JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, C11007, doi:10.1029/2005JC003412, 2006

Surface Kuroshio path in the Luzon Strait area derived from satellite remote sensing data

Dongliang Yuan,[1,2] Weiqing Han,[3] and Dunxin Hu[1]

Received 22 November 2005; revised 21 April 2006; accepted 7 July 2006; published 14 November 2006.

[1] Satellite ocean color, sea surface temperature, and altimeter data are used to study the surface Kuroshio path in the Luzon Strait area. The results suggest that the dominant path of surface Kuroshio intrusion in winter is a direct route from northeast of Luzon to southwest of Taiwan and then westward along the continental slope of northern South China Sea. Anticyclonic intrusions of the Kuroshio in the Luzon Strait area are observed during less than 30% of the time on average and in all four seasons of the year. Winter is the most favorable season for the formation of the anticyclonic intrusions. However, the Kuroshio is observed to deviate from the dominant path during only a little over one third of the wintertime on average. The loop currents of the Kuroshio, which feature prominent inflow-outflow currents in the Luzon Strait during the anticyclonic intrusions, are observed only occasionally, with more episodes in summer than in winter. The observation of more frequent loop currents of the Kuroshio in summer than in winter is a revision to the existing conclusion. These results demonstrate that the anticyclonic intrusion of the Kuroshio is a transient phenomenon rather than a persistent circulation pattern in the Luzon Strait area as suggested by some of the existing numerical model simulations. The growth and decay of the anticyclonic intrusions of the Kuroshio are closely related to the passages and evolution of mesoscale eddies in the Luzon Strait area. Each anticyclonic intrusion event lasts for a few weeks. Its termination sometimes results in a detached anticyclonic eddy propagating to the western basin along the continental slope of the northern South China Sea.

Citation: Yuan, D., W. Han, and D. Hu (2006), Surface Kuroshio path in the Luzon Strait area derived from satellite remote sensing data, *J. Geophys. Res.*, *111*, C11007, doi:10.1029/2005JC003412.

1. Introduction

[2] The Luzon Strait is a wide gap of the Pacific western boundary between Taiwan and Luzon (Philippines). The span of the strait is over 300 km with a sill depth of over 2000 m at the center of the strait. Observations indicate that the Kuroshio, which is the western boundary current of the North Pacific subtropical gyre, flows to the north along the east coasts of the Philippines and Taiwan [*Nitani*, 1972]. The path of the Kuroshio inside the Luzon Strait, however, is not clear at present. Hydrographic data show that the Kuroshio "short circuits" the Luzon Strait without a significant intrusion into the South China Sea in summer while it flows in an anticyclonic path in the northeastern South China Sea in winter [*Nitani*, 1972]. The path of the Kuroshio in the northeastern South China Sea has been resembled to the Loop Current in the Gulf of Mexico by *Li and Wu* [1989] and the name of "Kuroshio loop current" is introduced to represent the anticyclonic circulation pattern enclosed by inflow and outflow currents through the Luzon Strait. Later observations indicate that the Kuroshio loop current is primarily a winter phenomenon and its occurrence in summer has not been observed very often so far [*Wang and Chern*, 1987a; *Farris and Wimbush*, 1996; *Centurioni and Niiler*, 2004].

[3] Many important issues about the Kuroshio path in the Luzon Strait have not been resolved to date. First, it is not clear if the Kuroshio forms a persistent loop current in the Luzon Strait area in winter or if it is involved in the perpetual growth and eddy-shedding cycles as the Loop Current in the Gulf of Mexico does. Existing high-resolution numerical simulations seem to suggest a steady or quasi-steady loop current of the Kuroshio in the northeastern South China Sea [*Metzger and Hurlburt*, 1996, 2001; *Yang et al.*, 2002; *Xue et al.*, 2004; *Hsueh and Zhong*, 2004], which differ from the historical hydrographic data analyzed by *Qu* [2000] showing a north-south front of temperature and salinity across the Luzon Strait. The hydrographic data, however, are limited by the space and time coverage, which does not resolve the evolution of the Kuroshio loop current well, and thus may also be biased in the mean state. Modern satellite data are frequent over the Luzon Strait area and are advantageous in monitoring the evolution of the Kuroshio

---

[1] Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China.

[2] First Institute of Oceanography, State Oceanic Administration, Qingdao, China.

[3] Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, Colorado, USA.

0148-0227/06/2005JC003412$09.00

path. In this study, the winter climatology of the surface Kuroshio path in the Luzon Strait area is investigated based on the sea surface temperature (SST) data of the Pathfinder mission during 1985–1997, ocean color data of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) mission during 1997–2004, and mean geostrophic currents derived from satellite altimetry (section 2).

[4] The periods of expansion and eddy shedding of the Gulf of Mexico Loop Current have been studied by *Sturges and Leben* [2000] and are estimated to be from 3 to 17 months. Similar investigations of the Kuroshio loop current were conducted by *Jia and Liu* [2004]. However, their analysis relies on a model mean sea level field, which features a permanent Kuroshio loop current and thus limits the interpretation of the altimetry anomalies. In addition, the study has only estimated the periods between eddy shedding events. The periods of individual event of loop current expansion and eddy shedding and the periods without loop currents in the Luzon Strait area are not estimated. Their study has shown events of summer eddy shedding of the Kuroshio, but without a discussion of the structure of the loop currents. So far, there exist only primitive studies on eddy circulation in the Luzon Strait area. For example, it is not clear if every Kuroshio loop current sheds an anticyclonic eddy in the northeastern South China Sea and what the fate of the detached eddy is. The observation of the Kuroshio eddy by *Li et al.* [1998] does not disclose the history and destination of the detached eddy. All these issues are related to transient circulation in the vicinity of the Luzon Strait, which can be investigated using satellite SST, ocean color, and altimeter data.

[5] The paper is organized as follows. In Section 2, the satellite data and the Hellerman-Rosenstein wind stress product are introduced. In Section 3, the winter climatologies of the AVHRR SST data and the SeaWiFS ocean color data in the Luzon Strait area are presented and discussed. Then the transient evolution of the Kuroshio in the Luzon Strait is studied using the Moderate Resolution Imaging Spectroradiometer (MODIS) and the altimeter data. The final Section 4 contains summary.

2. Data

[6] The primary satellite data used to study the mean Kuroshio path in winter are the AVHRR global 9 km SST climatology produced by Jet Propulsion Laboratory of NASA and the monthly 9 km level 3 chlorophyll a concentration of SeaWiFS. The AVHRR product contains pentad (5-day) climatologies created by spatially and temporally Gaussian interpolating the highest-quality SST data of NOAA/NASA Pathfinder mission during 1985–1997 on a global grid of about 9.28 km resolution. The winter climatology in this study is averaged from this SST product using December through February data. The winter climatology of SeaWiFS chlorophyll a concentration data is averaged from the December through February monthly data of 1997–2004. The AVHRR data have nearly global coverage twice per day and SeaWiFS data once per day (only daytime). The frequent observations of the Kuroshio in the Luzon Strait suggest that the climatological averages are less biased than the hydrographic data.

[7] To study the transient evolution of the Kuroshio in the Luzon Strait, the latest SST and ocean color data of the MODIS instruments onboard of the Terra satellite are used. The MODIS infrared sensor (11 μm) is a heritage of the AVHRR sensor with improved sensor precision and spatial coverage/resolution. The nominal accuracy of MODIS SST data is 0.3 K. Besides the 11 μm SST, the MODIS instruments also measure SST at 4 μm. The structures of the Kuroshio loop current identified from the 11 μm SST or 4 μm SST are essentially the same. To reduce the cloudiness of the MODIS images, the level 3 weekly (8-day) global mapped data at 5 km resolution, which are aggregated from swath data, are used in this study to illustrate the surface Kuroshio path in the Luzon Strait. Because the focused Kuroshio loop current events have periods longer than a month, the use of the weekly product will not distort the structures of the loop current significantly. The MODIS SST products have separate daytime and nighttime archives. In this paper, only the MODIS/Terra 11 μm daytime SST data are shown, because the cloud covers at night and of MODIS onboard of the Aqua satellite are sometimes unfortunate.

[8] Besides the SST data, images of the chlorophyll a concentration of MODIS/Aqua are used to confirm the loop current structures in the SST images. Compared with the SST data, ocean color data of good quality are scarce and of poor coverage, because the reflectance of the ocean surface in the visible bands is very low (about 10%). However, the ocean color data can serve as a good confirmation of the SST features because the ocean color contrast across the Kuroshio front is usually large in winter. In comparison, the SST contrast across the Kuroshio front in the northeastern South China Sea is low even in winter. The SeaWiFS data reveal similar features as the MODIS/Aqua data but with a coarser spatial resolution. Their presentation is omitted here.

[9] In addition to the MODIS data, sea level anomalies and geostrophic currents from a merged product of TOPEX/Poseidon, Jason 1, and European Research Satellite altimeter observations are used to examine the circulation in the northeastern South China Sea. The sea level anomalies and geostrophic currents 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 (7 days) averaged 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. The geostrophic currents are calculated from the absolute dynamic topography, which consists of a mean dynamic topography (MDT) and the anomalies of the altimeter sea level. The method of estimating the MDT has been explained in detail by *Rio and Hernandez* [2004]. First, a guess of the MDT is computed by substracting the geoid model EIGEN-2 from the mean sea level determined from the altimeter data. Then the Levitus climatology is merged with the resulting MDT using optimal interpolation. Finally, a multivariate objective analysis is used to combine in situ measurements of XBT, CTD, and WOCE-TOGA

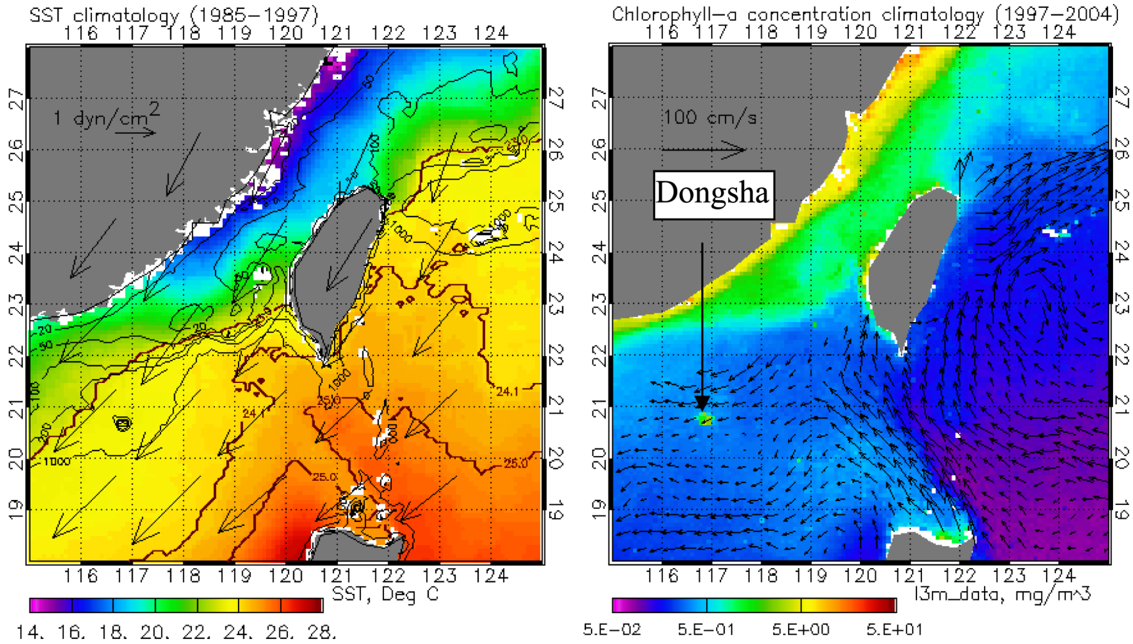


Figure 1. Winter climatologies of (left) AVHRR SST and (right) SeaWiFS chlorophyll a concentration in the vicinity of the Luzon Strait area. The SST climatology is based on December, January, and February data of 1985–1997. The Chlorophyll a concentration climatology is based on December, January, and February data of 1997–2004. The vectors in the SST plot are the Hellerman-Rosenstein wind stress, and those in the ocean color image are the mean geostrophic currents averaged for the winters (January, February, and December) of 2002 and 2003.

with the altimeter data. The resulting geostrophic currents have been validated with independent drifter data to have a root-mean-square difference of about 14 cm/s in the Kuroshio area [*Rio and Hernandez*, 2004].

