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Anti-cyclonic eddies northwest of Luzon in summer–fall observed by satellite altimeters

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[1] Anti-cyclonic eddies northwest of Luzon of the Philippines in summer-fall are identified in the merged data products of satellite altimeters of Topex/Poseidon, Jason-1 and European Research Satellites. The generation and propagation of the anti-cyclonic eddies, which are confirmed by satellite ocean color data, are found to be a seasonal phenomenon that is phase-locked to the onset of the southwesterly monsoon and the relaxation of the cyclonic wind curl in the northeastern South China Sea. The eddies originate from northwest of Luzon in summer, move across the northeastern South China Sea to reach the China continental slope in fall, and propagate southwestward along the continental slope in fall–winter, inducing shelfbreak current variations in the western South China Sea in fall–winter. The anti-cyclonic eddy discovered by Li et al. (1998) in the northern South China Sea is found to originate from northwest of Luzon and carry primarily the South China Sea waters. It does not appear to be an eddy shed from the Kuroshio in the Luzon Strait area as alluded by Li et al. (1998) and others. **Citation:** Yuan, D., W. Han, and D. Hu (2007), Anti-cyclonic eddies northwest of Luzon in summer–fall observed by satellite altimeters, *Geophys. Res. Lett.*, *34*, L13610, doi:10.1029/2007GL029401.

1. Introduction

[2] The South China Sea basin is connected to the Philippine Sea through the Luzon Strait, which is a gap of over 300 km wide in the western boundary of the North Pacific Ocean between Taiwan and Luzon. Observations show that episodes of strong Kuroshio intrusions and meso-scale eddies frequent the Luzon Strait area [*Wang et al.*, 2003; *Yuan et al.*, 2006; *Caruso et al.*, 2006]. *Wang et al.* [2005] studied the statistics of these eddies. However, no seasonal eddies are identified explicitly in these studies.

[3] *Li et al.* [1998] found an anti-cyclonic eddy centered at about 117.5°E, 21°N east of Dongsha Island in the summer of 1994. The chemical tracer analysis of *Li and Pohlmann* [2002] suggests that this eddy originates from the Kuroshio. Based on altimeter data, *Jia and Liu* [2004] suggest that this eddy originates from eddy shedding of the Kuroshio in the Luzon Strait area. However, *Jia and Liu*'s [2004] study uses a model mean sea level as the mean dynamic height of the altimeter sea level anomaly. Their calculation of the vorticity of the altimeter data is, therefore, contaminated by the model errors. *Li and Pohlmann*'s [2002] analysis of the chemical tracers is subject to complicated bio-geochemical processes, which are poorly understood today. According to *Li et al.* [1998], the anti-cyclonic eddy has salinity similar to the South China Sea water, which is much fresher than the Kuroshio water (see *Li et al.* [1998, Figure 4]). In the maximum salinity layer in the subsurface, the maximum salinity of the eddy has reached 34.75 psu, larger than the maximum salinity of ~34.7 psu west of Luzon but much less than the maximum salinity of 34.9 psu of the Kuroshio in approximately the same isopycnal layer. The significant salinity difference between the Kuroshio and the anti-cyclonic eddy suggests that the eddy may not originate from the Kuroshio, although it may mix a small portion of the high salinity water from the Kuroshio. This is more evident from the Satellite observations discussed below.

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2. Satellite Data

[4] The merged products of sea level anomalies from Topex/Poseidon, Jason-1, and European Research Satellite altimeter observations are used to examine the circulation in the northern South China Sea. The sea level anomalies are produced by the French Archiving, Validation, and Interpolation of Satellite Oceanographic Data (Aviso) project using the mapping method of *Ducet et al.* [2000]. The data are interpolated onto a global grid of 1/3° resolution between 82°S and 82°N and are archived in weekly frames. The sea level anomalies (SLA) are relative to a 7-year mean from January 1993 to December 1999. The altimeter data have had tidal and sea level pressure corrections incorporated. Over the shelf area, however, the data still contain aliases from tides and internal waves (O. Lauret, personal communication, 2005). Thus, the data over the shelf shallower than 200 m are masked out in the figures.

