An Oceanic Current against the Wind: How Does Taiwan Island Steer Warm Water into the East China Sea?

JIAYAN YANG

Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

(Manuscript received 3 January 2006, in final form 26 January 2007)

ABSTRACT

Along the Taiwan Strait (<100 m in depth) a northeastward flow persists in all seasons despite the annually averaged wind stress that is strongly southwestward. The forcing mechanism of this countercurrent is examined by using a simple ocean model. The results from a suite of experiments demonstrate that it is the Kuroshio that plays the deciding role for setting the flow direction along the Taiwan Strait. The momentum balance along the strait is mainly between the wind stress, friction, and pressure gradient. Since both wind stress and friction act against the northward flow, it is most likely the pressure gradient that forces the northward flow, as noted in some previous studies. What remains unknown is why there is a considerable pressure difference between the southern and northern strait. The Kuroshio flows along the east coast of Taiwan, and thus the western boundary current layer dynamics applies there. Integrating the momentum equation along Taiwan's east coast shows that there must be a pressure difference between the southern and the northern tip of Taiwan to counter a considerable friction exerted by the mighty Kuroshio. This same pressure difference is also felt on the other side of the island where it forces the northward flow through Taiwan Strait. The model shows that the local wind stress acts to dampen this northward flow. This mechanism can be illustrated by an integral constraint for flow around an island.

1. Introduction

The western boundary current (WBC) is required in a wind-driven gyre for closing the interior transport and for dissipating the momentum and vorticity imposed by the wind stress. However, the areas along the western boundaries, like any other coastal seas, are typically shallow and distinctly different from the interior ocean where the depth is typically several thousand meters. The WBC often flows along the slope and even the shelf edge, which can be as far as several hundred kilometers away from the land–sea boundary itself. The interaction between the WBC and marginal seas is complex and strongly depends on the local forcing and bathymetry (Brink 1998). In this study, we attempt to address how the Kuroshio (KC), the WBC in the subtropical North Pacific Ocean, affects the flow through the Taiwan Strait.

The Kuroshio, which carries the integrated transport of the wind-driven flow over the entire subtropical North Pacific Ocean, flows along the continental slope to the east of the South China Sea (SCS) and the East China Sea (ECS). It flows along the east coast of Taiwan before entering the Okinawa Trough as it continues its northeastward journey. Along the west coast of Taiwan in the Taiwan Strait, a current that is parallel to the Kuroshio transports warm and saline water from SCS into the ECS (Fig. 1). The most fascinating feature of this current is that it persists northeastward in all seasons (Beardsley et al. 1985; Chuang 1986; Fang et al. 1991; Su et al. 1994; Zhu et al. 2004) even though the annually averaged wind stress is decidedly southwestward against it (Na et al. 1992). Previous studies have given this current different names, some considering it as a northward extension of the South China Sea Warm Current (SCSWC) while others regard it as a seasonal branch of the Taiwan Warm Current (TWC). To avoid confusion, the northward flow through the Taiwan Strait will be referred to as the Taiwan Strait Current (TSC) hereinafter in this paper.

Observations showed that this current is mainly baro-

Corresponding author address: Jiayan Yang, Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA 02543.
E-mail: jyang@whoi.edu

