary productivity of the Bohol Sea in particular, and the ocean in general. Upwelling would conserve the potential vorticity generated by the Iligan Bay Eddy, and this upwelling is evident in the doming of isotherms in temperature sections across 124°E (Figure 5). In addition, the

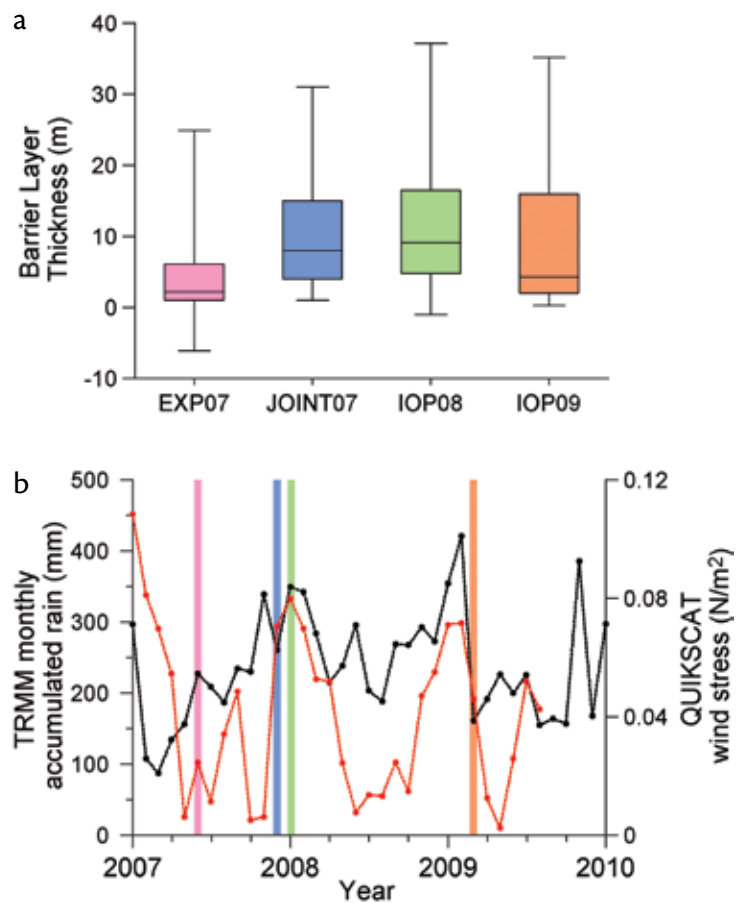


Figure 8. (a) Box-whisker plots of barrier layer thickness in the Bohol Sea during the four PhilEx cruises. The caps at the ends of the boxes indicate extreme values (minimum and maximum), the boxes are defined by lower and upper quartiles, and the center lines in the boxes indicate the median. (b) Tropical Rainfall Measuring Mission (TRMM)-derived accumulated rain and QuikSCAT-derived wind stress from 2007 to 2009 averaged for the region bounded by 7°30'–11°00'N and 122°30'–126°30'E. Colored rectangles along the time axis indicate the cruise periods (pink, blue, green, and orange for the exploratory cruise of 2007, the Joint US/Philippines Cruise of 2007, IOP-08, and IOP-09, respectively).

absence of doming isothermals during the Joint Cruise of 2007 and IOP-08 (Figure 5b,c) may be taken as an indication that upwelling was suppressed in the presence of a thick barrier layer. These cruises occurred during a strong La Niña when precipitation is known to be above normal (Juneng and Tangang, 2005; Lyon et al., 2006), and the barrier layer was thicker and more prevalent. Furthermore, CDOM was above average while chlorophyll *a* was below average during the DJF months of 2007–2008 (Figure 9), another indication that riverine runoff was enhanced, the barrier layer was thicker, and upwelling was reduced for this period. The opposite appears to occur during the DJF months of 2002–2003, an El Niño period.

To determine whether the

El Niño-Southern Oscillation (ENSO) signal was reflected in the phytoplankton dynamics in the Bohol Sea, we used empirical orthogonal function (EOF) analysis of chlorophyll *a* following the methodology of Garcia and Garcia (2008). Sea-viewing Wide Field-of-view Sensor (SeaWiFS)-derived and Moderate Resolution Imaging Spectroradiometer (MODIS)-derived monthly chlorophyll *a* concentrations were log-transformed, smoothed through double-pass running averages (12 months and 2 months), then Z-normalized before analysis. Smoothing or filtering was done to emphasize interannual scale variability. We used data from both satellites to assemble a data set that was temporally extensive (SeaWiFS) and spatially fine (MODIS). Although

comparisons between the two data sets were beyond the scope of the study, the spatially (Figure 10) and temporally (Figure 11, where the data sets overlap) coherent patterns we identified point to the strength of the patterns, as discussed below.