[5] In addition to the SLA, a product of total geostrophic current is also used. The geostrophic currents are calculated from the absolute dynamic topography consisting of a mean dynamic topography (MDT) and the SLA of the altimeters. The method of estimating the MDT has been explained in detail by *Rio and Hernandez* [2004]. The resulting total geostrophic currents have been compared with independent drifter data to have a root-mean-square difference of 14 cm/s in the Kuroshio area. Compared with the geostrophic velocity based on along track data, the mapped product has the advantage of combining the information from ascending, descending, and neighboring tracks and can provide better estimation even at the cross track points. It also allows a more rigorous treatment of measurement errors and is technically the only means of extracting

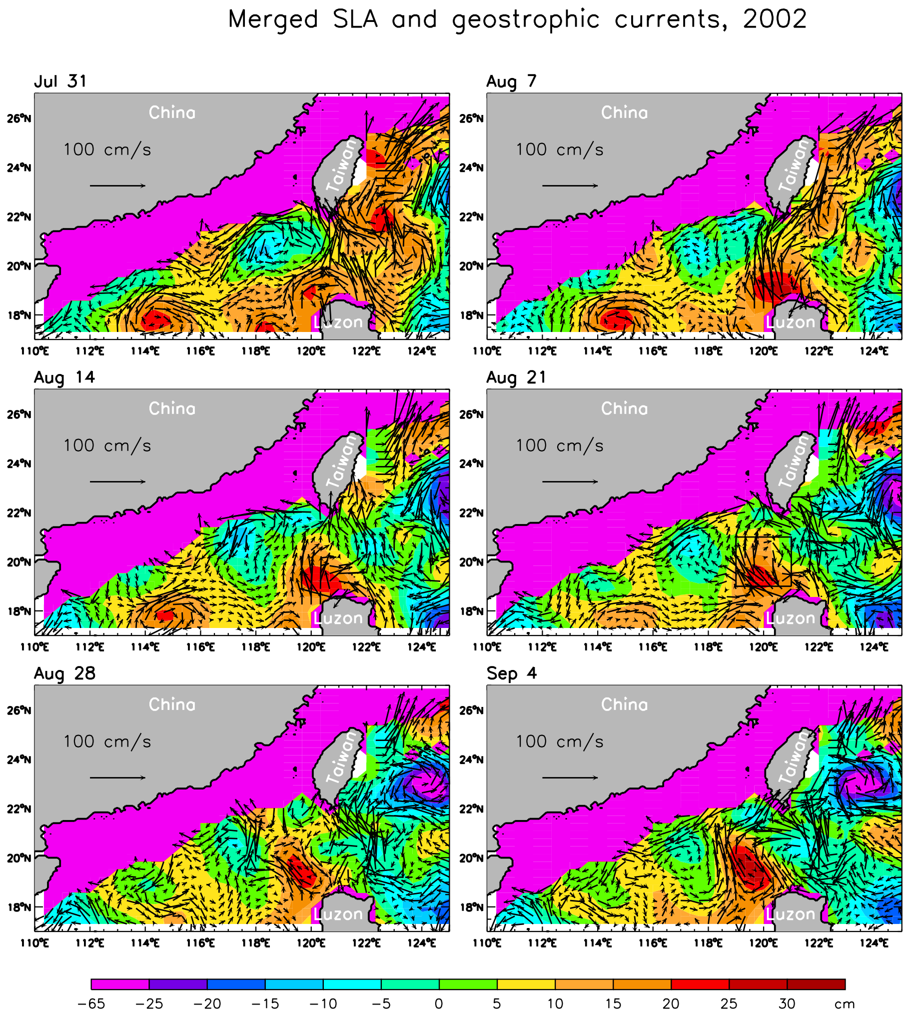

Figure 1. Total geostrophic currents and sea level anomalies. Units are cm for the sea level and cm/s for the currents. The rectangle in the August 21 panel defines the area where time series of averaged sea level anomalies, wind stress, and wind stress curl are plotted in Figure 2. The last panel shows the routes of all the LWE migration during 1993–2004. The initial and end positions of the eddies are marked with asterisks and triangles, respectively.

velocity from a combination of several altimeters [*Le Traon and Morrow*, 2001].

