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Origins of the Kuroshio and Mindanao Current

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LONG-TERM GOALS

The boundary currents off the east coast of the Philippines are of critical importance to the general circulation of the Pacific Ocean. The westward flowing North Equatorial Current (NEC) runs into the Philippine coast and bifurcates into the northward Kuroshio and the southward Mindanao Current (MC). The partitioning of the flow into the Kuroshio and MC is an important observable. Quantifying these flows and understanding bifurcation dynamics are essential to improving predictions of regional circulation, and to characterizing property transports that ultimately affect Pacific climate. Fluctuations in the Kuroshio and MC can significantly impact variability downstream. For example, the Kuroshio penetrates through Luzon Strait into the South China Sea and onto the East China Sea shelf. The Kuroshio front dramatically alters stratification and may impact internal wave climate. This study incorporates observation, theory, and modeling to make fundamental advances in our knowledge of the origins of the Kuroshio and Mindanao current.

OBJECTIVES

The objectives of this program include quantifying flows and water properties, improving understanding of the dynamics of a bifurcation region, and establishing predictability of the three major currents in the region. The observational approach will have two major thrusts: (1) quantifying the fluxes of mass, heat, and salt in the NEC, Kuroshio, and MC, and (2) establishing Lagrangian patterns of flow. To quantify the seasonal cycle and to obtain an initial measure of interannual variability, these observations will be sustained over a three-year period. The bifurcation region is an

interesting target, but the stagnation point of a turbulent flow is not an easy quantity to observe. The sustained observations will provide a test for models of the regions, and at the same time will be available for assimilation in models.

APPROACH

The proposed observing system employs a suite of complementary platforms to meet the challenges posed by this vast, highly variable study area. Guided by previous studies and by directed analysis of historical data, long-endurance autonomous gliders will be tasked to collect repeat occupations of key sections across the NEC, MC and Kuroshio. Because previous observational programs show that the Kuroshio sometimes reaches nearly to the coast, where glider operations can be difficult and risky, small arrays of moored instruments will augment glider sections to resolve the nearshore regions. Drifters and floats will be used to illuminate the pathways by which the NEC ultimately forms the Kuroshio and MC. Numerical efforts will aid interpretation and explore the predictive capabilities of regional models.

WORK COMPLETED

Gliders

Gliders are being used to observe the NEC and the Mindanao Current. Two Sprays are deployed from Palau every 4-5 months, one that proceeds northward across the NEC, and one that heads westward towards the MC. Operations commenced in June 2009 under a previous grant, and have continued uninterrupted. Turnarounds have occurred in September 2009, February 2010, June 2010, November 2010, April 2011, and August 2011. The data set to date includes 11 crossings of the Mindanao Current, and 10 sections across the NEC (Figure 1). The next turnaround is scheduled for December 2011.

For the first time during this project, it appears that we may be losing a glider. The glider was deployed in April 2011, and made a successful section across the Mindanao Current. On its closest approach to Mindanao, a few miles from shore, something caused the tail fin to be dislodged, likely because of a physical encounter with a person, vessel, or fish. The glider continues to function correctly, except that we have lost the ability to control heading. So, it is functioning as a freely drifting profiling float. The currents have taken it into the Celebes Sea, where we have slowed its profiling interval to once per day. Because deployment duration is a strong function of the frequency of profiling, we expect a very long deployment. We will attempt recovery if the glider is advected into a region where operations from a small boat would be safe.

Analyses so far are focusing on two issues: (1) flows in the NEC and Mindanao Current, and (2) submesoscale variability. Geostrophic currents through each section are calculated, referenced using the glider-observed depth-average velocity. The core of the Mindanao Current is found to be as strong as 1.5 m/s southward, with northward flows in the Mindanao Undercurrent approaching 1 m/s. The mean NEC is emerging from the collection of sections. Westward flow is confined mainly to the upper 500 m, and is strongest just north of Palau, where it peaks at about 0.5 m/s. Layers of high thermohaline variability are observed on isopycnals in the salinity maximum near 100 m, and in the salinity minimum near 400 m. The persistence of these layers will be a subject of continuing analysis. A study of these layers as they exist in the Kuroshio was submitted to Oceanography magazine (Rudnick et al. 2011).

Drifters
The principal scientific objective of the OKMC drifter component is to map the near surface circulation that leads to the seasonal formation of the Kuroshio in the South Philippines Sea. The methodology is to enhance the historical data by deploying drifters from Korean merchant vessels that cross the Luzon Strait and the South Philippines Sea approximately every 35 days on a route from Kaohsiung, Taiwan to eastern Australia. The HYUNDAI Shipping Co picks up the drifters in Taiwan from Professor Ruo-Shan Tseng at National Sun Yat-Sen University. The deployments started in August 9, 2010 and to date we had twelve successful deployment cruises (9 drifters for each deployment).