DOI: 10.1175/JPO3134.1

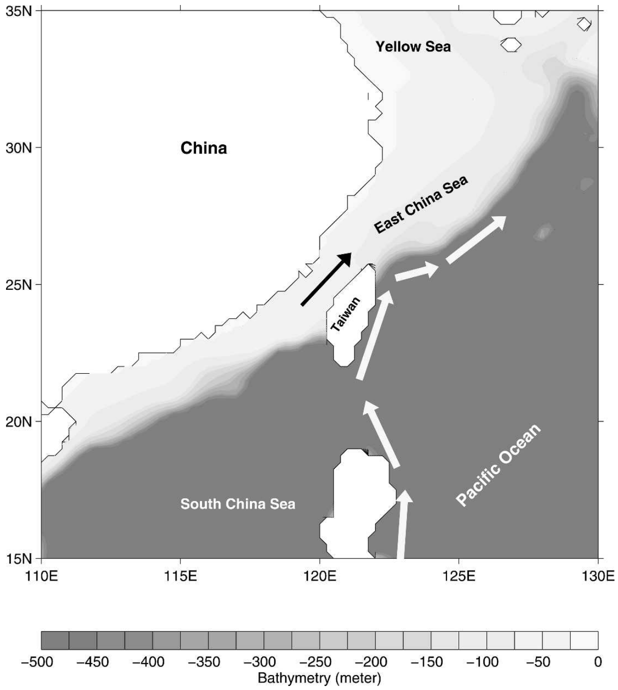

FIG. 1. The bathymetry in the vicinity of Taiwan Island. The white arrows indicate the pathway of the Kuroshio—the WBC of the subtropical gyre in the North Pacific Ocean. The black arrow is the TSC, which transports warm and saline water from the SCS to the ECS. The paper investigates why the TSC flows northeastward against the annually averaged wind stress.

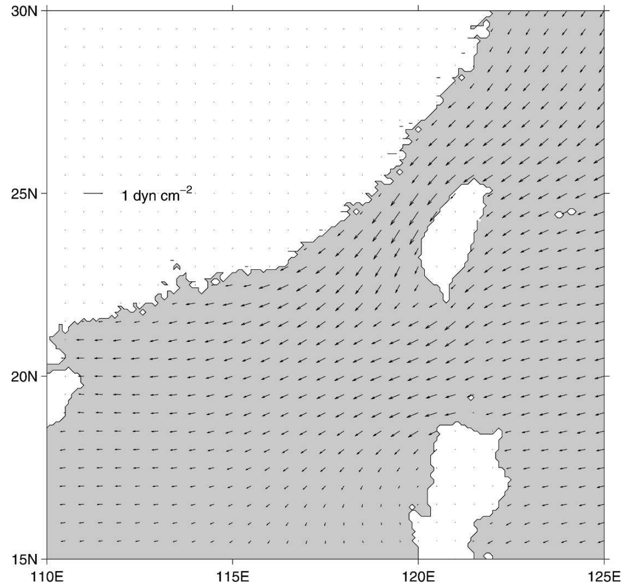

FIG. 2. The annually averaged vectors of surface wind stress that were derived from ship observations (da Silva et al. 1994). The wind is directed southwestward opposite to the direction of the TSC shown in Fig. 1.

tropic (e.g., Chuang 1986; Fang et al. 1991) and its northward transport varies from 1 Sv (1 Sv $\equiv 10^6$ $m^3\,s^{-1}$) in December–May to 3.1 Sv in June–November based on direct observations (Fang et al. 1991). The strong seasonality is related to the monsoonal forcing. The wind over the area in ECS is strongly southward in the winter and weaker but northward in the summer. The yearly average is unambiguously southward against the TSC (Fig. 2). The majority of physical oceanographic studies in this area have been descriptive based on data or model simulations [see Su (1998) for a comprehensive review]. Chuang (1986) examined the data from one current-meter mooring off the southwest coast of Taiwan and confirmed a northward flow in all seasons. He ruled out the direct wind stress forcing as the main mechanism since the northward flow was observed to be against a strong southwestward wind in the winter. He suggested a number of possible mechanisms, including the branching current from Kuroshio through Bashi Channel, but nevertheless claimed that it was impossible to pin down the leading mechanism with data from a single mooring. The dynamic mechanism for forcing this current to flow against the wind stress remains unexplained.

2. Model and result

The goal of this study is to investigate what forces TSC to flow against the wind. A barotropic ocean circulation model is used here:

$$\frac{Du}{Dt} - fv = -g\frac{\partial \eta}{\partial x} + \frac{(\tau_S^x - \tau_B^x)}{\rho h},$$

$$\frac{Dv}{Dt} + fu = -g\frac{\partial \eta}{\partial y} + \frac{(\tau_S^y - \tau_B^y)}{\rho h}, \quad \text{and}$$

$$\frac{Dh}{Dt} + h\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0, \tag{1}$$

where D/Dt is the rate of change following the fluid; η is the sea surface height; h is the total layer thickness; (u, v) are the zonal and meridional velocity components, respectively; ρ is the constant density; $\boldsymbol{\tau}_B$ is the bottom drag; and $\boldsymbol{\tau}_S$ is the surface wind stress. The annually averaged wind stress from ship-based observations (da Silva et al. 1994) is used to force the model. The bottom drag is calculated by the following formula:

$$\boldsymbol{\tau}_B = \rho C_D|\mathbf{u}|\mathbf{u}, \tag{2}$$

where $C_D = 5 \times 10^{-3}$ is the drag coefficient. The model resolution is ⅛° in space and 20 s in time. The staggered Arakawa-C grid is used. The minimum water depth is