[6] The largest mesoscale circulation features of this geostrophic current product in the Luzon Strait area have been validated extensively with satellite ocean color and sea surface temperature data by *Yuan et al.* [2006]. In addition to those validations, we also use MODIS/Aqua observations to confirm the mesoscale circulation associated with the eddy generation in this study. All comparisons show consistent large eddy circulation in the Luzon Strait area in the three satellite datasets. Indeed, according to *Le Traon and Morrow* [2001], the contamination of noise in the altimeter velocity field is significantly suppressed at wavelengths of 100 km or larger at 20°N.

[7] Two wind stress products are used to examine the potential dynamics of the eddy. One is the European Center for Medium-Range Weather Forecasts (ECMWF) 40-year reanalysis (ERA40) monthly wind stress, which is available only up to 2001. The other is the monthly wind stress calculated from the 3-day QuikSCAT wind, which is available since July 1999. Because the ERA40 winds have had the QuikSCAT data assimilated, the two fields match well by choosing a reasonable drag coefficient for QuikSCAT wind stress [*Han et al.*, 2007].

3. Results

[8] The SLA and the total geostrophic currents in the northern South China Sea during late July through early September of 2002 suggest clearly that an anti-cyclonic eddy is generated off the northwest coast of Luzon (Figure 1). We shall call this anti-cyclonic eddy "Luzon Warm Eddy (LWE)" in the following text. The LWE grows in size and reaches over the China continental slope across the northeastern South China Sea in fall. From there, it moves southwestward and induces current variations over the shelfbreak. The migration speed of this eddy varies significantly, ranging from zero (September 25 through October 9) to 17 cm/s (September 11–25). During fall 2002, the speed of southwestward migration of the eddy along the continental slope is about 8.7–14.9 cm/s.

[9] The existence of the anti-cyclonic eddy has been confirmed by ocean color observations of MODIS and SeaWiFS instruments since 1997. Figure 2 shows MODIS/

