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Continental Slope Flow Northeast of Taiwan

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ABSTRACT

Hydrographic observations and current measurements with a Shipboard Acoustic Doppler Current Profiler over the continental shelf–slope junction northeast of Taiwan during 10–17 August 1994 allow the construction of the mesoscale flow pattern generated by the collision of the Kuroshio and a stretch of the continental shelf that has turned to run nearly east–west. The pattern is made up of a deflected Kuroshio mainstream to the east, an intrusion of Kuroshio water onto the continental shelf region, a counterclockwise circulation over Mien-Hwa Canyon (MHC) immediately northeast of Taiwan, a deep southwestward countercurrent along the northern wall of MHC, and a seaward outflow of continental shelf water around the northern coast of Taiwan. The hydrography features a cold dome over the west side of MHC that consisted of subsurface Kuroshio water. A temperature–salinity plot of all the station data shows the incorporation in the neighborhood of Taiwan of continental shelf water into the Kuroshio.

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1. Introduction

The sharply curved continental shelf–slope junction northeast of Taiwan has been shown to cause disruptions in the Kuroshio that are fundamental to the exchange between the continental shelf water of the East China Sea and the

Kuroshio (Chern et al. 1990; Hsueh et al. 1992; Hsueh et al. 1993; Hsueh et al. 1997). The Kuroshio originates from the North Equatorial Current and flows northward along the eastern coasts of Luzon and Taiwan. Upon reaching the northern tip of Taiwan, the Kuroshio collides with the continental shelf break, which is here trending in a nearly east–west orientation and generates a complex mesoscale flow pattern. A major consequence of this collision is that the Kuroshio proper is deflected to flow along the shelf break to the east and then north (Nitani 1972). A part of the Kuroshio water, however, intrudes over the continental shelf to form, perhaps, the branch current found in long-term geomagnetic electrokinetograph (GEK) measurements and in sea surface temperature (SST) data taken by the *NOAA-8* satellite (Qiu and Imasato 1990). Current meter observations on the inshore side of the Kuroshio along the continental shelf break northeast of Taiwan indicate the existence of a southwestward countercurrent (Chuang and Wu 1991; Tang and Yang 1993). There is evidence that the countercurrent, which appears to exist year round at depths greater than about 150 m, is yet another flow feature brought about by the blocking of the Kuroshio by the continental shelf break (Hsueh et al. 1993). Inshore of the countercurrent, a cold water mass is often found over the outer continental shelf that has hydrographic properties similar to the Kuroshio subsurface water at about 300-m depth (Uda and Kishi 1974; Fan 1980; Liu et al. 1992; Chern and Wang 1989). A plausible explanation of this continental shelf presence of the Kuroshio subsurface water appears to be the uplifting of the countercurrent water as the southwestward flow of the countercurrent encounters the north–south trending continental shelf break just north of Taiwan (Hsueh et al. 1997). The uplifted countercurrent water is then carried by the often-present northeastward surface current onto the outer continental shelf where its presence has been observed in several recent hydrographic surveys (Hsueh et al. 1992; Hsueh et al. 1993).

In addition to having the spatial structure alluded to above, the flow pattern generated by the collision of the Kuroshio with the continental shelf northeast of Taiwan also changes in time. Long-term GEK measurements reveal a seasonal shift in the position of the Kuroshio axis northeast of Taiwan (Sun 1987). It appears to migrate shoreward in fall and winter and seaward in spring and summer. This seasonal migration is corroborated with current meter observations that show an on-shelf intrusion of the Kuroshio about one month into the winter monsoon season, giving rise to the appearance of a shoreward displacement of the Kuroshio (Tang and Yang 1993). The wintertime intrusion has also been found in hydrographic observations (Hsueh et al. 1992). Accompanying the intrusion is the disappearance of the countercurrent in the upper ocean (<150 m). As the northeasterly wind collapses in the spring, the on-shelf intrusion of Kuroshio ceases (Chuang et al. 1993). At greater depths, the southwestward countercurrent persists year round (Tang and Yang 1993). There undoubtedly are variabilities on shorter timescales associated with changes in the Kuroshio that are probably less pronounced for detection and more difficult to sample (see later in section 3). At any rate, the on-shelf intrusion of the Kuroshio, countercurrent, and the uplifting of Kuroshio subsurface water are all flow features important in bringing about a vigorous mixing between the continental shelf water and the Kuroshio (Hsueh et al. 1997).

