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Connectivity among straits of the northwest Pacific marginal seas

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[1] The connectivity among straits of the northwest Pacific marginal seas is investigated with a primitive-equation ocean circulation model simulated for 10 years from 1994 to 2003. Over the simulation interval the temporal and spatial means and variations of the model sea surface temperature are comparable to those of the satellite sea surface temperature. The model transport through the straits shows good agreement with the available observations and a high seasonality in the Taiwan Strait, the Korea Strait, and the Soya Strait but relatively low seasonality in the Tsugaru Strait. The Kuroshio and Taiwan Warm Current (TWC) are two sources of water flowing through the Korea Strait. The volume transport in the Korea Strait is dominated by the Kuroshio in winter (83%) and by the TWC in summer (66%). Relative to the transport through the Korea Strait, the transport percentages of the Tsugaru Strait connecting to the northwest Pacific Ocean are 79% in winter and 65% in summer. The seasonality of the Korea Strait transport is positively correlated with the cross-strait wind stress. The drifter experiments show that it takes about 4 months for most of the drifters deployed in the Taiwan Strait to enter the Korea Strait and more than 2 months to travel from the Korea Strait to the Tsugaru and Soya straits.

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1. Introduction

[2] The northwest Pacific Ocean has four major marginal seas: the East China Sea (ECS), the Yellow Sea (YS), the South China Sea (SCS), and the Japan/East Sea (JES) (Figure 1). The ECS has a shallow shelf directly connected to the Pacific Ocean. The YS is also very shallow (average depth of 44 m) and a tide-dominated sea. The SCS and JES are deep basins surrounded by many islands. These marginal seas are connected to each other and the Pacific Ocean by four straits: the Taiwan Strait between China and Taiwan, the Korea Strait between Korea and Kyushu island of Japan, the Tsugaru Strait between the two northern islands of Japan (Honshu and Hokkaido), and the Soya Strait between the Sakhalin island of Russia and Hokkaido. The current system through the straits is complex. It is important to identify the circulation and variability in the marginal seas and their relation to each other and the northwest Pacific Ocean because the currents among the marginal seas distribute heat, salt, and other material through the straits.

[3] It is accepted that the Tsushima Current (TC) flows into the East/Japan Sea (EJS) through the Korea Strait and then flows out to the northern part of the Pacific Ocean through the Tsugaru Strait and Soya Strait [*Moriyasu*, 1972; *Teague et al.*, 2003]. However, the origin of the current is still debated since there are limited direct observational data of its path, and the unique hydrographic characteristics of the TC are too slight to trace its path. There are two major views of the origin of the TC. One is that the current separates directly from the Kuroshio around 30°30′N, 129°E, southwest of Kyushu Island of Japan [*Uda*, 1934; *Nitani*, 1972; *Lie et al.*, 1998]. The other is that the TC is a continuation of the Taiwan Warm Current (TWC) originating from the Taiwan Strait, flowing northeastward on the continent shelf of the ECS, and entering the Korea Strait as the TC [*Beardsley et al.*, 1985; *Fang et al.*, 1991; *Zhu et al.*, 2004]. The existence of the TWC in the Taiwan Strait is well established during summer [*Fang et al.*, 1991; *Zhu et al.*, 2004], but recent measurements [*Zhu et al.*, 2004] suggest the TWC is episodic in winter and spring.

[4] Connectivity between the Taiwan Strait and the Korea Strait has been examined in several previous studies [*Isobe*, 1999; *Teague et al.*, 2003; *Kim et al.*, 2005; *Guo et al.*, 2006]. A numerical experiment [*Isobe*, 1999] shows that there is little connection in fall 1999 but strong connectivity between two straits during other seasons. Current observations also suggest little connectivity in fall 1999 [*Teague et al.*, 2003]. On the other hand, *Guo et al.* [2006] suggest that

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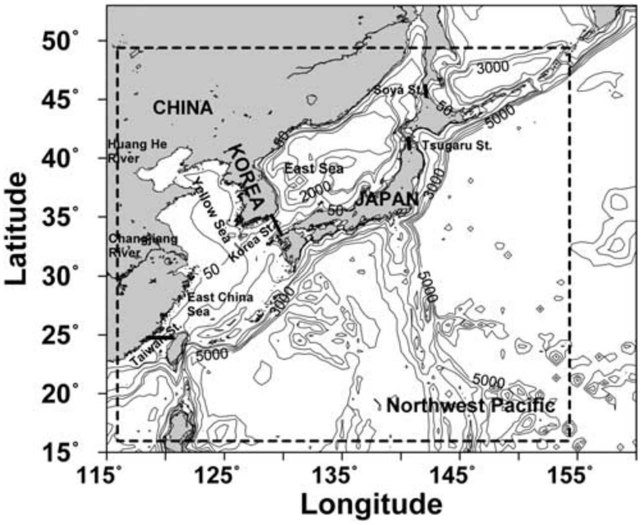

