CITATION

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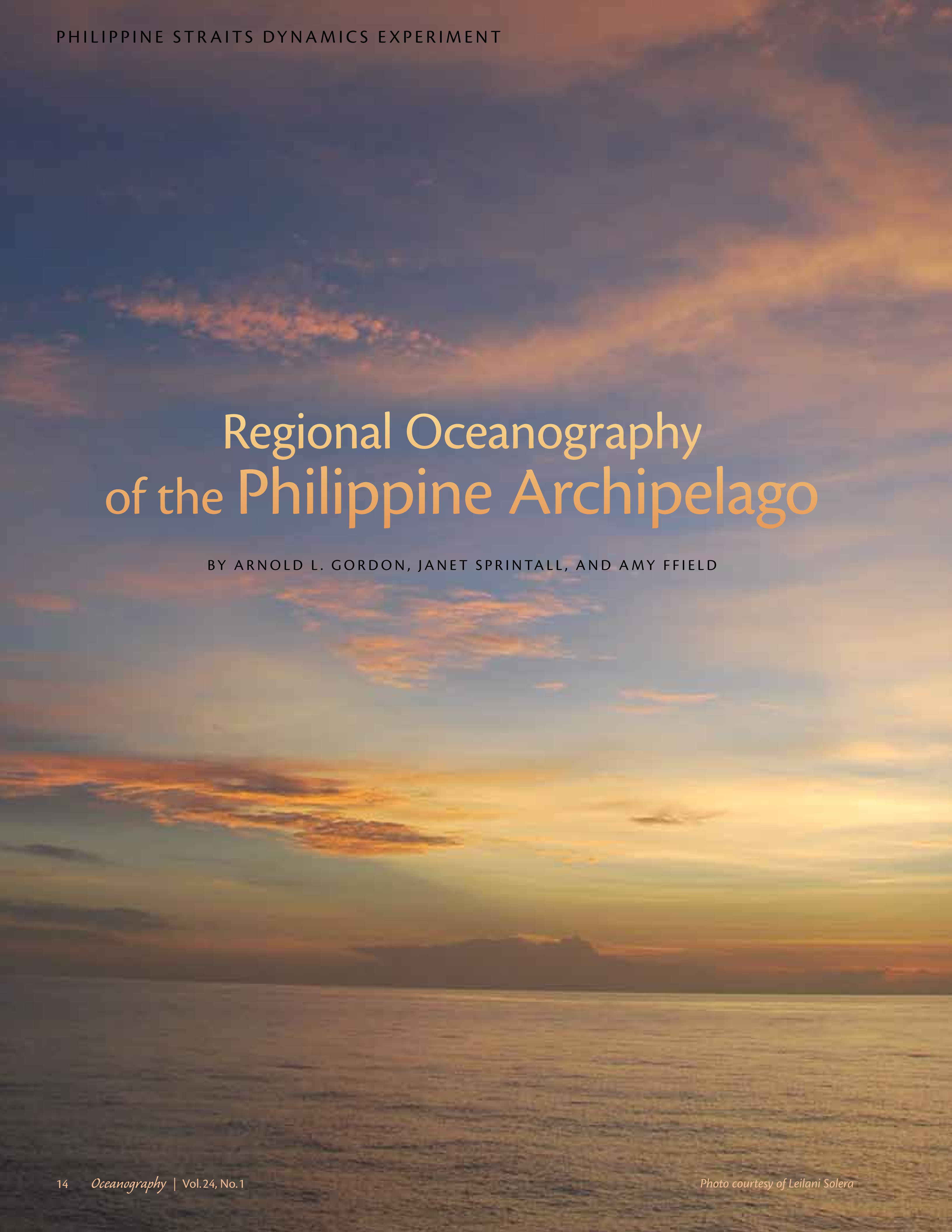

Regional Oceanography of the Philippine Archipelago

BY ARNOLD L. GORDON, JANET SPRINTALL, AND AMY FFIELD

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ABSTRACT. Confined by the intricate configuration of the Philippine Archipelago, forced by the monsoonal climate and tides, responding to the remote forcing from the open Pacific and adjacent seas of Southeast Asia, the internal Philippine seas present a challenging environment to both observe and model. The Philippine Straits Dynamics Experiment (PhilEx) observations reported here provide a view of the regional oceanography for specific periods. Interaction with the western Pacific occurs by way of the shallow San Bernardino and Surigao straits. More significant interaction occurs via Mindoro and Panay straits with the South China Sea, which is connected to the open Pacific through Luzon Strait. The Mindoro/Panay throughflow reaches into the Sulu Sea and adjacent Bohol and Sibuyan seas via the Verde Island Passage and Tablas and Dipolog straits. The deep, isolated basins are ventilated by flow over confining topographic sills that causes upward displacement of older resident water, made more buoyant by vertical mixing, which is then exported to surrounding seas to close the overturning circulation circuit.

INTRODUCTION

Following multiple pathways, waters of the western Pacific enter the complex, multidimensional array of seas and straits that form the impressive archipelago stretching some 3400 km from Southeast Asia to Australia. The northern segment of this system is the Philippine Archipelago (Figure 1a), where the North Equatorial Current bifurcation near 14°N (Nitani, 1972; Toole et al., 1990; Qiu and Lukas, 1996; Qu and Lukas, 2003) forms the western boundary for the equatorward-flowing Mindanao Current and the nascent poleward-flowing Kuroshio. Pacific water seeps into the Sibuyan and Bohol (Mindanao) seas by way of the shallow San Bernardino and Surigao straits, respectively, and in greater volume through the 2200-m-deep Luzon Strait into the South China Sea (Metzger and Hurlburt, 1996, 2001; Centurioni et al., 2004; Qu et al., 2006). From the South China Sea, the flow enters into the Sulu Sea through Mindoro and Panay straits, and eventually into the western Bohol (Mindanao) Sea through Dipolog Strait, and perhaps into the Sibuyan Sea by way of the Verde Island Passage and Tablas Strait. The South China Sea also has access to the southern Sulu Sea via Balabac Strait. The Sibutu Passage links the southern Sulu Sea to the Sulawesi Sea.

Once within the confines of the Philippine Archipelago, circulation and stratification are subjected to monsoonal winds that are textured by passages between island morphology (Pullen et al., 2008, 2011; May et al., 2011), by sea-air heat and freshwater fluxes including river outflow, and by regions with strong tidal currents. Overflow across < 500-m-deep topographic sills ventilates the depths of isolated basins, the Sulu Sea, and the smaller Bohol and Sibuyan seas.

The Office of Naval Research sponsored the Philippine Straits Dynamics Experiment (PhilEx) with a goal of exploring the oceanography and dynamics in the narrow straits and deep basins of the Philippine Archipelago using both observations and model output. During PhilEx fieldwork, conductivity, temperature, depth, and dissolved oxygen measurements were obtained, and lowered acoustic Doppler current profiler ($CTD-O_2$/LADCP)

