Continental Shelf Research 201 (2020) 104122

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: http://www.elsevier.com/locate/csr

Research papers

Wind stress over the Pacific Ocean east of Japan drives the shelf circulation east of China

Dezhou Yang [a,b,c,*], Rui Xin Huang [d], Xingru Feng [a,b,c], Jifeng Qi [a,b,c], Guandong Gao [a,b,c], Baoshu Yin [a,b,c,e,**]

[a] CAS Key Laboratory of Ocean Circulation and Waves, Institute of Oceanology, Chinese Academy of Sciences, Qingdao, 266071, China
[b] Pilot National Laboratory for Marine Science and Technology(Qingdao), Qingdao, 266237, China
[c] Center for Ocean Mega-Science, Chinese Academy of Sciences, 7 Nanhai Road, Qingdao, 266071, China
[d] Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA, USA
[e] University of Chinese Academy of Sciences, Beijing, China

ARTICLE INFO

Keywords:
East China Sea
Kuroshio
Shelf circulation
Cross-shelf intrusion

ABSTRACT

In the western Pacific Ocean, the Kuroshio cross-shelf intrusion and the shelf circulation are vital components of the coastal environment. However, the key dynamic factors driving them remained unclear. Our model and theoretical analysis show that wind stress over the open Pacific Ocean east of Japan drives a net equatorward water flux of 2.2 Sv, and this flux sets up a south-north sea surface drop from the East China Sea (ECS) to the Japan Sea which drives a throughflow of 2.6 Sv poleward through the Tsushima Strait. This throughflow requires a shelf circulation in the ECS to balance the mass flux. Thus, the Kuroshio Current must intrude onto the ECS shelf and there must be a poleward flowing Taiwan Warm Current through Taiwan Strait. It is the wind stress over the Northeastern Pacific Ocean interior rather than the local wind that drives and regulate both the Kuroshio cross-shelf intrusion and the shelf circulation.

1. Introduction

The Yellow Sea, East China Sea (ECS), and South China Sea are marginal seas of the western Pacific Ocean which are surrounded by more than 2 billion population, nearly one third of the world population (Zheng et al., 2006). These populations are impacted by all coastal manifestations of global climate change such as rising sea level (Anderson et al., 2001) and severe typhoons, harmful algal blooms and hypoxia (Wang et al., 2017; Wang and Wu, 2009; Zhou et al., 2017a). There is the broadest continental shelf east of China in the world ocean, and also is very steep shelf break along which the Kuroshio Current flows (see Fig. 1). The huge amount of nutrients, heat and water transport from the Kuroshio to the marginal seas play an important role in the shelf circulation dynamics and coastal ecosystem (Chen, 1996; Su, 1998; Wu et al., 2017; Zhou et al., 2017b). The strong boundary current, steep shelf break, and local forcing lead to a complicated current system (see Fig. 1) consisting of the Kuroshio intrusion branch currents, (Ichikawa and Beardsley, 2002; Qiu and Imasato, 1990; Yang et al., 2012), the Taiwan warm current (TWC) (Guan and Fang, 2006; Hu et al., 2010) and the Taiwan-Tsushima Warm Current System (Fang and Zhao, 1988; Ichikawa and Beardsley, 2002).

This shelf circulation system has been extensively studied. The TWC and the Kuroshio intrusion branch currents are the most dominant feature of this shelf circulation system (Su et al., 1994). Guan and Fang (2006) reported the currents of the South China Sea Warm Current, the Taiwan Strait Warm Current and the upwind TWC in winter. On basis of the tidal station records and land leveling, Fang et al. (1991) and Fang and Zhao (1988) postulated that the difference between sea surface elevations in the western tropic Pacific and the northwestern Pacific could generate a current starting from the northeast part of the South China Sea, passing through the Taiwan Strait, East China Sea, Korea Strait, Japan Sea and Tsugaru/Soya Straits, and finally joining the Oyashio.

Another important part of the shelf circulation system is a Kuroshio branch current northeast of Taiwan which was reported in (Ichikawa and Beardsley, 2002; Qiu and Imasato, 1990) and the planetary β-effect and Taiwan Island are thought to be the main driving factors for this current. The bottom Ekman layer is reported as one of the mechanisms driving the northward branch current (Jacobs et al., 2000). In addition,

* Corresponding author. Center for Ocean Mega-Science, Chinese Academy of Sciences, 7 Nanhai Road, Qingdao, 266071, China.
** Corresponding author. Center for Ocean Mega-Science, Chinese Academy of Sciences, 7 Nanhai Road, Qingdao, 266071, China.
E-mail address: yangdezhou@qdio.ac.cn (D. Yang).

https://doi.org/10.1016/j.csr.2020.104122
Received 21 October 2019; Received in revised form 2 March 2020; Accepted 11 April 2020
Available online 20 April 2020
0278-4343/© 2020 Elsevier Ltd. All rights reserved.

Oey et al. (2010) argued that the cooling solely gives rise to more northward Kuroshio intrusion in winter. Guo et al. (2006) suggested that the change of density field northeast of Taiwan was the major driving force for the Kuroshio intrusion.

On the other hand, Yang et al. (2012, 2018) reported that there were two submarine Kuroshio branch currents in the ECS deep water, and these branch currents showed a "topographic beta spiral" due to the upwelling induced by the collision between the northward flowing Kuroshio Current and the west-east running shelf break.

These studies were mostly focused on the local forcing factors. Despite many recent advances, the driving mechanisms of both the shelf circulation and onshore intrusion of Kuroshio remain to be further explored. Moreover, the relation between the shelf circulation and open ocean circulation is unclear. Here, we examine the lowest order dynamic mechanism and main force responsible for driving the shelf circulation and the Kuroshio intrusion onto the ECS shelf.

The ECS shelf circulation is mainly composed of the TWC and the Kuroshio branch currents (Su et al., 1994). It is important to note that the Taiwan Strait (TWS) and Tsushima Strait (TUS) (see Fig. 1) are two natural choke points for the water transport of the shelf circulation. The annual mean volume flux through TWS is about 1.2 Sv(1 Sv $= 10^6 m^3 s^{-1}$) (Chen et al., 2016; Hu et al., 2010; Isobe, 2008), and that through TUS is about 2.6 Sv (Ito et al., 2014; Na et al., 2009; Takikawa and Yoon, 2005; Teague et al., 2005). Thus, the remaining 1.4 Sv transport must be supplied by onshore Kuroshio intrusion across the ECS shelf break (Isobe, 2008). It seems that a half of the volume flux through TUS comes from the Taiwan-Tsushima Warm Current System, and another half comes from the Kuroshio intrusion. However, the formation of the Kuroshio onshore intrusion and TWC remains unclear.

