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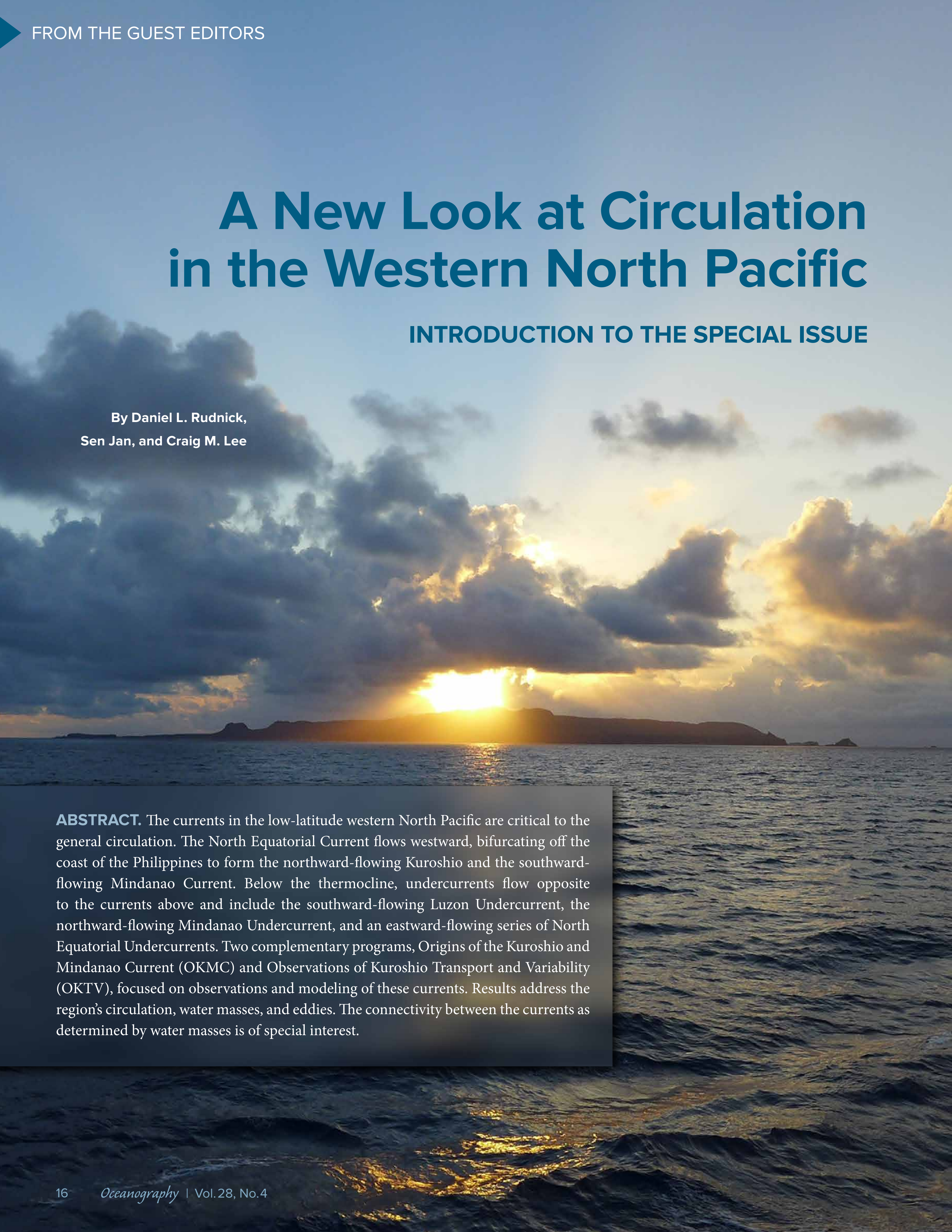

A New Look at Circulation in the Western North Pacific

INTRODUCTION TO THE SPECIAL ISSUE

By Daniel L. Rudnick,
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ABSTRACT. The currents in the low-latitude western North Pacific are critical to the general circulation. The North Equatorial Current flows westward, bifurcating off the coast of the Philippines to form the northward-flowing Kuroshio and the southward-flowing Mindanao Current. Below the thermocline, undercurrents flow opposite to the currents above and include the southward-flowing Luzon Undercurrent, the northward-flowing Mindanao Undercurrent, and an eastward-flowing series of North Equatorial Undercurrents. Two complementary programs, Origins of the Kuroshio and Mindanao Current (OKMC) and Observations of Kuroshio Transport and Variability (OKTV), focused on observations and modeling of these currents. Results address the region's circulation, water masses, and eddies. The connectivity between the currents as determined by water masses is of special interest.