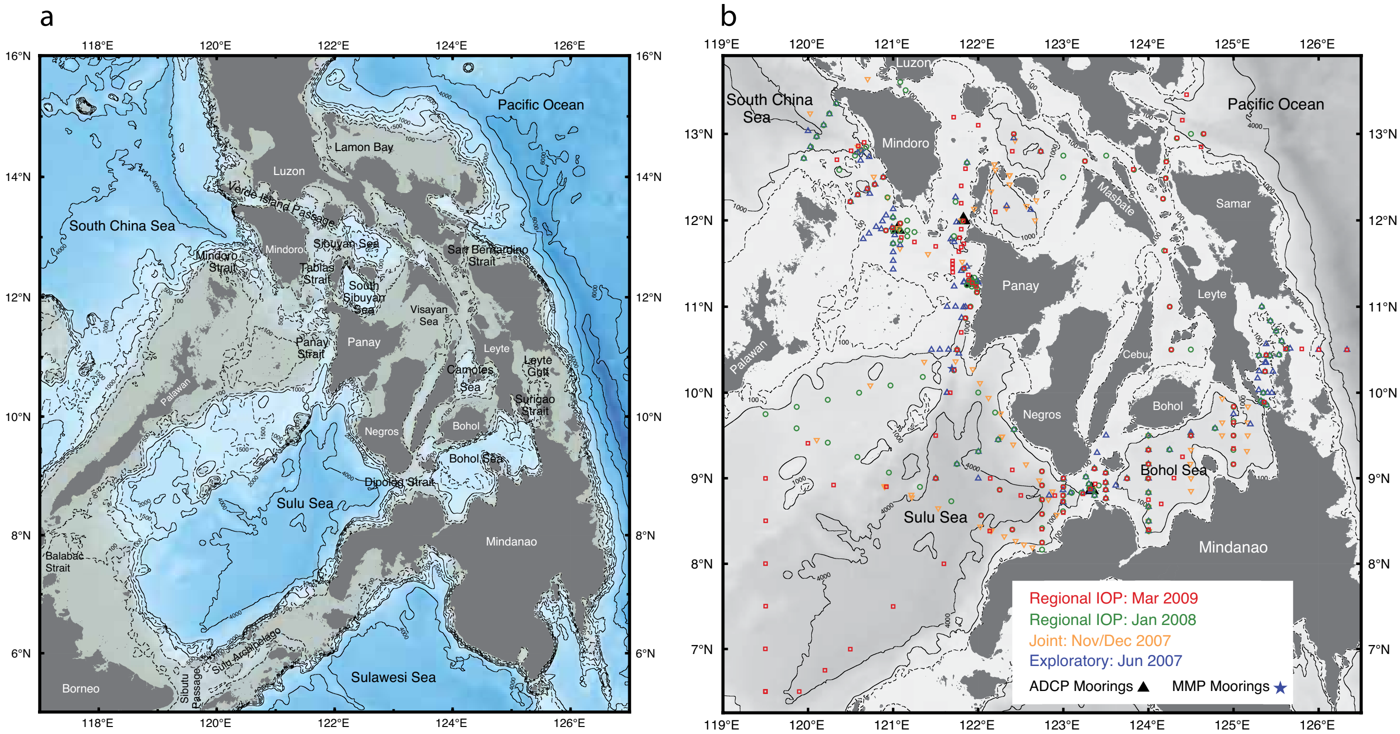

Figure 1. (a) Bathymetry of the seas and straits of the Philippine Archipelago from Smith and Sandwell (1997) and http://topex.ucsd.edu/marine_topo. (b) Conductivity, temperature, depth, and dissolved oxygen, and lowered acoustic Doppler current profiler (CTD-O_2/LADCP) stations obtained by the four PhilEx cruises identified within the figure legend. PhilEx mooring positions are indicated.

stations were made during the exploratory cruise of June 2007 and two regional Intensive Observational Period cruises in the winters of January 2008 (IOP-08) and March 2009 (IOP-09; Figure 1b). CTD casts were also undertaken during the Joint US/Philippines Cruise of November and December 2007. All PhilEx cruises were conducted from R/V *Melville*, whose underway sea surface water system provides sea surface temperature (SST) and salinity (SSS) at high resolution, as well as other meteorological and oceanographic parameters. The hull-mounted shipboard 75- and 150-kHz ADCP system measures circulation of the upper hundreds of meters of the water column along the ship track. The cruise data provide nearly synoptic views of regional water-column circulation and stratification. Moorings (Figure 1b) provide time series of the currents within major straits. Data from MacLane Labs moored profilers (MMPs; Figure 1b) characterize the internal wave environments (Girton et al., 2011). Satellite remote sensing provides a variety of regional observations, such as SST, sea level, ocean color, and wind. The Panay Island-based high-frequency (HF) radar array provides high-resolution sea surface current information in Panay Strait. In situ measurements of ocean currents and properties are provided by towed instrumentation and free-floating sensors, such as surface drifters (Ohlmann, 2011), profilers (Girton, 2011), and gliders. Biological parameters closely related to the ocean physical processes are also a component of PhilEx (Cabrera et al., 2011; Jones et al., 2011). Model studies (Hurlburt et al., 2011; Arango et al., 2011; May et al., 2011) complete the suite of methods employed by PhilEx researchers to investigate the oceanographic conditions and processes within the Philippine Archipelago.

The coupled ocean/atmosphere is characterized by variability across a

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wide range of spatial and temporal scales. Beyond tidal forcing and daily weather conditions are intraseasonal Madden Julian Oscillations, seasonal monsoon forcing, and interannual El Niño-Southern Oscillation (ENSO), plus decadal and longer fluctuations. A recurring question arises when dealing with observational data, which inherently have gaps in spatial and temporal coverage: how typical are the observations of the entire region, and of the longer-term "climate" conditions? Observations can be "leveraged" by being used to evaluate model output, or directly assimilated into the models, thus allowing for a reliable model-based glimpse of this fuller spectrum of events.

In addition to a change in the winds, the monsoon brings a change in precipitation to the Philippine Archipelago, which is expected to be reflected in surface layer thermohaline seasonal stratification. Although there are localized variations due to the interaction of the wind with orographic lifting processes and subsequent river runoff, in general, over the ocean waters, the winter monsoon brings a time of less rainfall and the summer more rainfall (Figure 2a). However, comparison of the actual rainfall for a specific year to the average annual cycle reveals precipitation anomalies (Figure 2b), which may be expected to induce anomalies in the surface layer thermohaline stratification. During the eight months prior to the June 2007 exploratory cruise, there was an anomalous dry period, an accumulative response to the El Niño of the preceding year, whereas the IOP-08 and IOP-09 cruises were conducted during anomalously wet periods.

The objective of this paper is to provide an introduction to the regional setting in order to place in context the information presented in the collection of studies described in this special PhilEx issue of *Oceanography*. Each topic included in this regional introduction has been covered by PhilEx researchers (e.g., published to date are Han et al., 2008; Rypina et al., 2010; Tessler et al., 2010), is presented in this special issue of *Oceanography*, or will be further developed in future publications. Here, we use data from the regional PhilEx hydrographic cruises and moored time series measurements to describe the flow pattern and water mass distribution within the Philippine Archipelago. Our goal is to determine the potentially important first-order processes that might lead to observed circulation patterns within the major Philippine basins of the Sulu and Bohol seas, and to provide schematic overviews of the circulation to serve as a guide to the more detailed studies that are found in this issue of *Oceanography* or are to follow.

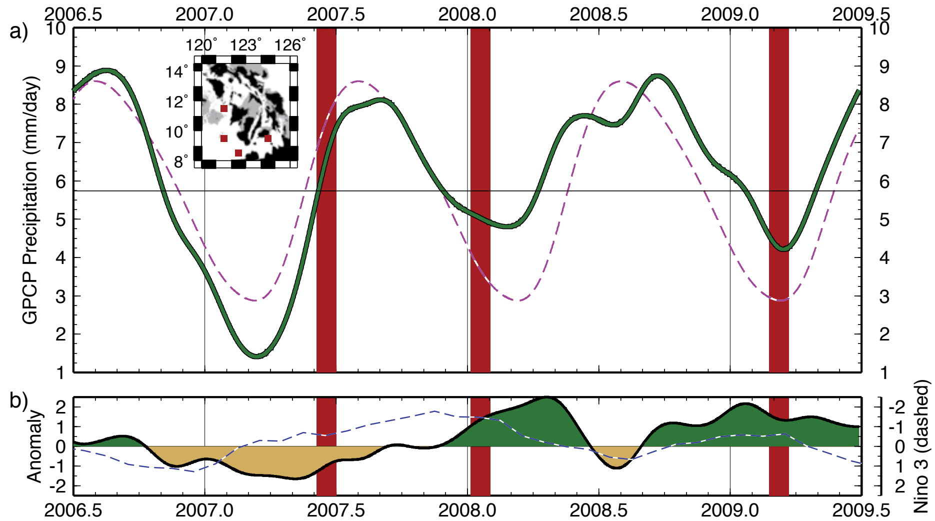

Figure 2. (a) The averaged precipitation time series (green line), mean-annual time series (purple dashed line), and mean (thin horizontal black line) are shown for data from locations near/within the Philippine seas. (b) The anomaly time series (green=wet, yellow=dry) is shown, along with Nino3 (blue dashed line) for comparison. In (a), the four precipitation data locations are indicated by red squares on the map inset. On both (a) and (b), the three PhilEx cruise periods are indicated by vertical red bars. The precipitation data are from the GPCP Satellite-Gauge (SG), One-Degree Daily (1DD), Version 1.1 data set that is produced by optimally merging estimates computed from microwave, infrared, and sounder data, and precipitation gauge analyses from October 1996 to June 2009 (http://lwf.ncdc.noaa.gov/oa/wmo/wdcamet-ncdc.html#version2).

REGIONAL STRATIFICATION AND CIRCULATION

The Sea Surface Layer

Surface-layer circulation observed by the shipboard ADCP (Figure 3a,b) for IOP-08 and IOP-09 brings out the complexity of the pattern of surface currents and the relationship to SST.