Figure 1. Bottom topography of the northwest Pacific model domain. The dashed box represents the nested model domain. The thick solid lines represent the sections monitoring transports in the straits and the Kuroshio. Contour lines are water depths in meters.

about half of the water passing the Korea Strait originates from the Taiwan Strait in summer, but 20% in winter on the basis of a tracer experiment in their numerical model. *Kim et al.* [2005] propose that the TC consists both of water originating from the Taiwan Strait and water originating directly from the Kuroshio on the basis of the observed oxygen isotope in spring.

[5] At the downstream end of the TC, there are available observations showing some connectivity between the Korea Strait and the Tsugaru/Soya straits; *Ito et al.* [2003] report a mean transport of 1.5 Sv in the Tsugaru Strait from 4 months of observations from November 1999 to March 2000. However, the observation period is too short to identify the seasonal variation in the Tsugaru Strait. There are even fewer transport observations in the Soya Strait, and the observation periods are even shorter. Moreover, the relative volume transport among straits relative to the Korea Strait is still unknown and not studied yet.

[6] In this study, the connectivity among the Taiwan Strait, Korea Strait, Tsugaru Strait, and Soya Strait is investigated through a numerical modeling study of the northwest Pacific marginal seas. The simulation results reveal the interannual and seasonal variations of the volume transport for all straits, and the relations between transport variations and seasonal wind fields. Section 2 describes the model and its implementation in a domain representing the northwest Pacific Ocean. In section 3 the performance of the model is evaluated by comparisons with extensive in situ and remotely sensed data. The variations of the transport for the straits are evaluated in section 4 along with connectivity among the straits in section 5. The summary and concluding remarks are given in section 6.

2. Model Description

[7] We use the Regional Ocean Modeling System (ROMS) for this study [*Haidvogel and Beckmann*, 1999; *Curchitser et al.*, 2005]. The model domain ranges from 16°N to 49°N and from 116°E to 154°E (dashed box in Figure 1). It includes the ECS, the YS, the JES, and the northwestern part of the Pacific Ocean. The horizontal grid has a nominal resolution of 0.1° with 20 vertical sigma levels and 330 × 390 horizontal grid points. The barotropic and baroclinic time steps are 9 and 90 s, respectively. The bottom topography used for the model is from ETOPO5, with a minimum depth of 5 m. Open boundary data are obtained from a regional northwest Pacific (NWP) model [*Seo et al.*, 2009]. The NWP model domain ranges from 15°N to 53°N and from 115°E to 160°E and has a horizontal resolution of 0.25° (Figure 1). The NWP model is nested into a data assimilative global model (Estimating the Circulation and Climate of the Ocean (ECCO); http://www.ecco-group.org/). The global model has a nominal resolution of 1°. We will focus on the high-resolution (0.1°) model in this paper rather than the regional NWP model or the global model.

[8] Freshwater discharges from Changjiang (Yangtze) River and Huang He (Yellow) River were included. The Changjiang discharge was estimated from the precipitation using the relationship between the precipitation and discharge in the work of *Senjyu et al.* [2006]. For the Huang He discharge, climatological data were used because its discharge is 1 order smaller than that of the Changjiang River. Tidal forcing was applied along the open boundaries using 10 major tidal components in order to include the tidal mixing effect on the sea surface temperature [*Egbert and Erofeeva*, 2002]. Vertical mixing is calculated by the KPP scheme [*Large et al.*, 1994]. Chapman, Flather, and clamped boundary conditions were used for free surface elevation, barotropic momentum, and baroclinic momentum, respectively [*Marchesiello et al.*, 2001]. The horizontal viscosity coefficient was set to 300 m^2/s.

[9] The surface atmospheric forcings for the hindcast simulation from 1994 to 2003 were daily mean winds and monthly mean heat fluxes from the European Center for Medium range Weather Forecasting (ECMWF). A bulk-flux formulation (based on the work of *Fairall et al.* [1996]) was used for calculation of the surface flux. The model was initialized with temperature, salinity, velocity, and sea surface height from the NWP model from January 1993. A 2-year spin-up run was performed using 1993 atmospheric forcing data to adjust the model ocean state for the hindcast simulation. The calculations examined in this study were for the period of 1994–2003.