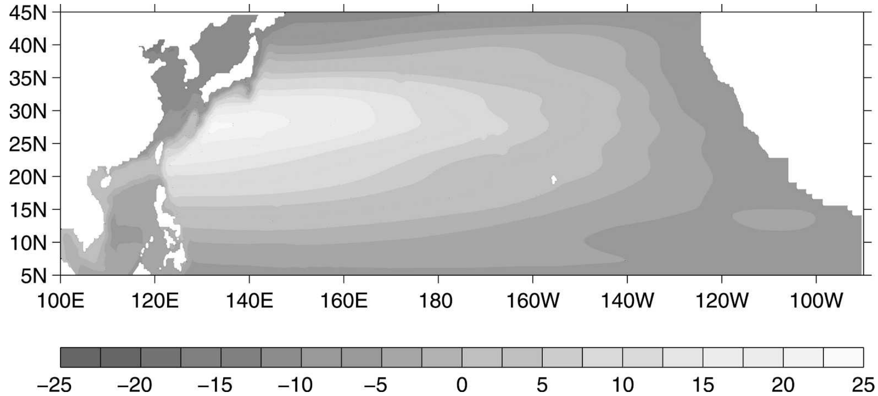

FIG. 3. The SSH deviation (cm) simulated by the barotropic model that has a resolution of 1/8°. The model used the bathymetry shown in Fig. 1 and was forced by the annually averaged wind stress shown in Fig. 2. The Kuroshio transport outside Taiwan Island is about 28 Sv, consistent with observations. The flow is nearly geostrophic, so the SSH contours are essentially the flow pathways.

set to be 25 m. We follow the same computational scheme as given by Dube et al. (1986). For instance, the model is integrated by using the leapfrog scheme for every 99 time steps and then by forward time scheme for one step to avoid the computational mode (Dube et al. 1986). The eastern and western boundaries are solid walls along which the no-normal-flow condition is applied. The northern and southern boundaries are open and the radiational condition is used (Camerlengo and O'Brien 1980).

The model reached a steady state after a 30-yr integration. The results from the model simulation at the end of the 30th year are presented as follows to elucidate the interplays between Kuroshio and local wind stress forcing. In the *standard run*, the model is forced by observed wind stress (da Silva et al. 1994) over the whole tropical and subtropical North Pacific Ocean from 5°S to 45°N. Despite its simplicity, the model simulates a subtropical gyre (Fig. 3) that resembles well the observation, including the pathway of the Kuroshio. The transport of Kuroshio outside the east coast of Taiwan is 28 Sv, consistent with the observation (Ichikawa and Beardsley 1993; Feng et al. 2000). The focus of this paper is the circulation in the vicinity of Taiwan where we will concentrate our discussion. The model flow along the Taiwan Strait is northeastward just like the observed one (Fig. 4) with a transport of about 1.5 Sv, as compared with the observed one of 2 Sv (Fang et al. 1991). The sea surface height averaged across Taiwan Strait at 22°N is about 6.8 cm higher than that at 25°N, and thus the SSH slope is 2.06×10^{-7}. This is within the observed range from 1.5×10^{-7} to 2.33×10^{-7} as estimated by Chuang (1985), but less than 2.62×10^{-7} computed by Fang et al. (1991) whose calculation was based solely on tide stations along the Chinese coast. So the model appears to do a reasonable job in reproducing the sea level variations.

What role does the Kuroshio play in determining the flow through the Taiwan Strait? In the next experiment, a smaller domain between 100° and 130°E is used and the wind stress forcing is turned off. The pressure and velocity fields from the standard run, shown in Figs. 3 and 4, are applied along 130°E as the boundary condition. The same radiational open-boundary condition (Camerlengo and O'Brien 1980) is applied along the northern and southern boundaries. This smaller-domain experiment (referred to as the *Kuroshio-forcing run*) would be equivalent to the situation in which wind stress is applied only in the vast interior from 130°E to the eastern boundary and with no wind stress forcing between 100° and 130°E. (The result is identical to the standard run if the wind stress is turned on between 100° and 130°E according to an experiment not shown here.) The information of interior forcing to the east of 130°E is contained in the boundary condition along 130°E and thus passed over to the smaller domain. As expected, a very robust Kuroshio, which is forced by wind stress over the whole subtropical basin, flows along the continental slope, very similar to the case from the standard run. In the standard run, the wind stress locally along Taiwan Strait is against the flow (Figs. 2 and 4). So without local wind forcing, the TSC transport in this KC-forcing run is actually stronger than that from the standard run (Fig. 5). The northward velocity at 24°N reaches as high as 24 cm s^{-1} in this Kuroshio-forcing run, considerably higher than 12 cm s^{-1} in the standard run (Fig. 6).