[10] The geostrophic currents in winter are shown in this study to be in excellent agreement with the SST and ocean color images. In summer, when both the SST and ocean color contrasts between the Kuroshio and the South China Seawaters are weak, the geostrophic currents serve as the only observation to identify the Kuroshio loop current in the Luzon Strait. We have calculated the geostrophic currents in August–September 1994 based on the anomalies of the geostrophic currents associated with the SLA and the mean geostrophic currents of 2002–2004 and compared them with the eddy event observed by *Li et al.* [1998]. The overall structures of the geostrophic currents agree with those of the hydrographic data very well in terms of the position of the eddy and the path of the Kuroshio mainstream (not shown), suggesting the veracity of the data in summer. The product of the total geostrophic currents only starts from 2002. The circulation in the Luzon Strait before 2002 is examined from the anomalies of the geostrophic currents associated with the sea level anomalies.

[11] In the discussion of the winter mean circulation, the Hellerman-Rosenstein wind stress [*Hellerman and Rosenstein*, 1983], which is based primarily on ship and in situ measurements of the wind speeds from 1870 to 1976, is used to represent long-term climatology of the wind forcing in winter. The scatterometer winds from the SeaWinds instrument onboard of the QuikScat satellite are also examined for the wind conditions at the time of the Kuroshio loop currents.

3. Results

[12] In this section, we first use the AVHRR SST and SeaWiFS chlorophyll a concentration climatologies to describe the mean circulation in the Luzon Strait in winter. Then we use the weekly SST, ocean color, sea level anomalies, and geostrophic currents to study the transient evolution of the Kuroshio in the Luzon Strait area.

3.1. Climatology

[13] Figure 1 shows the winter climatologies of AVHRR SST based on the Pathfinder data of 1985–1997 and of chlorophyll a concentration based on the SeaWiFS measurements of 1997–2004. The SST climatology agrees well with the mean AVHRR SST map of 1985–2002 compiled by *Ho et al.* [2004]. The averaged geostrophic currents in the winters (January, February, and December) of 2002 and 2003 are plotted over the SeaWiFS image for comparison. Because of the short time series of the total geostrophic current data (2002–2005), the long-term mean circulation corresponding to the SST and ocean color climatologies cannot be obtained. Since the Kuroshio forms significant anticyclonic intrusions in the winter of 2004–2005, the structure of the geostrophic currents during that period will be discussed in the next section.

[14] The AVHRR SST fronts have been smoothed due to the coarse resolution and the Gaussian interpolation. However, the Kuroshio path can still be identified from the

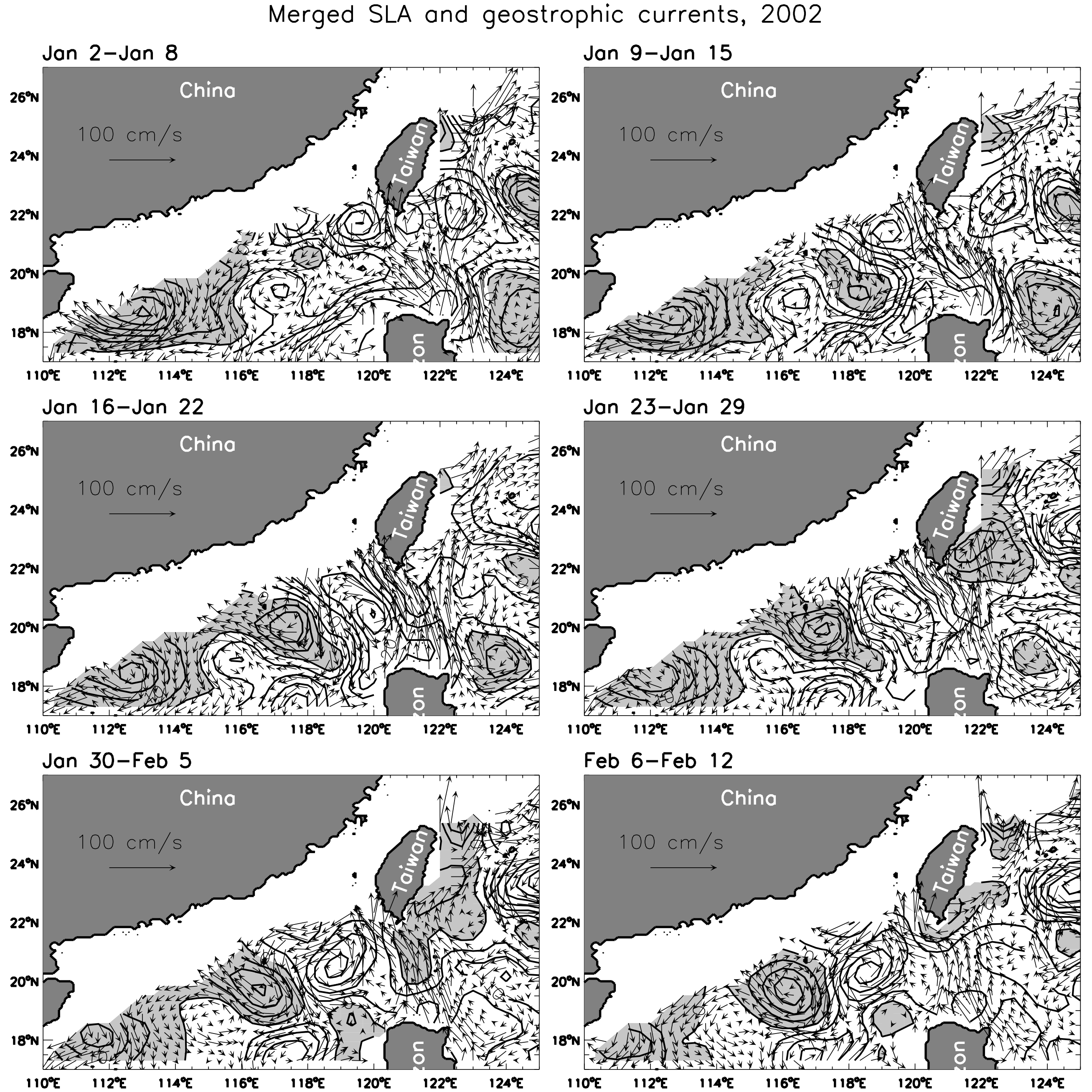


Figure 2. Sea level anomalies in early 2002 relative to the 1993–1999 climatology from the merged altimeter product (colors). The vectors are the geostrophic currents calculated from the merged absolute dynamic topography. Units are cm for the sea level and cm/s for the currents. Contour interval for sea level is 5 cm. Positive sea level anomalies are shaded. The data over the shelf shallower than 200 m have incorporated significant aliases from tides and internal waves and are masked out.

image. The boundary of the Kuroshio and the South China Seawater is indicated by a cold water wedge (see the 25°C contour) on the western side of the Kuroshio warm tongue extending from northeast of Luzon into the South China Sea. There is also a warm SST tongue extending northward from west of Luzon, consistent with the recirculation of the South China Sea water observed in this area [*Xu and Su*, 1997; *Fang et al.*, 1998]. The wind during winter in this area is dominated by the northeasterly monsoon, as illustrated by the Hellerman-Rosenstein wind stress vectors. The recirculation currents west of Luzon are evidently against the wind, and their possible dynamics have been discussed primitively by *Fang et al.* [1998] and *Chu et al.* [1999]. Other features of the SST climatology include the cold SST along the Fujian and Guangdong coasts of China [*Wang et al.*, 2001], the Kuroshio east of Luzon and Taiwan [*Nitani*, 1972], and the warm SST tongue in the eastern Taiwan Strait along the Penghu Channel [*Liang et al.*, 2003]. These features of

Table 1. List of Anticyclonic Intrusion Events of the Kuroshio in the Luzon Strait Area Since Late 1992[a]

Start Date (Year Day/Year)	End Date (Julian Date)	Duration, days	Absence Period, days	Zonal Intrusion Days in Winter	Eddy Shedding
D337/1992	D35/1993	63		49	y
D161/1993	D196/1993	35	126	0	y
D329/1993	D6/1994	42	133	28	n
D33/1994	D61/1994	28	28	21	y
D110/1994	D131/1994	21	49	0	y
D313/1994	D11/1995	63	182	42	n
D347/1995	D143/1996	161	336	28	n
D297/1996	D16/1997	84	154	47	y
D296/1997	D365/1997	70	280	31	y
D196/1998	D210/1998	14	196	0	y
D350/1998	D69/1999	84	140	28	n
D111/1999	D153/1999	42	42	0	y
D335/1999	D47/2000	77	182	63	y
D187/2000	D208/2000	21	140	0	y
D292/2000	D306/2000	14	84	0	n
D334/2000	D362/2000	28	28	28	y
D67/2001	D81/2001	14	70	0	n
D326/2001	D340/2001	14	245	6	y
D79/2002	D93/2002	14	105	0	y
D120/2003	D141/2003	21	392	0	y
D162/2003	D197/2003	35	21	0	y
D232/2003	D260/2003	28	35	0	y
D337/2003	D365/2003	28	77	14	n
D21/2004	D49/2004	28	21	28	y
D70/2004	D112/2004	42	21	0	n
D154/2004	D196/2004	42	42	0	y
D217/2004	D245/2004	28	21	0	y
D315/2004	D27/2005	77	70	35	y
D41/2005	D97/2005	56	14	18	n
Total	29 cases	1274	3234	466	

[a] The periods are calculated on the basis of weekly data and are therefore uncertain by a week or so.

SST are also reflected in the SeaWiFS chlorophyll a concentration climatology even though the averaging period of the ocean color data is different from that of the SST data.