INTRODUCTION

The currents off the east coasts of Taiwan and the Philippines are of critical importance to the general circulation of the Pacific Ocean (Figure 1). The North Equatorial Current (NEC) heads westward centered roughly at 13°N, hits the coast of the Philippines, and bifurcates into the Kuroshio heading northward and the Mindanao Current (MC) heading southward. The Kuroshio starts as a weak and variable current off the Philippine coast, and it strengthens as it passes Luzon Strait (Lien et al., 2014), sometimes looping into the strait. By the time the Kuroshio progresses northward off the east coast of Taiwan, it is a strong and well-defined current, but with marked temporal and spatial variations (Jan et al., 2015). In contrast, the Mindanao Current is strong very close to the bifurcation region, apparently being fed by the relatively steady southern portion of the NEC. This special issue of *Oceanography* is devoted to a new description of these important currents and their associated water masses.

Undercurrents in the region are less well observed and understood theoretically than the currents that extend to the surface. Fundamentally new findings concerning the undercurrents have been reported during the past few years and are described in the articles in this issue. While the existence of the Luzon Undercurrent beneath the Kuroshio, the Mindanao Undercurrent, and an undercurrent beneath the NEC have been suggested by observations for some time, the sustained observations reported here provide convincing evidence for the persistence of these undercurrents.

Most of the work reported here is derived from two linked programs: Origins of the Kuroshio and Mindanao Current (OKMC), sponsored by the US Office of Naval Research, and Observations of Kuroshio Transport and Variability (OKMC), sponsored by the Ministry of Science and Technology, Taiwan (ROC). OKMC focused on the NEC, the bifurcation region, the Mindanao Current, and the Kuroshio in the environs of Luzon Strait. OKTV concentrated efforts on the Kuroshio off the coast of Taiwan. Together, the observation and modeling results of OKMC/OKTV provide a new view of the region that is reported in the following pages.

Three themes have arisen through the course of our investigations in the western Pacific. The first, and perhaps overarching, theme is circulation. The general outline that the NEC feeds the Kuroshio and MC must be correct, but to flesh out this outline requires knowledge of how flow is partitioned in the bifurcation region, how each boundary current strengthens as it proceeds away from this region, and whether these processes are predictable in models. A broad framework like this was not conceivable for subthermocline circulation in the region at the beginning of these studies, but we believe such a framework has now been achieved. Establishing the connectivity of these flows has traditionally been achieved through tracking water masses defined by extrema in water properties. In this region, the dominant salinity extrema are the maximum near 200 m depth known as North Pacific Tropical Water (NPTW), and the salinity minimum near 400 m that is the signal of North Pacific Intermediate Water (NPIW). These water masses and their modification through mixing are the second theme running through many of the articles in this issue. The oldest theories of gyre circulation, found in the work of Norwegian oceanographer Harald Sverdrup (1888–1957), suggest that meridional flow driven by the Ekman pumping of wind stress curl across the basin must be balanced by the flow in intense western boundary currents. Thus, the control of western boundary currents is set by conditions to the east, and this control arrives at the western boundary through westward-propagating waves and eddies. Mesoscale eddies are a dominant feature of the flow