The purpose of the paper is to present and discuss observations from a recent field experiment to demonstrate that all the aforementioned flow features, previously observed individually, perhaps arise from a single event: the collision of the Kuroshio with the continental shelf northeast of Taiwan. Despite the importance of these flow features, up until now, there has been no systematic measurement of currents that could adequately map in totality the flow pattern northeast of Taiwan. Apart from the variability in time, a major difficulty has been the small spatial scales of the flow at any given moment, making it difficult to capture the pattern with a limited number of moored current-meter arrays. Given the apparently large timescales involved, a viable way of mapping the flow within a given season appears the use of a shipboard acoustic Doppler current profiler (SADCP).

Based on the above considerations, an underway current mapping experiment with a SADCP was conducted 10–17 August 1994 in the area immediately northeast of Taiwan. A phase averaging of measurements obtained with a time separation of 68.31 h (5.5 times the period of the M_2 tide) is used to eliminate high-frequency noises that are dominated by the M_2 tide. The efficacy of the phase-averaging method is evaluated with the help of current measurements at more than 10 moored arrays scattered in time over a period of 5 yr since the inception of the Kuroshio Edge Exchanges Process (KEEP) study by the Republic of China.

The paper is organized as follows. The field observation and error analysis of the phase-averaging method are described in section 2. A discussion and the conclusions are found in section 3.

2. Observations

a. Experiment and errors

Figure 1 shows cruise tracks, indicated by solid line segments, and hydrographic stations, marked by the alphabetized squares. The bathymetry is shown by depth contours (200–1000 m at intervals of 200 m) drawn in thin curves. Two canyon formations mark the continental shelf–slope junction northeast of Taiwan: Mien-Hwa Canyon (MHC) (just northeast of the line from station E to station H) to the south and the North Mien-Hwa Canyon (NMHC) (just southwest of the line from station M to station P) to the north. Along the cruise track, currents are measured under way using a 153-kHz SADCP mounted on the hull of the R/V *Ocean Researcher I.* Temperature and salinity as functions of depth are obtained from lowering at each hydrographic station a Seabird Conductivity–Temperature–Depth instrument. There are a total of 26 hydrographic sampling stations, dotting the cruise tracks at intervals of 14 n mi. Current measurements are recorded every minute in depth bins of 8 m from a depth of 16 m to 304 m. The ship velocity, obtained from using the Global Positioning System, is subtracted from the SADCP measurements to yield earth-referenced current velocities. There are two major sources of error for this measurement procedure. One is due to the misalignment of the SADCP unit and the other is due to random errors in the GPS fixes. The first source can be avoided by properly calibrating the SADCP unit (Joyce 1989; Tang and Ma 1995). The effect of the second one can be minimized by averaging. The resulting root-mean-square error in current velocity in the present study is ±3.5 cm s^{-1}.

In addition, the tracks are traced and hydrographic stations occupied twice at a separation in time of 68.31 h, 5.5 times the period of the M_2 tide. (In the interest of maintaining this time separation, SADCP measurements in the neighborhood of station A and hydrographic casts at stations A, P, U, X, and Y during the second pass are omitted.) The purpose of the repetition is so that every measurement is made twice at a phase difference of 180° for the M_2 tide, locally the main tidal component. It is expected that the average of the two measurements will provide a subtidal frequency signal free from the contamination of the tides. [The standard method for the removal of tidal signals depends upon the construction of tidal currents from a harmonic analysis based on observed current time series at carefully selected locations (Candela et al. 1992).] The presence, in the study area, of both barotropic and baroclinic tidal currents with small spatial scales, often as small as 10 n mi, renders the standard approach inadequate (Tang and Lee 1996).