Results of the EOF analysis showed that the long-term pattern in chlorophyll *a* is closely associated with the ENSO signal and its rain anomalies. The spatial pattern of the dominant first mode (explaining 57% and 56% of the variability in the SeaWiFS and MODIS data, respectively) separated the embayment areas off northern Mindanao from the rest of the Bohol Sea basin (Figure 10), clearly denoting the influence of riverine runoff. The predominantly positive values

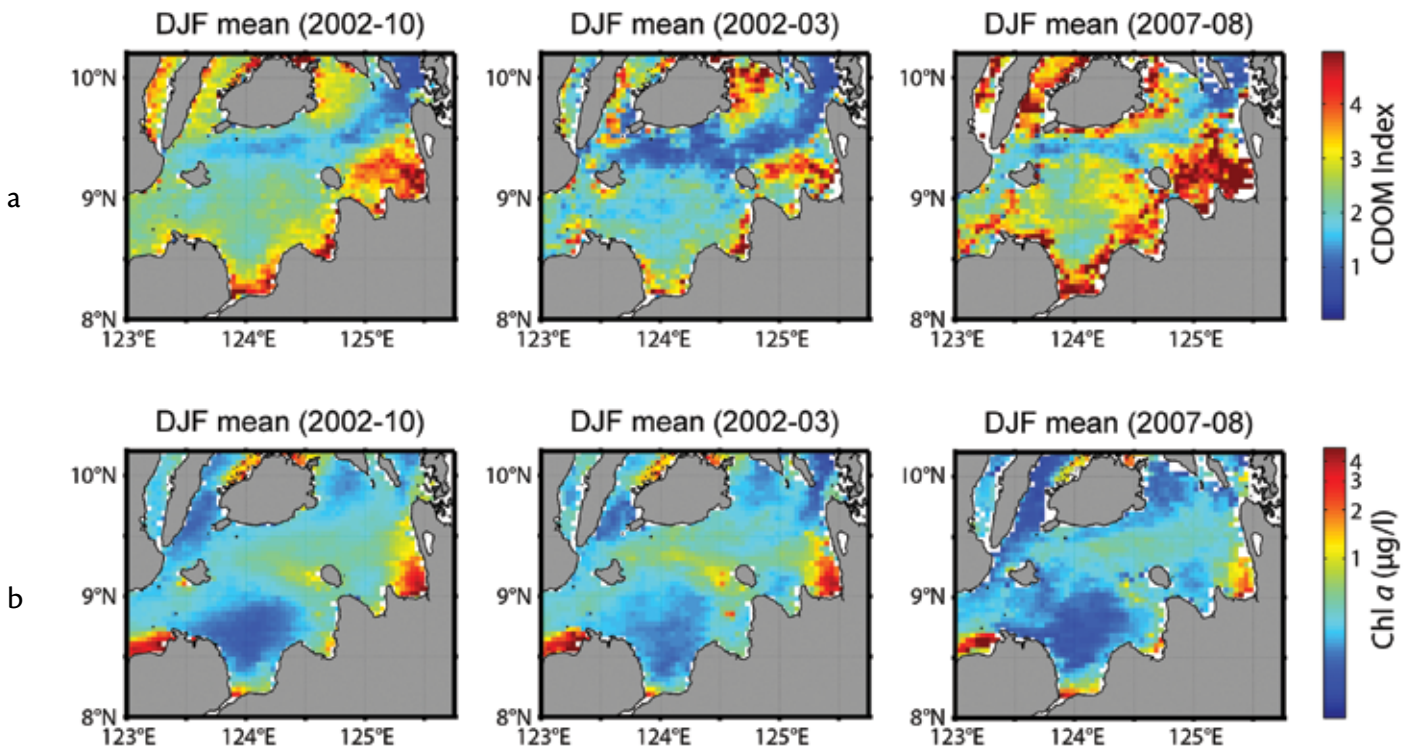


Figure 9. DJF averages of CDOM (a) and chlorophyll *a* (b) for the whole period of 2002 to 2010 compared to DJF averages during El Niño year of 2002–2003 and La Niña year of 2007–2008. Only the December to February composites are provided because the CDOM and chlorophyll *a* concentrations were shown to be highest during the northeast monsoon season.