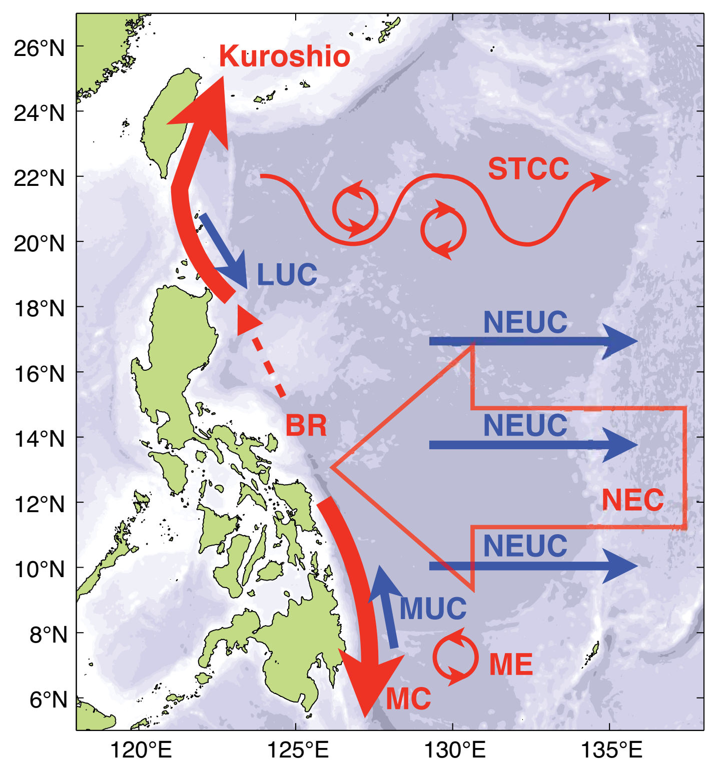

FIGURE 1. Map of the western Pacific, including major currents and features above (red) and below (blue) the thermocline. The North Equatorial Current (NEC) is a broad westward flow that hits the Philippine coast in the Bifurcation Region (BR). From the BR, the Mindanao Current (MC) heads southward. The Kuroshio is difficult to identify close to the BR, but it strengthens as it proceeds northward. The Subtropical Countercurrent (STCC) is a weak flow in a region dominated by eddies. The Mindanao Eddy is a semi-permanent cyclonic feature off the coast of Mindanao, Philippines. Subthermocline boundary currents include the Mindanao Undercurrent (MUC) heading northward and the Luzon Undercurrent (LUC) heading southward. These boundary currents feed the eastward North Equatorial Undercurrent (NEUC) jets below the NEC.

field east of the Kuroshio in the region of the Subtropical Countercurrent (STCC). Thus, a third theme has to do with the eddy processes and their effects on the large-scale circulation. The observant reader may identify the three themes of (1) circulation, (2) water masses, and (3) eddies repeated throughout this special issue.

In the following, we summarize highlights of recent work, including material covered in the papers to follow. The discussion is organized by the dominant current in the region, starting with the NEC, followed by the weak currents in the bifurcation region. A great deal of our effort was spent in the Kuroshio, ranging from its passage across Luzon Strait to its powerful presence off Taiwan. We close with the Mindanao Current, which is perhaps the least studied of the currents in this region.

METHODS

A variety of observational platforms were used in our studies, but there was special emphasis on autonomous platforms that could collect observations without direct support from a research vessel (Figure 2). This autonomous approach to regional oceanography distinguishes our effort from past studies in the region. For example, underwater gliders (Rudnick et al., 2004) were used extensively to measure the major currents in the region, including the NEC, the Kuroshio, and the MC. In total, gliders completed over 40 missions, with 13,000 dives to as deep as 1,000 m, in 4,700 days. A total of 27 profiling floats were deployed, providing profiles to 2,000 m on a five-day repeat cycle, significantly augmenting Argo coverage in a region where floats deployed elsewhere rarely tend to go. A total of 260 surface drifters, drogued at 15 m depth, were deployed between 2010 and 2013 on a roughly regular schedule of eight drifters per month. A variety of moorings were deployed in strategic locations, including current meters in Lamon Bay in the bifurcation region, six 75 kHz acoustic Doppler current profilers (ADCPs) and five HPIES (a combination of horizontal electric field sensors and pressure inverted echo sounders) in the southern Luzon Strait, and three ADCPs, five PIESs, one CPIES (a PIES with a current sensor), and more than 18 ship survey cruises in the Kuroshio off eastern Taiwan.