The direct connection of the Philippine seas to the western Pacific is through San Bernardino Strait, with a sill depth of 92 m near 12°47'N, 124°14'E, and Surigao Strait, with a sill depth

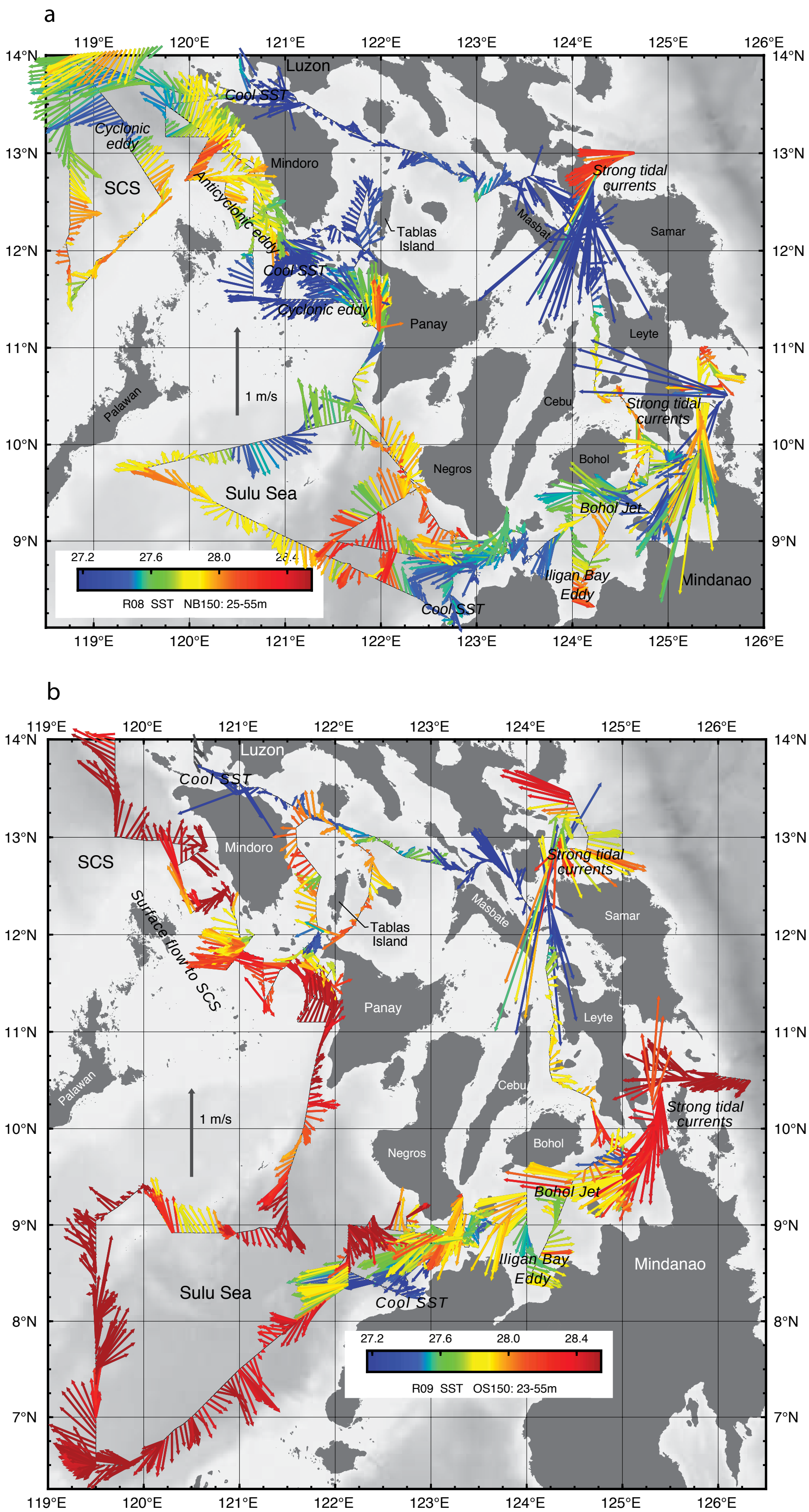

Figure 3. Current vectors from the shipboard-mounted 150-KHz ADCP system within the 25- to 55-m layer color coded by sea surface temperature (SST). A 1 m s^{-1} arrow is given for scale. SCS is the South China Sea. Various features are shown in italics. (a) PhilEx regional cruise January 2008. (b) PhilEx regional cruise March 2009.

of 58 m near 10°17'N, 125°50'E (both topographic estimates are from http://topex.ucsd.edu/marine_topo; Smith and Sandwell, 1997). A comparison of the thermohaline water-column profile within these straits to that of the western Pacific depicts an environment of vigorous mixing, with possible upwelling of subsill-depth western Pacific water entering into the confines of the straits. The currents within San Bernardino and Surigao straits were the strongest observed during all the PhilEx cruises. In each strait, the average speed of the upper 50 m for the one- to two-day ship occupation was about 0.5 m s^{-1} from the western Pacific to the interior seas. However, the strong tidal currents obscure the nontidal flow and therefore prohibit meaningful estimation of the nontidal throughflow, other than suggesting that it is likely that the direction of the throughflow was into the Philippine interior seas.

The shipboard ADCP and water-column temperature/salinity profiles do not show clear continuity of the San Bernardino water into the Sibuyan or Camotes seas. In contrast, the Surigao Strait characteristics do intrude into the Bohol Sea within a well-defined surface current across the northern Bohol Sea, linking the Surigao Strait throughflow to Dipolog Strait with export into the Sulu Sea. South of this "Bohol Jet" is a cyclonic circulation feature that we call the Iligan Bay Eddy, found on all of the PhilEx cruises, near 124°E (Figure 3). Generation of the Iligan Bay Eddy is not coupled to a sea surface ocean color signal, as may be expected from upwelling usually associated with a cyclonic circulation pattern (Cabrera et al., 2011). The Bohol Jet enters the

Sulu Sea, though its path once within the Sulu Sea is not clear. Relatively cool SST is observed south of the Bohol Jet extension into the eastern Sulu Sea, a consequence of upwelling along the Zamboanga coast (Villanoy et al., 2011).

Sulu Sea surface layer circulation (Figure 3) displays much mesoscale activity at horizontal scales of ~ 100 km, with varied SST and SSS, rather than a clear basin-scale gyre. However, these synoptic "snapshots" offered by the shipboard ADCP mapping do not allow for conclusions about the general circulation pattern of the Sulu Sea as each cruise covered different segments of the this sea. The warmer SST observed in March 2009 relative to January 2008 may be partly the normal seasonal signal, though in 2009 the survey extended further to the south, and 2008 tended to have stronger winds and surface currents. The January 2008 surface circulation of the Sulu Sea east of 120°E is cyclonic, with northward flow along the eastern boundary that continues into Panay Strait and southward flow west of 121.3°E. The Sulu circulation was anticyclonic in June 2007 (not shown). The March 2009 cruise data covers different parts of the Sulu Sea so that direct comparison with January 2008 is not practical, though again we find northward flow in the eastern Sulu Sea and within Panay Strait, albeit relatively subdued relative to January 2008.

In Mindoro and Panay straits, the January 2008 currents form energetic eddies in response to complex wind stress curl (Rypina et al., 2010; May et al., 2011; Pullen et al., 2011), though on average, the surface currents are directed toward the South China Sea. In June 2007, the surface flow was weak and toward the South China Sea. In March 2009, the surface flow in Panay and Mindoro straits, with less mesoscale activity, was also toward the South China Sea. In January 2008, there was a strong cyclonic eddy in the South China Sea adjacent to Mindoro Strait (Pullen et al., 2008). The surface current in Tablas Strait displayed a weak cyclone (note westward flow at 121.8°E between Mindoro Island and Tablas Island, Figure 3), though the tendency in March 2009 was for flow out of the Sibuyan Sea into the Panay-Mindoro corridor. The throughflow of the relatively cool SST of the Verde Island Passage was weak, slightly toward the west in January 2008, and toward the east in March 2009.

> "PHILEX DID MUCH TO ADVANCE OUR UNDERSTANDING THE WATERS OF THE PHILIPPINE ARCHIPELAGO."