Because the presence of high-frequency noises other than that associated with the M_2 tide, this phase-averaging procedure does not eliminate the contamination completely. Upon making use of data from moored current meter arrays deployed before in the general area, the overall error of the phase-averaged current velocities can be estimated. Each time series from moored current meter measurements is high-pass filtered with a cutoff period at 72 h to produce a time series that contains the high-frequency signal only. The residual velocities, u_ε and v_ε, are then calculated as follows:

$$u_\varepsilon = \frac{U(t_i) + U(t_i + \Delta t)}{2}$$

$$v_\varepsilon = \frac{V(t_i) + V(t_i + \Delta t)}{2},$$

where $U(t_i)$ and $V(t_i)$ are the eastward and northward velocities recorded at time t_i and Δt is 68.31 h. Both these residuals will be zero if only a constant amplitude M_2 tide is present. The rms of the residual for over the 39 time series used turns out to be 11 cm s^{-1}, a fair estimate of the imperfection of the phase averaging procedure for the study area northeast of Taiwan.

b. Measurements

Figure 2 shows the phase-averaged current vectors at 16, 104, and 200 m over the continental shelf–slope junction northeast of Taiwan. The overall pattern features the main flow of the Kuroshio to the northeast, a northwestward branch current across the continental shelf break just northwest of NMHC, and a counterclockwise circulation immediately northeast of Taiwan. The speed in the main flow of the Kuroshio decreases with depth from a maximum of over 100 cm s^{-1} at 16 m to 80 cm s^{-1} at 104 m and about 40 cm s^{-1} at 200 m. At about 25°40′N, the Kuroshio separates from the continental shelf break. Part of the flow on the left-hand side of the Kuroshio intrudes onto the continental shelf over NMHC. The turning to the northeast of the intrusion flow at the 16-m depth seems to indicate that the intrusion is the beginning of a meander (see Hsueh et al. 1997). The branch current formed by the intrusion has speeds that decrease with depth and seems to develop a gradual turning with depth to the west. Thus, at depths greater than 100 m, the branch current appears as just a part of the counterclockwise circulation centered about MHC. This part of the counterclockwise circulation is apparently just that observed as the deep countercurrent earlier (Chuang and Wu 1991; Tang and Yang 1993). The counterclockwise turning eddy structure dominates throughout the water column immediately northeast of Taiwan during this particular experiment.

Figures 3a–e show, respectively, vertical sections of northeastward velocities along the five southeast–northwest oriented track segments from the one farthest away from Taiwan to the one next to Taiwan. Portions with negative (southwestward) velocities are shaded. It is clear that the countercurrent begins at about 100 m in the section farthest from Taiwan (Fig. 3a). It becomes fully developed along the shelf break at 200 m in Fig. 3b and combines with the seaward flow at the surface just east of Taiwan in Fig. 3e. It is worthwhile to note that in the surface layer above the countercurrent in Figs. 3a and 3b, the velocities contain a northward component, indicating an on-shelf intrusion (see Figs. 4a and 4b below). Figures 4a–e show a southeastward velocity component in the same sections. The countercurrent at 200 m in the third section from Taiwan is clearly southwestward. This deep southwestward flow gradually changes to a southeastward flow in sections close to Taiwan, giving strong evidence for an outflow of continental shelf water toward the Kuroshio just northeast of Taiwan.

Figures 5a and 5b show, respectively, eastward and northward velocity component sections along the first meridional track at about 123.4°E. Figures 5c and 5d show the same along the second meridional track at about 123.7°E. It is interesting to note that along the first track, the Kuroshio flow is not yet organized following the deflection by the shelf break and becomes somewhat better organized in the second section slightly farther to the east. It is also interesting to note that in the deflected Kuroshio, the core of velocity maximum is situated at a depth of about 200 m, in contrast to the near-surface appearance of the northward flow maximum indicated in Figs. 3b and 4b, for example. A core appears at a shallower depth in Fig. 5c and the magnitude of the velocity decreases toward the center of the core. In Figs. 3a and 3b, in the deeper cores below 150 m, the velocity does increase toward the center of the core, giving rise to a secondary maximum.) In fact, before the collision with the continental shelf, the velocity maximum is clearly right at the surface (not shown). The lowering of the maximum velocity core appears accompanied with the lowering of the thermocline (not shown) in the deflected Kuroshio, consistent with the Bernoulli principle, which demands a higher baroclinic pressure in the neighborhood of the collision (Hsueh et al. 1993). It is expected that the maximum velocity core will gradually rebound to being near the surface farther to the east, away from the point where the Kuroshio first encounter the continental shelf northeast of Taiwan.