3. Performance of Hindcast Simulations

3.1. Assessment of Sea Surface Temperature

[10] The temporal mean and standard deviation of the simulated SST are compared with those of the satellite SST from 1994 to 2003 (Figure 2). The satellite observations are 4 km data collected using the NOAA/AVHRR Pathfinder Version 5 distributed by Jet Propulsion Laboratory (http://poet.jpl.nasa.gov/). The paths of the Kuroshio, the TC, and the East Korean Warm Current (EKWC) are indicated by warm SST signatures. The Kuroshio, characterized by the warm water southwest of Japan, is defined in the simulation. The TC in the JES and EKWC [*Cho and Kim*, 2000] are also relatively well defined by warm water in the simula-

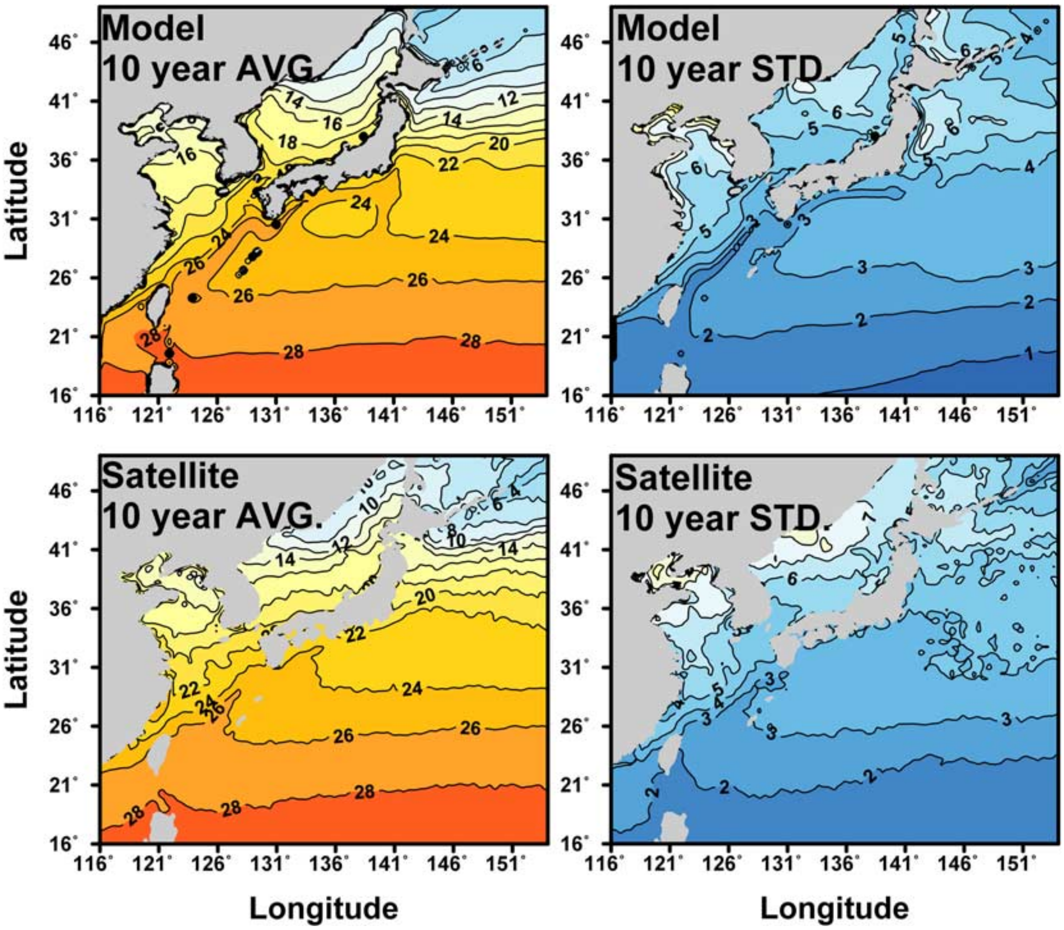

Figure 2. (top) Mean surface temperature and standard deviation from the model and (bottom) satellite observations, from January 1994 to December 2003.

tion. In general, the distribution of isotherms, and the maximum and minimum of the simulated mean SST are similar to those from the observations. Large temporal variances of SST (more than 7°C) are found in the coastal region of the YS and in the frontal region southeast of the Tsugaru Strait. Small variances (less than 2°C) are found in the southern area. Also, low variability of the Kuroshio is a common feature in both the model and the data.