Water-Column Stratification

Upper 400-m Profiles

With descent into the water column, the warm, low-salinity surface water above the top of the thermocline at 50–70 m rapidly gives way to cooler, saltier water at 200 m (Figure 4, upper panels). The potential temperature (θ) drops by ~ 10°C over only 100 m, from 70 to 170 m, coinciding with an intense pycnocline in which density increases by nearly three sigma-0 units, from 22.5 to 25.2. The June 2007 early summer SST was about 2° warmer than in January 2008 or March 2009. The SSS range between cruises amounts to 1.0 psu, with the lowest SSS in January 2008. The highest SSS is in June 2007, a consequence of the normal dry season compounded by the drier conditions of an El Niño (Figure 2). The lowest SSS was observed in January 2008 (as well as during the Joint Cruise of late 2007), a consequence of the phasing out of the previous wet season, whereas in March 2009, nearly two more months into the dry season, SSS was slightly more elevated. The lowest SSSs (< 33.4) are observed in the Bohol Sea and the South China Sea entrance to Mindoro Strait during the winter regional cruises, perhaps a consequence of the delayed river runoff from their respective larger neighboring landmasses of Mindanao and Luzon. The Sibuyan and Camotes seas' SSSs are between 33.4 and 33.6. The seasonal influence determined by comparing the salinity differences between the PhilEx cruises is found to reach to about 130 m, into the mid thermocline.

The relatively warm thermocline data (Figure 4) are from the western Pacific adjacent to San Bernardino and Surigao straits. In the salinity profiles, these stations display a pronounced salinity

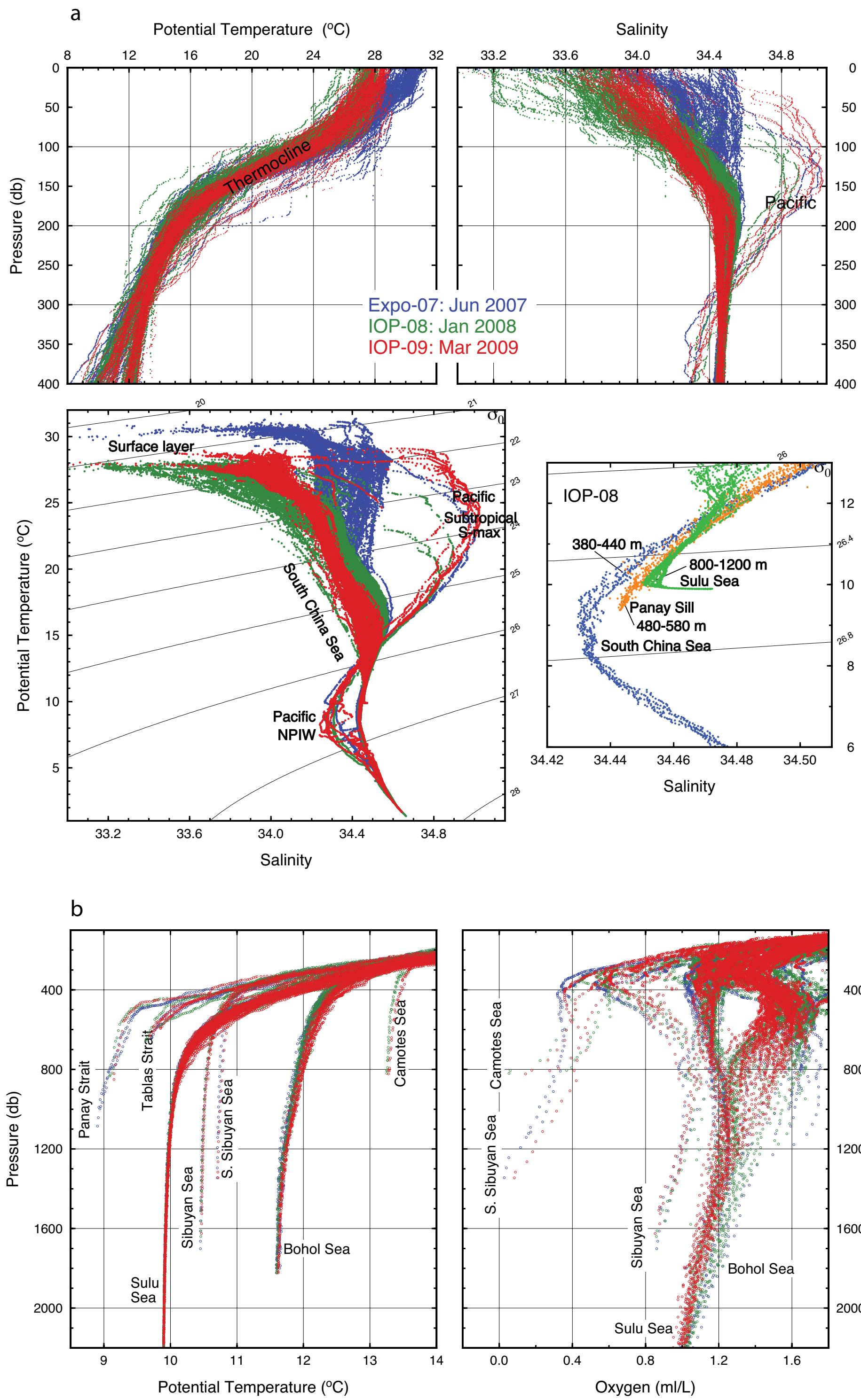

Figure 4. CTD temperature and salinity obtained on the June 2007 PhilEx exploratory cruise, the January 2008 regional cruise, and the March 2009 regional cruise. (upper panels) Potential temperature and salinity profiles with pressure (depth) for the upper 400 m for the three PhilEx cruises. (lower panels) Potential temperature and salinity scatter plot. The lower right panel shows the 6° to 13°C strata.

maximum (s-max) in the 75–250 m, 16° to 28°C interval that marks North Pacific Subtropical Water. Although the shallow San Bernardino and Surigao straits block s-max water, North Pacific Subtropical Water has access to the South China Sea via Luzon Strait. However, at the South China Sea entrance to Mindoro Strait, the pronounced s-max core in the 20° to 28°C range is greatly attenuated with only a weak s-max near 28°C as observed in the June 2007 cruise data, or a temperature/salinity (T/S) flexure near 25°C in data from the regional 2008 and 2009 cruises, and a deeper s-max near 16°C (Figure 4). The processes within the South China Sea that attenuate the North Pacific subtropical s-max are beyond the scope of this paper.

A salinity minimum (s-min) is observed from 350 to 600 m in the western Pacific stations, marking North Pacific Intermediate Water, which also has access to the South China Sea via Luzon Strait. An attenuated but still visible s-min near 10°C is observed in Mindoro and Panay straits. It is this water that provides the overflow into the Sulu Sea (Tessler et al., 2010). The θ/S structure (Figure 4, lower left panel) further brings out the stratification features of the Philippine waters, particularly the "gap" between the western North Pacific saline subtropical water and fresher thermocline water of the Philippine waters, as well as the attenuated North Pacific Intermediate Water s-min in Mindoro and Panay straits.

Two CTD stations (Figure 4, upper panels) in the southern Sulu Sea from

March 2009 show relatively warm, salty water between 125 and 150 m, marking the trough of solitons observed in that area (Jackson et al., 2011).

Deep Basin Ventilation

The Philippine seas are composed of numerous deep basins isolated from one another by topographic barriers. There is the open deep Pacific Ocean to the east; there are the relatively large seas to the west and south of the Philippines (the Sulu, South China, and Sulawesi seas); and there are the smaller interior seas, most notably the Bohol and Sibuyan seas, and the still smaller Visayan and Camotes seas (Figure 1). Below roughly 500 m, these seas have marked differences in θ (and S) and oxygen values from each other and from the source water column of the open western North Pacific. The deep Sulu Sea has a potential temperature of 9.9°C, the deep Bohol Sea 11.6°C, and the Sibuyan Sea 10.4°C; the southern Sibuyan Sea is slightly warmer at 10.7°C, with the warmest isolated basin; and the Camotes Sea has a bottom potential temperature of 13.2°C.

These marked property differences are a product of sill depths of the topographic barriers to the neighboring seas. The isolated deep basins are ventilated by spillover at the topographic barriers that then descend to the depths, replacing resident water made less dense by vertical mixing. The resident water is lifted upward by denser overflow water, and is subsequently exported to the surrounding seas to close the overturning circulation cell. As these waters are reduced in oxygen by the rain of organic material from the sea surface, their export to neighboring seas can be traced as an oxygen minimum. For example, the Bohol Sea oxygen minimum near 12°C is observed spreading near 300 m throughout the Sulu Sea, with traces entering into Panay Strait.

The effective sill depths are found by matching the bottom temperature with the temperature profile of the external source water. The shallower the sill, the warmer the basin waters. The relationship of source sill depth θ/S to deep basin water θ/S depends on the mixing environment at the controlling sill and the mixing/entrainment environment of the descending plume: the effective sill depth is less deep than the deepest passage as determined by sonic surveys. The warmest deep basin is the interior Camotes Sea, with a controlling sill depth of less than 300 m. The oxygen of the Camotes deep water is near 0 ml l^{-1}, indicating slow ventilation relative to the oxygen consumption. The oxygen levels of the bottom water of the southern Sibuyan Sea are also near 0 ml l^{-1}. They are slightly warmer than the bottom water of the main Sibuyan Sea. The South Sibuyan Sea has an effective sill depth of ~ 400 m, while the main Sibuyan Sea has an effective sill depth of ~ 500 m. The oxygen minimum of the Sibuyan Sea serves as the overflow water source for the South Sibuyan Sea, which, with further oxygen consumption, accounts for the near zero oxygen (< 0.3 ml l^{-1}) of the southern Sibuyan Sea bottom water.