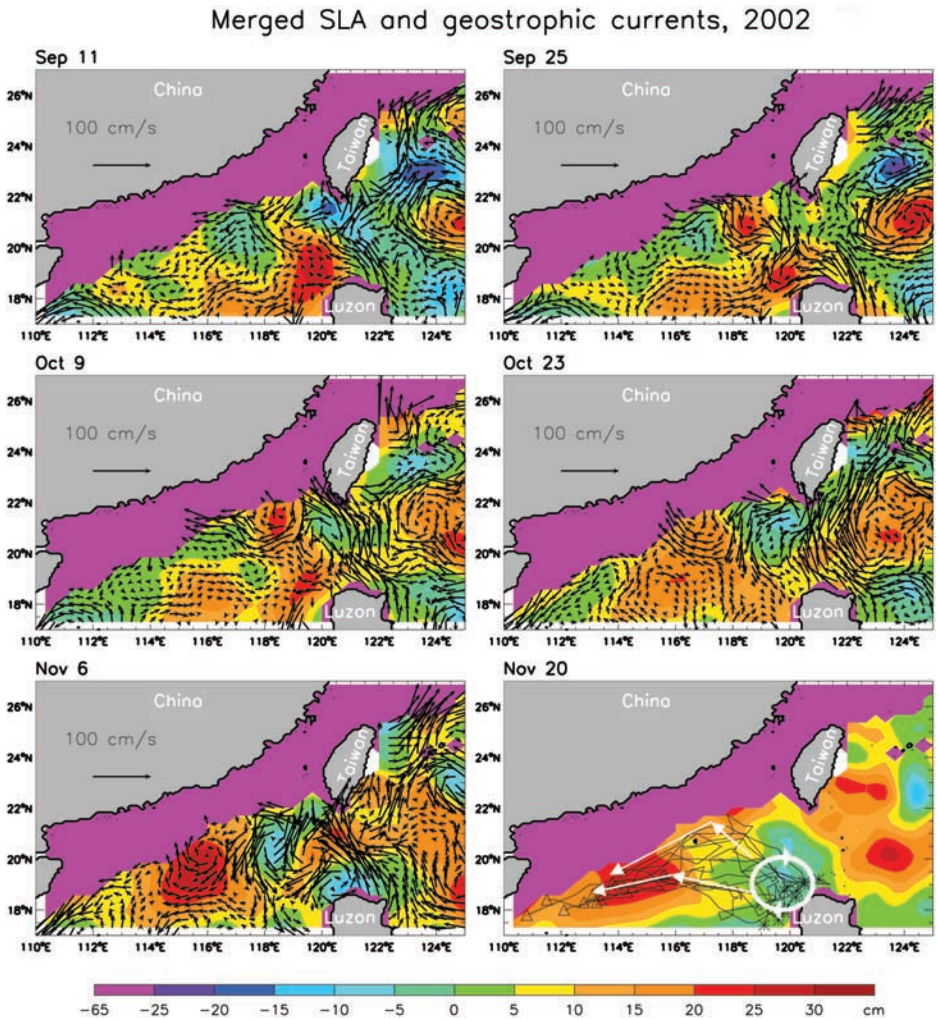

Figure 1. (continued)

Aqua chlorophyll concentration during August 21–28 of 2002 together with the total geostrophic currents on August 21, 2002. The significant anti-cyclonic eddy identified by the geostrophic currents northwest of Luzon is evidenced by the offshore extension of a high chlorophyll concentration filament observed by MODIS/Aqua. This eddy is not associated with an eddy-shedding event of the Kuroshio in the Luzon Strait as evidenced by the area of low SLA southwest of Taiwan (Figure 1) and the low chlorophyll concentration along the direct path of the Kuroshio in the Luzon Strait (Figure 2). The eddy is fed by the west Luzon current composed mainly of the re-circulating water of the South China Sea as suggested by *Xu and Su* [1997], *Fang et al.* [1998], and *Yuan et al.* [2006], with some entrainment/engulfment of the Kuroshio water as evidenced in Figures 1 and 2. In September 2002, the eddy split into two anti-cyclonic eddies for a brief period, but then re-merged again. However, this kind of eddy splitting does not occur every year. The diameter of the anti-cyclonic eddy in summer-fall is about 100–200 km, larger than the resolved wavelengths in the mapped altimeter velocity product at 20°N [*Le Traon and Morrow*, 2001].

[10] Further analyses suggest that the LWE is a seasonal phenomenon. The last panel of Figure 1 shows the routes of the eddy migration in the altimeter data since 1993, one for each year. Generally, the LWE propagates northwestward after it separates from the coast of Luzon. In some years, the LWE follows the southern route because of some random anti-cyclonic eddy events in the Luzon Strait that block the northward migration of the LWE. *Wang et al.* [2003] show these routes before, but didn't affirm that the eddy is a seasonal phenomenon. Figure 3 (solid line) shows the time series of averaged SLA in an area northwest of Luzon (see August 21 panel of Figure 1 for the location of the area). The seasonal recurrence of the eddy is clearly indicated by the positive SLA northwest of Luzon (Figure 3, top) and the westward propagation of the eddy (Figure 3, bottom) in every summer-fall season. The eddy can usually be tracked for longer than 5 months after its generation, except that it demises after 3 months in 2000. The area-averaged SLA exceed 10 cm in each year, which is larger than the error bar of about 5 cm of the altimeter data at wave lengths of 100 km or larger in this area [*Le Traon and Morrow*, 2001]. The lifetime averages of the maximum SLA of the eddy range from 17 cm to 27 cm, larger than the estimate of 15 cm