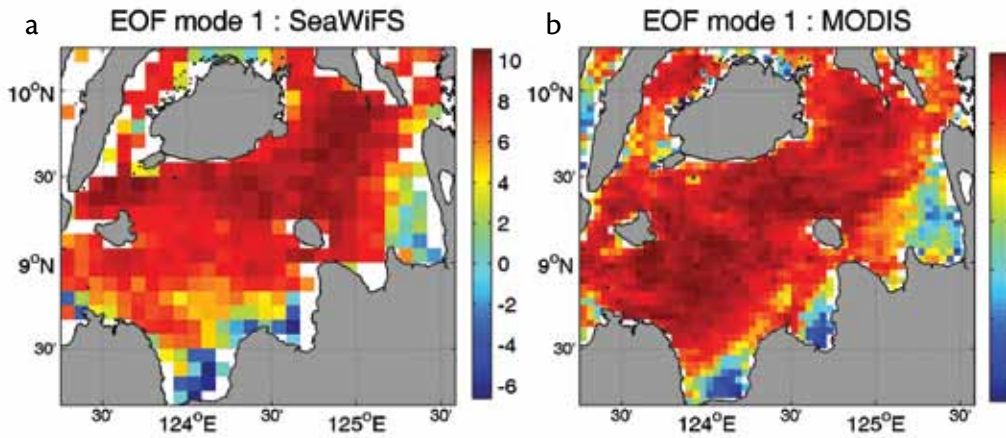


Figure 10. Spatial pattern of the dominant mode resulting from the empirical orthogonal function analysis of (a) Sea-viewing Wide Field-of-view Sensor (SeaWiFS)-derived and (b) Moderate Resolution Imaging Spectroradiometer (MODIS)-derived chlorophyll *a* in the Bohol Sea. Only the first mode is shown here because more than half of the variance is already explained by this mode (57% and 56% for SeaWiFS and MODIS data, respectively). Values for (b) were inverted by multiplying with -1 to facilitate visualization and discussion.

indicate that a large part of the Bohol Sea responds positively to the reduced rains during El Niño and negatively to the enhanced rains during La Niña conditions (Figure 11). The trends are highly significant ($p < 0.001$), with EOF mode 1 being positively correlated with ENSO 3.4 anomalies ($r = 0.7$ for SeaWiFS, $r = 0.38$ for MODIS data) and negatively correlated with Tropical Rainfall Measuring Mission (TRMM) rain anomalies ($r = -0.63$ for SeaWiFS, $r = -0.51$ for MODIS data). Although winds are reported to weaken during El Niño years (Wu and Chan, 2005), the trend is not apparent in the wind data for the Bohol Sea. A quasi-biennial oscillation is more obvious, and this is also reflected in chlorophyll *a* variability through the second mode (plot not shown as variance explained by mode 2 is less than 15%).

More than two decades ago, Barber and Chavez (1983) demonstrated climate-driven, specifically ENSO-driven, variation in phytoplankton productivity. The advent of satellite remote sensing of ocean color spawned several additional studies documenting interannual and decadal trends in phytoplankton variability (Gregg and