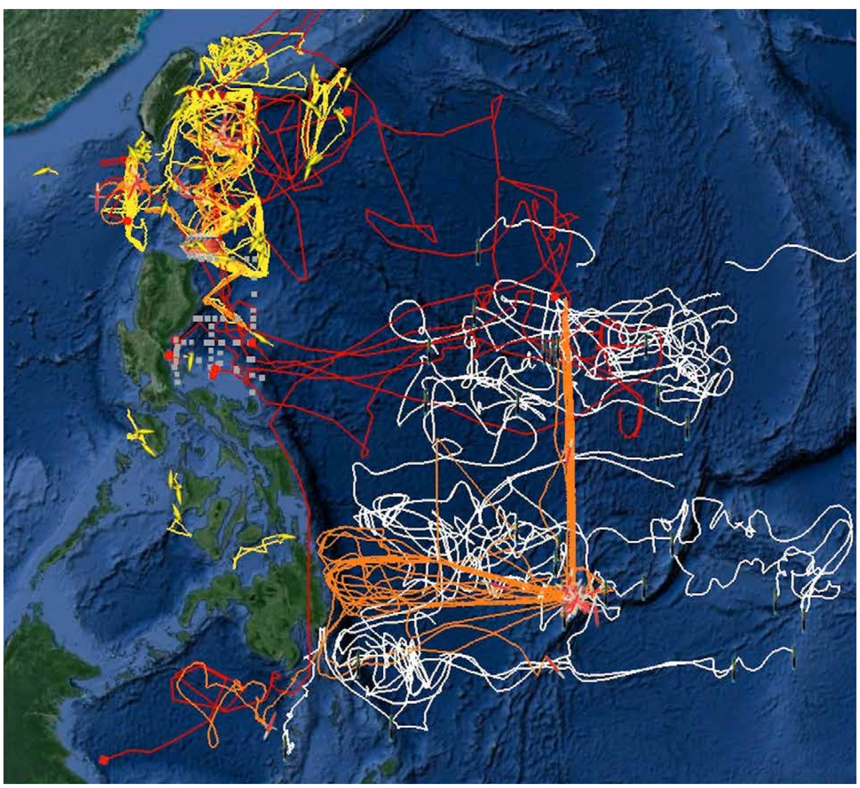

FIGURE 2. Tracks and locations of observational platforms during the Origins of the Kuroshio and Mindanao Current (OKMC) and Observations of Kuroshio Transport and Variability (OKTV) programs. The underwater gliders Spray (orange) and Seaglider (yellow) were deployed to observe the NEC, the MC, and the Kuroshio. The profiling floats SOLO-II (white) and EM-Apex (red) were broadly deployed throughout the region. Subsurface moorings, pressure inverted echo sounders (PIES), and ship stations (symbols) provided higher density observations at key locations.

The programs had a goal of contributing to establishing predictability through state-of-the-art numerical models. A global eddying ocean model, the Parallel Ocean Program (POP), was used to provide context on the longest times and largest length scales. The MITgcm assimilating model was used to provide hindcast state estimates using the array of observations. The intention was to embed these modeling activities throughout the observational program, so there is no separate modeling article in this issue. However, the reader will find modeling results in several of the articles to follow. This combined observational/modeling approach to regional oceanography has proven effective, and we hope it to be an example for the future.

NORTH EQUATORIAL CURRENT (NEC)

The broad westward flow of the NEC feeds the low-latitude western boundary of the North Pacific (Figure 1). During the planning stages of our programs in 2008, observational knowledge of the NEC came from occasional ship surveys and, at the surface, from satellite observations and surface drifters. The Argo array had reached 2,600 floats (Roemmich and Gilson, 2009) on its way to its current 3,800, allowing comprehensive observation of interior currents such as the NEC. OKMC augmented Argo in the NEC, and new analyses were possible. In an effort to access finer temporal and spatial scales, sustained glider deployments from Palau were undertaken from June 2009 to January 2014, yielding repeated sections across the NEC.

As the Argo array was brought to its current size during the next several years, this transformational data set was analyzed with an eye toward the NEC and its undercurrents (Qiu et al., 2013b). The westward-flowing NEC is found to be broad, extending from about 8°N (just north of Palau) to about 25°N in a longitude range of 130°E–135°E, with a patch of eastward surface flow between 17°N and 20°N. The NEC is shallowest and swiftest at its southernmost extent, and it deepens and slows toward the north. Below and to some extent embedded in the NEC are a series of subthermocline eastward jets centered near 9°N, 13°N, and 18°N. On the basis of an eddy-resolving general circulation model, a simple 1.5-layer nonlinear model, and Rossby wave interaction theory, Qiu et al. (2013a) concluded that the NEC undercurrent jets are the result of a triad Rossby wave interaction. These waves originate at the ocean basin's eastern boundary through annual forcing and propagate westward to interact with one another and eventually form the North Equatorial Undercurrent (NEUC) jets. In a study of the subthermocline circulation at the western boundary, Qiu et al. (2015) found that the NEUC jets are fed by convergences on scales shorter than 400 km. Underwater gliders deployed on a line along 134.3°E between Palau at 8°N and 17°N provided 19 sections over 4.5 years between June 2009 and January 2014 (Schönau and Rudnick, 2015). These high-resolution observations confirm the presence of the NEUC jets, and their persistence, as they appear in every section.

The NEC moves the region's dominant water mass, the high-salinity NPTW, to the west. Analysis of observations from gliders and Argo focused on this water mass as the source water for the MC and the Kuroshio (Schönau and Rudnick, 2015). The decay of the NPTW salinity maximum as the water flows westward in the NEC is consistent with a horizontal eddy diffusivity of 10^4 m^2 s^{-1} on scales of hundreds of kilometers. Evidence of the stirring that may lead to this large diffusivity is found in the strong fine-scale variance of salinity on isopycnals in the NPTW maximum layers. The NEUC jets are distinguished by carrying water of different thermohaline characteristics in the same depth range as NPIW, but not with the same extreme freshness. These distinct thermohaline characteristics of the NEUC jets may be useful for identifying their origins along the western boundary. In this issue, **Qiu et al.** synthesize these recent observational results and take advantage of models to explain aspects of the variability of the NEC and the undercurrents.