This can be further shown in the next experiment in which only the local wind stress is used. The same smaller model domain, between the western boundary

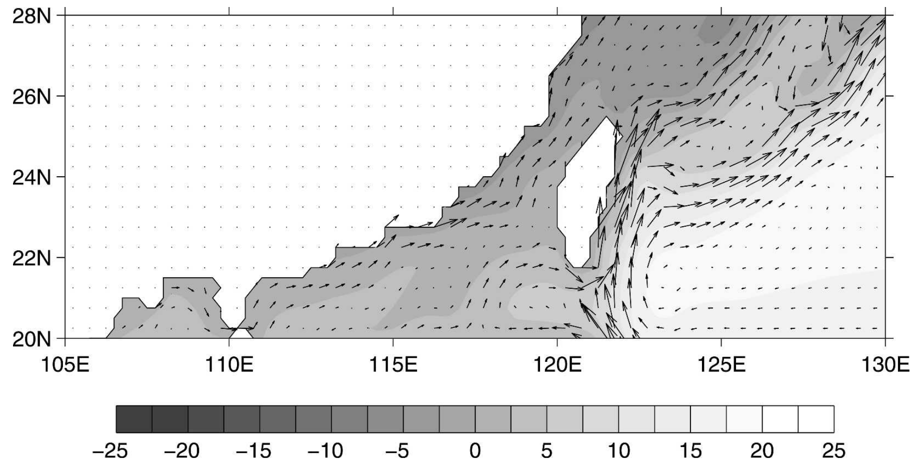

FIG. 4. The flow vectors and contours of SSH deviation (cm; shading) from the standard run that uses wind stress over the whole model domain. The model successfully simulates a northeastward flow through the Taiwan Strait. The transport through the strait at 24°N is about 1.5 Sv.

and 130°E is used. An open-boundary condition along 130°E is used to allow signals to propagate outward from the model domain. No information from the forcing in the interior is used and so the Kuroshio is expected to be absent. The wind stress is turned on inside the smaller model domain. The model indeed produces a very different circulation pattern without visible WBC (Fig. 7). The local wind stress, which is southwestward along the China coast (Fig. 2), drives a southward flow along the Taiwan Strait (Fig. 7), the opposite to the observed flow direction as schematized in Fig. 1. This indicates that TSC is forced primarily by the Kuroshio, and the wind stress acts to oppose the northeastward TSC.

The momentum balance along Taiwan's east coast is mainly maintained by the pressure gradient, the surface wind stress, and the friction (the nonlinear term is one order of magnitude smaller and the Coriolis term is zero because of the no-normal-flow condition). For simplicity we assume that the boundary is oriented in the north–south direction and so the linear and steady momentum equation can be simplified as