[15] The winter climatologies of the AVHRR SST and SeaWiFS ocean color suggest that the dominant path of the Kuroshio in the Luzon Strait is a direct route from northeast of Luzon to southwest of Taiwan in winter. From there, the Kuroshio water extends westward along the continental slope of the northern South China Sea, as indicated by the westward extension of the Kuroshio front there (see the 24 °C contour). The low concentration of chlorophyll a along the dominant path is consistent with the SST climatology. The climatological path of the Kuroshio derived from the SST and ocean color images is in agreement with the geostrophic currents averaged during the winters of 2002 and 2003. This agreement and those in the following text validate the geostrophic current product in the Luzon Strait area.

[16] Relatively low concentration of chlorophyll a is also found in the area further southwest of Taiwan, which extends westward, indicating vestige of the Kuroshio loop currents in the climatology. Indeed, the loop current is evident in the geostrophic currents if we add the winter currents of 2004–2005, because strong anticyclonic eddies occur in the winter of 2004–2005. Nevertheless, the dominant path of the Kuroshio from the southeast to the northwest in the Luzon Strait is unmistakable in the ocean color climatology. These structures are consistent with the historical hydrographic data analyzed by *Qu* [2000] and the observations of the Kuroshio branch current in the western South China Sea along the continental slope [*Chan*, 1970; *Guo et al.*, 1985; *Shaw*, 1991; *Qu et al.*, 2000; *Centurioni and Niiler*, 2004]. The transport of the Kuroshio intrusion into the Luzon Strait, however, cannot be obtained from these satellite images.

[17] An important result from the satellite climatologies is that the primary path of the Kuroshio in the Luzon Strait area in winter appears to be a direct route from northeast of Luzon to southwest of Taiwan, rather than a persistent Kuroshio loop current. Analysis of all the MODIS and SeaWiFS weekly images suggests that the Kuroshio follows the direct path in the Luzon Strait during most of the time as illustrated by the geostrophic currents in the winter of 2002 in Figure 2, i.e., no loop current is present in most of the images. The loop current is present in the Luzon Strait area only occasionally as identified from the SST, ocean color, and geostrophic current data and is evidently a transient phenomenon of the northeastern South China Sea circulation (see section 3.2). Here the variations of the Kuroshio in the Luzon Strait are significantly different from the variations of the Loop Current in the Gulf of Mexico. The latter features a perpetual expansion and eddy shedding cycle [*Hurlburt and Thompson*, 1980; *Sturges et al.*, 1993; *Yuan*, 2002], which reflects a momentum imbalance produced by the inflow and outflow through the Yucatan and Florida Straits [*Pichevin and Nof*, 1997]. This kind of perpetual growth of the Kuroshio loop current is not seen in the Luzon Strait area (Figure 2). The Kuroshio loop current appears to be affected by nondeterministic eddy activities that frequent the area from both the Philippine Sea and the South China Sea (see section 3.2). The different variations of the two loop currents in the western Pacific and the western Atlantic oceans suggest that the dynamics of the circulation in these two areas are different.

[18] The above discussions suggest that the Kuroshio loop current may not play a dominant role in the mean circulation of the northeastern South China Sea. The variability of the Kuroshio path needs to be simulated well by a numerical model in order that the heat, salt, momentum, and mass exchange between the South China Sea and the Kuroshio can be estimated. The study of *Hsueh and Zhong* [2004] also suggests that the Kuroshio loop current has significant impact on the circulation in the northern South China Sea. Existing numerical simulations seem to have significant difference from the satellite observations [e.g., *Metzger and Hurlburt*, 1996, 2001; *Yang et al.*, 2002; *Xue et al.*, 2004; *Hsueh and Zhong*, 2004]. Recent data assimilation conducted by the Naval Research Laboratory, however, has improved the simulation of the Kuroshio path in the Luzon Strait area significantly (http://www7320.nrlssc.navy.mil/EAS16_NFS/).

3.2. Transient Circulation in the Luzon Strait Area

[19] The weekly data of MODIS SST, ocean color, and sea level anomalies and the geostrophic currents of the merged altimeter data have been analyzed to study the transient evolution of the Kuroshio path in the Luzon Strait area. The results suggest that the Kuroshio sometimes experience significant anticyclonic intrusions in the northeastern South China Sea. Table 1 lists all the anticyclonic

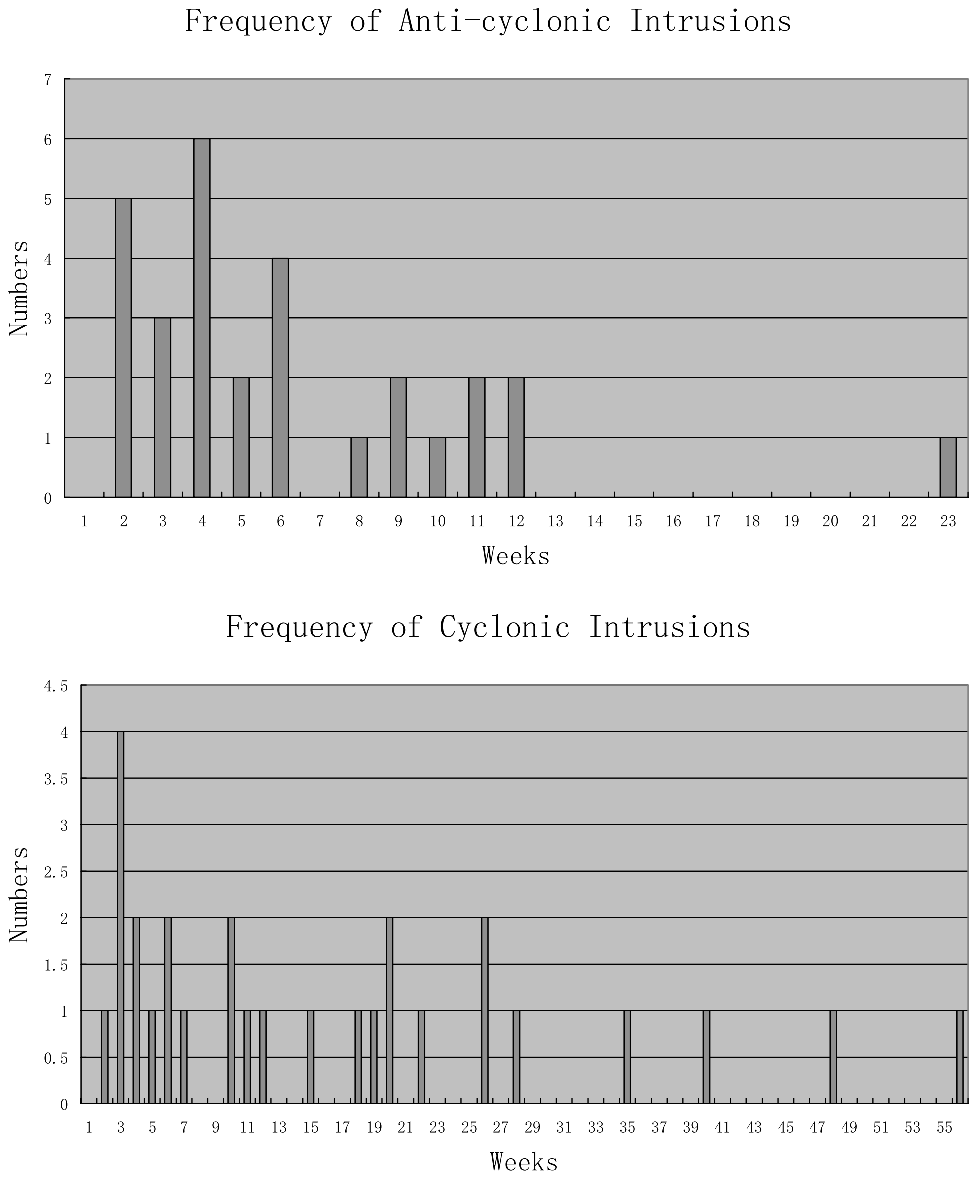


Figure 3. Frequency of anticyclonic and cyclonic intrusions of the Kuroshio in the Luzon Strait area based on Table 1. The x coordinates show the periods of the intrusions. The y coordinates show the number of events during the altimetry data period.

intrusion events of the Kuroshio in the Luzon Strait area identified from the altimeter data from late 1992 to early 2005. The absence periods in Table 1 are calculated between the events. The numbers of occurrence of the anticyclonic intrusions and the absence events in Table 1 are plotted against the periods in Figure 3. The anticyclonic intrusions sometimes result in the Kuroshio mainstream in alignment with the zonal direction in the Luzon Strait. This usually happens when the southern boundary of an anticyclonic eddy southwest of Taiwan expands past the 21° N and approaches the 20° N in the Luzon Strait (see section 3.2.1). The periods of zonal intrusions in winter in the fifth column of Table 1 record such eddy activities during December, January, and February of the altimetry period. When the anticyclonic eddy is small, the Kuroshio path in the Luzon Strait is close to the climatological path presented in the previous section.

[20] From Table 1, it is clear that the total period of anticyclonic intrusions of the Kuroshio, which includes the growth, mature, and decay states, covers less than one third of the total period of data. The total period of the zonal intrusions of the Kuroshio in December, January, and February of the 13 winters is only 466 days (the fifth column in Table 1), which is slightly over one third of the total 1170 days in winter. This indicates the dominance of the direct route of the Kuroshio intrusion over the anticyclonic path. Table 1 also shows that the winter anticyclonic intrusions after the year 2000 are less frequent than in the years before, suggesting lower-frequency variations of the northern South China Sea circulation.