BIFURCATION REGION AND CONNECTIVITY

The northward-flowing Kuroshio and the southward-flowing MC originate at the bifurcation of the NEC, off the Philippine coast. The bifurcation latitude impacts the partitioning of westward-flowing subtropical water between the MC and the Kuroshio, and thus the water mass structure of the equatorial and northwest Pacific regions they feed (Toole et al., 1990; Qu and Lukas, 2003). The bifurcation latitude varies with depth and responds to both local and remote forcing over a broad range of spatial and temporal scales. Based on analyses of extensive historical data from the 1998 World Ocean Database (NOAA), Qu and Lukas (2003) calculated an annual mean bifurcation latitude of 13.3°N for the upper 100 m layer and ~20°N at ~1,000 m depth. Seasonal mean, vertically integrated (0–1,000 m) geostrophic flow exhibited a bifurcation latitude of 14.8°N in July (summer) and 17.2°N in December (winter). Qiu and Chen (2010) averaged the sea surface height anomaly (SSHA) over a region bounded by 12°N–14°N and 127°E–130°E to produce a proxy that extends backward to 1962 and correlates well with more recent estimates of bifurcation latitude. Prior to the 1970s, bifurcation latitude varied only weakly, followed by elevated variability in a three to five year band in the 1980s and quasi-decadal variability since the 1990s. At longer time scales, Hu et al. (2015b) report a southward migration of bifurcation latitude, from 15.5°N to 13.7°N, over the past 60 years. Western boundary current transports respond to changes in bifurcation latitude, with southward (northward) shifts resulting in increased (decreased) transports within the Kuroshio and decreased (increased) transports within the MC (Kim et al., 2004). The reported southward trend in bifurcation latitude thus implies an accompanying increase in Kuroshio transport that could have significant impacts on climate in northeast Asia.

OKMC and OKTV investigations focused on the connections between bifurcation latitude and observed variability in Kuroshio transport and water mass structure, and on the biological implications of these linkages. Two springtime hydrographic surveys (2011 and 2012) of the nascent Kuroshio in the vicinity of Lamon Bay characterized water mass variability under different NEC bifurcation latitudes (Gordon et al., 2014). In 2011, the bifurcation latitude shifted north, and water mass structure in Lamon Bay reflected increased input from the Kuroshio recirculation and weakened NEC input. The 2012 southward shift in bifurcation latitude was accompanied by amplified salinity extrema in the NPTW and NPIW, consistent with weakened input from Kuroshio recirculation and elevated northward transports supplying tropical waters from the NEC. Lien et al. (2014) use sea level anomaly slope as a proxy for Kuroshio transport to identify transport variability that they ascribe to seasonality in impinging eddies and in the wind-driven migration of NEC bifurcation latitude. Further downstream, 23.75°N and northward, the relationship between bifurcation latitude and Kuroshio transport is less clear (Jan et al., 2015), warranting future investigation.

Variations in the north- and southflowing water masses also impact biological variability and the health of fisheries in the downstream regions (Kimura et al., 2001; Kim et al., 2004; Qiu and Chen, 2010). **Cabrera et al.** relate Lamon Bay chlorophyll concentrations to changes in source waters. Chlorophyll was elevated in 2011, when water mass properties reflected significant input from the Kuroshio recirculation, but depressed in 2012, when tropical waters carried within the NEC drove observed water mass variability. Additional analysis of remotely sensed SSHA and ocean color suggests that strong NEC inflow confines elevated chlorophyll to regions near the coast, while periods dominated by Kuroshio recirculation exhibit broader regions of elevated chlorophyll that extend well offshore.

KUROSHIO

North of the NEC bifurcation region, the Kuroshio has been intensively observed at different sections along its route (Figure 3) using different observational technologies over the past few years. Based on observational data collected from two ship surveys off eastern Luzon in May 2011 and May 2012, Gordon et al. (2014) showed a northward-flowing western boundary current to be first observed near 16.5°N. This location can be regarded as the beginning of the Kuroshio. Results from the ship surveys suggests this "young" Kuroshio is bracketed by an anticyclone to its northeast around 16°N–17°N and 123.5°E–124.5°E and a cyclone to its southwest in Lamon Bay. It is inferred that the change in NEC bifurcation point affects the strength and position of the two cyclonic and anticyclonic dipoles and, in turn, the water masses fed into the young Kuroshio. A more southerly position of the NEC bifurcation leads to more NEC thermocline water input into Lamon Bay and the Kuroshio, whereas a northward shift of the bifurcation corresponds to a dominance of North Pacific subtropical thermocline water in Lamon Bay. The transport across 16.5°N and 18.35°N sections (between 122.4°E and 124.3°E, and in the upper 600 m) was 9.2 Sv and 10 Sv, respectively, during the May 2011 survey, but increased to 14.3 Sv and 16.7 Sv during the May 2012 survey, presumably due to a southward migration of the bifurcation point.