The coldest deep basin is that of the Sulu Sea. The source of deep Sulu Sea water is generally considered to be South China Sea water entering through Mindoro Strait (Broecker et al., 1986).

> “[PHILEX] POINTS THE WAY TOWARD FURTHER, MORE QUANTITATIVE RESEARCH AND ILLUSTRATES THE NEED FOR HIGH SPATIAL AND TEMPORAL RESOLUTION IN BOTH OBSERVATIONS AND MODELING.”

However, the deep salty bottom water of the Sulu Sea does not match a sole South China Sea source (Figure 4, lower right panel). Quadfasel et al. (1990) recognized that the density of the South China Sea source cannot reach the bottom of the Sulu Sea unless there is substantial addition of suspended sediment to make for a denser blend. Based on evidence from sedimentary records of the Sulu Sea, Quadfasel et al. (1990) suggest that episodic turbidity currents from the South China Sea at intervals of several decades (on average 50 years) may have played an important role in plunging dense water toward the bottom of the Sulu Sea. However, this still would not explain the salty bottom water of the Sulu Sea.

PhilEx observations of stratification and currents between June 2007 and March 2009 reveal a strong overflow between 400- to 570-m depth from Panay Strait into the Sulu Sea (Tessler et al., 2010). The overflow water is derived from approximately 400-m deep in the South China Sea. Sulu Sea stratification indicates that the overflow does not descend below 1250 m in the Sulu Sea, but rather settles above high-salinity deep water. The mean observed overflow transport at the sill is 0.32 Sv, with a residence time of 11 years in the affected Sulu layer from 575 to 1250 m.

While Sulu Sea ventilation to ~ 1250 m is drawn from the 570-m-deep northern sill in Panay Strait, we speculate that the deeper Sulu water may be derived from the Sulawesi Sea to the south by way of the Sibutu Passage. The Sibutu Passage sill is around 350 m, but delivers denser water into the Sulu Sea than does the South China Sea. This is primarily because of the shallower pycnocline of the Sulawesi Sea compared to that found in the South China Sea, and the strong tidal heaving of the Sibutu Passage pycnocline that can lead to rather startling solitons within the Sulu Sea (Apel et al., 1985).

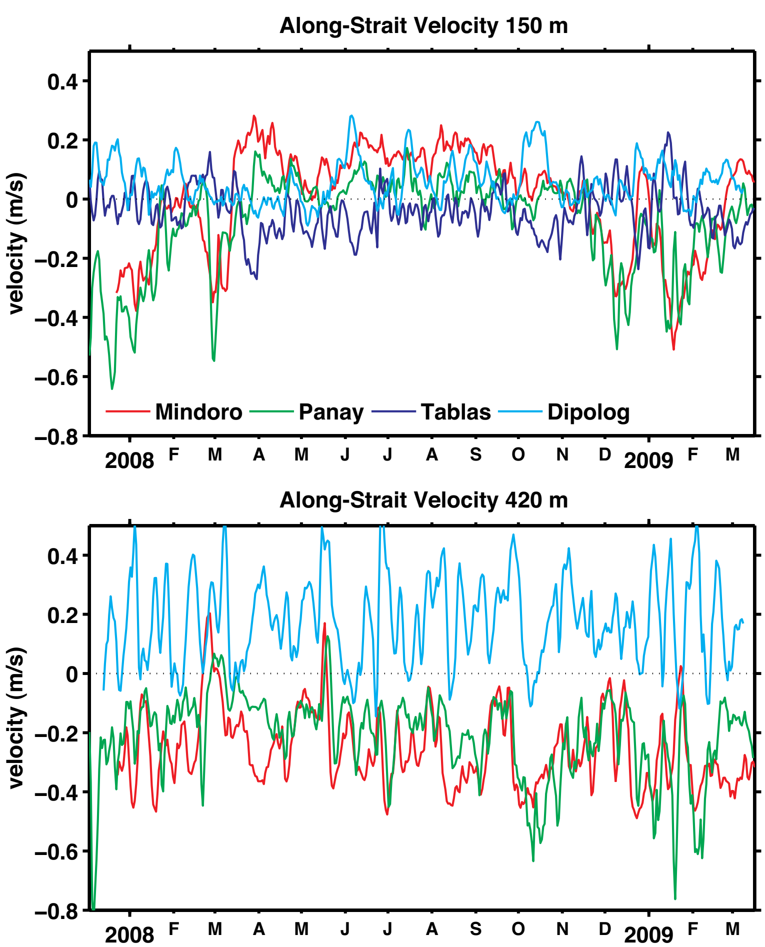

Figure 5. Along-strait velocity at 150 m and 420 m measured at the moorings shown in Figure 1.

TIME SERIES

The time series of moored velocity observations provide a longer-term context for the "archipelago-scale" fieldwork undertaken as part of PhilEx (Figure 1), such as the synoptic shipborne flow and property measurements of the regional survey described above, and the short-term drifter deployments (Ohlmann et al., 2011). The high-resolution time series data from the moorings are also used as an important metric to test the veracity of numerical models in the Philippine region (e.g., Hurlburt et al., 2011; Pullen et al., 2011).

The current measurements from the PhilEx moorings (Figure 5) in Mindoro, Panay, Tablas, and Dipolog straits (see Figure 1 for locations) reveal much variability and baroclinity over the ~ 15-month deployment period. At 150 m, the strong southward flows at Mindoro and Panay are evident as two intraseasonal (30–60 day) pulses during the northeast monsoon (December–February). During the southwest monsoon (April–October) when the flow is mainly northward at 150 m in Mindoro and Panay, the flow is more southward at Tablas. Some of this southward Tablas flow is probably siphoned off to contribute to the stronger northward flow observed at Mindoro compared to Panay during this period. The along-strait flow at 150 m in Dipolog Strait exhibits more of a short-period (15–20 day) signal and is primarily eastward. At 300-m depth, the flow in all four passages is also characterized by short-period variability (not shown). At 420 m, there is high coherence between the consistently strong southward flow through Mindoro and Panay straits. At this depth, the flow is near bottom in Mindoro Strait and often slightly stronger than that observed at Panay Strait, although the deeper, near-bottom flow in Panay Strait (~520 m) can reach velocities of > 1 m s^{-1}. This strong benthic overflow contributes to the ventilation of the deep Sulu Sea (Tessler et al., 2010). In Dipolog Strait, the near-bottom 420-m flow is strongly eastward from the Sulu Sea into the Bohol Sea, although as in the shallower layers, the flow here is also characterized by strong 15–20-day variability.

BOHOL SEA

With a sill depth of 504 m, the 47-km-wide (as measured between the 100-m isobaths) Dipolog Strait between Negros and Mindanao separates the Bohol Sea from the Sulu Sea and is the deepest connection of the Bohol Sea to surrounding seas. The Dipolog Strait is of prime importance in ventilating the subsurface layers of the Bohol Sea. The eastern end of the Bohol Sea is connected to the Pacific Ocean across the broad, shallow Leyte Sea through the 58-m-deep Surigao Strait, where there appears to be a small net flow of surface water into the eastern Bohol Sea. As described above, Surigao inflow streams across the northern Bohol Sea to be exported into the Sulu Sea through Dipolog Strait. The northern Bohol Sea is connected to San Bernardino Strait by way of a 330-km-long narrow channel that runs through the Camotes Sea to enter the Bohol Sea both to the east and west of Bohol Island. This channel has an 18-m-deep constriction to the north-east of Bohol Island and a 3-km-wide, though deep (280 m), channel to the northwest of Bohol Island. PhilEx observations indicate that the throughflow (based on ADCP and CTD data) in these channels is negligible, but this channel may be an effective way to deliver river runoff from the islands of the central Philippines, and reduce the SSS of the northern Bohol Sea.