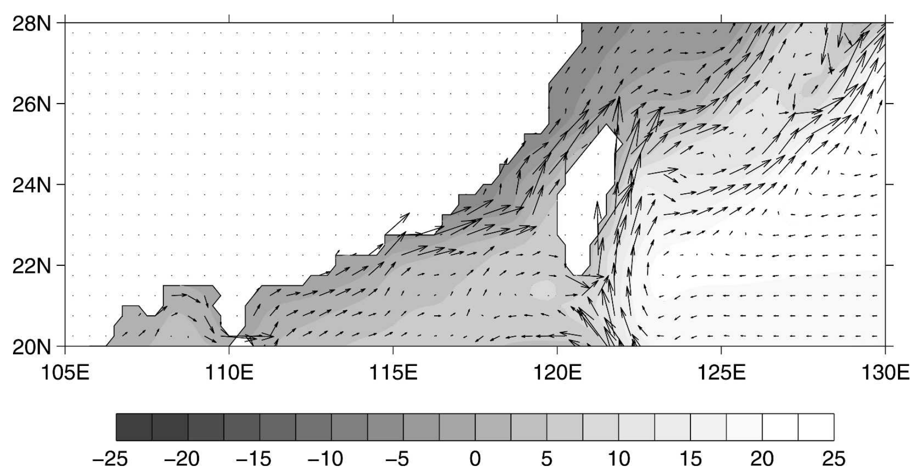

FIG. 5. The model SSH deviation and flow vectors from the Kuroshio-forcing experiment. The wind stress was turned off and a smaller model domain, from 100° to 130°E, is run by applying the SSH and velocity from the standard run as boundary conditions along 130°E. The effect is to remove the local wind stress forcing but retain the basin-scale forcing east of 130°E (the information is contained in the boundary condition along 130°E). It is interesting to note that the model results in the vicinity of Taiwan Island are very similar to that from the standard run even though the local wind stress has been turned off. This strongly indicates that the northward flow through Taiwan Strait is not due to the local wind stress.

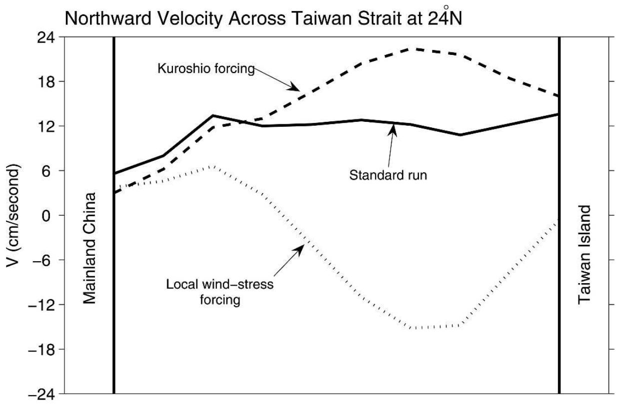

FIG. 6. The profile of the meridional velocity across Taiwan Strait. It is interesting to note that velocity in this case without the local wind stress forcing (dashed line) is stronger than that from the standard run (solid line). This is consistent with our analyses that the local wind stress forcing is against the TSC. The dotted line is the experiment that used only the local wind stress without Kuroshio. The flow is mostly southward.

$$0 = -\frac{\partial p}{\partial y} + \frac{\tau_S - \tau_B}{h}, \qquad (3)$$

where τ_S and τ_B are the wind stress and bottom drag, respectively. If the local wind stress is small compared with the friction exerted by the WBC, the pressure difference between the northern and southern tip of the island equates the accumulative friction integrated along the boundary:

$$p_n - p_s = -\int_s^n \frac{\tau_B}{h}\, dy. \qquad (4)$$

This pressure difference is set by friction associated with the WBC along Taiwan's east coast, but it is also felt off the west coast of Taiwan. Inside the Taiwan Strait, the velocity vectors are directed mainly in the along-strait direction ($\mathbf{l}$). The cross-channel component of the velocity ($\mathbf{u} \cdot \mathbf{n}$) is small, and so the Coriolis term is small for the momentum balance in the along-strait direction. The nonlinear term is small almost everywhere inside the strait (more than an order of magnitude smaller than the pressure gradient term). Therefore, the pressure difference in (4) becomes the dominant term and is balanced by the friction and wind stress.

3. An integral constraint for circulation around an island

The above discussion regarding how the Kuroshio exerts its strong influence on the other side of the island can be explained more systematically by a classic theorem in fluid dynamics, namely, the conservation of circulation around an island. For an inviscid and unforced flow, the circulation around an island is conserved:

$$\partial/\partial t\left(\oint_C \mathbf{u} \cdot d\mathbf{l}\right) = 0, \qquad (5)$$

where the integration is along the entire coastline C of the island. Equation (5) is the classic Kelvin theorem. The Coriolis force term vanishes because of the no-normal-flow condition. The pressure and the momentum flux are continuous around the island and so the integral of their gradients are zero. Friction and external forcing such as the wind stress can change the circulation around the island and so (5) becomes

$$\partial/\partial t\left(\oint_C \mathbf{u} \cdot d\mathbf{l}\right) = \oint_C \frac{1}{\rho h}(\boldsymbol{\tau}_S - \boldsymbol{\tau}_B) \cdot d\mathbf{l}.$$

For a steady flow, it becomes

$$\oint_C \frac{1}{\rho h}(\boldsymbol{\tau}_S - \boldsymbol{\tau}_B) \cdot d\mathbf{l} = 0. \qquad (6)$$

A simple balance is established between the drag and wind stress integrated along the entire island. The more detailed discussion of (5) and (6) can be found in textbooks of geophysical fluid dynamics (e.g., Pedlosky 1979), and here we only discuss its application in our study. We will refer to (6) as the *around-island integral constraint*.