[21] Each anticyclonic intrusion of the Kuroshio lasts for a few weeks typically (Figure 3). The exception is the event in the winter of 1995–1996, which lasts throughout the winter-spring seasons owing to a strong anticyclonic eddy

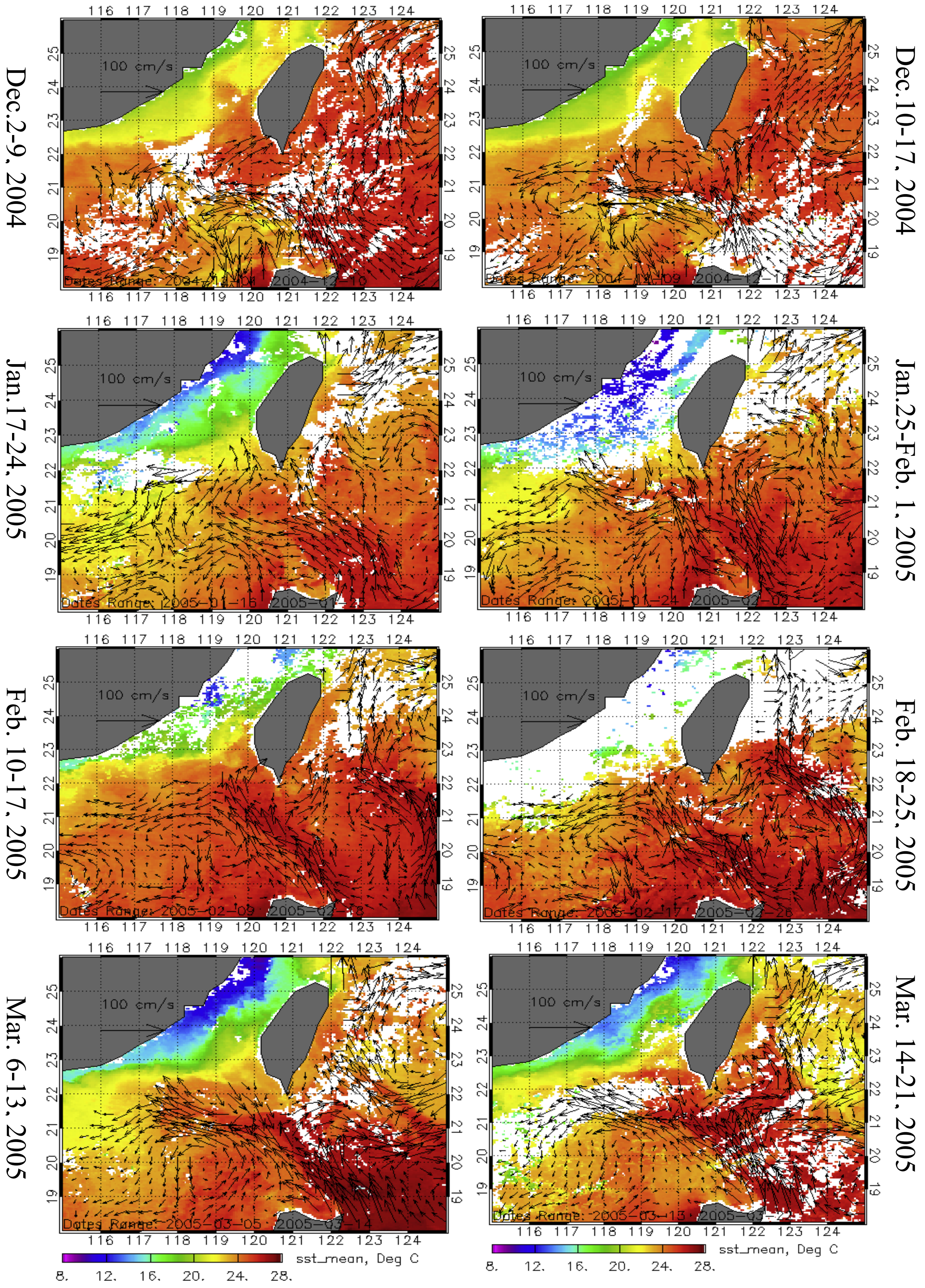


Figure 4. MODIS/Terra weekly (8-day) mean SST over the Luzon Strait area. The vectors are the geostrophic currents based on the absolute dynamics topography. White areas indicate bad retrievals.

dominating the circulation southwest of Taiwan (not shown). The total period without the anticyclonic intrusion in the Luzon Strait area, however, is much longer than that with the intrusion (Table 1). The absence periods are from a few weeks to longer than a year (Figure 3). The longest period of absence occurs from 2001 through 2003. The satellite weekly images suggest that an eddy is shed from a Kuroshio intrusion into the Luzon Strait in late November 2001, followed by a very weak (and controversial) anticyclonic intrusion event in late March 2002 lasting for only two weeks. Then, there is no anticyclonic intrusion of the Kuroshio in the northeastern South China Sea until May of 2003. This has put the longest period in records without the anticyclonic intrusion in the Luzon Strait area at more than 12 months (16 months if the weak event is not counted), which is comparable with the longest period of 17 months of no eddy shedding by the Gulf of Mexico Loop Current in 1998–1999 [*Sturges and Leben*, 2000].

[22] Table 1 also shows that the anticyclonic intrusions of the Kuroshio occur not only in winter but also in summer. However, the events in summer and in other seasons tend to be rare and brief compared with winter events. This suggests that the winter seasonal conditions favor the formation of the anticyclonic intrusions of the Kuroshio in the Luzon Strait area. Most of the anticyclonic intrusions of the Kuroshio shed an anticyclonic eddy, which migrates along the continental slope of the northern South China Sea to the western basin (Table 1). These eddies and other anticyclonic rings have northeastward currents over the shelf break associated with them and play a role of enhancing the against-wind South China Sea Warm Current over the shelf break in winter. During the year of 2003 and 2004, a number of anticyclonic intrusion events have been identified from the satellite observations. In particular, in the winter of 2004–2005, two consecutive anticyclonic intrusions of the Kuroshio have been observed by the satellite instruments, which have recorded the shortest period without an anticyclonic intrusion of the Kuroshio in the Luzon Strait area at merely 2 weeks or less.

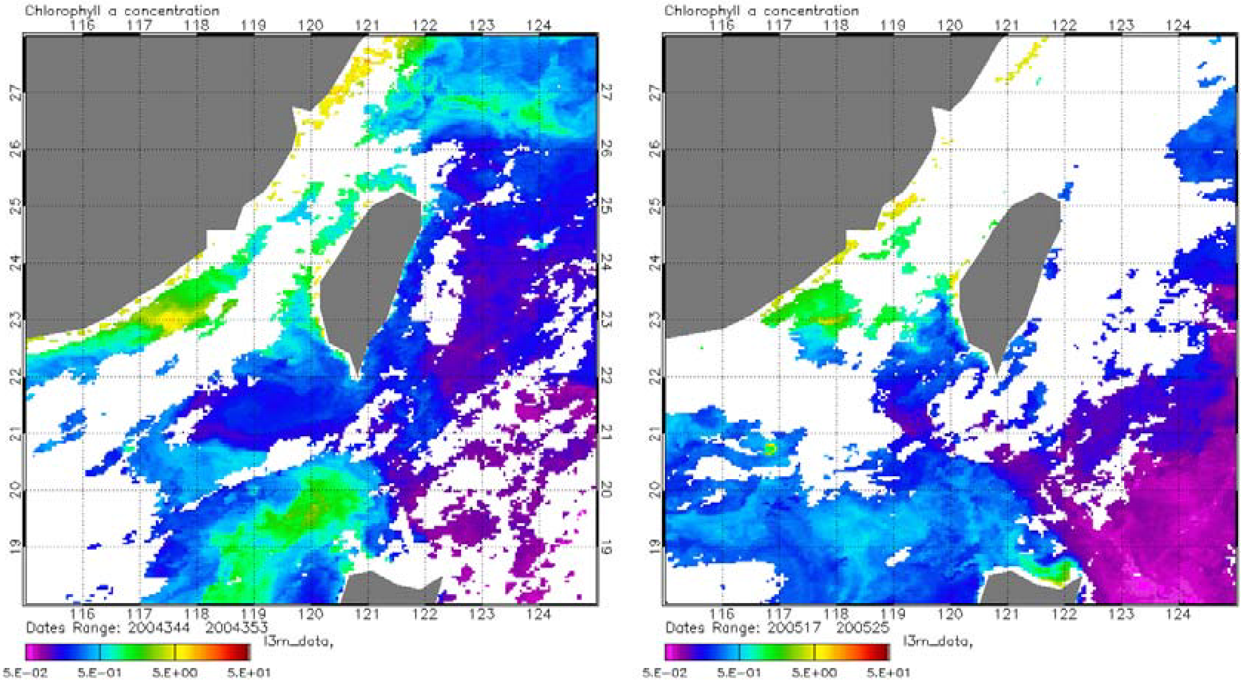
3.2.1. Winter of 2004–2005

[23] The images of the MODIS weekly SST and the geostrophic currents during December 2004 through March 2005 are shown in Figure 4. The ocean color images are shown in Figure 5. All through the winter of 2004–2005, the wind stress measured by the scatterometer is persistently from the northeast in a pattern very similar to that of the Hellerman-Rosenstein wind stress. Their images are omitted here. The geostrophic currents show circulation structures in good agreement with the SST and ocean color images. During 2–9 December 2004, warm water from the Kuroshio is accumulating off the southwest coast of Taiwan. The geostrophic currents suggest that an anticyclonic intrusion of the Kuroshio is developing in the Luzon Strait area. However, the mainstream of the Kuroshio stays at the climatological path during this period. In the next week or so, the anticyclonic intrusion is fully developed in the northeastern South China Sea, with the Kuroshio mainstream entering the South China Sea through the Luzon Strait zonally along roughly the 20° N–21° N latitude band. The western boundary of this intrusion has extended past the 118° E longitude as seen in the chlorophyll a concentration of MODIS/Aqua during 10–17 December 2004 (Figure 5), which has captured a good part of this intrusion event. Here, the Kuroshio front is seen more clearly in the ocean color images than in the SST and geostrophic current data. The low chlorophyll a concentration in the center of the anticyclonic circulation is characteristic of the Kuroshio water from the Philippine Sea and is clearly different from the surrounding South China Sea waters. A filament from the anticyclonic intrusion is seen entering the Taiwan Strait through the Penghu Channel. The upwelling center off the northwest coast of Luzon, which is revealed by a maximum chlorophyll a concentration, has previously been studied by *Shaw et al.* [1996], *Qu* [2000], and *Yang and Liu* [2003]. The northward extension of the South China Sea recirculating current along the west coast of Luzon can also be identified in the SST, ocean color, and geostrophic current data.

[24] The anticyclonic intrusion lasts through December of 2004. During 17–24 January 2005, the intrusion is seen to retreat, as indicated by the shrinking of the warm SST area compared to that in December 2004 (Figure 4) and by the geostrophic current (Figure 4) and the ocean color data (Figure 5). During 25 January through 1 February 2005, there is no longer a complete circular current in the northeastern South China Sea in the SST and Ocean color images, except that a remnant of the Kuroshio intrusion is still seen southwest of Taiwan (Figure 5). During 10–17 February 2005, the Kuroshio is seen to return to the winter climatological path (Figures 4 and 5). At this time, the first anticyclonic intrusion event is regarded as finished. The period of this event is about two and half months (Table 1).