The LADCP profiles reveal the highly layered circulation profile within Dipolog Strait (Figure 6), with two layers of inflow into the Bohol Sea and two outflow layers. Near the topographic sill where the PhilEx mooring was sited, the flow into the Bohol Sea occurs within the thermocline from roughly 80 to 200 m and in the benthic layer overflow at the Dipolog sill. The 150-m and 420-m time series (Figure 5), which show eastward flow, are consistent with the LADCP data. The two layers exported into the Sulu Sea consist of the surface water of the upper 50 m and a second layer centered at 300 m. The inflow/outflow

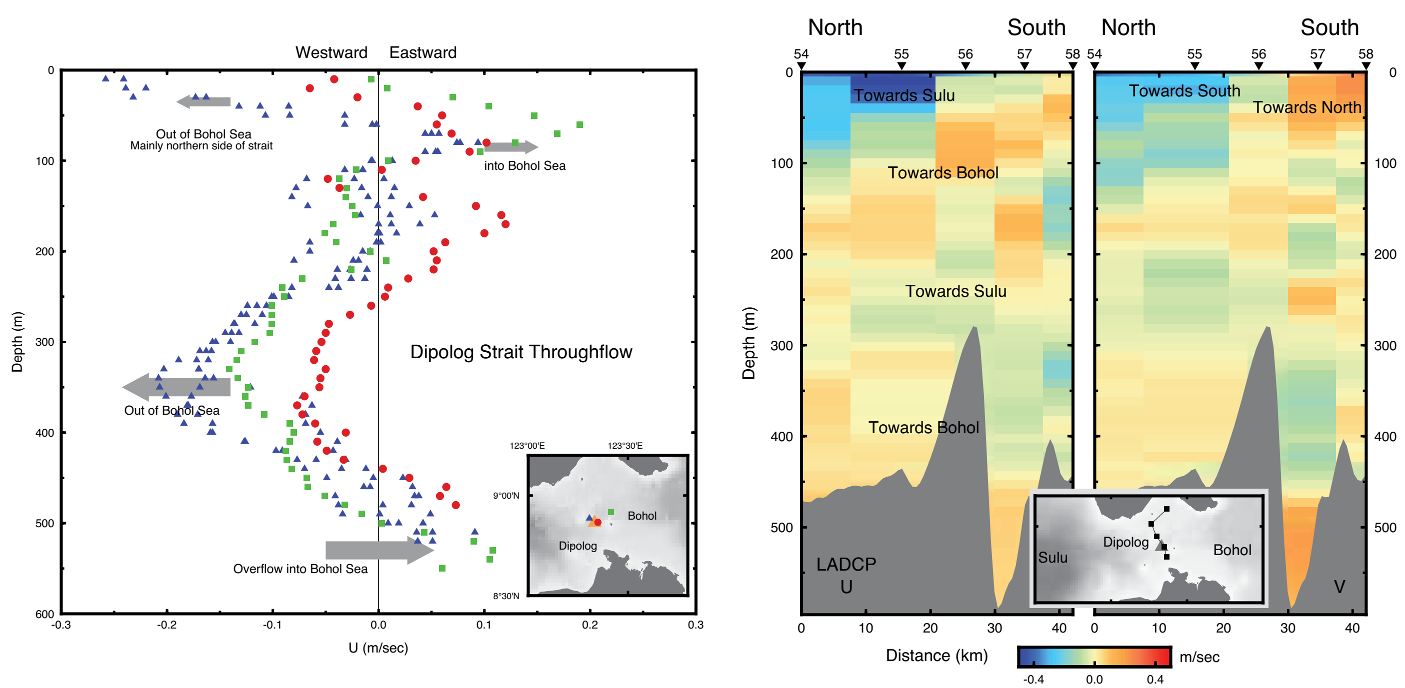

Figure 6. Regional 2008 LADCP data from within Dipolog Strait. (left) LADCP profiles of the zonal flow within the deep channel shown in the map insert. The position of the moorings is shown as a yellow triangle. (right) The LADCP section across Dipolog Strait showing zonal and meridional currents.

cores are tilted across Dipolog Strait (Figure 6), with the outflow strongest at the northern side of the strait and the inflow strongest along the southern side, consistent with the Coriolis force; the deep overflow is confined by the constrictive seafloor topography.

One can envision a double estuary overturning circulation within the Bohol Sea (Figure 7). The shallow estuary circulation is composed of surface water outflow to the Sulu Sea, compensated with upwelling by entrainment of thermocline inflow waters into the Bohol Sea, bolstered by the Surigao throughflow. The deeper estuary overturning circulation is controlled by dense water overflow to the depths of the Bohol Sea within the lower 50–100 m of Dipolog Strait, with export in the 300–350-m interval toward the Sulu Sea derived from the upwardly displaced resident water. This water is low in oxygen (~ 1.3 ml l^{-1}) and is the likely source of a low-oxygen core within the Sulu Sea within that depth interval. Estimates from the LADCP and mooring time series suggest that the deep overturning circulation amounts to ~ 0.2 Sv. The westward transport in the upper limb of the shallow cell, as estimated from the PhilEx cruises' LADCP data across Dipolog Strait, may amount to ~ 0.5 Sv, part of which is drawn from Surigao Strait. As the LADCP average for the lower limb is ~ 0.2 Sv, the Surigao Strait throughflow is probably around 0.3 Sv, assuming the Bohol Sea river inflow is negligible.

MINDORO AND PANAY THROUGHFLOW

Mindoro and Panay straits connect the Sulu Sea with the South China Sea. These straits exhibit much variability in depth and width. Apo Reef near 12.66°N represents a significant obstacle within Mindoro Strait (Ohlmann, 2011). Between Mindoro and Panay straits south of the Semirara islands (11°N, 121°30'E), there is an east-west offset of the these straits, where Tablas Strait connects Mindoro and Panay straits with the Sibuyan interior sea. The sea between Mindoro and Panay straits may be considered a triple junction of connective passages. This region received much PhilEx attention in the form of process studies. That analysis is under way, and

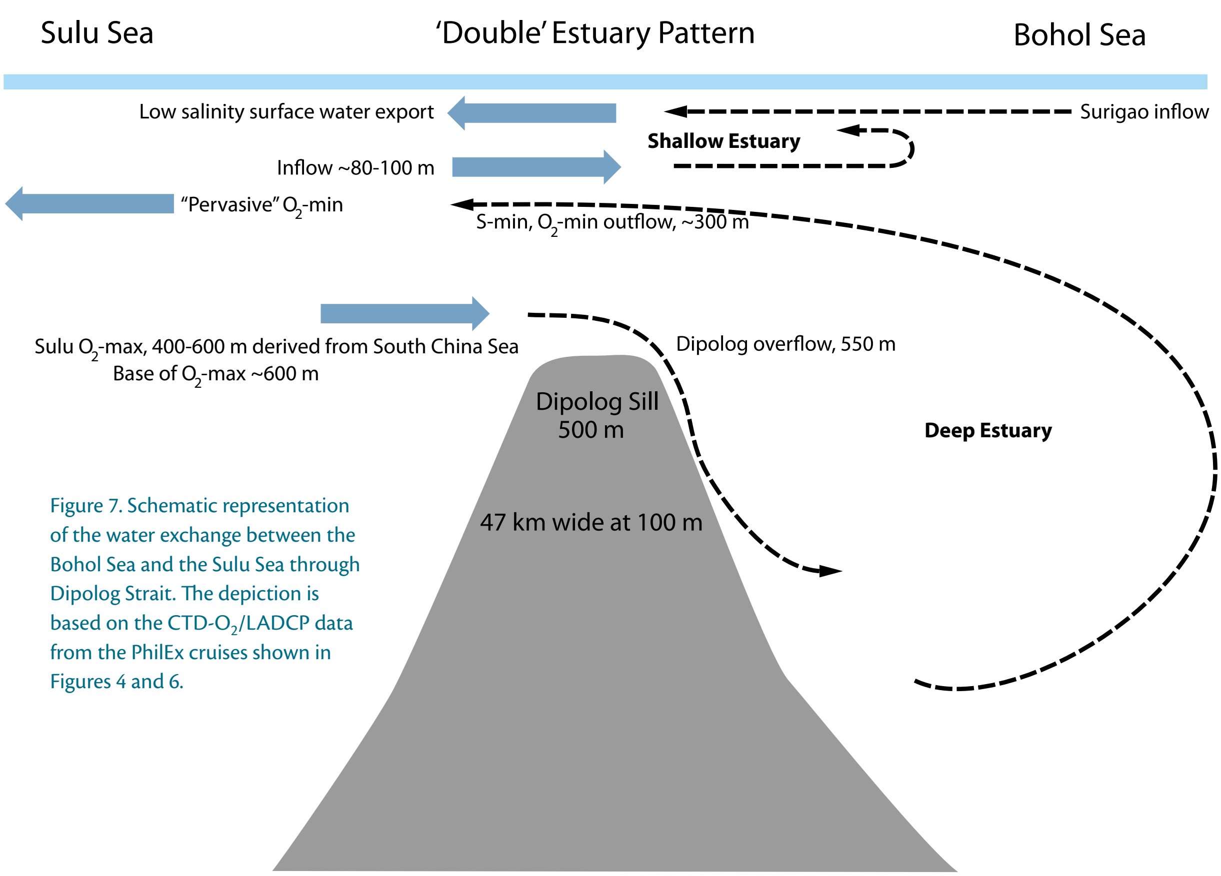

Figure 7. Schematic representation of the water exchange between the Bohol Sea and the Sulu Sea through Dipolog Strait. The depiction is based on the CTD-O_2/LADCP data from the PhilEx cruises shown in Figures 4 and 6.

outside of the scope of this regional oceanography view.