2. Numerical experiments and results

To address this fundamental question, we set up a numerical model based on the Regional Ocean Modeling Systems (Shchepetkin and McWilliams, 2005). The model domain covers the Pacific Ocean (99°E–68°W; 40°S-67°N). The horizontal resolution in the model is 5' × 5′cosϕ (ϕ is latitude), and there are 31 nonlinear, terrain-following sigma layers in the vertical direction, with higher vertical resolution near the surface and bottom. This model is driven by monthly mean climatological wind stress, heat flux and freshwater flux at the sea surface taken from the Comprehensive Ocean-Atmosphere Data Set (COADS) (Diaz et al., 2002). Fig. 2 shows these climatological monthly mean wind stress at January, April, July and October, respectively.

We use the temperature and salinity data from the World Ocean Alas 13 (WOA13) (Locarnini et al., 2013; Zweng et al., 2013) to initialize the model ocean. In combination with the monthly mean satellite climatology data of absolute dynamic height (Dee et al., 2011), the WOA13 is also used to calculate the geostrophic current according to thermal wind relation (Pedlosky, 1986). The monthly mean geostrophic current is vertically integrated in the whole water column, and then is applied to the open western and southern boundaries as the barotropic boundary conditions to force the model. We choose the radiation boundary conditions for the 3-dimension temperature, salinity and ocean current along the open boundary (Marchesiello et al., 2001). This model has been run for 21 years for spin-up and the model results in the last model year are used to examine the shelf circulation. This 21-year run is used as the control run. In addition, we carried out two additional numerical experiments. In case 1, the wind stress over the whole ECS (as depicted by the dash-line box in Fig. 3) was set to zero, the model initialized by the output from the 17th model year of control run was run for 4 years

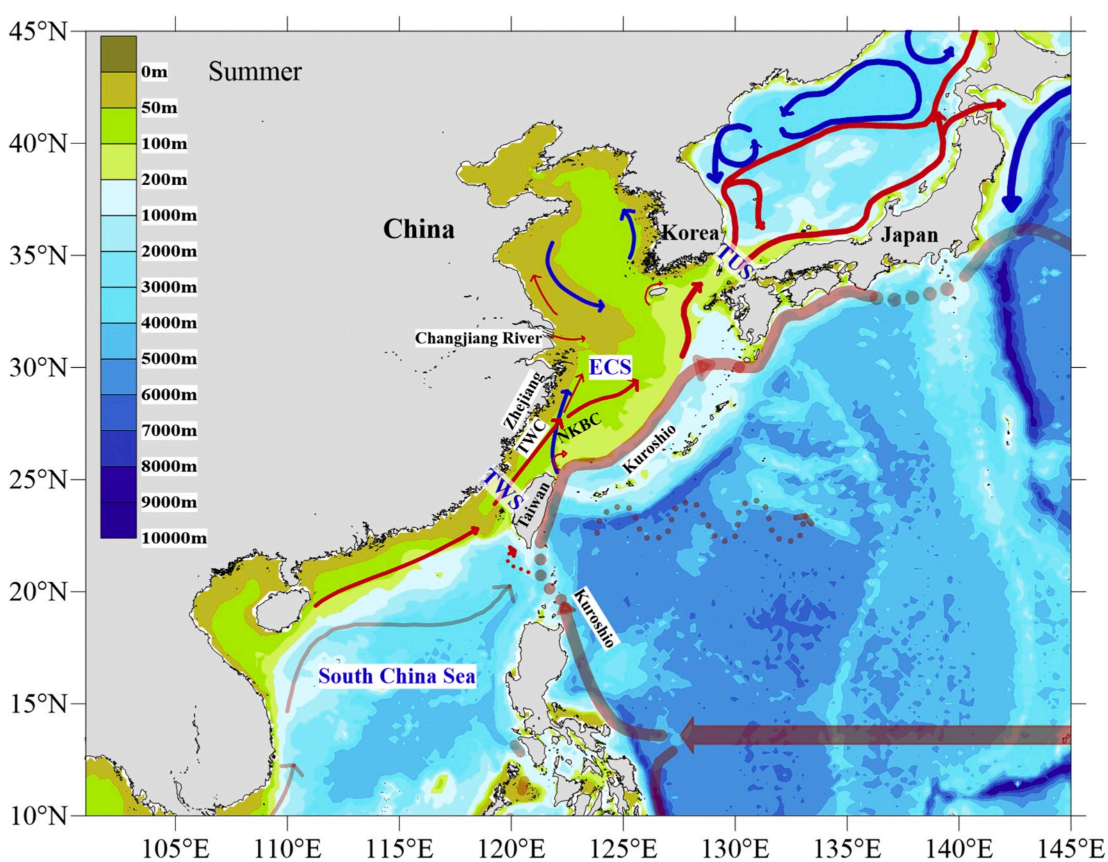

Fig. 1. Ocean bathymetry (Amante and Eakins, 2009) and a schematic diagram of summertime ocean circulation pattern after (Guan and Fang, 2006; Hogan and Hurlburt, 2005; Yang et al., 2012; Zheng et al., 2006). NKBC is the Nearshore Kuroshio branch current. Currents related to continental shelf are highlighted by low transparency, while high transparency for others. TWS and TUS are Taiwan Strait and Tsushima Strait, respectively.