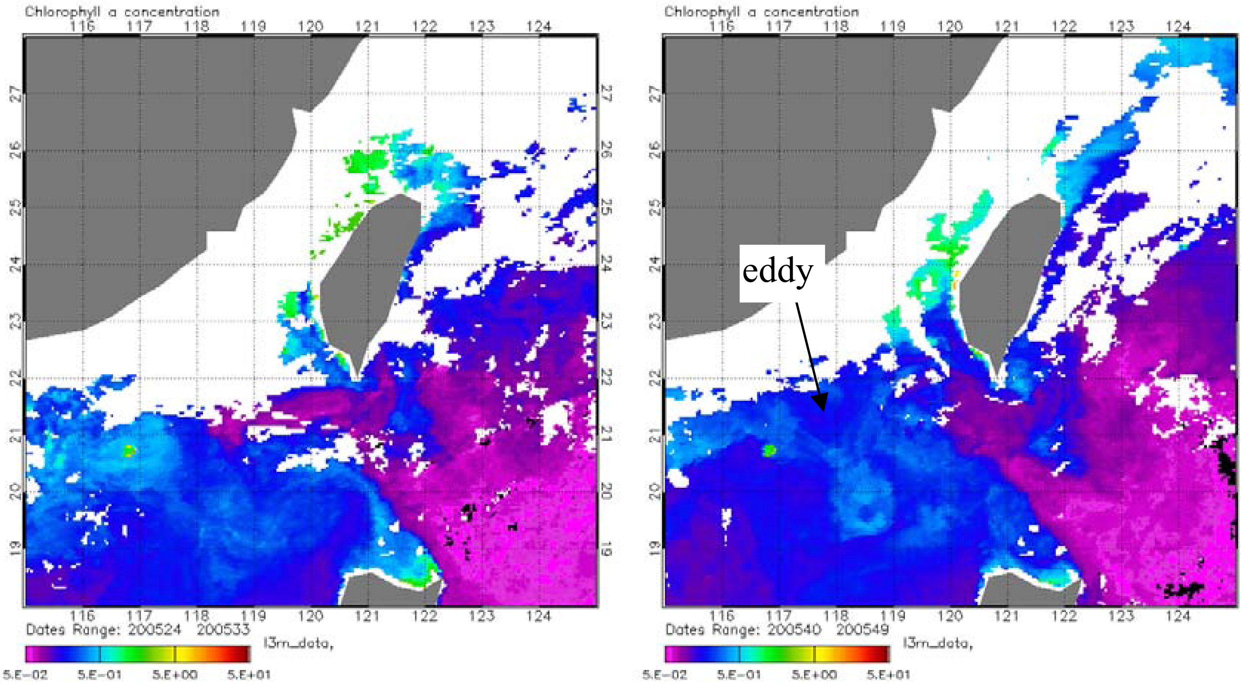
[25] The continuous evolution of sea level anomalies and the geostrophic currents during this anticyclonic intrusion of the Kuroshio is presented in Figure 6. The first anticyclonic intrusion event has evidently shed an eddy to the west of the South China Sea, as seen in the sea level anomalies and in the ocean color image at the end of the event (Figure 5). The low chlorophyll a concentration in a circular feature over the continental slope of the northern South China Sea centered at (117.8° E, 21.5° N) east of Dongsha Island suggests that the eddy originates from the Kuroshio, which is in agreement with the sea level anomalies (Figure 6). In the next few weeks, the eddy moves westward and is dissipated or absorbed by the surrounding flow and does not survive westward beyond 116° E (not shown). However, in other anticyclonic intrusion events of the Kuroshio we have inspected, sometimes the shed eddy gets intensified as they leave the Luzon Strait and can reach the far western basin along the continental slope of the south China shelf. The eddy induces northeastward current over the shelf break, contributing to the against-wind flow of the South China Sea Warm Current in winter. The life span of the detached eddy seems to depend more on the interactions with the surrounding flows than on its initial strength shed from the anticyclonic intrusion. These complete cycles of eddy shedding and propagation in the northeastern South China Sea and the detailed structures of the circulation associated with them are disclosed for the first time thanks to the satellite data products.

[26] The second anticyclonic intrusion event begins in 18–25 February 2005, almost immediately after the first event is over. A small eddy is clearly visible southwest of Taiwan in the SST and geostrophic current data in Figure 4. This eddy expands westward past the 118° E longitude in



Dec. 10-17, 2004

Jan. 17-24, 2005



Jan. 25-Feb. 1, 2005

Feb. 10-17, 2005

Figure 5. MODIS/Aqua chlorophyll a concentration over the Luzon Strait area. White areas indicate bad retrieval. Unit is mg m^{-3}.

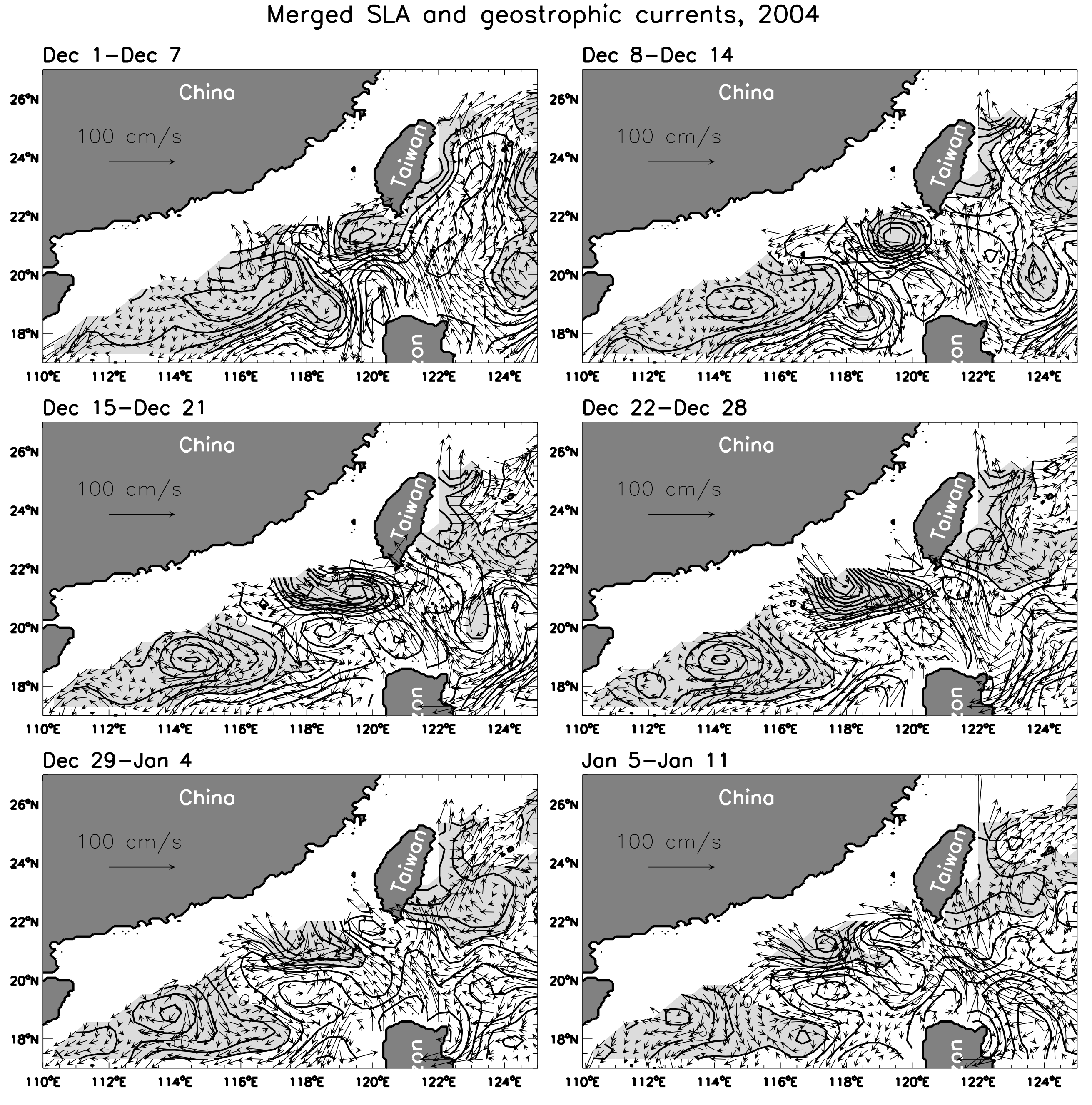


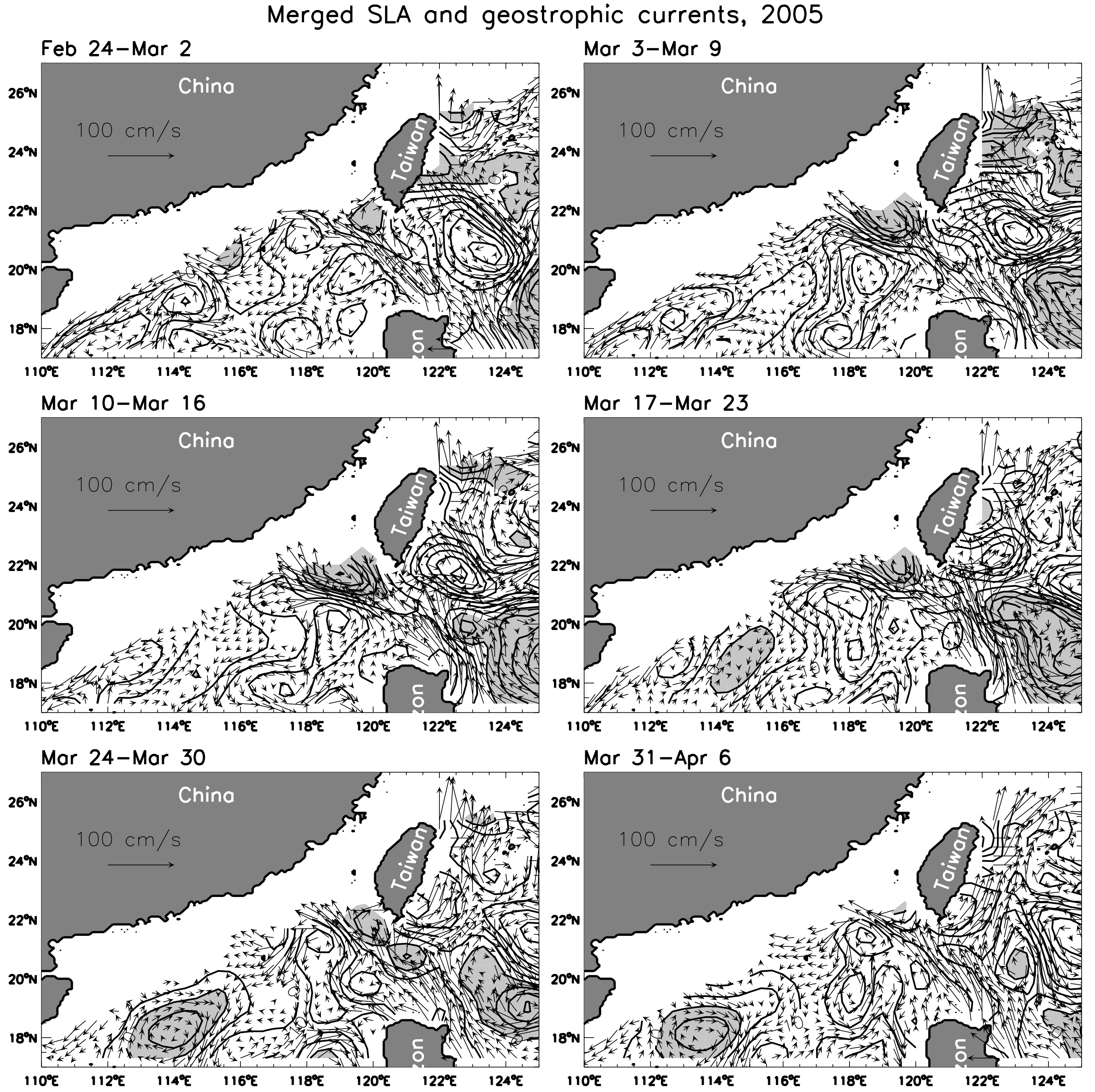
Figure 6. Same as Figure 2, except for December 2004 through January 2005.

early-middle March, after which the Kuroshio is seen to return to its winter climatological path within a week or two. The period of the second anticyclonic intrusion is about one and half month, slightly shorter than the first event. The time elapse between the two anticyclonic intrusions is about two weeks (Table 1), representing the shortest period of absence of anticyclonic intrusions in the Luzon Strait area in records.