[11] To examine seasonal variation, we compared SST for 1 month in each season: February, May, August, and November. The selected months represent winter, spring, summer and fall respectively. The seasonal variations in the observations and simulation are comparable in many aspects (Figure 3). Both the modeled and observed SST distributions show similar seasonal variation. The range of seasonal variations is about 2°C in the southern area and more than 10°C in the northern area. The locations of isotherm contours are comparable for all seasons although the satellite SST is not as smooth owing to the gridding of the data. Despite the relatively coarse model resolution, the path of the Kuroshio in the simulation is clearer than that in the satellite data. This difference may arise because the simulated SST is a bulk temperature whereas the satellite SST is a surface-skin temperature. Also, the daily composite satellite data we used may not show a distinct path of the Kuroshio owing to temporal and spatial interpolation during the compositing process.

3.2. Assessment of Modeled Current

[12] The simulated monthly mean surface velocity shows the seasonal variation of the current system (Figure 4). The northeastward current in the Taiwan Strait shows weak flow in fall and winter but strong flow in spring and summer. The TC entering into the Japan/East Sea through the Korea Strait is relatively weak in winter but strong in other seasons. The Kuroshio passing east of Taiwan follows the continental slope west of Ryukyu Islands, Japan. The current flows south of Japan and then separates from the Japanese coast between 33°N and 36°N. Compared to the seasonal variability in the Kuroshio, the currents in the marginal seas and straits show remarkable variability.

[13] Observations of the currents through the straits are limited owing to heavy ship traffic and active fishing, but observations of long-term transport through the Korea Strait have been reported recently. *Teague et al.* [2002, 2005] estimate its transport on the basis of the currents observed from 12 bottom-mounted acoustic Doppler current profilers (ADCPs) along two cross sections between May 1999 and March 2000. The mean transport during the whole period is 2.7 Sv in the Korea Strait, respectively. The maximum