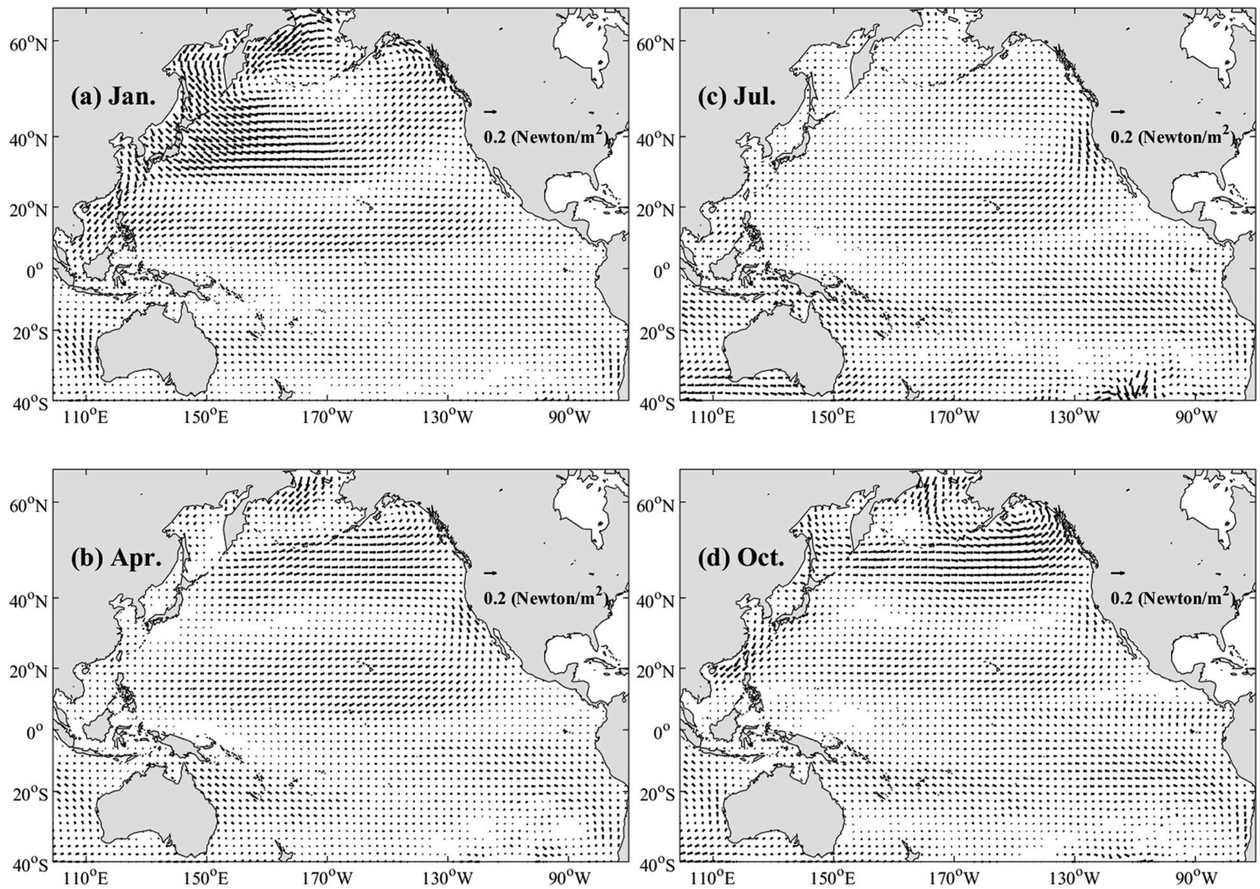

Fig. 2. Climatological monthly mean wind stress on (a) January, (b) April, (c) July, and (d) October from the Comprehensive Ocean-Atmosphere Data Set (COADS) (Diaz et al., 2002).

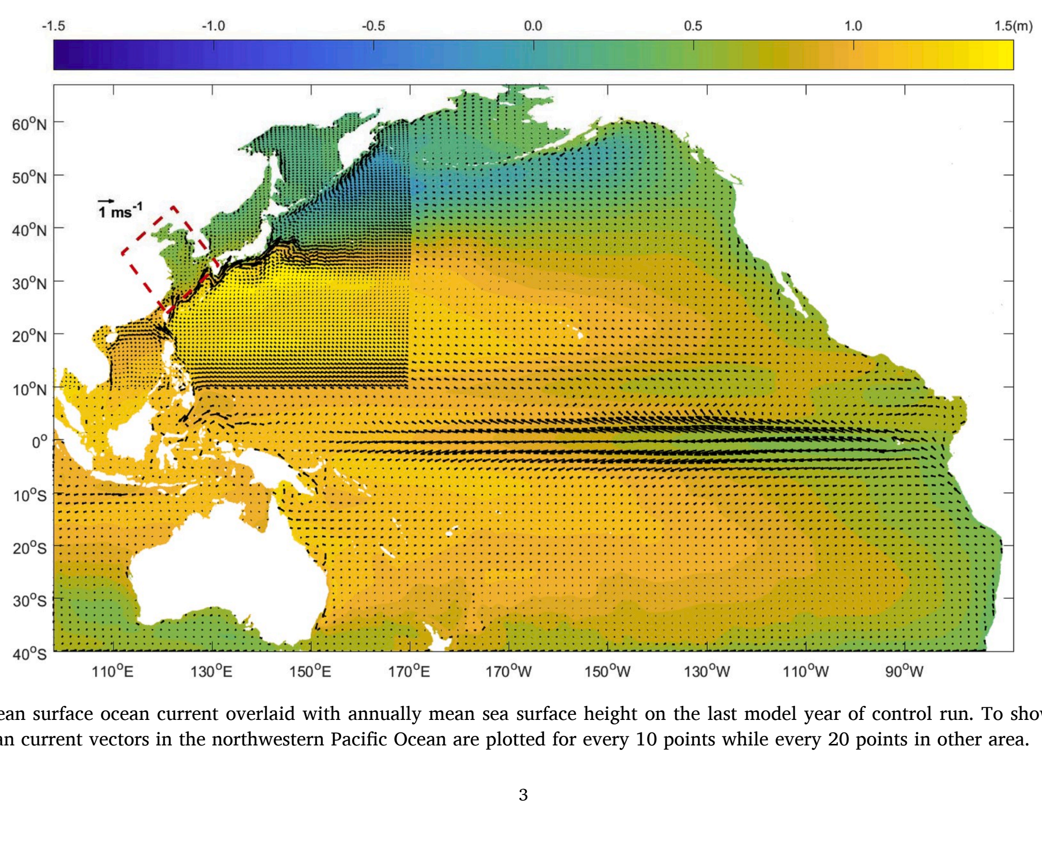

Fig. 3. Annually-mean surface ocean current overlaid with annually mean sea surface height on the last model year of control run. To show western boundary current clearly, ocean current vectors in the northwestern Pacific Ocean are plotted for every 10 points while every 20 points in other area.

and the output in the last model year is used to do the dynamic analysis. In case 2, we run the model in a similar way, except that the TWS is closed (see Fig. 4b).

As shown in Fig. 4, the model can properly reproduce the main characteristics of western boundary current of the Pacific Ocean and the ECS shelf circulation. Since our focus is on the lowest order dynamics regulating the shelf circulation, only the annual mean model results are shown. The shelf circulation has a poleward transport year around, as it appears to be counter-wind in winter and downwind in summer (Guan and Fang, 2006). To examine the influence of wind stress on the shelf circulation we compare the shelf circulations simulated with or without wind forcing over the ECS. In contrast to the control run, the TUS volume flux only increases 4%, when the wind stress is removed (Fig. 4c). Moreover, the cross-shelf water exchange has been slightly changed, and water transport through TWS increases relative to the control run (see Figs. 4c and 5). Hence, including the wind stress over the ECS seems to slightly increase the transport through the TWS, but it also slightly decreases cross-shelf transport of the Kuroshio Current. Overall, the wind stress seems to diminish the shelf circulation. Therefore, local wind stress is not the dominant force for driving the annual mean shelf circulation, although it plays an important role on the seasonal variation of shelf circulations (Wu et al., 2014).

As suggested by Fang and Zhao (1988), there is a south-north surface difference which gives rise to a pressure force driving a northward flowing flow from South China Sea to TUS. Why is there such a sea surface slope? Is this barotropic force the main factor driving the shelf circulation? As a test, we closed the TWS. However, when the TWS is closed, the volume flux through TUS shows a negligible variation (less than 5%, see Fig. 4c) only. In other words, the TUS volume flux is insensitive to whether the TWS is closed or not. In contrast, the cross-shelf volume flux (see Fig. 5) shows a significant variation with respect to the control run. When the TWS is closed, the Kuroshio intrusion northeast of Taiwan is significantly enhanced. In this case the cross-shelf volume flux of the Kuroshio is increased from 0.7 Sv to 2.0 Sv to compensate the loss of volume flux through the TWS. Therefore, the total amount of poleward water transport in the ECS and through the TUS is nearly independent of whether the TWS is open or closed, i.e. the dynamic effect of the south-north pressure gradient built up by the gyre-scale circulation cannot be cut off by closing the TWS.