We would like to point out here that the around-island integral constraint (6) is different from the original *island rule* derived by Godfrey (1989) who, in an attempt to estimate the Indonesian Throughflow transport, integrated the momentum equation along a closed path that includes the west coast of Australia, two zonal lines across the Pacific basins at the northern and southern tips of Australia, and the eastern boundary of the Pacific Ocean within these two latitudes. The integration yields a balance between the wind stress integral and the vorticity advection across the two latitudes in the interior basin. As discussed by Pedlosky et al. (1997), Godfrey's island rule cleverly avoids areas of strong friction, such as in the WBCs so that it does not have to deal with friction. The path line of the integral in (6) is along the entire coastline of an island and does not involve the interior ocean, a key difference from Godfrey's island rule. This is similar to what was discussed by Pedlosky et al. (1997) except that we consider here the bathymetric changes. In terms of dynamics, we emphasize the role of friction, exerted by the WBC, in promoting the cross-shelf interactions.

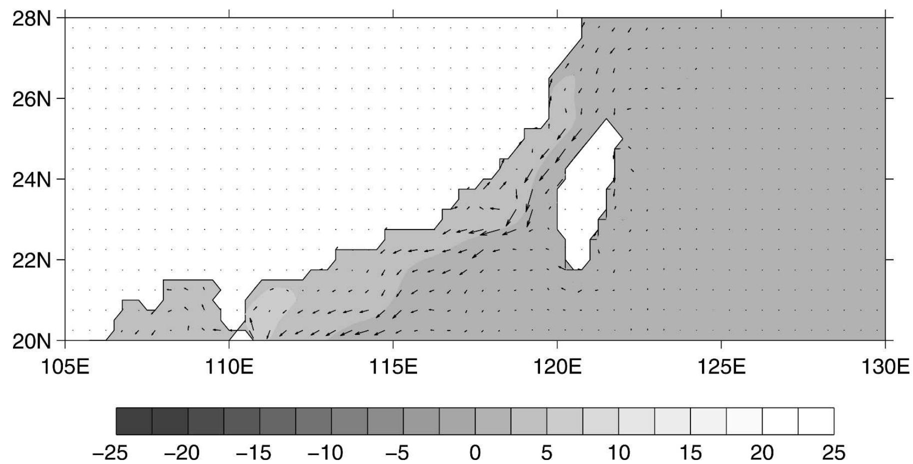

FIG. 7. The result from the local wind forcing experiment. The same small model domain, like the one shown in Fig. 5, was used. The wind stress was turned on but an open-boundary condition was used along 130°E. This effectively turns off the basin-scale forcing to the east of 130°E and consequently, the KC is absent. With forcing from only the local wind stress, the flow through Taiwan Strait is southwestward and along the wind direction (see the velocity profile in Fig. 6). This further supports our conclusion that the TSC is forced by the Kuroshio instead of the local wind stress.

The Kuroshio flows northward along the island's east coast with a transport of about 20–30 Sv (Ichikawa and Beardsley 1993; Feng et al. 2000) and exerts a strong drag in the southward direction. In the model, the local wind stress is insufficient to balance this KC-induced friction, and thus an along-boundary pressure gradient is required. However, the flow along Taiwan's west coast inside the Taiwan Strait would feel the same pressure difference between the southern and northern tip of the Island. A southward drag associated with a northward flow is required since the wind stress alone is not sufficient to counter the pressure gradient inside the strait.

Figure 2 shows that the wind stress is southwestward along both sides of the island and thus tends to cancel each other in the around-island integral in (6). However, the water depth, averaged across KC is considerably deeper than the averaged depth inside the strait (Fig. 1). So the averaged wind stress per unit depth along KC is less than that in Taiwan Strait. Consequently, the net integration of the wind stress per unit depth along the island is positive in the counterclockwise direction, in the opposite sign of the integration of the drag exerted by the Kuroshio. If the wind stress is strong enough to counter the Kuroshio drag, a steady balance could be achieved between them without a contribution from the current along the west coast of Taiwan. The Kuroshio, which represents the wind-driven oceanic transport integrated across the whole Pacific Ocean, is perhaps too strong for the local wind stress to counter.