Figure 6 shows the infrared image of the study area on 12 August 1994. Figure 7 shows the temperature distribution at 16 m from the hydrographic survey. The similarity between the two is noted. A patch of anomalously cold water is found in both figures just north of Taiwan. The location generally agrees with that of the counterclockwise circulation pattern noted before. The hydrographic properties of the water in the cold pool indicate that the water originated from the subsurface Kuroshio water modified by mixing with the shelf water (see below).

Figure 8 shows the temperature–salinity plot for all the hydrographic stations occupied in the experiment. The data can be clearly classified into two groups. Data in one group, represented with solid curves, show the *T*–*S* associations found in the Kuroshio and the on-shelf intrusion current. There is no significant difference between these associations. Data in the other group, represented by strings of station alphabetically, show associations found in the area of the cold water patch. This latter group of data shows a gradual change in *T*–*S* properties from those of the Kuroshio at stations near NMHC to those of the cooler and fresher water near Taiwan, indicating a mixing of the Kuroshio intrusion water with continental shelf water. Particularly noteworthy are data from stations D, G, and K on the inshore edge of the Kuroshio. The *T*–*S* properties from these stations are distinct from those of the Kuroshio, but the currents at these stations (see Fig. 2) either go toward or are forced in the direction of the Kuroshio, indicating an incorporation of the outflow of continental shelf water into the Kuroshio immediately next to the northern coast of Taiwan. Part of this water probably reenters the continental shelf area with the current intrusion farther to the north.

3. Discussion and conclusions

A near-synoptic pattern is obtained of the flow northeast of Taiwan where the Kuroshio impinges on the continental shelf from observations made during a single cruise in the summer of 1994. Although the observations appear to capture the key features of the mesoscale flow, several issues emerge that are important to the circulation. There is the question of the makeup of the water mass on the inshore side of the Kuroshio. There is evidence that water from the South China Sea, which has nearly the same *T*–*S* properties as those found at stations C, D, G, and K, may be present along the inshore edge of the Kuroshio (C.-S. Chern 1996, personal communication). The incorporation of South China Sea water probably occurs near the southern tip of Taiwan. Thus, the modification of water mass along the inshore edge of the Kuroshio may not be due to mixing with just the East China Sea water. In fact, the outflow around the northern coast of Taiwan probably contains South China Sea water in the first place. It appears that to understand the modification of the Kuroshio in the study region, it is necessary to treat the South China Sea, Taiwan Strait, and the East China Sea as a whole.

That the Kuroshio on-shelf intrusion is found in a summer cruise brings the variability question to a head. Conventional wisdom has been that the time most favorable for the intrusion is some time after the beginning of the northeast monsoon when the continental shelf water becomes sufficiently cool, and thus heavy, so that the shoreward spread of light surface Kuroshio water is facilitated (Chao 1990; Hsueh et al. 1993). The observation of the present cruise provides a counterexample to that rule of thumb.

The snapshot observation also precludes a look at the evolution in time of the mesoscale flow pattern. The passage of eddies imbedded in the Kuroshio can, from time to time, alter patterns of flow on the outer continental shelf within a given season. Kuroshio variabilities on time scales of 100 days or so have been discovered in a study of the cross-Kuroshio sea level difference and the position of the Kuroshio front in Tokara Strait for a 6-yr period (Ichikawa et al. 1997).

To conclude, it seems that the spatial pattern of the flow over the continental shelf–slope northeast of Taiwan can consist of an on-shelf intrusion of the surface Kuroshio, a southwest countercurrent at about 200 m, and a counterclockwise circulation just offshore of the northern tip of Taiwan that gives rise to an outflow of the continental shelf water toward the Kuroshio.