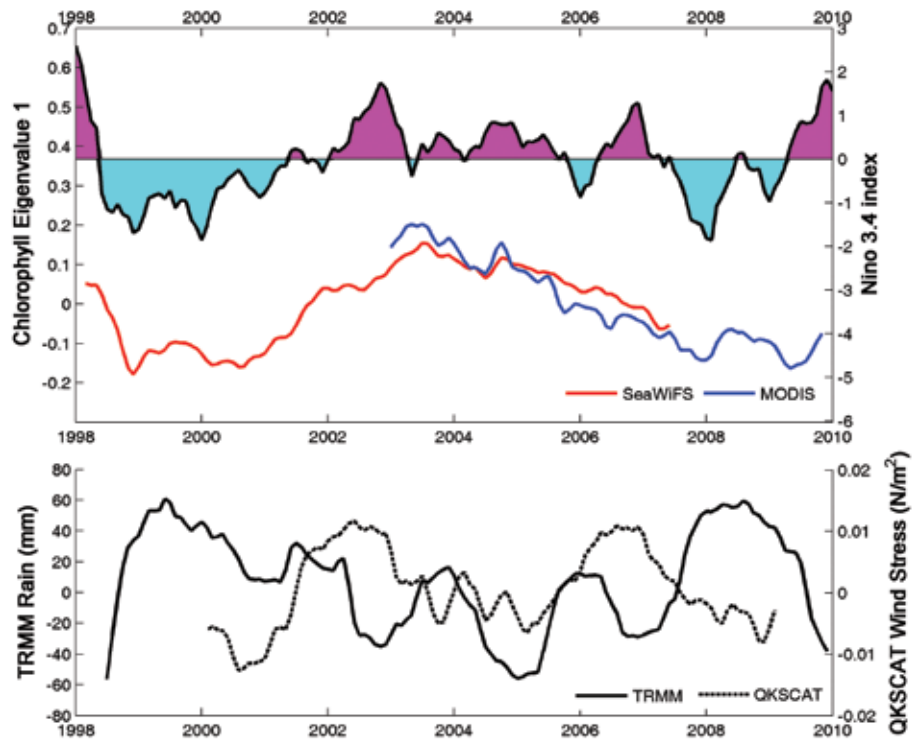


Figure 11. Temporal pattern of the mode 1 eigenvalues resulting from empirical orthogonal function analysis of SeaWiFS and MODIS chlorophyll *a* data. Eigenvalues for MODIS data were inverted by multiplying with -1. For comparison, the figure also shows the temporal evolution of the Niño 3.4 index (in shades of magenta and cyan; data from <http://www.cpc.noa.gov/data/indices/sstoi.indices>), TRMM-derived rain anomalies (black line), and QuikSCAT-derived wind stress anomalies (dashed line). Rain and wind stress data are 12-month running averages for the whole Bohol Sea ($7^{\circ}30' - 11^{\circ}00'N$, $122^{\circ}30' - 126^{\circ}30'E$), from the TRMM microwave imager (<http://disc2.nascom.nasa.gov/Giovanni/tovas>), and from the QuikSCAT scatterometer (http://apdrc.soest.hawaii.edu/dods/public_data/satellite_product/QKSCAT), respectively.

Conkright, 2002; Behrenfeld, et al., 2006; Martinez et al., 2009). Common among these studies is the emphasis on the warming temperatures and the resulting increase in stratification as the connection that links climate to phytoplankton.

In this paper, we specifically pinpoint the barrier layer as a mechanism by which climate, or ENSO dynamics, exerts its effect on phytoplankton in this part of the world. The weaker (stronger) precipitation during El Niño (La Niña) causes the formation of a thinner (thicker) barrier layer, which in turn would cause weaker (stronger) stratification. Stratification is a means by which the nutrient-deficient surface layer is maintained, causing lower phytoplankton biomass and productivity. El Niño conditions would thus theoretically intensify phytoplankton productivity while La Niña conditions would reduce it. This result is counterintuitive


on barrier-layer control of upwelling and entrainment may very well be applicable to areas under the influence of the monsoons or the Intertropical Convergence Zone. Furthermore, future trends in phytoplankton may be better constructed based on predicted changes of not only temperature but also rainfall.

SUMMARY

The dynamics of entrainment and eddy formation in the Bohol Sea is evident from currents and ocean color data. Entrainment appears to be enhanced during the northeast monsoon season and is more pronounced in the eastern basin than the western basin. The cyclonic eddy detected in the western basin was found to be anomalous, with a warm and low-chlorophyll core that does not conform to the paradigm of eddy upwelling. This abnormality is attributed to the presence of a shallow mixed layer

year. A thick barrier layer constrains the upwelling and entrainment resulting from the cyclonic eddy and overturning, estuarine-like circulation in the Bohol Sea. A response is the reduction in blooms of phytoplankton that normally occur in the Bohol Sea during the northeast monsoon. Long-term trends in chlorophyll variability followed trends in rainfall and the ENSO 3.4 index, further supporting the control exerted by the barrier layer in the upwelling and entrainment dynamics in the Bohol Sea. Thus, the freshwater-induced barrier layer is one mechanism by which ENSO influences primary productivity in the Bohol Sea with enhanced (reduced) productivity during El Niño (La Niña).