Results from these experiments imply that there is another dynamic factor dominating the volume flux through TUS. This dynamic factor is very strong and it requires a nearly constant volume flux (2.2 Sv) through TUS regardless of whether there is wind stress in the local area or not. Moreover, it does not depend on the topography east of China either. Even if the TWS is closed, the circulation system can still drive the Kuroshio water to offset the volume flux through the TUS.

3. The major mechanism driving water mass flux through the TUS

To identify the major dynamic factors regulating the shelf circulation, we use the general form of momentum balance,

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}\cdot\nabla\boldsymbol{u} + f\vec{k}\times\boldsymbol{u} = -\frac{1}{\rho}\nabla p + \boldsymbol{F}_H + \boldsymbol{F}_Z, \tag{1}$$

where $\vec{k}$ is a vertical unit vector, f is planetary vorticity, $\boldsymbol{u}$ represents the velocity vector, and $\boldsymbol{F}_H(\boldsymbol{F}_Z)$ represents horizontal (vertical) turbulent momentum mixing due to smaller scale motions (Pedlosky, 1996). Integrating this equation along line C-D (see Fig. 7) and from the sea bottom (z_b) to the sea surface (η) leads to,

$$T_n = \frac{1}{f}\int_C^D \left\{ \int_{z_b}^{\eta} \left[\underbrace{-\partial u/\partial t}_{accel} \underbrace{-\boldsymbol{u}\cdot\nabla u}_{adv} \underbrace{-\nabla p/\rho}_{prsgrd} \underbrace{+\boldsymbol{F}_{\mathrm{H}}}_{hvisc} \right] dz \underbrace{+\boldsymbol{\tau}_{wind}}_{wind} \underbrace{-\boldsymbol{\tau}_{bottom}}_{bstr} \right\} dx, \tag{2}$$

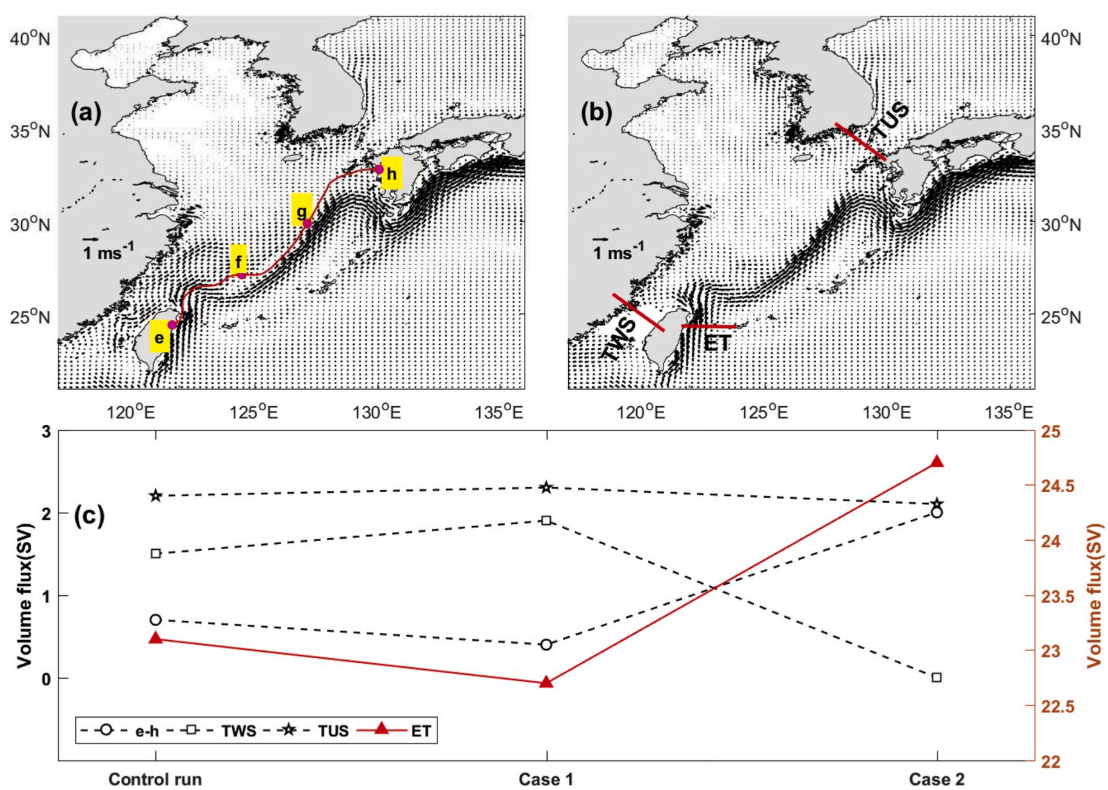

Fig. 4. (a) and (b) are the enlarged ocean current maps in the ECS from case 1 and 2, respectively. The line e-h indicates the integration line along which the cross-shelf volume flux is calculated. (c) shows the volume flux across the transects Taiwan Strait (TWS), Tsushima Strait (TUS) and east of Taiwan (ET) and e-h, for control run, case 1 and 2, respectively.