The young Kuroshio grows stronger on its transit northward. To observe the fullest extent of Kuroshio transport before it enters Luzon Strait, six ADCP moorings were deployed along 18.75°N between 122°E and 122.87°E from June 2012 through June 2013 (Lien et al., 2014). The resulting data show an annual mean transport of 15 Sv in the upper 450 m with strong temporal variations of greater than 10 Sv in a time scale of only 10 days. The position of the Kuroshio axis was found to be stable over the one-year observation period. The slope of sea level anomaly (SLA) across the ADCP array can be a proxy for estimating the Kuroshio transport there. The variability in Kuroshio transport at 18.75°N is attributed to westward-propagating eddies that impinge on the Kuroshio and the meridional shift of the NEC bifurcation. **Lien et al.** synthesize comprehensive in situ data collected by multiple observational methods together with numerical simulations and provide detailed flow structure, transport, and water mass properties, with a focus on the Luzon Undercurrent (LUC) around 18.75°N. The transport of the LUC is quantified to have an annual mean of 2–7 Sv with a standard deviation of 0.5 Sv. Water masses from the NEC, West Philippine Sea (WPS), and Lamon Bay were found in the Kuroshio there. The LUC is sourced from WPS water, mostly the lower portion of NPIW. Model simulations agree well with observed aspects of the Kuroshio.

After entering Luzon Strait, the Kuroshio senses no lateral boundary to its west flank and migrates markedly in zonal directions. Surface drifter trajectories show that the Kuroshio's path leaps across the strait in summer, but that it shifts more westward in winter, to the northern South China Sea, where it makes an anticyclonic loop (in an aspect called intrusion) that is similar to the Loop Current in the Gulf of Mexico (Centurioni et al., 2004). **K.-C. Yang et al.** show that the westward-propagating eddies that reach Luzon Strait could modify the Kuroshio path and strength. On the other hand, the density front across the Kuroshio, which is measured by the difference in density over its width, is strengthened when the current encounters denser South China Sea water to the west (Jan et al., 2015). For a geostrophic current such as the Kuroshio, an intensified density front across the current is associated with increased vertical shear in velocity along its direction. Assuming the depth of no motion in the current velocity profile is fixed, the velocity should be strengthened and the thickness of the current is thus deepened in the upper layer due to the thermal wind effect.

The Kuroshio becomes a distinct western boundary current adjacent to the east coast of Taiwan. From a climatological point of view, a well-organized Kuroshio bounded by velocity stronger than 0.2 m s^{-1} (hereafter, the Kuroshio core current) is 140 km wide and ~400 m thick with a mean maximum core velocity of 0.9 m s^{-1} located at 20 m depth and 35 km from the coast of Taiwan (Rudnick et al., 2011). The mean transport (in the upper 450 m) is increased from ~15 Sv at the 18.75°N section to ~17 Sv at 23.5°N (Jan et al., 2015) off the central east coast of Taiwan. Conspicuous results from the nine ship surveys conducted by the OKTV program reveal sizable variations in the Kuroshio's hydrographic structure, maximum velocity position, volume/heat/salinity transport, and water mass composition (Jan et al., 2015). The transport of the Kuroshio core current, calculated using the directly measured velocity, varied between 10.46 Sv and 22.92 Sv, which is less correlated with the zonal SLA slope east of Taiwan than that off northeastern Luzon (Jan et al., 2015). **Y.J. Yang et al.** further analyze the data acquired by multiple observational platforms under the OKTV program. They elaborate on the time mean and standard deviation of velocities, temperature, and salinity collected along three transects across the Kuroshio, then compare numerical simulations and high-frequency radar observations with the observational data, with an emphasis on eddy and typhoon influences on the Kuroshio. Notably, the two-velocity maxima (dual core) feature in the Kuroshio is easily seen from the time mean of velocity in the two southern OKTV transects.