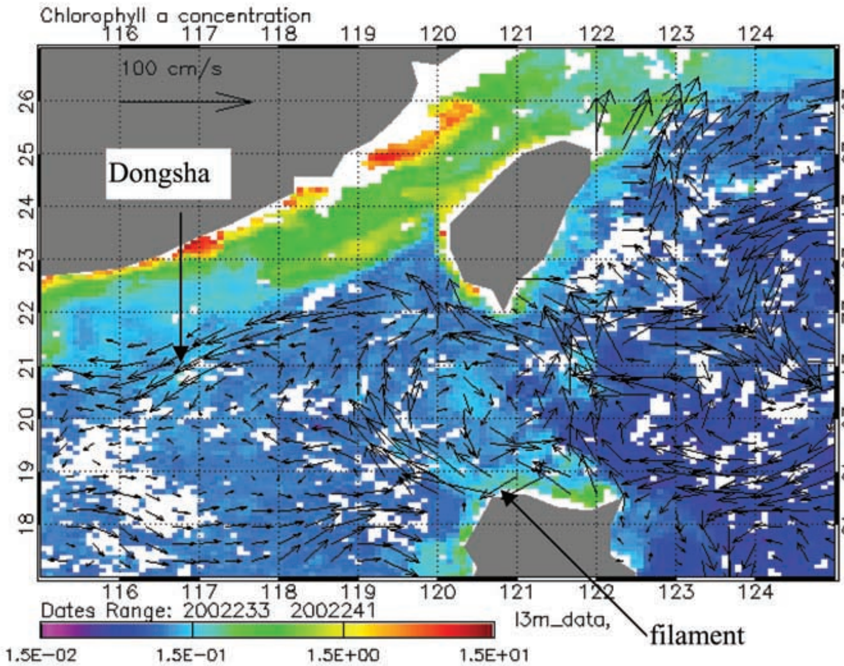

Figure 2. Total geostrophic currents on August 21, 2002, and the ocean color observations of MODIS/Aqua during August 21–28, 2002. White areas indicate cloud covers or bad retrieval.

by *Wang et al.* [2003]. The lifetime averages of the LWE diameter, on the other hand, range from 233 km to 269 km, smaller than the estimate of 307 km by *Wang et al.* [2005]. The difference might be due to the different data products used in these two studies but may also reflect the fact that *Wang et al.*'s [2005] analysis has included other eddies besides the LWE in their estimate.

[11] To shed some light on the dynamics of the LWE, Figure 3 (top) also shows the time-series of meridional wind stress and stress curl averaged over the area northwest of Luzon (August 21 panel of Figure 1). Apparently, the onset of the southwesterly monsoon (dotted) and the annual minimum of wind stress curl (dashed) precede the high SLA associated with the LWE. The cross-correlation between the monthly mean SLA and the meridional wind

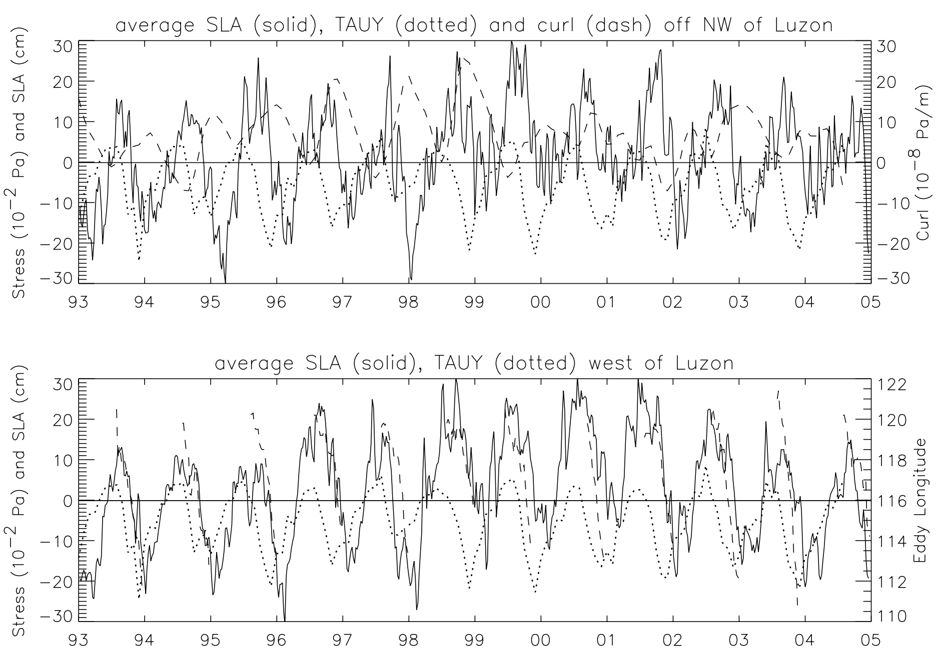

Figure 3. Time series of averaged sea level anomalies, meridional wind stress component, and wind stress curl in an area (top) northwest and (bottom) west of Luzon. The longitudes of the LWE centers are plot in the bottom panel with dash curves.