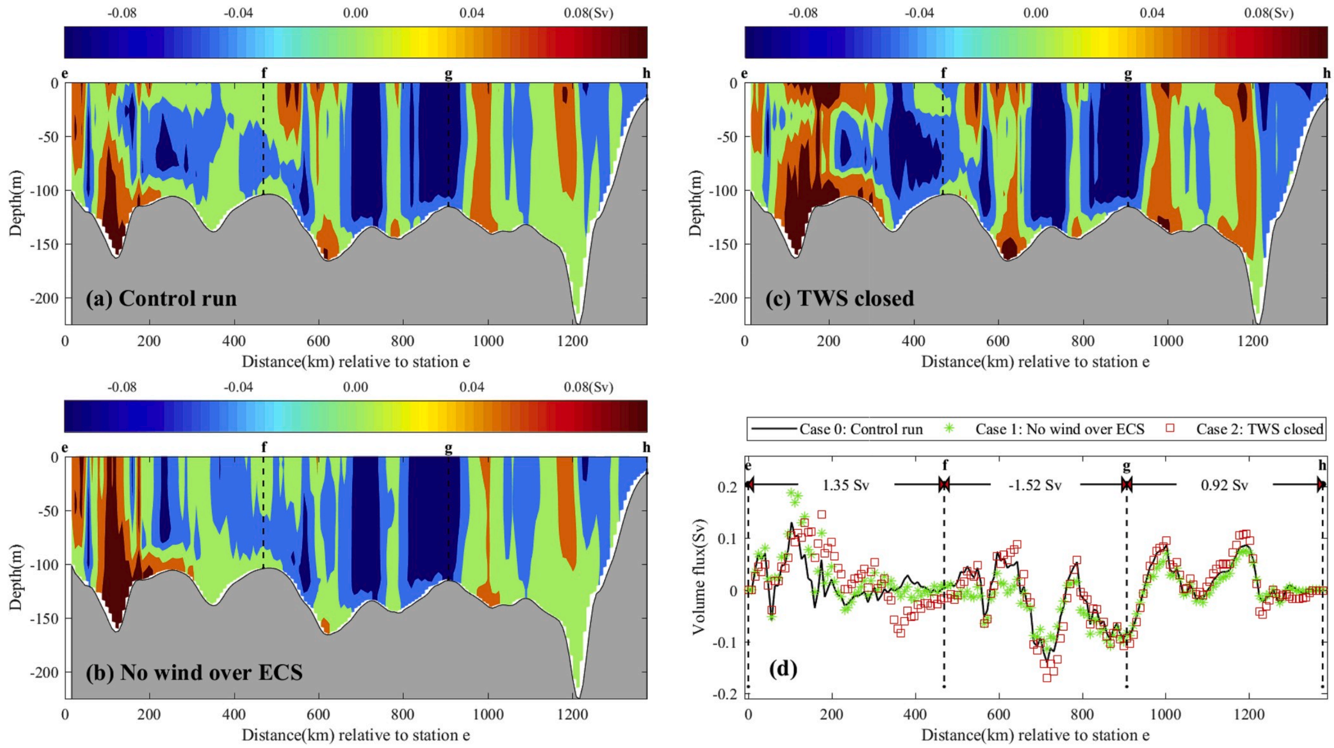

Fig. 5. (a–c) Annual mean cross-shelf volume flux for three cases. (d) vertically integrated volume flux across the line e-h (see Fig. 4) where the numbers show volume flux for case 2.

where $T_n = \int_C^D \int_{z_b}^{\eta} v dz dx$, and τindicates wind or bottom stress per unit density. Thus, volume flux T_n is composed of six terms: T_{accel} T_{adv} T_{prsg} T_{hvisc} T_{wind}, and T_{btm}, where $T_{accel} = \frac{-1}{f}\int_C^D \int_{z_b}^{\eta} \frac{\partial u}{\partial t} dz dx$, and the other terms are similarly defined. Fig. 6 shows the volume flux contributions from each term in eq. (2) for the 21-year control run. It is important to note that wind stress term T_{wind} plays a leading role by creating a −4.6 Sv (equatorward) volume flux. It is interesting to note that the pressure term T_{prsgrd} play a role opposite to the wind stress term. When wind stress drives water masses in motions, a pressure gradient force is set up, which acts as a resistance against the motions. On the other hand, the contributions from other terms are negligible, comparing with these two terms.

It is very important to note that model results show a net equatorward volume flux of 2.2 Sv across line C-D (see Figs. 6 and 7). Note that wind stress is the primary and external driving force, which is the primary source of this volumetric flux; on the other hand, pressure force is part of the response of the circulation system to the wind force. According to mass conservation law, this annual mean volume flux must be

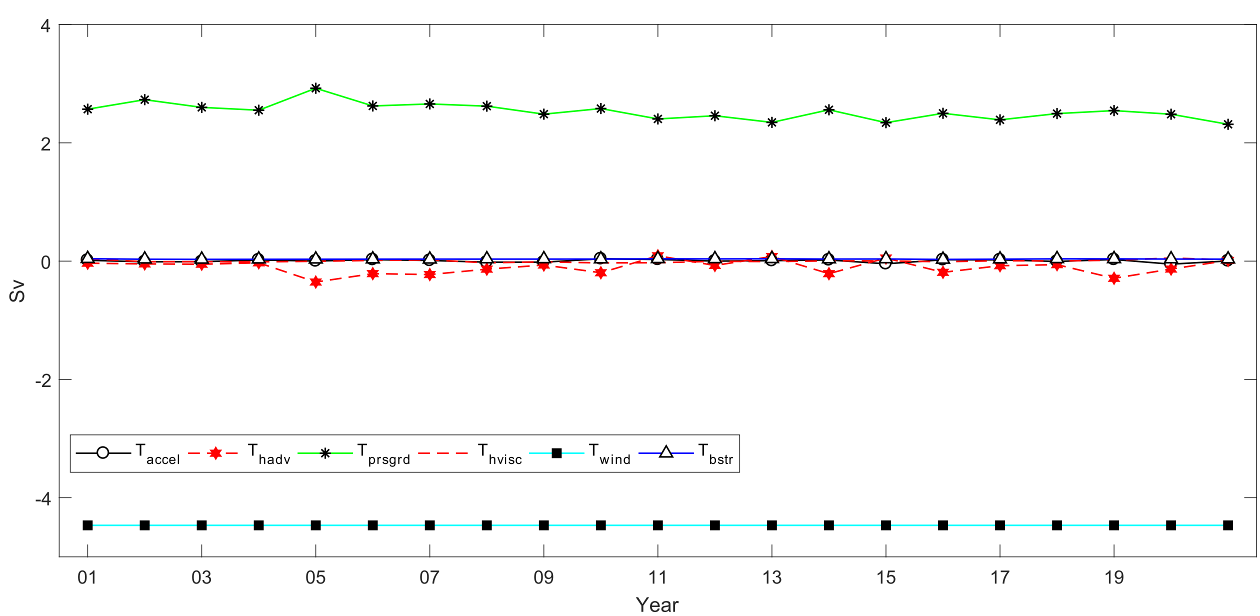

Fig. 6. Time series of volume flux contribution from each term in equation (2) during the 21-year control run.

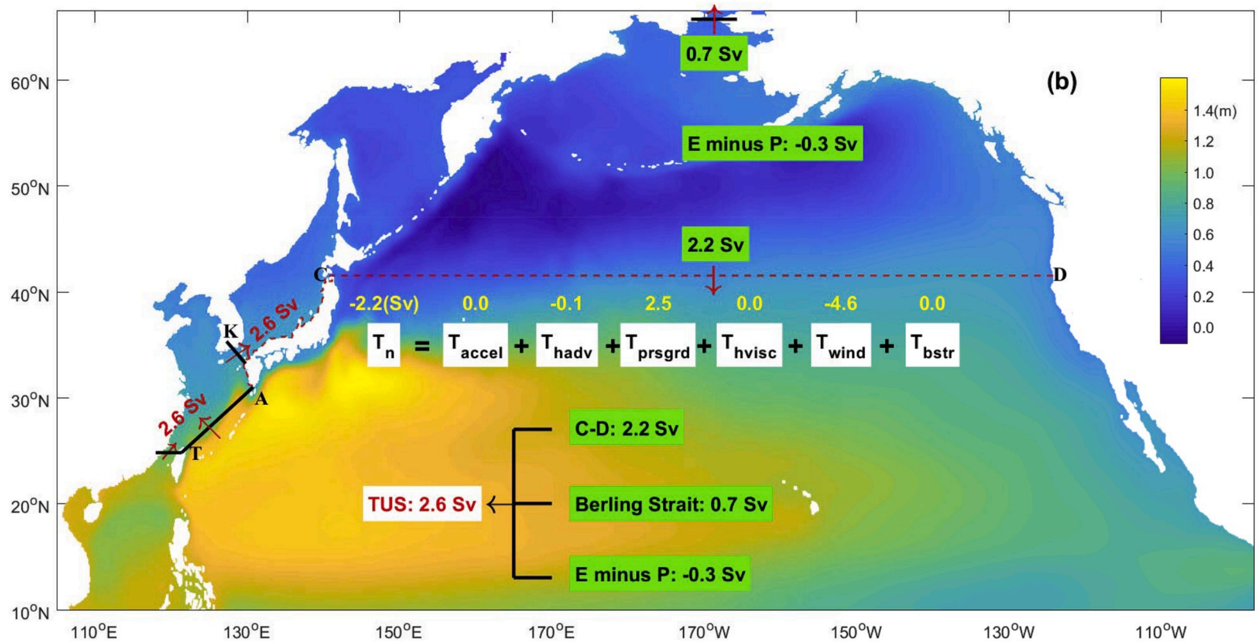

Fig. 7. A sketch showing that the shelf circulation is mainly regulated by the circulation in the open ocean. The contour map shows the annually averaged sea surface height on the last model year.