K.-C. Yang et al. examine two possible processes that may cause the dual core in the velocity structure of the Kuroshio southeast of Taiwan, supported by glider observations along transects off eastern Luzon and Taiwan and satellite altimeter observations. One process is associated with the westward shift of the Kuroshio in Luzon Strait in winter, which diffuses the current as it passes through the strait to the sea off southeastern Taiwan. This weakened flow and a relatively strong northward current east of the Luzon island arc, possibly branching from the western boundary current, form two velocity maxima on the onshore and offshore sides of the Kuroshio. The other process is attributed to anticyclonic eddies that affect the Kuroshio in the southeastern part of Luzon Strait. The increase of northward flow adjacent to

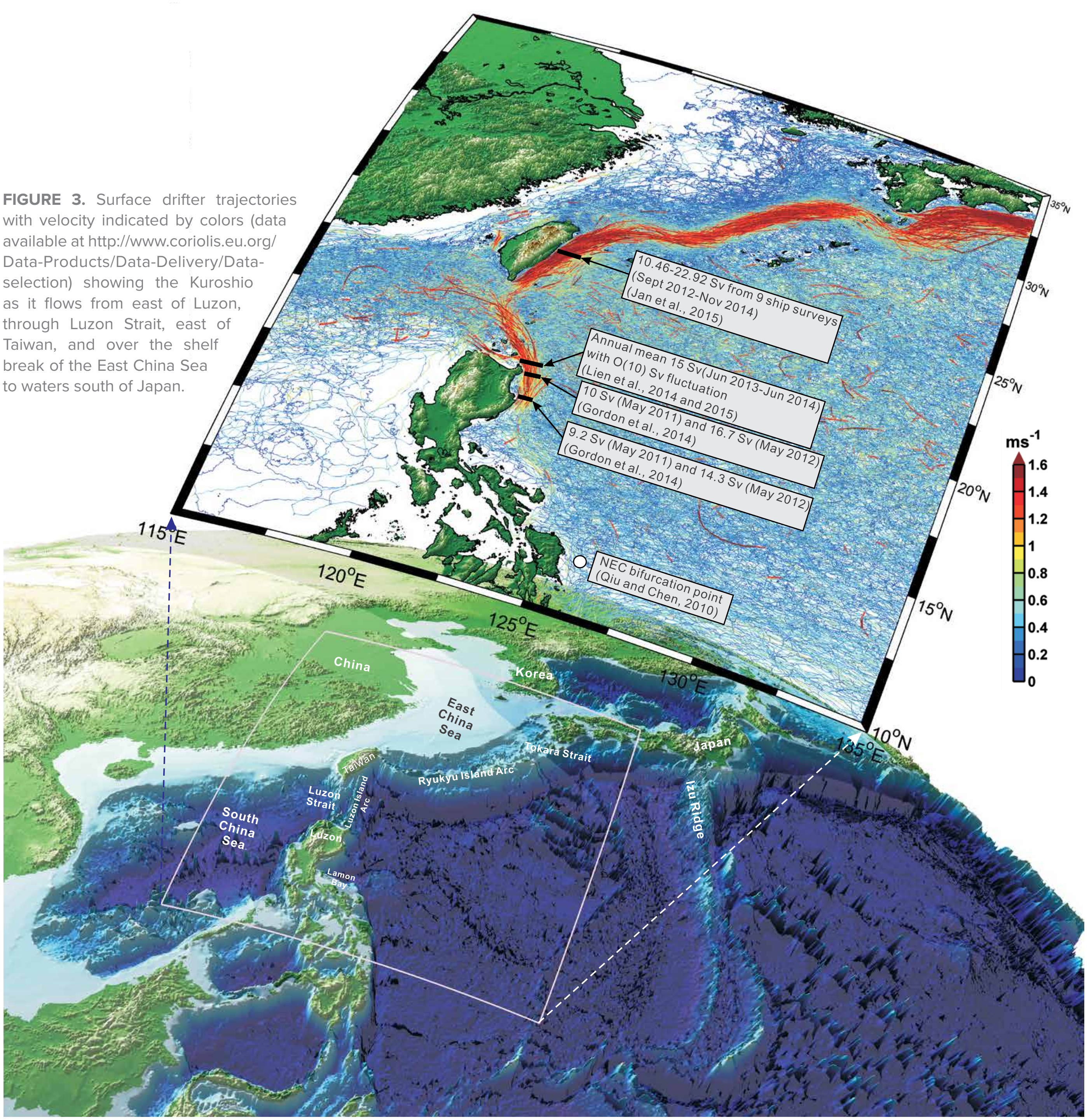

FIGURE 3. Surface drifter trajectories with velocity indicated by colors (data available at http://www.coriolis.eu.org/Data-Products/Data-Delivery/Data-selection) showing the Kuroshio as it flows from east of Luzon, through Luzon Strait, east of Taiwan, and over the shelf break of the East China Sea to waters south of Japan.

the western half of an anticyclonic eddy enhances the flow and causes the offshore core downstream. **K.-C. Yang et al.** also classify water masses involved in the two processes.