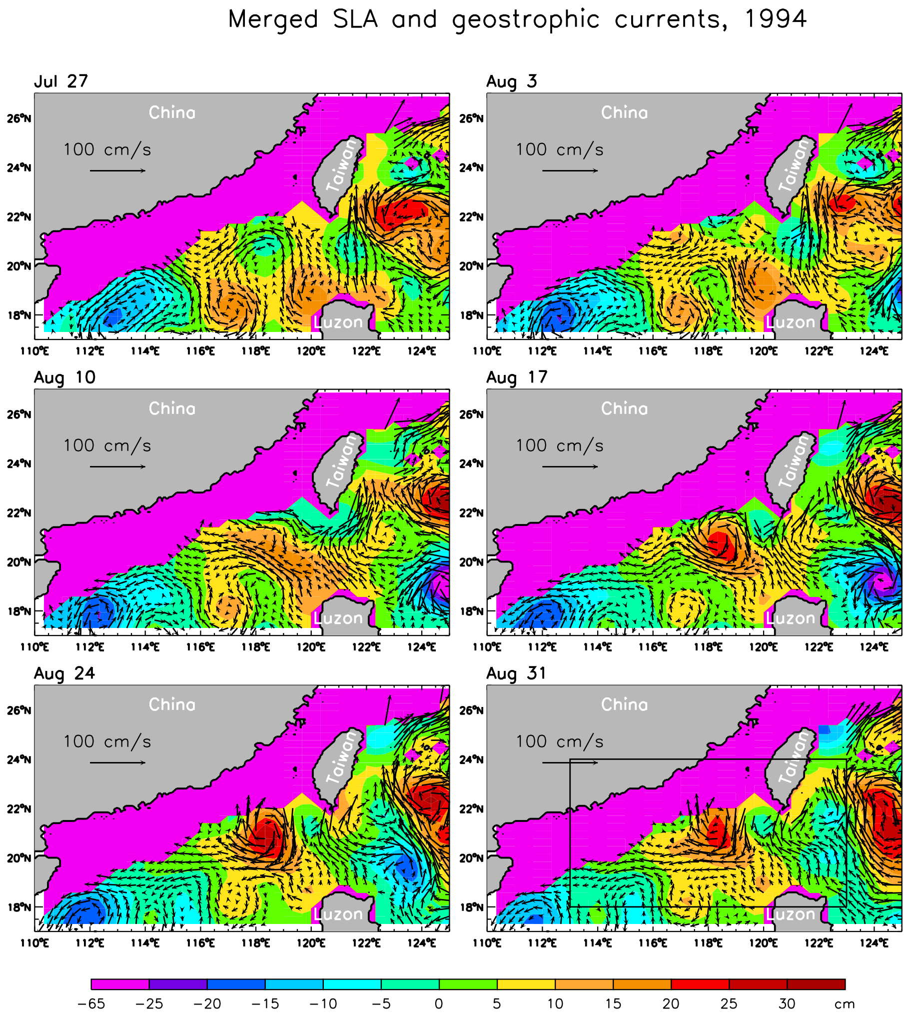

Figure 4. Same as in Figure 1 except for 1994. The rectangular frame in the August 31 panel delineates the area where surface geopotential anomalies relative to 1000 db have been calculated by *Li et al.* [1998] based on in situ hydrographic data.

stress reaches the maximum of 0.67 (above 85% significance level) when the winds lead by two months. In comparison, the cross-correlation between the wind curl and the SLA reaches the maximum negative value of −0.4 (above 80% significance level) if the wind curl leads by one month. The relatively low levels of significance are due to the small sample size of the monthly data. The correlations suggest that the southwest monsoonal winds and the minimum wind stress curl may play an important role in generating the LWE, possibly through driving the west Luzon current and through facilitating the positive sea level anomalies to grow and expand northwest of Luzon, respectively. Indeed, the averaged SLA in an area west of Luzon between 119°–120°E, 16°–18°N correlate well with the meridional wind stress, with a maximum cross-correlation of 0.64 (above 85% significance level) if the winds lead the SLA by one month (Figure 3, bottom).

[12] The complicated westward propagation (stalled during September 25–October 9 and 17 cm/s during September 11–25) and splitting of the LWE (Figure 1) suggest that the LWE is not a free long Rossby wave, which should propagate westward at about 7.1 cm/s for the first baroclinic mode based on the stratification of historical hydrographic (WOA01) data. The eddies may be generated by the momentum imbalance of the northward flowing west Luzon current turning eastward into the Luzon Strait [*Pichevin and Nof*, 1997]. The detailed dynamics of the eddy and its interannual variability are unknown and are beyond the scope of this short paper.