compensated by the net volume fluxes through TUS, Bering Strait, and evaporation or precipitations north of the line K–C-D. In fact, the volume flux through Bering Strait is estimated as a poleward flux of 0.7 Sv for climatology mean before 2000 (Woodgate, 2018), and the volume flux contribution from the evaporation and precipitation is estimated as −0.3 Sv based on the data set of COADS (Diaz et al., 2002). Thus, it is clear that the ECS shelf circulation is dominantly driven by this equatorward volume flux of 2.2 Sv. Thus, the 2.6 Sv volume flux through TUS will be properly balanced by the net equatorward flux of 2.2 Sv, poleward flux of 0.7 Sv through Bering Strait and the flux of −0.3 Sv from the evaporation and precipitation. It is reasonable to say that wind stress over the Pacific Ocean east of Japan drives a net equatorward volume flux of 2.2 Sv and this flux must be compensated primarily by that through the TUS.

In other words, this net equatorward volume flux will lower the sea surface level north of line C-D, but will raise that south of the line C-D, which is favorable to set up a barotropic pressure gradient along the coasts of China. This north-south sea surface slope favors the northward shelf circulation which transport shelf water through the TUS and Tsugaru/Soya Straits to complete the ocean circulation. This process could be clearly illustrated by a reduced gravity model. In such a model, the gradient of layer thickness along the western boundary is linked to the wind stress curl in the ocean interior, and sea surface height (SSH) is directly linked to the upper layer thickness gradient, $\nabla\eta = (g'/g)\nabla D$; Thus, equation (4.44) in (Huang, 2010) can be rewritten as

$$\frac{\partial\eta}{\partial y} = -\frac{1}{\rho_0 g D}(x_e - x_w)\frac{\partial\tau^x}{\partial y} < 0, \tag{3}$$

where η is SSH, g gravity, D the thickness of upper layer in a 1.5 layer model, τ^x is the zonal component of the wind stress, x_e and x_w are the locations of the eastern and western boundary in the Pacific Ocean, respectively. The right hand side of equation (3) is negative, because of the negative wind stress curl east of Japan. Thus, along the western boundary (in the subtropical gyre) the sea surface height will decrease poleward, that is to say, the sea level in the ECS will be higher than that in the Japan Sea. This south-north barotropic pressure gradient is the main cause for the poleward shelf circulation. It is important to note that this sea surface height pattern is mainly set up by the basin scale wind stress rather than local wind. In other words, the basin scale wind stress provides a background pressure field for the marginal seas (see Fig. 7), which is the main factor regulating the shelf circulation system.

Accordingly, the volume flux through TUS are subject to the wind stress variation over the Pacific Ocean. In the northeastern Pacific Ocean, there is well-known Pacific Decadal Oscillation (PDO) (Zhang et al., 1997). The shelf circulation should be subject to this interannual variability. To examine this, we carried out a 20-year hind-cast run from 1981 to 2000, where the model is forced by monthly mean wind stress from ECWMF (https://apps.ecmwf.int/datasets/data/interim-full-moda/levtype=sfc/) (Dee et al., 2011). We also run two additional cases: in case 1 the wind stress is set to zero over the ECS, and in case 2 the TWS is closed. The annual mean volume fluxes through the TUS (T_{TUS}, T_{TUS1}, and T_{TUS2}) are outputted for these three cases, as shown in Fig. 8.

Same as the climatology run, the contributions from wind stress and pressure gradient are one order of magnitude larger than others (see Fig. 8a and b). It is important to note that the net volume flux (T_n) across line C-D is significantly correlated with the PDO index with a correlation parameter of 0.7, as shown in Fig. 8c. Moreover, the PDO index and volume flux through TUS are negatively correlated, and the correlation coefficient reaches its maximum when we use 5-year lag.

When the wind stress over the ECS is cut off or the TWS is closed, the volume flux through TUS (see T_{TUS1} and T_{TUS2} in Fig. 8) remains relatively steady, similar to the climatology run. It is worthy iterating that the local wind over ECS tends to decrease the TUS volume flux, as well as the Kuroshio intrusion. The cut off of the local wind leads to ~10% increase of the total flux through TUS and the closing of TWS tends to reduce the total flux through TUS about 10%. In other words, the contribution from local wind stress is one order of magnitude smaller than that from the open sea. Thus, it is reasonable to say that the TUS volume flux and its interannual variation are mainly regulated by the wind stress in the open ocean. In other words, the shelf circulation over the ECS and Kuroshio intrusion are mainly regulated by wind stress in the open ocean.

4. Conclusion

Although the ECS shelf circulation has been extensively studied, the dynamic connection between the shelf circulation and the open ocean