The normal Kuroshio intrusion gives the appearance of a branch current. In fact, it may just be a part of a meander that eventually rejoins the Kuroshio farther to the northeast along the continental shelf break, bringing continental shelf water into the Kuroshio. Thus, along the stretch of the continental margin northeast of Taiwan, most of the time, continental shelf water is incorporated into the Kuroshio. (The divergence of the Kuroshio flow farther to the northeast as the shoaling topography of the Kyushu coast is approached reclaims the water mass for the marginal seas.)

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Figures

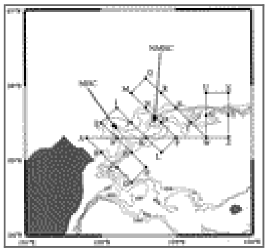

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Fig. 1. Cruise tracks and hydrographic stations for the KEEP cruise on 10–17 August 1994. The bathymetry is shown with thin depth contours from 200 to 1000 m at intervals of 200 m.

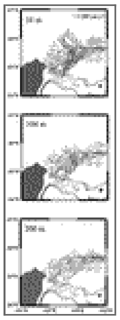

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Fig. 2. Phase-averaged current vectors from SADCP observations at depth (a) 16, (b) 104, and (c) 200 m. The bathymetry is shown with thin depth contours from 200 to 1000 m at intervals of 200 m.

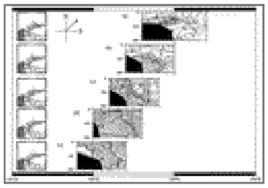

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Fig. 3. Vertical sections of northeastward velocity components along tracks connecting stations (a) Q to W, (b) M to P, (c) I to L, (d) E to H, and (e) A to D. The depth range is from the surface to about 300 m. The continental shelf is darkened. The values are contoured at intervals of 10 cm s^{-1}. The zero contour is shown in heavy line. Portions of negative values (representing velocity components that are southwestward) are shaded.

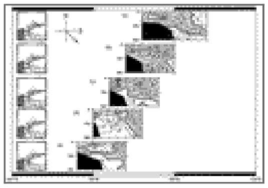

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Fig. 4. Vertical sections of southeastward velocity components along tracks connecting stations (a) Q to W, (b) M to P, (c) I to

L, (d) E to H, and (e) A to D. The depth range is from the surface to about 300 m. The continental shelf is darkened. The values are contoured at intervals of 10 cm s^{-1}. The zero contour is shown in heavy line. Portions of negative values (representing velocity components that are northwestward) are shaded.

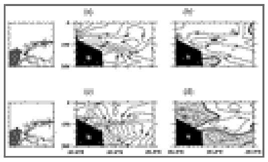

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Fig. 5. Vertical sections of (a) eastward and (b) northward velocity components along the track connecting stations U and W and of (c) eastward and (d) northward velocity components along the track connecting stations X and Z. The depth range is from the surface to about 300 m. The continental shelf is darkened. The values are contoured at intervals of 10 cm s^{-1}. The zero contour is shown in heavy line. Portions of negative values are shaded.

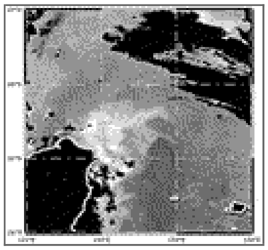

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Fig. 6. Infrared image of the sea surface temperature in the study area obtained by *NOAA-11* on 12 August 1994. Light shading indicates low surface temperature.

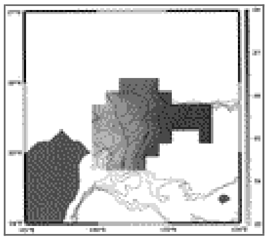

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Fig. 7. Temperature distribution at 16 m from the hydrographic survey conducted during 10–17 August 1994. The temperature is contoured at intervals of 1°C. The depth contours are thin.

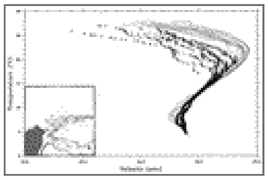

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Fig. 8. Temperature–salinity plot of all the hydrographic station data from the survey during 10–17 August 1994. The solid curves represent *T–S* associations found at stations in the Kuroshio. The *T–S* associations found at stations, of which the station letters are shown in the locator map inset, are represented with strings of the station letters.

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