[27] During the second anticyclonic intrusion event, a strong cyclonic eddy is seen migrating northward on the eastern side of the Luzon Strait (Figure 7). This eddy blocks the Kuroshio transport east of Taiwan and produces the offshore branch of the Kuroshio in the Philippine Sea. It is hypothesized that this eddy forces the Kuroshio intrusion into the South China Sea by blocking the transport east of Taiwan. Further study is needed to verify this hypothesis. The termination of the second anticyclonic intrusion also generates an anticyclonic eddy east of Dongsha Island as seen in the sea level anomalies (Figure 7). This eddy is quickly dissipated locally or absorbed by the background circulation and does not survive westward beyond the Dongsha Island. An EOF analysis of the structures of the cyclonic and anticyclonic intrusions of the Kuroshio in the northeastern South China Sea is conducted by *Caruso et al.* [2006].

3.2.2. Summer Loop Current of the Kuroshio

[28] The Kuroshio loop current is traditionally defined as an anticyclonic circulation feature enclosed by both inflow


Merged SLA and geostrophic currents, 2005

Feb 24–Mar 2

Mar 3–Mar 9

Mar 10–Mar 16

Mar 17–Mar 23

Mar 24–Mar 30

Mar 31–Apr 6

Figure 7. Same as Figure 2, except for February through April of 2005.

and outflow of the Kuroshio through the Luzon Strait [*Li and Wu*, 1989]. The difference between a Kuroshio loop current and an anticyclonic eddy event is the existence of the inflow-outflow currents in the Luzon Strait for the loop current. According to this criterion, neither of the two anticyclonic intrusion events in the winter of 2004–2005 qualifies for a Kuroshio loop current, because the outflow in the northern Luzon Strait is prominently missing. The eddy events in the winter of 2004–2005 also suggest that the identification of the Kuroshio loop currents in the Luzon Strait area without the total geostrophic current data is somewhat difficult, because both the loop currents and the anticyclonic eddies feature similar SST, ocean color, and sea level anomalies in the northeastern South China Sea. The Kuroshio loop current can be identified clearly from the total geostrophic currents, which are available during 2002–2005. In this section, we report a few events of summer loop current in the Luzon Strait area based on the total geostrophic current data. Because of the scarcity of the summer loop currents in the existing observations, we present all four events observed in the summers of 2003 and 2004 for future references.

[29] Figures 8, 9, and 10 show the sea level anomalies and the total geostrophic currents in the summers of 2003 and 2004 associated with the Kuroshio loop currents. The inflow-outflow currents of the Kuroshio in the Luzon Strait associated with the loop currents are clearly present and distinctly different from the anticyclonic eddy events in the winter of 2004–2005. The loop currents are evidently associated with migration of anticyclonic eddies from north

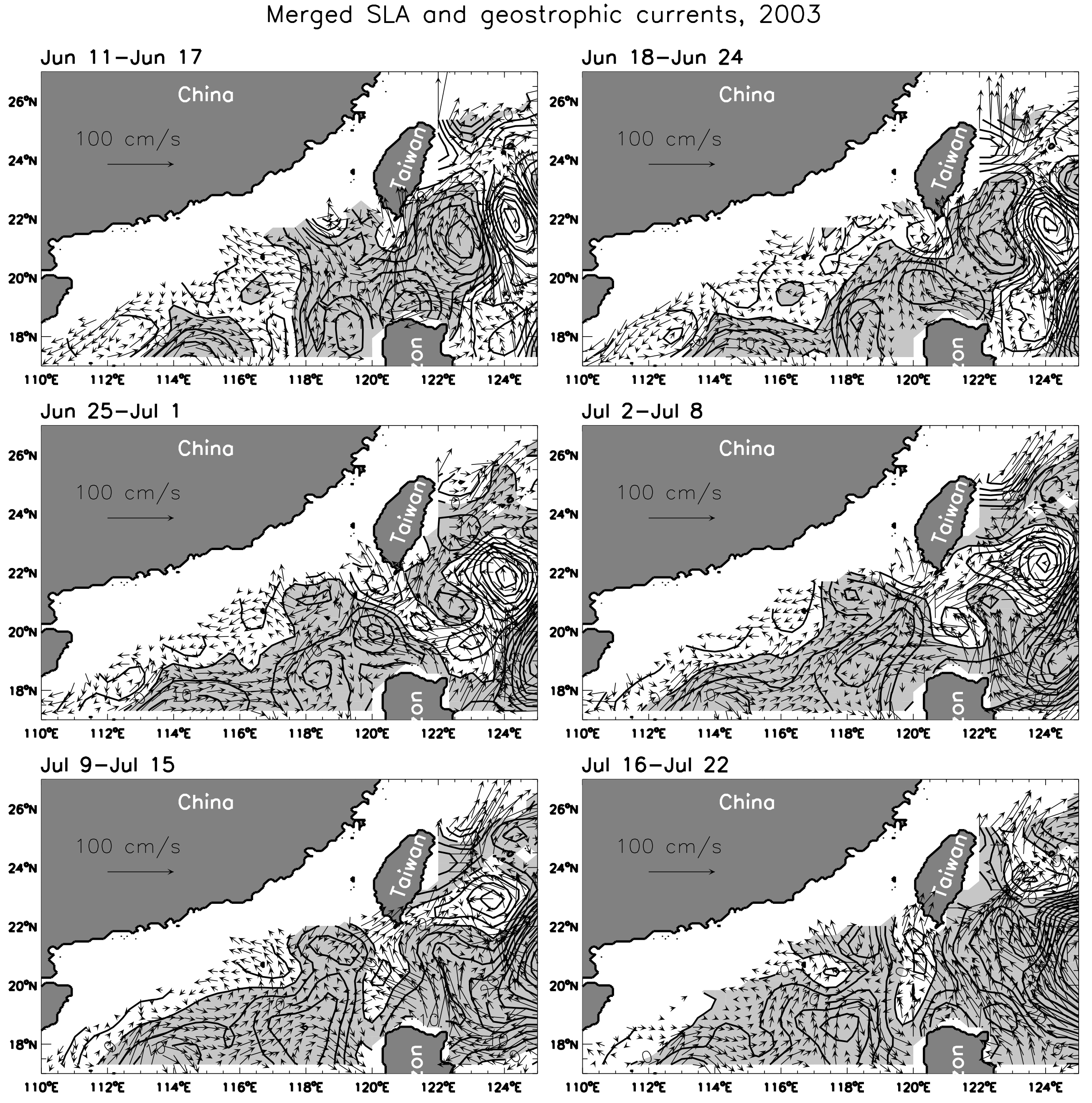


Figure 8. Same as Figure 2, except for June through July of 2003.

of Luzon (southern Luzon Strait) in a northwest direction toward the continental slope of the northern South China Sea, whereby they move further westward or are dissipated/absorbed. The association of the Kuroshio loop currents with the activities of the mesoscale eddies suggests that the Kuroshio loop current in the Luzon Strait is an nondeterministic process as suggested by *Metzger and Hurlburt* [2001], at least in summer.

[30] In comparison with the summer Kuroshio loop currents, the presence of the Kuroshio loop currents in winter during the period of 2002–2004 is rare. The only credible Kuroshio loop current in winter during this period occurs during 21 January through 18 February 2004 (figure not shown). Here, the total geostrophic currents seem to suggest more episodes of the Kuroshio loop currents in summer than in winter, at least during the period of 2002–2004. In view of the fact that the Kuroshio flows primarily northwestward into the Luzon Strait from northeast of Luzon, we speculate that the surface Ekman transport forced by the northeasterly monsoon plays the role of suppressing the Kuroshio outflow through the northern Luzon Strait in winter. In comparison, the summer southwesterly monsoon facilitates the outflow through the northern Luzon Strait.

[31] An intrusion of the Kuroshio into the Luzon Strait is induced by passage of a strong cyclonic eddy on the Philippine Sea side of the Luzon Strait during August–September 2004, as shown in Figure 11. This intrusion event can be compared with the second anticyclonic intru-

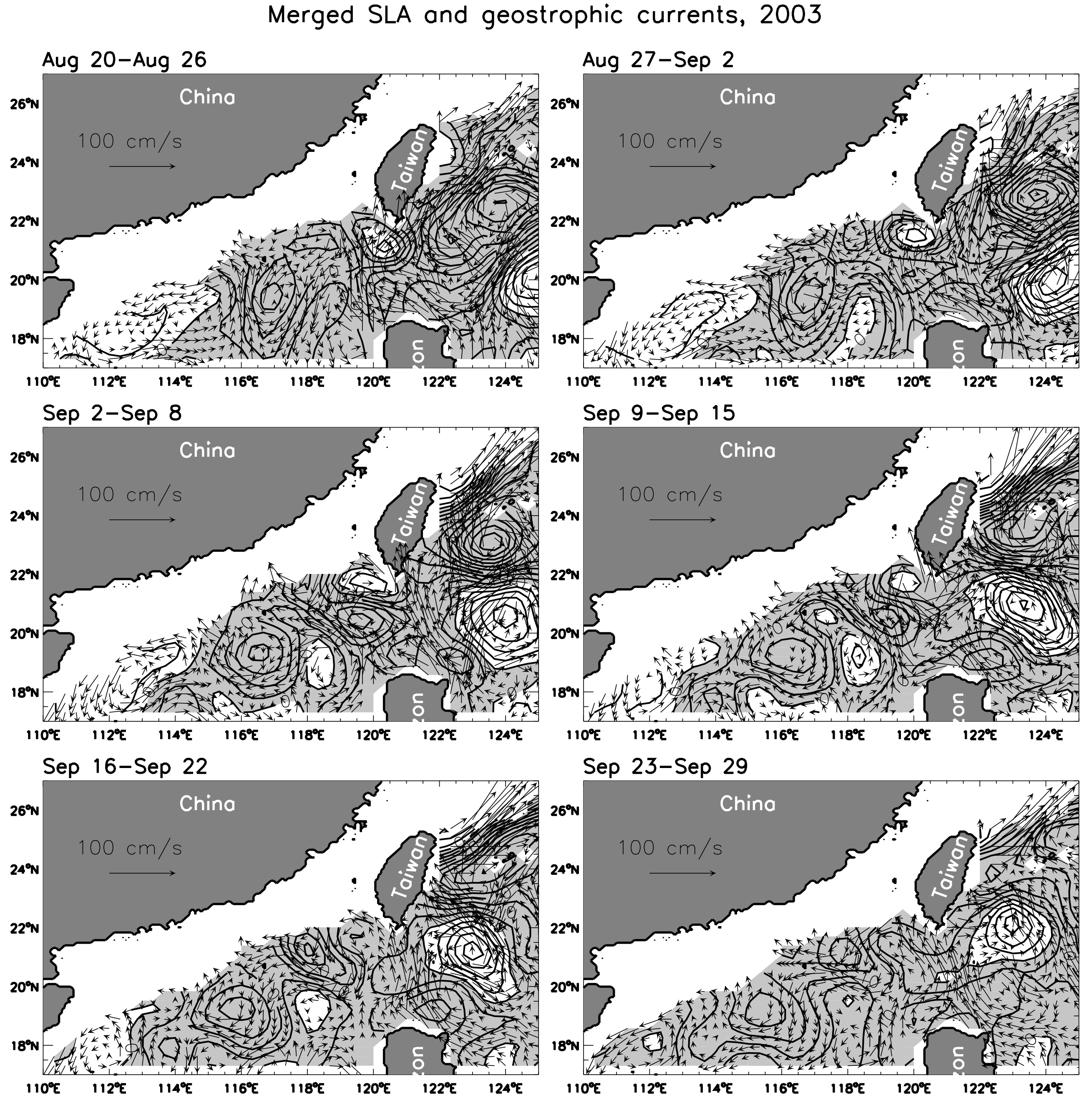


Figure 9. Same as Figure 2, except for August through September of 2003.