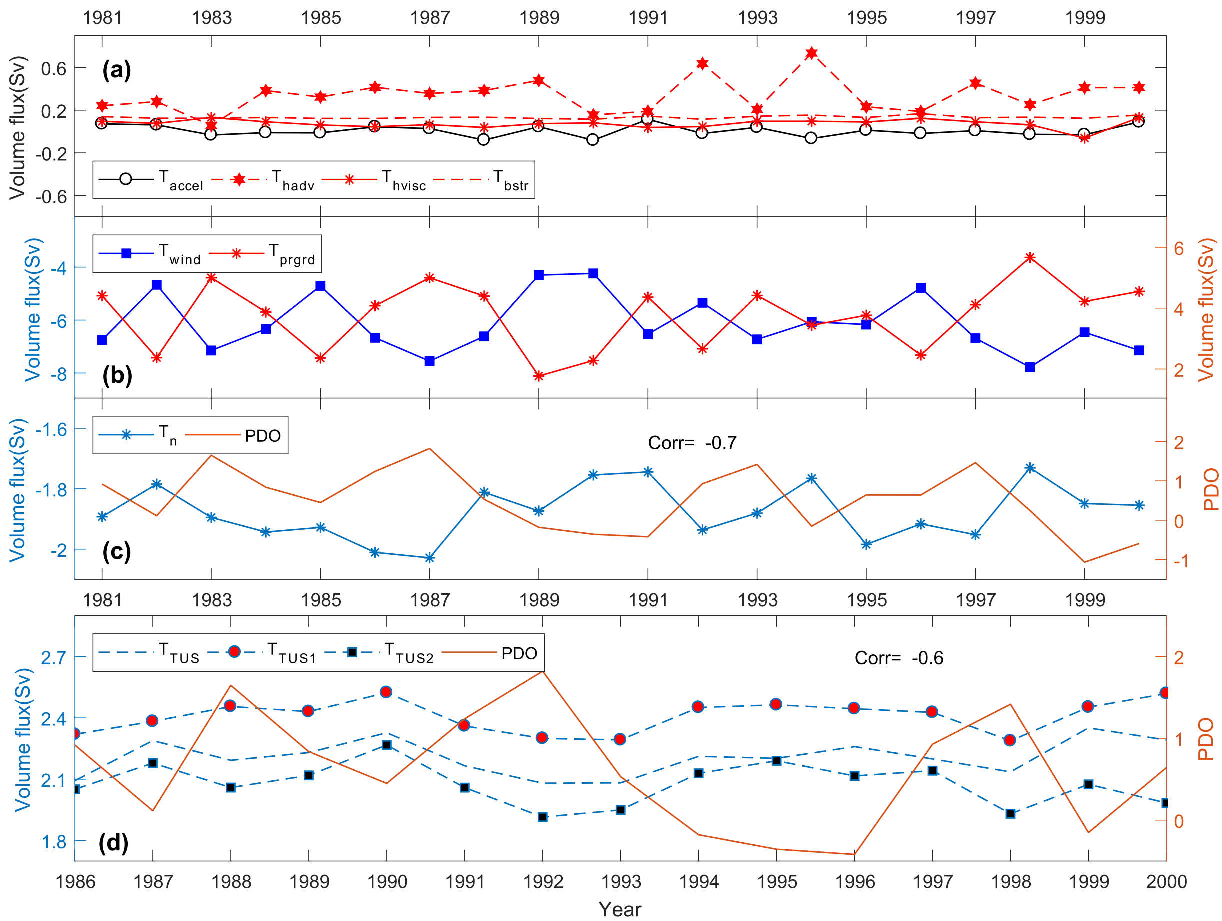

Fig. 8. Time series of volume flux contribution from each term in equation (2) for the hindcast run. (c) Time series of net volume flux east of Japan and PDO index. (d) Time series of volume flux through TUS from 1986 to 2000. In (d), the abscissa of PDO index is from 1981 to 1995 whose variation leads 5 years to that of the TUS volume flux. T_{TUS}, T_{TUS1}, and T_{TUS2} are the volume flux through TUS for the control run, case 1 and 2, respectively.

circulation remained unclear. Here, this circulation is clearly demonstrated through numerical experiments and theoretical analysis.

Wind stress over the open Pacific Ocean east of Japan drives a net equatorward volume flux of 2.2 Sv in the open ocean east of Japan. This flux is determined by the wind-driven ocean circulation in the Pacific Ocean interior; whatever the bathymetry of the ECS is (TWS is closed or not), there must be a poleward compensating shelf circulation in the ECS to offset this equatorward volume flux. Thus, there must be the Kuroshio intrusion and a poleward ECS shelf circulation to complete this ocean circulation gyre, and this volumetric flux must move through the ECS, TUS, Japan Sea and Tsugaru/Soya Straits, and finally joining the Oyashio. Due to the shallow bathymetry of TWS, the TWC can only contribute a flux of 1.2 Sv, and the rest part of 1.4 Sv must come from the Kuroshio intrusion onto the ECS shelf. Therefore, for the time scales longer than one year and to the lowest order, the ECS shelf circulation and the Kuroshio onshore intrusion are determined by the remote wind stress east of Japan rather than the local wind stress. Furthermore, it should take 5 years for the PDO signals to affect the shelf circulation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDB42040201), National Key Research, Development Program of China (2017YFC1404000, 2016YFC1401601 and 2017YFA0604102), the National Natural Science Foundation of China (NSFC) (41876019), the Foundation for Innovative Research Groups of NSFC (41421005), and NSFC-Shandong Joint Fund for Marine Science Research Centers (U1406401). It was also supported by the High Performance Computing Center at the IOCAS, and Youth Innovation Promotion Association CAS. Model outputs are available upon request from the corresponding authors (yangdezhou@qdio.ac.cn).

References

Amante, C., Eakins, B.W., 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis, vol. 24. NOAA Technical Memorandum NESDIS NGDC. https://doi.org/10.7289/V5C8276M.

Anderson, J., Rodriguez, A., Fletcher, C., Fitzgerald, D., 2001. Researchers focus attention on coastal response to climate change. Eos, Transactions American Geophysical Union 82 (44), 513–520. https://doi.org/10.1029/01EO00304.

Chen, C.T.A., 1996. The Kuroshio intermediate water is the major source of nutrients on the East China Sea continental shelf. Oceanol. Acta 19 (5), 523–527.

Chen, H.W., Liu, C.T., Matsuno, T., Ichikawa, K., Fukudome, K., Yang, Y., Doong, D.J., Tsai, W.L., 2016. Temporal variations of volume transport through the Taiwan Strait, as identified by three-year measurements. Continent. Shelf Res. 114, 41–53. https://doi.org/10.1016/j.csr.2015.12.010.

Dee, D.P., et al., 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q. J. Roy. Meteorol. Soc. 137 (656), 553–597. https://doi.org/10.1002/Qj.828.

Diaz, H., Folland, C., Manabe, D., Parker, Reynolds, Woodruff, S., 2002. Workshop on Advances in the Use of Historical Marine Climate Data, pp. 377–380.

Fang, G., Zhao, B., Zhu, Y., 1991. Water volume transport through the Taiwan Strait and the continental skelf of the east China sea measured with current meters. In:

Takano, K. (Ed.), Elsevier Oceanography Series. Elsevier, pp. 345–358. https://doi.org/10.1016/S0422-9894(08)70107-7.

Fang, G.H., Zhao, B.R., 1988. A note on the main forcing of the Northeastward flowing current off the southeast China coast. Prog. Oceanogr. 21 (3–4), 363–372. https://doi.org/10.1016/0079-6611(88)90014-6.

Guan, B.X., Fang, G.H., 2006. Winter counter-wind currents off the southeastern China coast: a review. J. Oceanogr. 62 (1), 1–24.

Guo, X., Miyazawa, Y., Yamagata, T., 2006. The Kuroshio onshore intrusion along the shelf break of the east China sea: the origin of the Tsushima warm current. J. Phys. Oceanogr. 36 (12), 2205–2231.

Hogan, P.J., Hurlburt, H.E., 2005. Sensitivity of simulated circulation dynamics to the choice of surface wind forcing in the Japan/East Sea. Deep-Sea Res Pt Ii 52 (11–13), 1464–1489. https://doi.org/10.1016/j.dsr2.2005.01.013.