Modeling
Further MITgcm forward and adjoint modeling studies of the OKMC region have been performed. A regional domain with 1/6° horizontal grid resolution has been run with several forcing products and compared with both historical observations and OKMC glider profiles. The temperature-salinity structure of the model is set by the HYCOM initial conditions and boundary conditions and shows that some adjustments will be needed to match the observations. On the other hand, the dynamical sensitivity calculated from the model adjoint has been shown to be useful in predicting the SSH and transport at the boundary from wind stress within the basin to the east, in agreement with earlier work using a tropical ocean model with coarser resolution. The model shows that sensitivity of SSH and transport to wind stress curl spreads to the east going backwards in time as suggested by the theory, but it also spreads in latitude, and shows considerable sensitivity to the equatorial waveguide. This is a generalization of standard Sverdrup transport or Island Rule theory, and includes time-dependence with realistic advection and wave propagation without making the long-wave approximation. The results are in the final stages of preparation for publication.

To address the objectives of this study, output from data assimilative global 1/12° Hybrid Coordinate Ocean Model (HYCOM) was examined for the period 2006-2010. Our first goals were to examine the partitioning of flow into the Kuroshio and Mindanao Currents and to quantify the seasonal migration of the North Equatorial Current (NEC) bifurcation off the Philippines. We defined the bifurcation latitude as the zero value of meridional velocity averaged over a two-degree band offshore of the Philippine coast. The bifurcation latitude was in its most southerly (northerly) position from April through July (October –through December). Volume transports over the top 500 m of the water column were calculated across 8°, 18.5°, 20°, and 22.5°N to identify the strength and number of cores in the Kuroshio and Mindanao Currents. Seasonal climatologies of depth-integrated velocity in the upper 500 m of the water column were constructed in stream co-ordinates to better identify the origins of the two currents as well as intrusions into the Luzon Strait. Intrusions were further studied using Lagrangian particles that were released in a line off 18.5°N (at the northern tip of the Philippines) in winter and summer composites of 15 m velocities. Intrusive activity was strongest during the winter months. Finally details of the regional variability were examined to the north and south of the bifurcation.

RESULTS

With OKMC started just over one year ago, the most signficant results lay in the future. At this stage, the following results are most evident.

- Strong stirring is evident in the salinity extrema. This feature is consistent with the relatively young age of the water in the extrema relative to the inflection level between.
- The mean NEC is becoming clearer, with the strongest flows in the south and near the surface.
- SSH in the region is found to be sensitive to wind stress curl throughout the basin to the east, with special sensitivity in the equatorial waveguide.
- From historical and new drifter observations, a strong westward Winter Subtropical Current (WSC) is found in the Northwestern Pacific between 18°N and 23°N. The decadal strengthening of negative wind stress curl in the subtropical area north of Hawaii and west of 150°E is the main forcing of this newly observed seasonal current. The annual fluctuation of the WSC transport is reflected in the springtime Kuroshio transport in the south of Japan (Figure 2). The annual variation of the transport by WSC is also correlated with the North Pacific Index (NPI), which represents the strength of the Aleutian Low before the 1988/89 climate shift, but the correlation with teleconnection patterns or climate indices is not found after the 1988/89 shift. A paper describing these results was submitted to the Geophysical Research Letters in October 2011 (Lee et al, 2011).

IMPACT/APPLICATIONS

- The demonstration of glider utility in a strong western boundary current should influence future glider operations in similarly strong flows. Gliders are showing potential for the sustained observation of major ocean currents.
- The value of drifters for regional oceanography is being further established through this program.
- Quantifying the predictability of currents using basin-wide wind stress curl is helping to set bounds for the fidelity of ocean models.

RELATED PROJECTS

This project takes advantage of glider technology that has been developed through grants from several agencies including ONR, NSF, and NOAA.

PUBLICATIONS

Lee, D.-K., L. Centuroni and Y. Kim, 2011. The Wintertime Subtropical Current in the Northwestern Pacific. Submitted to Geophys. Res. Lett.

Rudnick, D. L., S. Jan, L. Centurioni, C. Lee, R.-C. Lien, J. Wang, D. Lee, R.-T. Tseng, Y. Y. Kim, and C.-S. Chern, 2011: Seasonal and mesoscale variability of the Kuroshio near its origin. *Oceanography*, submitted.