sion event of the Kuroshio in the winter of 2004–2005 presented above. The eddy event produces offshore sway of the main Kuroshio stream in the Philippine Sea and reduces the speeds and transport of the Kuroshio east of Taiwan, facilitating the formation of an intrusion either by reducing the advection of the potential vorticity in the Luzon Strait [*Sheremet*, 2001] or by blocking the Kuroshio transport east of Taiwan (19–25 August in Figure 11). The winter intrusions are stronger and last longer than the summer events probably because the winter northeasterly winds generate surface Ekman transport through the entire Luzon Strait into the South China Sea, facilitating the Kuroshio intrusion [*Wang and Chern*, 1987b]. However, the comparison of the summer and winter intrusion events suggests that the primary dynamics of the intrusion is not due to the wind.

[32] The altimeter data of sea level anomalies and geostrophic currents indicate clearly that the Kuroshio water can reach the western South China Sea through eddy propagation in summer. Historical hydrographic data indeed suggest the presence of Kuroshio water over the continental slope west of Dongsha Island in summer [*Qiu et al.*, 1984; *Qu et al.*, 2000]. In the past, the source of this Kuroshio water was a puzzle because people believed that the Kuroshio did not intrude into the South China Sea in summer through the Luzon Strait [*Guan*, 1990; *Shaw*, 1991]. Here, the altimeter data suggest that the Kuroshio can intrude into the South China Sea in all four seasons and

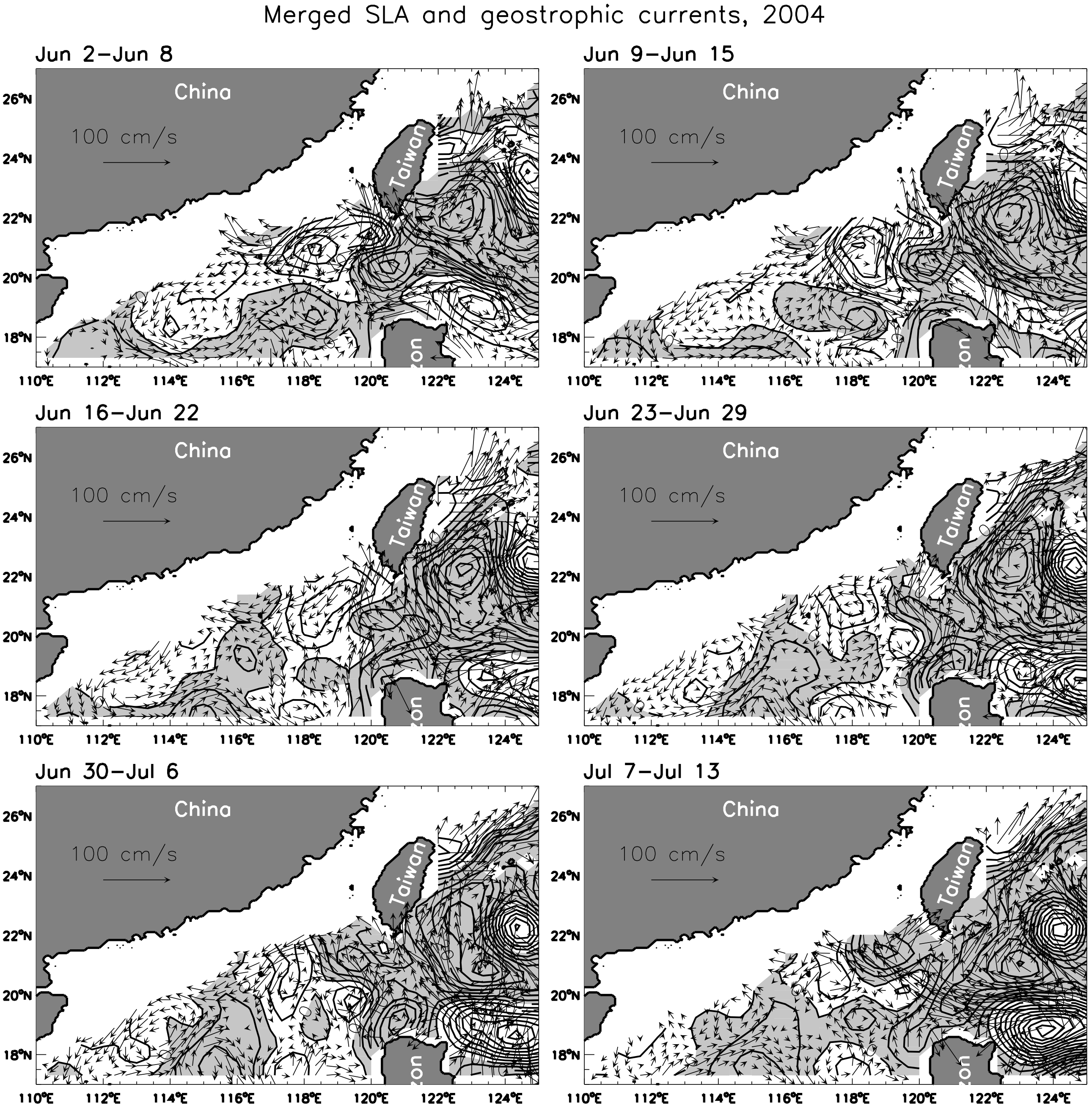


Figure 10. Same as Figure 2, except for June through July of 2004.

its water can reach the western South China Sea either through a mean branch current or through eddy propagation (D. Yuan et al., Anti-cyclonic eddies northwest of Luzon during summer-fall observed by satellite altimetry, submitted to *Geophysical Research Letters*, 2006).

4. Summary

[33] The climatological and transient paths of the Kuroshio in the northeastern South China Sea are studied using satellite SST, ocean color, and altimeter data. The images of the winter SST and ocean color climatologies suggest that the dominant path of the Kuroshio in the Luzon Strait in winter is a direct intrusion from northeast of Luzon to southwest of Taiwan without a loop current. Consistent with historical hydrographic observations, the SST and ocean color climatologies suggest westward expansion of the Kuroshio water along the continental slope of the northern South China Sea from the Luzon Strait in winter. The mean surface path of the Kuroshio in the Luzon Strait area in winter shows significant difference from existing model simulations of the Kuroshio paths in the northeastern South China Sea. Further modeling studies to reduce the difference is necessary for better understanding of mass, momentum, and heat exchange through the Luzon Strait. An against-wind flow along the west coast of Luzon is suggested by the SST and ocean color climatologies and

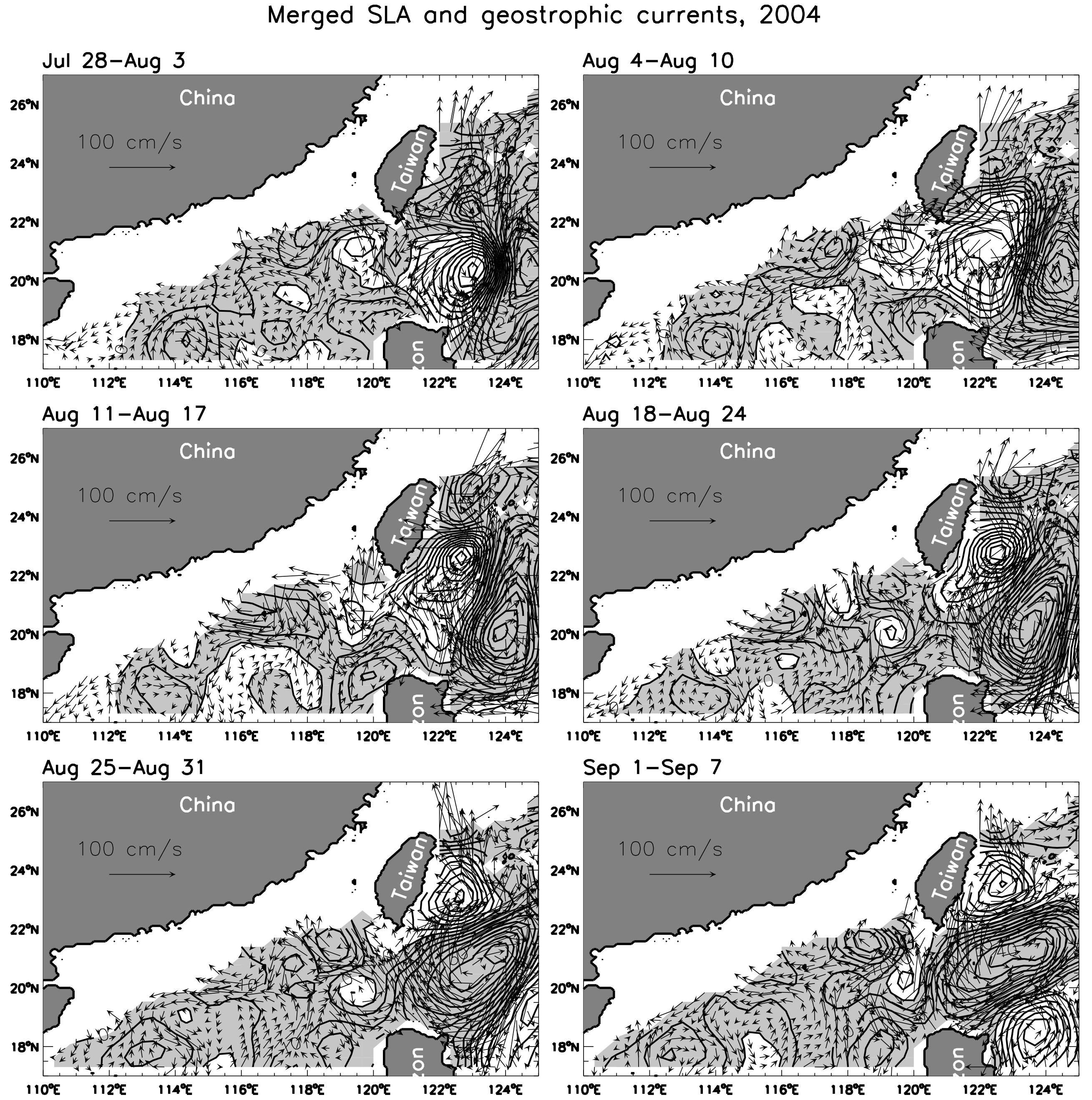


Figure 11. Same as Figure 2, except for July through September of 2004. The panels show the evolution of a loop current in the Luzon Strait associated with a passage of a cyclonic eddy on the Philippine Sea side of the Luzon Strait.

confirmed by the geostrophic currents of the altimeter data, the dynamics of which will be studied in a separate paper.