4. Summary and discussion

The major dynamical barrier for interactions between the deep ocean and shallow coastal seas, as discussed elegantly by Brink (1998), is the constraint by the Taylor–Proudman Theorem. If a three-dimensional flow in the deep basin is governed by geostrophy, the flow at all depth is directed along the isobaths even though the velocity magnitude varies with the depth (Brink 1998). In other words, the deep-oceanic forcing in the shallow coastal seas is inhibited by the continental slope. This barrier can be overcome by external forcing, friction, and nonlinearity. Taiwan is located right at the edge of the shelf break and the Kuroshio readily flows along its east coast. The enhanced friction along Taiwan's east coast, as governed by the western boundary layer dynamics, sets a pressure gradient between the southern and northern tips of the island. This same pressure difference forces the flow to be northward against the wind along Taiwan Strait. It is the location of Taiwan that makes this forcing mechanism so effective. If it were located farther inshore away from the shelf break, it would not interact so directly with the Kuroshio, and thus would be less effective in fostering the deep-oceanic forcing in the coastal seas. Even more drastically, one might wonder what would happen to the flow between the South and East China Seas if Taiwan were located elsewhere. We have done several experiments with island being moved outside of the model domain, and found that flow off the Chinese coast in general is much weaker. Figure 8 shows the

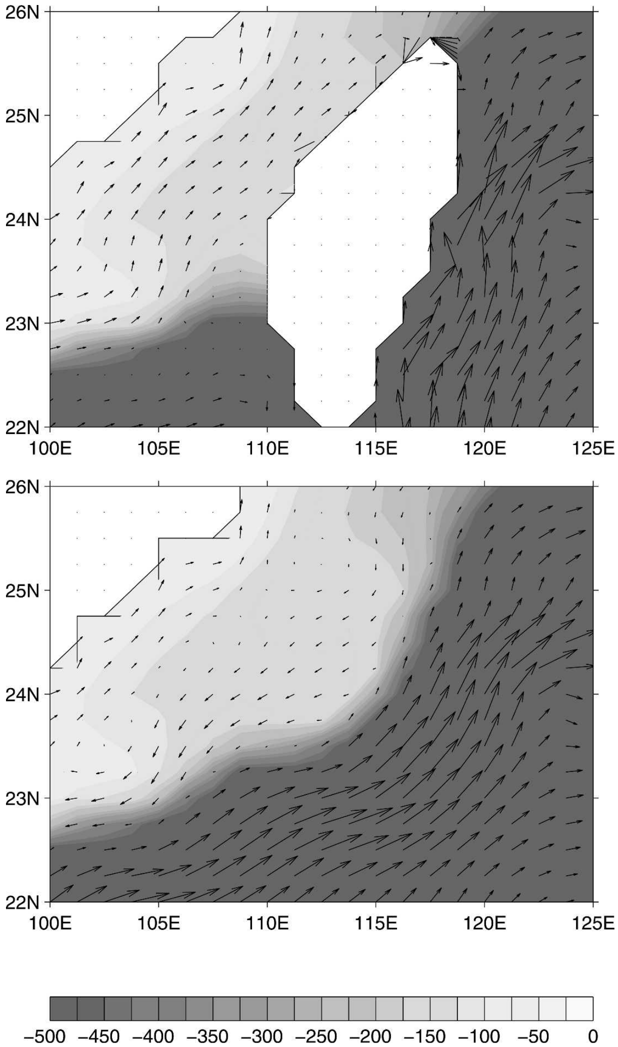

FIG. 8. The bathymetry (m) and flow fields in the vicinity of Taiwan from (top) the standard run and (bottom) a sensitivity run in which the island was moved to the outside of the model domain. Without the island, the Kuroshio flow mainly along the slope and the velocity is weak over the shelf regions. This comparison demonstrates again that the KC interaction with Taiwan is a leading mechanism for TSC.

comparison between the standard run and an experiment in which the island is replaced by a broad shelf similar to the surrounding areas. The flow from SCS to ECS is now mainly along the shelf break as part of the WBC when the island is moved elsewhere.