ACKNOWLEDGEMENTS

Olivia Cabrera thanks the Philippine Department of Science and Technology-Accelerated Science and Technology Human Resource Development (DOST-ASTHRD) Program for her scholarship. The authors thank the officers and crew of R/V *Melville* and all participants of the PhilEx cruises, especially Gil Jacinto and the Chemical Oceanography Lab for the nutrient data. Insightful comments from anonymous reviewers helped improve the manuscript. This work was supported by Office of Naval Research (ONR) Grant N00014-09-1-0582 to Lamont-Doherty Earth Observatory of Columbia University through Arnold Gordon and ONR Grant N00014-06-1-0686 and N00014-09-1-0807 to the University of Hawaii, through Pierre Flament. This work is Marine Science Institute contribution number 396 and Lamont-Doherty Earth Observatory contribution number 7435. 

“ THE DYNAMICS OF ENTRAINMENT AND EDDY FORMATION IN THE BOHOL SEA IS EVIDENT FROM CURRENTS AND OCEAN COLOR DATA. ”

for people familiar only with the warmer temperatures and low phytoplankton and fishery productivity caused by El Niño in the eastern Pacific.

The findings from this study provide a mechanistic context for the influence of climate on phytoplankton productivity in the Bohol Sea. Although the study area is a small basin, the findings

and, more importantly, to the presence of a barrier layer separating the mixed layer from the isothermal layer. During the 2008 La Niña, mixed-layer depths during the 2007 Joint Cruise (December) and IOP-08 (January) were very shallow, and we observed a barrier layer as thick as 37 m, a response that is related to the above average rainfall during this