[34] The satellite observations suggest that the anticyclonic intrusion of the Kuroshio is a transient rather than a persistent phenomenon of the Luzon Strait circulation. The total period of the anticyclonic intrusion of the Kuroshio covers less than 30% of the total data period. The observations show that the anticyclonic intrusion of the Kuroshio can occur during any season of the year, although winter is the most favorable season for the anticyclonic intrusion. The zonal intrusions of the Kuroshio into the Luzon Strait in winter, however, occur during only a little over one third of the wintertime on average. Each anticyclonic intrusion event lasts for a few weeks in general. The longest anticyclonic intrusion event, however, lasts for over 5 months in the winter of 1995–1996. The periods without the anticyclonic intrusion of the Kuroshio in the Luzon Strait area range from 2 weeks to more than 16 months. The shortest absence period occurs in the winter of 2004–2005, when two consecutive anticyclonic intrusions of the Kuroshio in the northeastern South China Sea are observed. The longest absence period takes place between November 2001 and May 2003. A few events of Kuroshio loop currents are identified from the altimeter data, with more episodes in

summer than in winter during 2002–2005. This seasonality will be examined further as longer time series of the total geostrophic current data become available.

[35] Westward movement of mesoscale eddies from the Luzon Strait area to the far western basin of the South China Sea is identified from the altimeter data. Further study on these eddies is important for the mass, moment, heat, and salt transports within the South China Sea and for the dynamics of the South China Sea Warm Current over the shelf break of the northern South China Sea in winter.

[36] **Acknowledgments.** The MODIS SST data are acquired from the Goddard Distributed Active Archive Center (DAAC) of NASA. The AVHRR SST and QuikScat SeaWinds scatterometer data are obtained from the PODAAC of the Jet Propulsion Laboratory. The MODIS/Aqua ocean color data and the SeaWiFS data are obtained from the SeaWiFS project of NASA Goddard Space Flight Center. The Hellerman-Rosenstein wind stress data are downloaded from NCAR database. The altimeter data are obtained from the Aviso Web site at http://www.jason.oceanobs.com/html/donnees/welcome_uk.html. D. Yuan is supported by the ''100-Expert Program'' of the Chinese Academy of Sciences, the National Basic Research of China (''973 program'') project ''Ocean-Atmosphere Interaction over the Joining Area of Asia and Indian-Pacific Ocean (AIPO) and Its Impact on the Short-Term Climate Variation in China'' (2006CB403600), and NSFC project 40676020. W. Han is supported by NSF OCE-0136836 and NSF OCE-0452917. D. Hu is supported by National Natural Science Foundation of China (NSFC) project D06-40552002 and by Qingdao Municipal Government project 02-KJYSH-03.

References

Caruso, M., G. G. Gawarkiewicz, and R. Beardsley (2006), Interannual variability of the Kuroshio Current intrusion in the South China Sea, *J. Oceanogr.*, *62*, 559–575.

Centurioni, L. R., and P. P. Niiler (2004), Observations of inflow of Philippine Sea surface water into the South China Sea through the Luzon Strait, *J. Phys. Oceanogr.*, *34*, 113–121.

Chan, K. M. (1970), The seasonal variation of hydrological properties in the northern China Sea, in The Kuroshio A symposium on the Japan Current, pp. 143–162, East-West Cent. Press, Honolulu.

Chu, P. C., N. L. Edmons, and C. Fan (1999), Dynamical mechanisms for the seasonal circulation and thermohaline variabilities, *J. Phys. Oceanogr.*, *29*, 2971–2989.

Ducet, N., P.-Y. Le Traon, and G. Reverdin (2000), Global high resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1/2, *J. Geophys. Res.*, *105*, 19,477–19,498.

Fang, G.-H., W.-D. Fang, Y. Fang, and K. Wang (1998), A survey of studies on the South China Sea upper ocean circulation, *Acta Oceanogr. Taiwan.*, *37*, 1–16.

Farris, A., and M. Wimbush (1996), Wind-induced Kuroshio intrusion into the South China Sea, *J. Oceanogr.*, *52*, 771–784.

Guan, B. (1990), Features of the summer circulation in the Bashi Strait and adjacent area (in Chinese with English abstract), *J. Oceanogr. Huanghai Baihai Seas*, *8*(4), 1–11.

Guo, Z. X., T. H. Yang, and D. Z. Qiu (1985), Wintertime South China Sea Warm Current and the southwestward current on its right (in Chinese with English abstract), *Trop. Oceanol.*, *4*(1), 1–9.

Hellerman, S., and M. Rosenstein (1983), Normal monthly wind stress over the world ocean with error estimates, *J. Phys. Oceanogr.*, *13*, 1093–1104.

Ho, C.-R., Q. Zheng, N.-J. Kuo, C.-H. Tsa, and N. E. Huang (2004), Observation of the Kuroshio intrusion region in the South China Sea from AVHRR data, *Int. J. Remote Sens.*, *25*(21), 4583–4591.

Hsueh, Y., and L. Zhong (2004), A pressure-driven South China Sea Warm Current, *J. Geophys. Res.*, *109*, C09014, doi:10.1029/2004JC002374.

Hurlburt, H. E., and J. D. Thompson (1980), A numerical study of loop current intrusion and eddy shedding, *J. Phys. Oceanogr.*, *10*, 1611–1651.

Jia, Y., and Q. Liu (2004), Eddy shedding from the Kuroshio bend at Luzon Strait, *J. Oceanogr.*, *60*, 1063–1069.

Li, L., and B. Y. Wu (1989), A Kuroshio loop current in the South China Sea? On circulation of the northeastern South China Sea (in Chinese), *J. Oceanogr. Taiwan Strait*, *8*(1), 89–95.

Li, L., W. D. Nowlin, and J. Su (1998), Anticyclonic rings from the Kuroshio in the South China Sea, *Deep Sea Res., Part I*, *45*, 1469–1482.

Liang, W.-D., T. Y. Tang, Y. J. Yang, M. T. Ko, and W.-S. Chuang (2003), Upper-ocean currents around Taiwan, *Deep Sea Res., Part II*, *50*, 1085–1105.

Metzger, E. J., and H. E. Hurlburt (1996), Coupled dynamics of South China Sea, the Sulu Sea, and the Pacific Ocean, *J. Geophys. Res.*, *111*, 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, *J. Phys. Oceanogr.*, *31*, 1712–1732.

Nitani, H. (1972), Beginning of the Kuroshio, in *Kuroshio: Physical Aspects of the Japan Current*, edited by H. Stommel and K. Yashida, pp. 129–163, Univ. of Wash. Press, Seattle.

Pichevin, T., and D. Nof (1997), The momentum imbalance paradox, *Tellus, Ser. A*, *49*, 298–319.

Qiu, D., T. Yang, and Z. Guo (1984), A westward current in the northeastern part of the South China Sea in summer (in Chinese with English abstract), *Trop. Oceanol.*, *3*(4), 65–73.

Qu, T. (2000), Upper-layer circulation in the South China Sea, *J. Phys. Oceanogr.*, *30*, 1450–1460.

Qu, T., H. Mitsudera, and T. Yamagata (2000), Intrusion of the North Pacific waters into the South China Sea, *J. Geophys. Res.*, *105*, 6415–6424.

Rio, M.-H., and F. Hernandez (2004), A mean dynamic topography computed over the world ocean from altimetry, in situ measurements, and a geoid model, *J. Geophys. Res.*, *109*, C12032, doi:10.1029/2003JC002226.

Shaw, P. T. (1991), The seasonal variation of the intrusion of the Philippine Sea water into the South China Sea, *J. Geophys. Res.*, *96*, 821–827.

Shaw, P. T., S.-Y. Chao, K.-K. Liu, S.-C. Pai, and C.-T. Liu (1996), Winter upwelling off Luzon in the northeastern South China Sea, *J. Geophys. Res.*, *101*, 16,435–16,448.

Sheremet, V. (2001), Hysteresis of a western boundary current leap across a gap, *J. Phys. Oceanogr.*, *31*, 1247–1259.

Sturges, W., and R. Leben (1992), Frequency of ring separation from the Loop Current in the Gulf of Mexico: A revised estimate, *J. Phys. Oceanogr.*, *30*, 1814–1819.

Sturges, W., and R. Leben (2000), Frequency of ring separations from the loop current in the Gulf of Mexico: A revised estimate, *J. Phys. Oceanogr.*, *30*, 1814–1819.

Sturges, W., J. C. Evans, S. Welsh, and W. Holland (1993), Separation of warm-core rings in the Gulf of Mexico, *J. Phys. Oceanogr.*, *23*, 250–268.

Wang, J., and C. S. Chern (1987a), The warm-core eddy in the northern South China Sea, I. Preliminary observations on the warm-core eddy, *Acta Oceanogr. Taiwan.*, *18*, 92–103.

Wang, J., and C. S. Chern (1987b), The warm-core eddy in the northern South China Sea, II. A simple mechanism for the establishment and development of the warm-core eddy, *Acta Oceanogr. Taiwan.*, *18*, 104–113.

Wang, D., Y. Liu, Y. Qi, and P. Shi (2001), Seasonal variability of thermal fronts in the northern South China Sea from satellite data, *Geophys. Res. Lett.*, *28*(20), 3963–3966.

Xu, J.-P., and J.-L. Su (1997), Hydrological analysis on the intrusion of the Kuroshio into the South China Sea: Observational results during the cruise from August to September in 1994 (in Chinese), *Trop. Oceanol.*, *16*, 1–23.

Xue, H., F. Chai, N. Pettigrew, D. Xu, M. Shi, and J. Xu (2004), Kuroshio intrusion and the circulation in the South China Sea, *J. Geophys. Res.*, *109*, C02017, doi:10.1029/2002JC001724.

Yang, H., and Q. Liu (2003), Forced Rossby wave in the northern South China Sea, *Deep Sea Res., Part I*, *50*, 917–926.

Yang, H., Q. Liu, Z. Liu, D. Wang, and X. Liu (2002), A general circulation model study of the dynamics of the upper ocean circulation of the South China Sea, *J. Geophys. Res.*, *107*(C7), 3085, doi:10.1029/2001JC001084.

Yuan, D. (2002), A numerical study of barotropicly forced intrusion in Desoto Canyon, *J. Geophys. Res.*, *107*(C2), 3010, doi:10.1029/2001JC000793.

W. Han, Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, CO 80309, USA.

D. Hu and D. Yuan, Institute of Oceanology, Chinese Academy of Sciences, 7 Nanhai Road, Qingdao 266071, China. (d_yuan2000@yahoo.com)