In addition, Japan is a much bigger island, and the Kuroshio also flows along its east coast. Our ongoing study indicates that the KC interaction with Japan contributes to the Tsushima Warm Current and has a broad impact on circulations over the Japan/China Sea, the East China Sea, and the Yellow Sea (Yang et al. 2007, manuscript submitted to *J. Phys. Oceanogr.*), but this is beyond the scope of this note.

Acknowledgments. The author thanks two reviewers for their constructive comments and suggestions, which helped to improve the revised version. This study has been supported by National Science Foundation through Grant OCE-0351055. The author benefited from discussions with Dr. Dexing Wu and his research group at the Ocean University of China. Our expanding collaboration in this area has also been supported by China's Science and Technology Ministry (2005CB422302 and 2006DFB21250).

REFERENCES

Beardsley, R. C., R. Limeburner, and H. Yu, 1985: Discharging of the Changjiang (Yangtze River) into the East China Sea. *Cont. Shelf Res.,* **4,** 57–76.

Brink, K. H., 1998: Deep-sea forcing and exchange processes. *The Sea,* K. H. Brink and A. R. Robinson, Eds., *Ideas and Observations on Progress in the Study of the Seas,* Vol. 10, John Wiley and Sons, 151–167.

Camerlengo, A. L., and J. J. O'Brien, 1980: Open boundary conditions in rotating fluids. *J. Comput. Phys.,* **35,** 12–35.

Chuang, W.-S., 1985: Dynamics of subtidal flow in the Taiwan Strait. *J. Oceanogr. Soc. Japan,* **41,** 65–72.

——, 1986: A note on the driving mechanisms of current in Taiwan Strait. *J. Oceanogr. Soc. Japan,* **42,** 355–361.

da Silva, A., A. C. Young, and S. Levitus, 1994: *Algorithms and Procedures*. Vol. 1, *Atlas of Surface Marine Data 1994,* NOAA Atlas NESDIS 6, 83 pp.

Dube, S. K., M. E. Luther, and J. J. O'Brien, 1986: Documentation of the FSU Indian Ocean Model. MASIG Tech. Rep., The Florida State University, 127 pp.

Fang, G., B. Zhao, and Y. Zhu, 1991: Water volume transport through the Taiwan Strait and the continental shelf of the East China Sea measured with current meters. *Oceanography of Asian Marginal Seas,* K. Takano, Ed., Elsevier, 345–358.

Feng, M., H. Mitsudera, and Y. Yoshikawa, 2000: Structure and variability of the Kuroshio Current in Tokara Strait. *J. Phys. Oceanogr.,* **30,** 2257–2276.

Godfrey, J. S., 1989: A Sverdrup model of the depth-integrated flow from the world ocean allowing for island circulations. *Geophys. Astrophys. Fluid Dyn.,* **45,** 89–112.

Ichikawa, H., and R. C. Beardsley, 1993: Temporal and spatial variability of volume transport of the Kuroshio in the East China Seas. *Deep-Sea Res.,* **40,** 583–605.

Na, J. Y., J. W. Seo, and S. K. Han, 1992: Monthly mean sea surface winds over the adjacent seas of the Korea Peninsula. *J. Oceanogr. Soc. Korea,* **27,** 1–10.

Pedlosky, J., 1979: *Geophysical Fluid Dynamics*. Springer-Verlag, 624 pp.

——, L. Pratt, M. Spall, and K. Helfrich, 1997: Circulation around islands and ridges. *J. Mar. Res.,* **53,** 1199–1251.

Su, J., 1998: Circulation dynamics of the China Seas north of 18N. *The Sea,* A. Robinson and K. H. Brink, Eds., *Regional Studies and Syntheses,* Vol. 11, John Wiley and Sons, 483–505.

——, Y. Pan, and X. Liang, 1994: Kuroshio intrusion and Taiwan Warm Current. *Oceanology of China Seas,* D. Zhou, Y. Liang, and C. Zeng, Eds., Kluwer Academic, 59–70.

Zhu, J., C. Chen, P. Ding, C. Li, and H. Lin, 2004: Does the Taiwan warm current exist in winter? *Geophys. Res. Lett.,* **31,** L12302, doi:10.1029/2004GL019997.