The 150-m and 450-m mooring time series (Figure 5) reveal much along-strait flow variability in Panay and Mindoro straits. The mean throughflow in Panay Strait at 150 m is northward, albeit weak from April through October, with strong southward flow during the winter months. The Panay Strait January 2008 and March 2009 LADCP profiles near the mooring site (Figure 8a) show a net transfer of surface water above ~ 100 m from the Sulu Sea into the South China Sea, with flow toward the Sulu Sea associated with the s-max below 150 m, and stronger flow below 400 m feeding the overflow into the Sulu Sea (Tessler et al., 2010). The South China Sea s-max is found throughout the Sulu Sea, and enters into the Bohol Sea as part of a deep limb of the shallow overturning circulation cell.

The Mindoro throughflow (Figures 5 and 8b) is similar to the Panay structure. The flow above 150 m is toward the South China Sea, that is, to the northwest (the along-strait orientation at the mooring site), with reversals during the winter months (Figure 5); below 300 m, the flow is toward Panay Strait with weak intervening flow.

A schematic of the Mindoro/Panay throughflow (Figure 9) provides a sense of the mean throughflow conditions. However, wind-induced energetic eddies as observed in January–February 2008 induce much intraseasonal activity in this region (Pullen et al., 2008, 2011) that can obscure the mean, longer-term conditions. In the upper 150 m, there is net flow toward the South China Sea. Eddies are generated as this flow encounters Apo Reef (Ohlmann, 2011). At and below 150 m, the flow is toward the Sulu Sea. Above ~ 500 m, this water spreads at a similar depth into the Sulu Sea, marking an s-max near 300 m and an oxygen maximum near 500 m, traces of which enter into the Bohol Sea. Spill over topographic sills occurs into the Semirara Sea (the isolated 1300-m-deep basin south of the Semirara islands) and over the Panay sill to depths of 1200 m in the Sulu Sea (Figure 4a, lower left panel; Tessler et al., 2010).

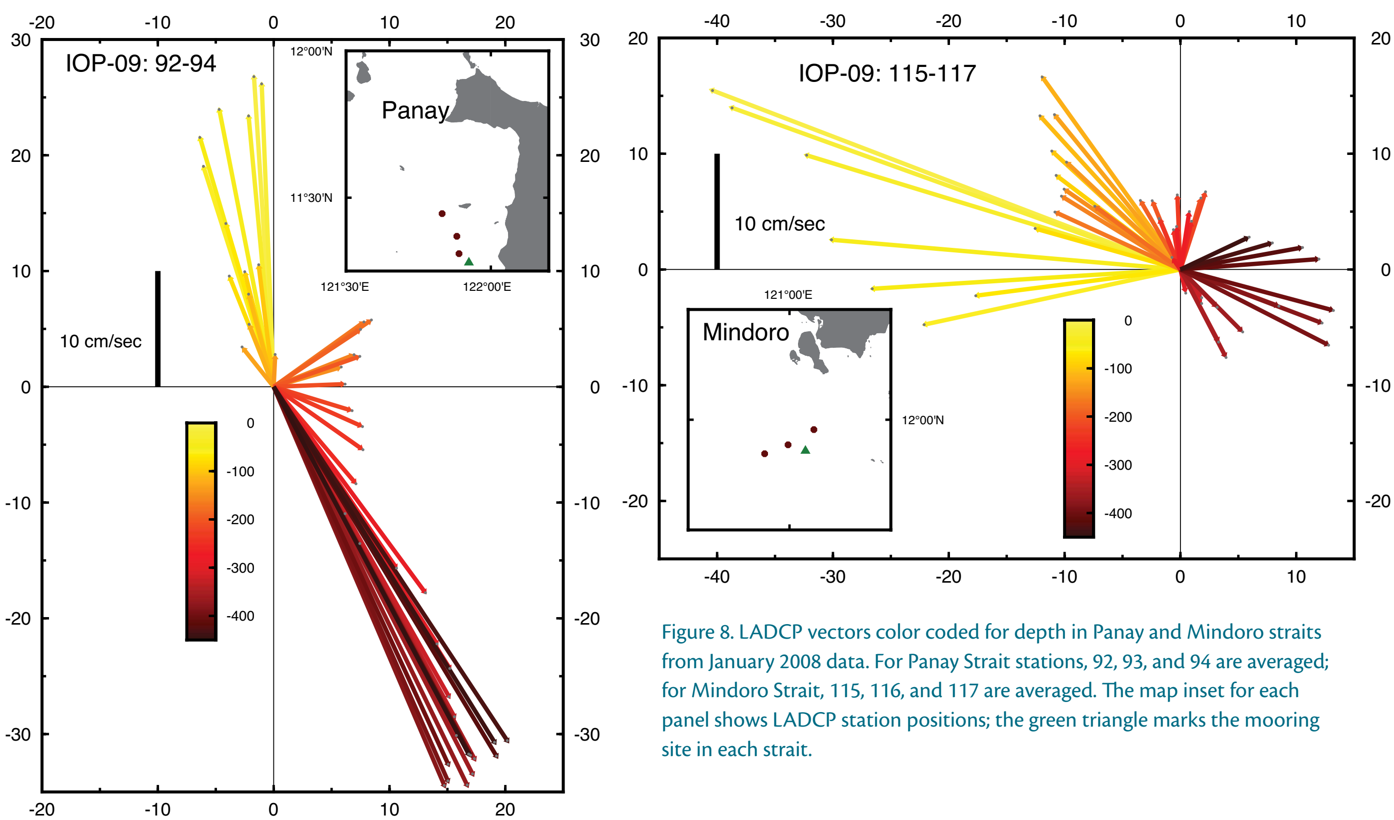

Figure 8. LADCP vectors color coded for depth in Panay and Mindoro straits from January 2008 data. For Panay Strait stations, 92, 93, and 94 are averaged; for Mindoro Strait, 115, 116, and 117 are averaged. The map inset for each panel shows LADCP station positions; the green triangle marks the mooring site in each strait.