Hu, J.Y., Kawamura, H., Li, C.Y., Hong, H.S., Jiang, Y.W., 2010. Review on current and seawater volume transport through the Taiwan Strait. J. Oceanogr. 66 (5), 591–610.

Huang, R.X., 2010. Ocean Circulation : Wind-Driven and Thermohaline Processes. Cambridge University Press.

Ichikawa, H., Beardsley, R., 2002. The current system in the Yellow and east China seas. J. Oceanogr. 58 (1), 77–92. https://doi.org/10.1023/a:1015876701363.

Isobe, A., 2008. Recent advances in ocean-circulation research on the Yellow Sea and east China sea shelves. J. Oceanogr. 64 (4), 569–584.

Ito, M., Morimoto, A., Watanabe, T., Katoh, O., Takikawa, T., 2014. Tsushima warm current paths in the southwestern part of the Japan sea. Prog. Oceanogr. 121, 83–93. https://doi.org/10.1016/j.pocean.2013.10.007.

Jacobs, G.A., Hur, H.B., Riedlinge, S.K., 2000. Yellow and East China Seas response to winds and currents. J Geophys Res-Oceans 105 (C9), 21947–21968. https://doi.org/10.1029/2000jc900093.

Locarnini, R.A., et al., 2013. In: Levitus, Temperature(S., Mishonov Technical, A. (Eds.), World Ocean Atlas 2013, NOAA Atlas NESDIS, vol. 73, p. 40.

Marchesiello, P., McWilliams, J.C., Shchepetkin, A., 2001. Open boundary conditions for long-term integration of regional oceanic models. Ocean Model. 3 (1–2), 1–20. Pii S1463-5003(00)00013-5Doi 10.1016/S1463-5003(00)00013-5.

Na, H., Isoda, Y., Kim, K., Kim, Y.H., Lyu, S.J., 2009. Recent observations in the straits of the East/Japan Sea: a review of hydrography, currents and volume transports. J. Mar. Syst. 78 (2), 200–205. https://doi.org/10.1016/j.jmarsys.2009.02.018.

Oey, L.Y., Hsin, Y.C., Wu, C.R., 2010. Why does the Kuroshio northeast of Taiwan shift shelfward in winter? Ocean Dynam. 60 (2), 413–426. https://doi.org/10.1007/s10236-009-0259-5.

Pedlosky, J., 1986. Geophysical Fluid Dynamics. Springer-Verlag, New York.

Pedlosky, J., 1996. Ocean Circulation Theory. Springer-Verlag, New York.

Qiu, B., Imasato, N., 1990. A numerical study on the formation of the Kuroshio counter current and the Kuroshio branch current in the east China sea. Continent. Shelf Res. 10 (2), 165–184.

Shchepetkin, A.F., McWilliams, J.C., 2005. The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. Ocean Model. 9 (4), 347–404. https://doi.org/10.1016/j.ocemod.2004.08.002.

Su, J., 1998. Circulation dynamics of the China Seas north of 18°N. Sea 11, 483–505.

Su, J.L., Pan, Y.Q., Liang, X.S., 1994. Kuroshio intrusion and Taiwan warm current. In: Zhou, D., et al. (Eds.), Oceanology of China Seas, vol. 1. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 59–77. https://doi.org/10.1007/978-94-011-0862-1_7.

Takikawa, T., Yoon, J.H., 2005. Volume transport through the Tsushima Straits estimated from sea level difference. J. Oceanogr. 61 (4), 699–708. https://doi.org/10.1007/s10872-005-0077-4.

Teague, W.J., Hwang, P.A., Jacobs, G.A., Book, J.W., Perkins, H.T., 2005. Transport variability across the Korea/Tsushima Strait and the Tsushima Island wake. Deep-Sea Res Pt Ii 52 (11–13), 1784–1801. https://doi.org/10.1016/j.dsr2.2003.07.021.

Wang, B., Chen, J.F., Jin, H.Y., Li, H.L., Huang, D.J., Cai, W.J., 2017. Diatom bloom-derived bottom water hypoxia off the Changjiang estuary, with and without typhoon influence. Limnol. Oceanogr. 62 (4), 1552–1569. https://doi.org/10.1002/lno.10517.

Wang, J.H., Wu, J.Y., 2009. Occurrence and potential risks of harmful algal blooms in the East China Sea. Sci. Total Environ. 407 (13), 4012–4021. https://doi.org/10.1016/j.scitotenv.2009.02.040.

Woodgate, R.A., 2018. Increases in the Pacific inflow to the Arctic from 1990 to 2015, and insights into seasonal trends and driving mechanisms from year-round Bering Strait mooring data. Prog. Oceanogr. 160, 124–154. https://doi.org/10.1016/j.pocean.2017.12.007.

Wu, C.-R., Wang, Y.-L., Lin, Y.-F., Chao, S.-Y., 2017. Intrusion of the Kuroshio into the south and east China seas. Sci Rep-Uk 7 (1), 7895. https://doi.org/10.1038/s41598-017-08206-4.

Wu, C.R., Hsin, Y.C., Chiang, T.L., Lin, Y.F., Tsui, I.F., 2014. Seasonal and interannual changes of the Kuroshio intrusion onto the east China sea shelf. J. Geophys. Res.: Oceans 119 (8), 5039–5051. https://doi.org/10.1002/2013JC009748.

Yang, D.Z., et al., 2018. Topographic beta spiral and onshore intrusion of the Kuroshio current. Geophys. Res. Lett. 45 (1), 287–296. https://doi.org/10.1002/2017gl076614.

Yang, D.Z., Yin, B.S., Liu, Z.L., Bai, T., Qi, J.F., Chen, H.Y., 2012. Numerical study on the pattern and origins of Kuroshio branches in the bottom water of southern East China Sea in summer. J Geophys Res-Oceans 117 (C2), C02014. https://doi.org/10.1029/2011jc007528.

Zhang, Y., Wallace, J.M., Battisti, D.S., 1997. ENSO-like interdecadal variability: 1900-93. J. Clim. 10 (5), 1004–1020. https://doi.org/10.1175/1520-0442(1997)010<1004:Eliv>2.0.Co.

Zheng, Q.N., Fang, G.H., Song, Y.T., 2006. Introduction to special section: dynamics and circulation of the Yellow, east, and south China seas. J Geophys Res-Oceans vol. 111. Artn.

Zhou, F., et al., 2017a. Investigation of hypoxia off the Changjiang Estuary using a coupled model of ROMS-CoSiNE. Prog. Oceanogr. 159, 237–254. https://doi.org/10.1016/j.pocean.2017.10.008.

Zhou, Z.X., Yu, R.C., Zhou, M.J., 2017b. Resolving the complex relationship between harmful algal blooms and environmental factors in the coastal waters adjacent to the Changjiang River estuary. Harmful Algae 62, 60–72. https://doi.org/10.1016/j.hal.2016.12.006.

Zweng, M.M., et al., 2013. World Ocean atlas 2013. In: Levitus, Salinity (S., Mishonov Technical, A. (Eds.), NOAA Atlas NESDIS, vol. 74, p. 33.