[13] It is worth noting that existing studies have investigated the dynamics of the so-called “Luzon Cold Eddy (LCE)” in the northeastern South China Sea, which refers to seasonal low SLA in the northeastern South China Sea during winter [*Shaw*, 1996; *Fang et al.*, 1998; *Qu*, 2000; *Yang and Liu*, 2003]. The LWE identified in this study is different from the LCE in that the dynamics of LCE are found to be linear Rossby waves forced by the wind curl variations [*Yang and Liu*, 2003] whereas the LWE is not a wind-driven Rossby wave because the wind curl northwest of Luzon is generally positive (Figure 3), which cannot produce anti-cyclonic eddies through linear dynamics.

[14] The early stage of the LWE is a part of the Luzon Strait circulation. However, there seems no definitive relation between the LWE and the formation of the Kuroshio loop current in the Luzon Strait in all the satellite images between 1993 and 2005. Figure 1 shows no significant anti-

cyclonic intrusion of the Kuroshio during the entire LWE events. The Kuroshio sometimes intrudes into the South China Sea and sheds eddies [*Yuan et al.*, 2006; *Caruso et al.*, 2006], but the process is found to be transient and non-deterministic and is not phase-locked to the seasonal cycle of the northern South China Sea circulation in contrast to the seasonal appearance of the LWE.

[15] The SLA and the total geostrophic currents in the northern South China Sea during late July through early September of 1994 suggest that the anti-cyclonic eddy observed over the continental slope east of Dongsha Island by *Li et al.* [1998] is an LWE and is generated off the northwest coast of Luzon in late July of 1994 (Figure 4). The altimeter data in the rectangular frame on August 31 have been compared with the surface geopotential anomalies relative to 1000 db of *Li et al.* [1998, Figure 7]. Both datasets show the positions of the three eddies centered at 115°E (cyclonic), 118°E (anti-cyclonic), and 120°E (cyclonic, southwest of Taiwan), and the Kuroshio main stream east of Taiwan. There are some minor differences between the altimeter and the hydrographic data, which may be due to aliasing of high frequency signals by the altimeter data and by the quasi-synoptical mapping of the hydrographic survey. The consistent eddy propagation in Figure 4 suggests that the signal is real and is not produced by interpolation errors which tend to be random. The eddy expands in the northwest direction and reaches the China continental slope across the northeastern basin of the South China Sea in early September. During the entire process, the Kuroshio in the Luzon Strait stays in a path from northeast of Luzon to southwest of Taiwan. No significant loop current of the Kuroshio is indicated by the total geostrophic currents during the period, suggesting that the eddy is not produced by eddy shedding of the Kuroshio loop current. The northwest Luzon origin of the eddy explains why its salinity is closer to that of the South China Sea water but much lower than that of the Kuroshio.

4. Summary

[16] The seasonal phenomenon of LWE is identified in this study based on the merged altimeter data of Topex/Poseidon, Jason-1, and European Research Satellites and satellite ocean color observations. The satellite data suggest that the eddy is generated off the northwest coast of Luzon in summer and is facilitated by the southerly wind and minimum wind curl. In late summer through early fall, the eddy reaches the China continental slope across the northeastern basin and migrates southwestward along the south China continental slope thereafter, inducing current variations over the shelf edge. The anti-cyclonic eddy observed by *Li et al.* [1998] is found to be an LWE, which is generated from northwest of Luzon instead of shed from the Kuroshio in the Luzon Strait area.

[17] **Acknowledgments.** The altimeter data are obtained from http://www.jason.oceanobs.com/html/donnees/. MODIS/Aqua ocean color data are downloaded from http://seawifs.gsfc.nasa.gov/. D. Yuan is supported by the "973 project" of China (2006CB403603), the "100-Expert Program" of the CAS, and the NSFC-40676020. W. Han is supported by NSF OCE-0452917 and NASA-1283568. D. Hu is supported by NSFC-D06-40552002 and by Qingdao Municipal Government Project 02-KJYSH-03.

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