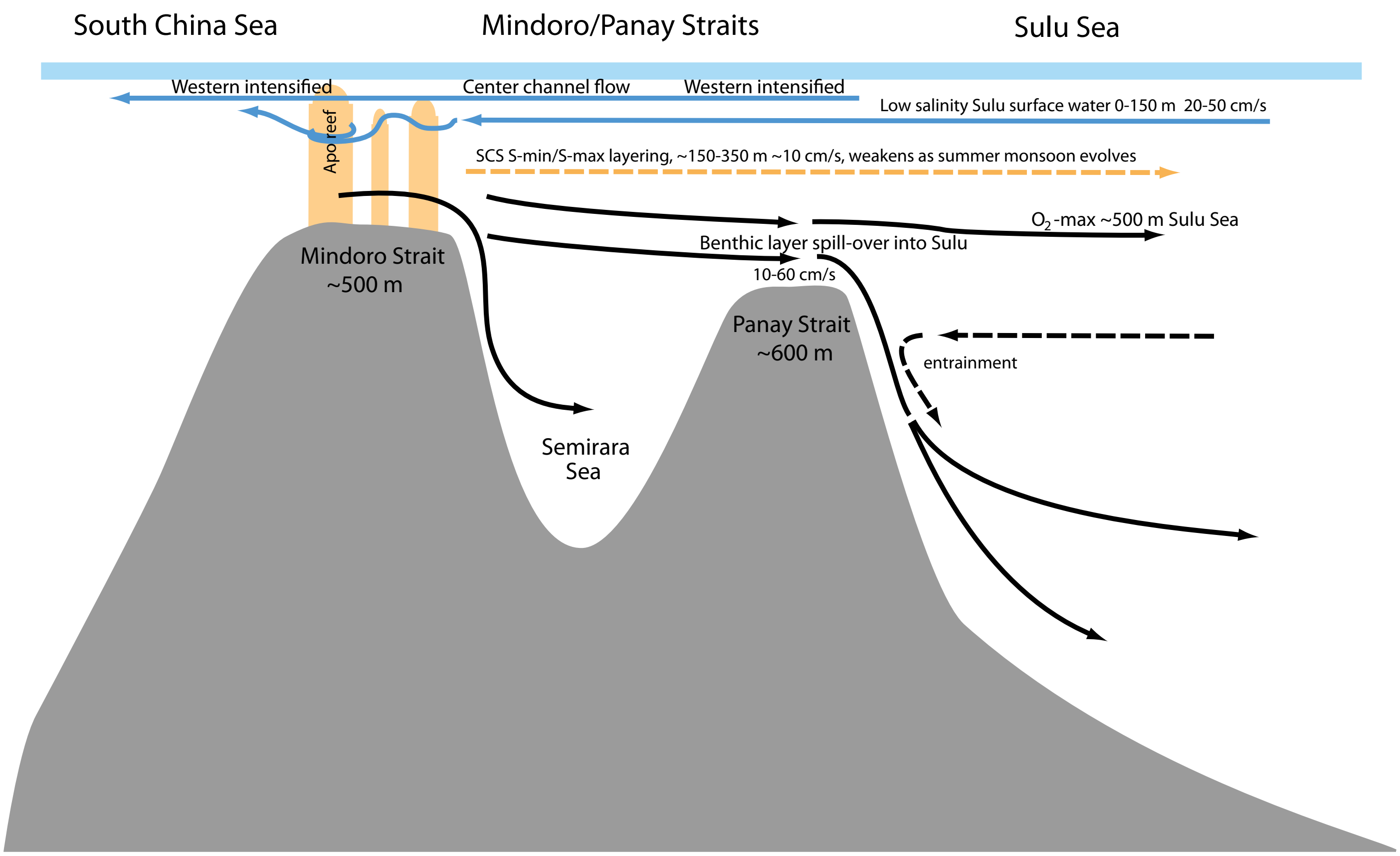

Figure 9. Schematic representation of the water exchange between the South China Sea and the Sulu Sea through Mindoro and Panay straits. The depiction is based on the CTD-O_2/LADCP data from the PhilEx regional 2008 and 2009 cruises.

CONCLUSION

The region stretching 3400 km from Australia to Southeast Asia, which may be referred to as a "mega" archipelago, separating the western Pacific and eastern tropical Indian oceans, represents a complex, yet fascinating oceanic environment. The western Pacific "sees" a porous western boundary, representing a challenge for both observational and model research to unravel. The regional circulation responds to strong monsoonal winds textured by mountainous islands, and to complex ocean bottom morphology—all amidst a multitude of isolated deep basins within a network of interconnecting straits. Their actions modify the thermohaline stratification and impact both climate and the marine ecosystem.

To provide context for the studies included in this collection of PhilEx results, this article presented a brief overview of a selection of topics depicting the regional oceanography of Philippine Archipelago waters. More thorough analysis of each topic has been done elsewhere or is presently in preparation.

PhilEx did much to advance our understanding of the waters of the Philippine Archipelago. It points the way toward further, more quantitative research and illustrates the need for high spatial and temporal resolution in both observations and modeling.

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REFERENCES

Apel, J.R., J.R. Holbrook, J. Tsai, and A.K. Liu. 1985. The Sulu Sea internal solitons experiment. *Journal of Physical Oceanography* 15(12):1,625–1,651.

Arango, H.G., J.C. Levin, E.N. Curchitser, B. Zhang, A.M. Moore, W. Han, A.L. Gordon, C.M. Lee, and J.B. Girton. 2011. Development of a hindcast/forecast model for the Philippine Archipelago. *Oceanography* 24(1):58–69.

Broecker, W., W. Patzert, R. Toggweiler, and M. Stuiver. 1986. Hydrography, chemistry, and radioisotopes in the Southeast Asian basins. *Journal of Geophysical Research* 91:14,345–14,354.

Cabrera, O.C., C.L. Villanoy, L.T. David, and A.L. Gordon. 2011. Barrier layer control of entrainment and upwelling in the Bohol Sea, Philippines. *Oceanography* 24(1):130–141.

Centurioni, L.R., P.P. Niiler, and D.K. Lee. 2004. Observations of inflow of Philippine Sea surface water into the South China Sea through the Luzon Strait. *Journal of Physical Oceanography* 34:113–121.

Girton, J.B., B.S. Chinn, and M.H. Alford. 2011. Internal wave climates of the Philippine seas. *Oceanography* 24(1):100–111.

Han, W., A.M. Moore, E. Di Lorenzo, A.L. Gordon, and J. Lin. 2008. Seasonal surface ocean circulation and dynamics in the Philippine Archipelago region during 2004–2008. *Dynamics of Atmospheres and Oceans* 47:114–137, doi:10.1016/j.dynatmoce.2008.10.007.

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.

Jackson, C.R., Y. Arvelyna, and I. Asanuma. 2011. High-frequency nonlinear internal waves around the Philippines. *Oceanography* 24(1):90–99.

Jones, B.H., C.M. Lee, G. Toro-Farmer, E.S. Boss, M.C. Gregg, and C.L. Villanoy. 2011. Tidally driven exchange in an archipelago strait: Biological and optical responses. *Oceanography* 24(1):142–155.

May, P.W., J.D. Doyle, J.D. Pullen, and L.T. David. 2011. Two-way coupled atmosphere-ocean modeling of the PhilEx Intensive Observational Periods. *Oceanography* 24(1):48–57.

Metzger, E.J., and H.E. Hurlburt. 1996. Coupled dynamics of the South China Sea, the Sulu Sea, and the Pacific Ocean. *Journal of Geophysical Research* 101:12,331–12,352.

Metzger, E.J., and H.E. Hurlburt. 2001. The nondeterministic nature of Kuroshio penetration and eddy shedding in the South China Sea. *Journal of Physical Oceanography* 31:1,712–1,732.

Nitani, H. 1972. Beginning of the Kuroshio. Pp. 129–163 in *Kuroshio: Its Physical Aspects*. H. Stommel and K. Yoshida, eds, University of Tokyo Press.

Ohlmann, J.C. 2011. Drifter observations of small-scale flows in the Philippine Archipelago. *Oceanography* 24(1):122–129.

Pullen, J., J.D. Doyle, P. May, C. Chavanne, P. Flament, and R.A. Arnone. 2008. Monsoon surges trigger oceanic eddy formation and propagation in the lee of the Philippine Islands. *Geophysical Research Letters*, 35, L07604, doi:10.1029/2007GL033109.

Pullen, J.D., A.L. Gordon, J. Sprintall, C.M. Lee, M.H. Alford, J.D. Doyle, and P.W. May. 2011. Atmospheric and oceanic processes in the vicinity of an island strait. *Oceanography* 24(1):112–121.

Qu, T., and R. Lukas. 2003. The bifurcation of the North Equatorial Current in the Pacific. *Journal of Physical Oceanography* 33(1):5–18.

Qu, T., Y. Du, and H. Sasaki. 2006. South China Sea throughflow: A heat and freshwater conveyor. *Geophysical Research Letters*, 33, L23617, doi:10.1029/2006GL028350.

Quadfasel, D., H. Kudrass, and A. Frische. 1990. Deep-water renewal by turbidity currents in the Sulu Sea. *Nature* 348:320–322.

Qiu, B., and R. Lukas. 1996. Seasonal and interannual variability of the North Equatorial Current, the Mindanao Current and the Kuroshio along the Pacific western boundary. *Journal of Geophysical Research* 101:12,315–12,330.

Rypina, I.I., L.J. Pratt, J. Pullen, J. Levin, and A.L. Gordon. 2010. Chaotic Advection in an Archipelago. *Journal of Physical Oceanography* 40:1,988–2,006, doi:10.1175/2010JPO4336.1.

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, http://topex.ucsd.edu/marine_topo.

Tessler, Z.D., A.L. Gordon, L.J. Pratt, and J. Sprintall. 2010. Transport and dynamics of the Panay sill overflow in the Philippine seas. *Journal of Physical Oceanography*, doi:10.1175/2010JPO4395.1.

Toole, J., R. Millard, Z. Wang, and S. Pu. 1990. Observations of the Pacific North Equatorial Current bifurcation at the Philippine coast. *Journal of Physical Oceanography* 20:307–318.

Villanoy, C.L., O.C. Cabrera, A. Yñiguez, M. Camoying, A. de Guzman, L.T. David, and P. Flament. 2011. Monsoon-driven coastal upwelling off Zamboanga Peninsula, Philippines. *Oceanography* 24(1):156–165.