REFERENCES

- Alejandrino, A.A., M.L. Diaz, R.C. Bruce, A.P. Basilio, C.E. Yñiguez, R.G. Salas, and H.B. Bayhon. 1976. *Principal River Basins of the Philippines*. Report No. 4, National Water Resources Council, Philippines, 82 pp.
- Arnone, R.A., A.M. Wood, and R.W. Gould Jr. 2004. The evolution of optical water mass classification. *Oceanography* 17(2):14–15. Available online at: http://www.tos.org/oceanography/issues/issue_archive/17_2.html (accessed December 30, 2010).
- Barber, R.T., and F.P. Chavez. 1983. Biological consequences of El Niño. *Science* 222:1,203–1,210.
- Behrenfeld, M.J., R.T. O'Malley, D.A. Siegel, C.R. McClain, J.L. Sarmiento, G.C. Feldman, A.J. Milligan, P.G. Falkowski, R.M. Letelier, and E.S. Boss. 2006. Climate-driven trends in contemporary ocean productivity. *Nature* 444:752–755.
- Chu, P.C., Q. Liu, Y. Kia, and C. Fan. 2002. Evidence of a barrier layer in the Sulu and Celebes Seas. *Journal of Physical Oceanography* 32:3,299–3,309.
- Coble P., C. Hu, R.W. Gould Jr., G. Chang, and A.M. Wood. 2004. Colored dissolved organic matter in the coastal ocean: An optical tool for coastal zone environmental assessment and management. *Oceanography* 17(2):50–59. Available online at: http://www.tos.org/oceanography/issues/issue_archive/17_2.html (accessed December 30, 2010).
- Corredor, J.E., J.M. Morell, J.M. López, J.E. Capella, and R.A. Armstrong. 2004. Cyclonic eddy entrains Orinoco River plume. *Eos, Transactions, American Geophysical Union* 85:197–208.
- Du, Y., D. Wang, P. Shi, P. Guo, and J. Chen. 2004. Barrier layer in the South China Sea and its relationship to the sea surface fluxes. *Chinese Journal of Atmospheric Sciences* 28:101–111.
- Falkowski, P.G., D. Ziemann, Z. Kolber, and P.K. Bienfang. 1991. Role of eddy pumping in enhancing primary production in the ocean. *Nature* 352:55–58.
- Garcia, C.A.E., and V.M.T. Garcia. 2008. Variability of chlorophyll-*a* from ocean color images in the La Plata continental shelf region. *Continental Shelf Research* 28:1,568–1,578.
- Gregg, W.W., and M.E. Conkright. 2002. Decadal changes in global ocean chlorophyll. *Geophysical Research Letters* 29:1,730–1,734.
- Gordon, A.L., J. Sprintall, and A. Ffield. 2011. Regional oceanography of the Philippine Archipelago. *Oceanography* 24(1):14–27.
- Hu, C., E.T. Montgomery, R.W. Schmitt, and F.E. Muller-Karger. 2004. The dispersal of the Amazon and Orinoco River plumes in the tropical Atlantic and Caribbean Sea: Observation from space and S-PALACE floats. *Deep-Sea Research Part II* 51:1,151–1,171.
- Hurlburt, H.E., E.J. Metzger, J. Sprintall, S.N. Riedlinger, R.A. Arnone, T. Shinoda, and X. Xu. 2011. Circulation in the Philippine Archipelago simulated by 1/12° and 1/25° global HYCOM and EAS NCOM. *Oceanography* 24(1):28–47.
- Juneng, L., and F.T. Tangang. 2005. Evolution of ENSO-related rainfall anomalies in Southeast Asia region and its relationship with the atmosphere-ocean variations in Indo-Pacific sector. *Climate Dynamics* 25:337–350.
- Lukas, R., and E. Lindstrom. 1991. The mixed layer of the western equatorial Pacific Ocean. *Journal of Geophysical Research* 96:3,343–3,357.
- Lyon, B., H. Cristi, E.R. Verceles, F.D. Hilario, and R. Abastillas. 2006. Seasonal reversal of the ENSO rainfall signal in the Philippines. *Geophysical Research Letters* 33, L24710, doi:10.1029/2006GL028182.
- Martinez, E., D. Antoine, F. D'Ortenzio, and B. Gentili. 2009. Climate-driven basin-scale decadal oscillations of oceanic phytoplankton. *Science* 326:1,253–1,256.
- McGillicuddy, D.J. Jr., A.R. Robinson, D.A. Siegel, H.W. Jannasch, R. Johnson, T.D. Dickey, J. McNeil, A.F. Michaels, and A.H. Knap. 1998. Influence of mesoscale eddies on new production in the Sargasso Sea. *Nature* 394:263–266.
- McGillicuddy, D.J. Jr., L.A. Anderson, N.R. Bates, T. Bibby, K.O. Buesseler, C.A. Carlson, C.S. Davis, C. Ewart, P.G. Falkowski, S.A. Goldthwait, and others. 2007. Eddy/wind interactions stimulate extraordinary mid-ocean plankton blooms. *Science* 316:1,021–1,026.
- Morel, A., and B. Gentili. 2009. A simple band ratio technique to quantify the colored dissolved and detrital organic material from ocean color remotely sensed data. *Remote Sensing of Environment* 113:998–1,011.
- O'Reilly, J.E., S. Maritorena, B.G. Mitchell, D.A. Siegel, K.L. Carder, S.A. Garver, M. Kahru, and C. McClain. 1998. Ocean color chlorophyll algorithms for SeaWiFS. *Journal of Geophysical Research* 103:24,937–24,954.
- Pan, A., X. Wan, J. Xu, X. Guo, and L. Li. 2006. Barrier layer in the northeastern South China Sea and its formation mechanism. *Chinese Science Bulletin* 51:472–479.
- Qu, T., and G. Meyers. 2005. Seasonal variation of barrier layer in the southeastern tropical Indian Ocean. *Journal of Geophysical Research* 110, C11003, doi:10.1029/2004JC002816.
- Qu T., Y. Du, J. Strachan, G. Meyers, and J. Slingo. 2005. Sea surface temperature and its variability in the Indonesian region. *Oceanography* 18(4):50–61.
- Sprintall, J., and M. Tomczak. 1992. Evidence of the barrier layer in the surface layer of the tropics. *Journal of Geophysical Research* 97:7,305–7,316.
- Smith, W.H.F., and D.T. Sandwell. 1997. Global seafloor topography from satellite altimetry and ship depth soundings. *Science* 277:1,957–1,962.
- Stewart, R.H. 2005. *Introduction to Physical Oceanography*. Available online at http://oceanworld.tamu.edu/resources/ocng_textbook/contents.html (accessed August 15, 2010).
- Wu, M.C., and J.C.L. Chan. 2005. Observational relationships between summer and winter monsoons over East Asia. *International Journal of Climatology* 25:437–451.
- Wyrski, K. 1961. *Physical Oceanography of the Southeast Asian Waters*. University of California, NAGA Report, No. 2, 195 pp.
- Zeng, L., Y. Du, S.P. Xie, and D. Wang. 2009. Barrier layer in the South China Sea during summer 2000. *Dynamics of Atmosphere and Oceans* 47:38–54.