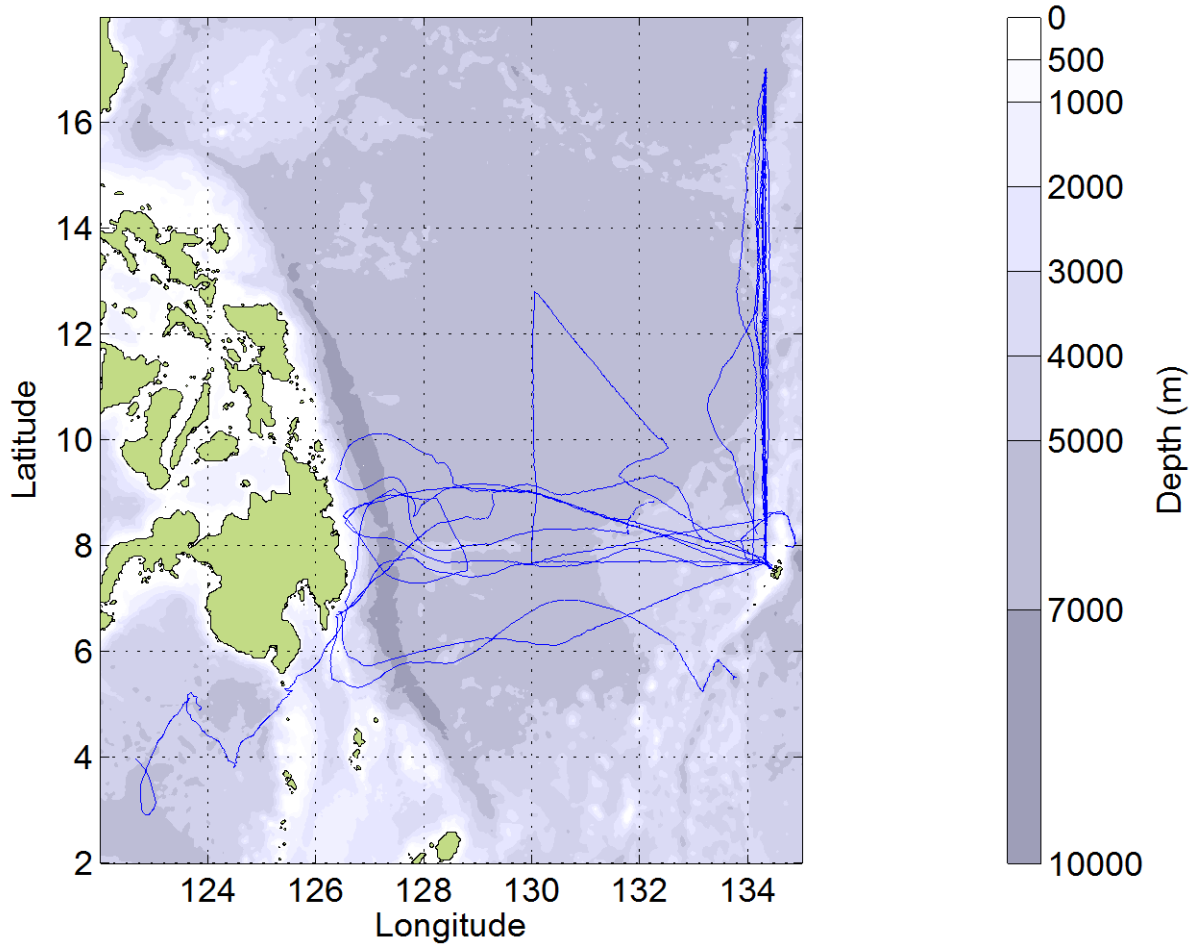

Figure 1. Spray glider trajectories for all deployments since June 2009.

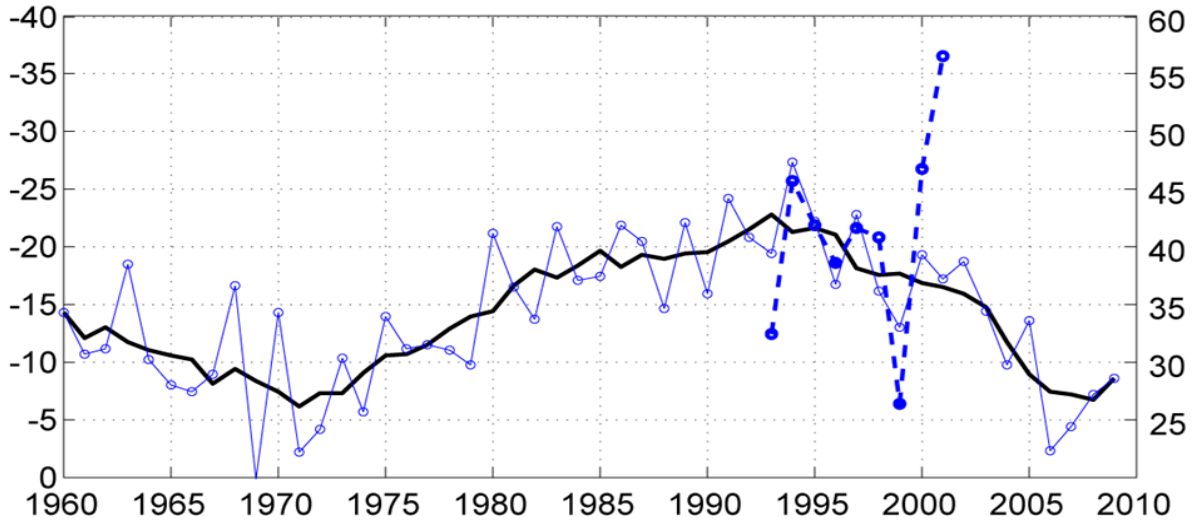

Figure 2. Mean Sverdrup transport in winter (October-March) near the western boundary between 18°N and 23°N and the Kuroshio transport (dashed line with right axis). The thick line is 5 year running mean transport.