Mensah et al. (2014 and 2015) conducted thorough analyses of the water masses associated with the Kuroshio using the hydrographic data obtained particularly from the OKMC and OKTV programs. Waters fed into the Kuroshio originate from the upstream Kuroshio, the South China Sea, and the North Pacific. In the tropical water layer, South China Sea Tropical Water and a mixture of Kuroshio and North Pacific tropical waters typically flow on the western and eastern flanks of the Kuroshio, respectively. In the intermediate water layer, South China Sea and Kuroshio origin waters are found mostly over the topographic trough southeast of Taiwan. North of Green Island, NPIW is predominant east of Taiwan. The temporal and spatial dominance of these water masses is complicated as a result of modifications by the East Asia monsoon, westward-propagating mesoscale eddies, and typhoons.

The journey of the Kuroshio continues from northeast of Taiwan, where it bumps into the continental shelf at the southern margin of the East China Sea. **Andres et al.** combined observations from the OKMC and OKTV programs with findings from earlier investigations to build a comprehensive picture of the Kuroshio's velocity structure, route, and transport as it travels from there along the shelf break of the East China Sea to waters southeast of Japan. Processes underlying the temporal variations of the seasonal Kuroshio intrusion into the East China Sea is re-addressed with a new temperature and sea level data set acquired at an island station northeast of Taiwan. These authors emphasize that the Kuroshio is also affected by westward-propagating mesoscale eddies as it hides behind the protective island chains of the Ryukyu island arc that separates the East China Sea from the North Pacific interior (Andres et al., 2008a, 2008b).

> "Future studies of the region will in turn benefit from the strong observational base provided during the past several years."

MINDANAO CURRENT (MC)

The MC is one of the least studied boundary currents of the North Pacific. The MC receives water from the NEC, and is a strong current just south of the bifurcation region (Fine et al., 1994). Heading southward, the MC feeds the equatorial current system and thus could play a part in important climate variability along the equator (Gu and Philander, 1997). The comparative lack of MC observations provokes questions about its strength and variability. Even more open to question is the existence of the Mindanao Undercurrent—as a mean flow or as a feature that reveals itself only through transient eddies.

The MC was a target of OKMC observations and models. Gliders were deployed from Palau to make the 800 km round trip to the coast of Mindanao and back, producing 19 sections across the MC. The combination of these data, Argo, and models are reported in **Schönau et al.**, with goals of describing the MC and its undercurrent. The connectivity of these western boundary currents with the NEC and undercurrents is a central focus of the article, addressed through tracking of identifiable water masses in the observations and models. Connectivity is found between the Mindanao Undercurrent and the southern NEUC jet, in what we believe to be the most comprehensive study of these currents to date.

SUMMARY

The general circulation above the thermocline in the low-latitude western North Pacific has been understood for some time, as in the seminal work of Fine et al. (1994), and the more recent review by Hu et al. (2015b). Results from the OKMC and OKTV programs presented in this special issue of *Oceanography* refine these views, especially of the Kuroshio off Luzon Strait and Taiwan, the NEC north of Palau, and the MC near 8°N. The influence of eddies was a special focus, especially on the developing Kuroshio as it progresses from the bifurcation region northward past Taiwan. Fundamental advances involve currents below the thermocline, including the Luzon Undercurrent, the Mindanao Undercurrent, and a series of jets that comprise the North Equatorial Undercurrents. Evidence of connectivity in these undercurrents is based on studies of water masses, with a strong case for connectivity between the northward-flowing Mindanao Undercurrent and the southernmost eastward NEUC jet.

This work appears during an era of increased interest in western Pacific circulation. Relevant concurrent efforts include the South Pacific Ocean Circulation and Climate Experiment (SPICE; Ganachaud et al., 2014), and the Northwestern Pacific Ocean Circulation and Climate Experiment (NPOCE; Hu et al., 2015a). The collective impact of these studies and the OKMC/OKTV work represented in this special issue is likely to result in a step change in understanding of the western Pacific. Ongoing analyses are likely to delve further into the variability of the area's important currents and water masses. The data sets from these experiments will be valuable for improving models for estimating ocean state and forecasting. Future studies of the region will in turn benefit from the strong observational base provided during the past several years.

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