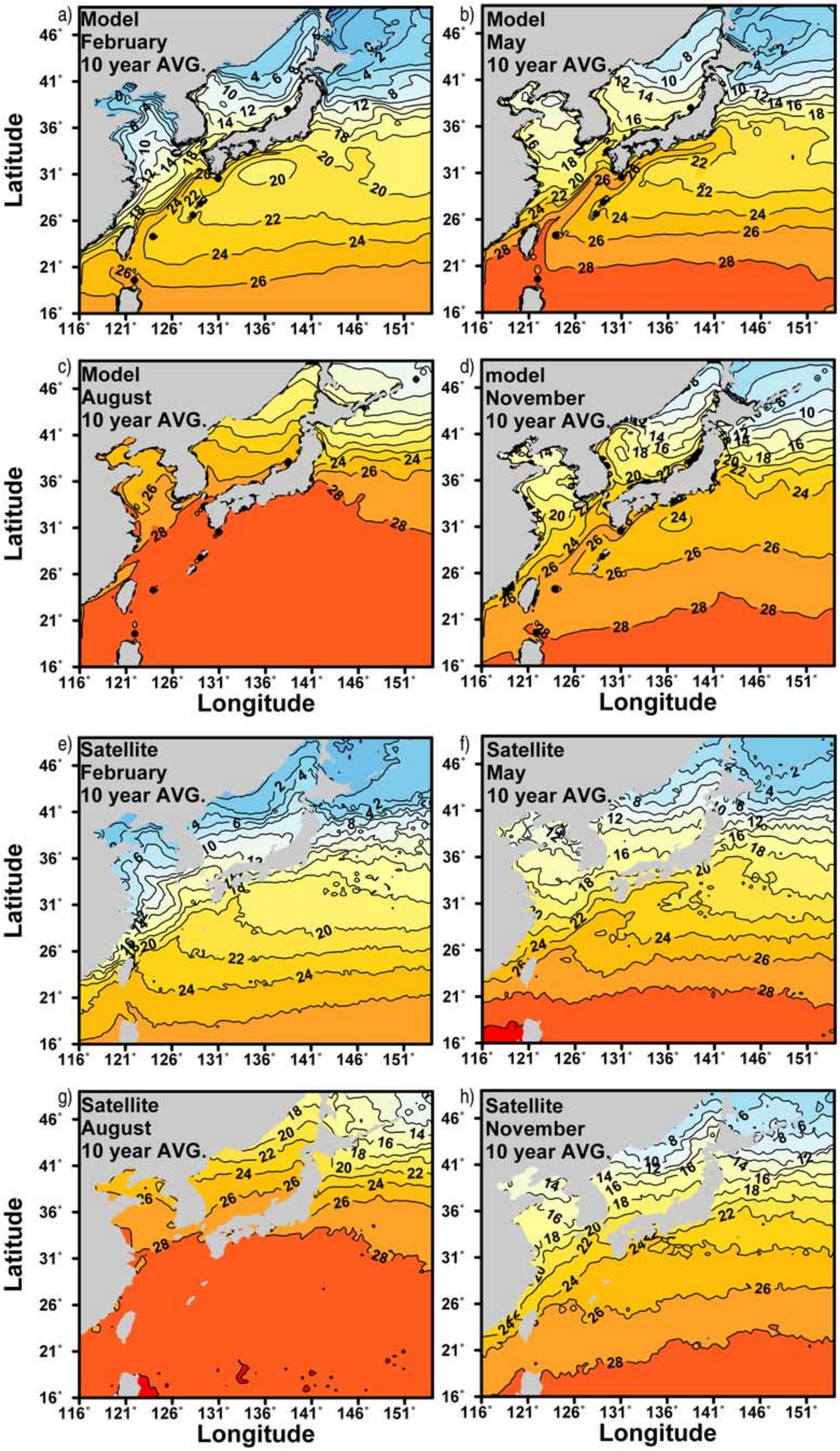

Figure 3. Temporally averaged mean sea surface temperatures from 1994 to 2003 for the (a–d) model and (e–h) satellite observations, in February, May, August, and November.

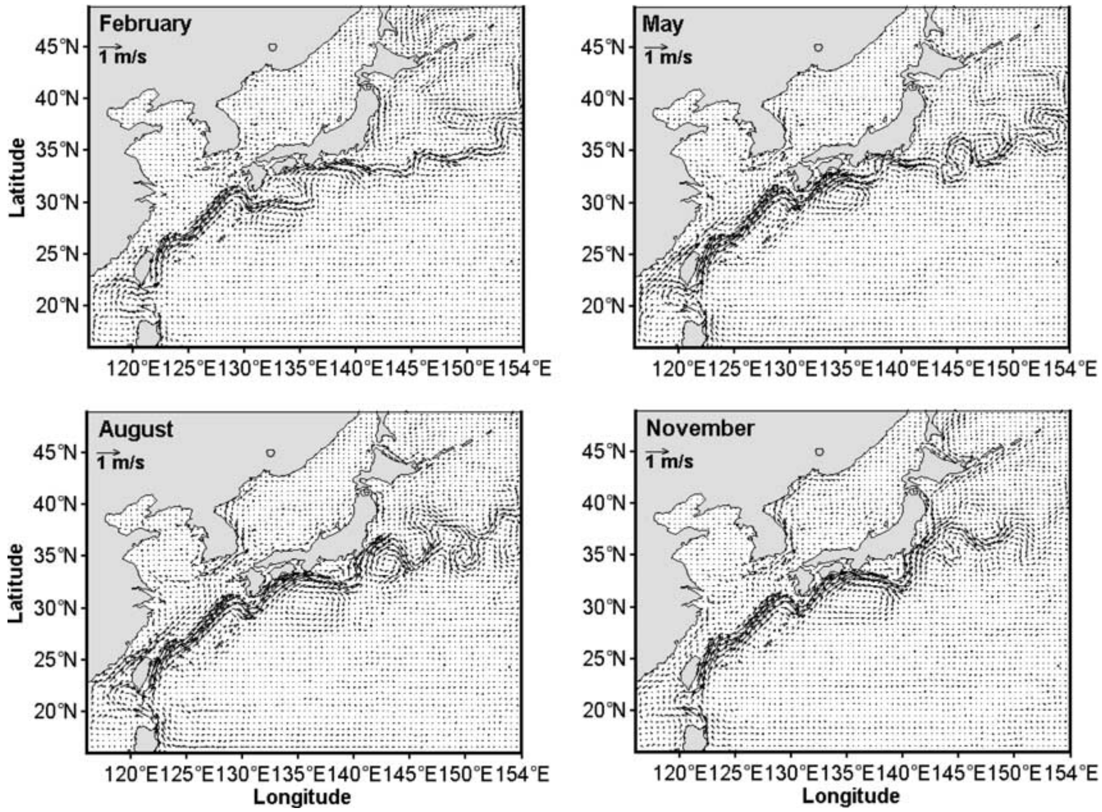

Figure 4. Temporally averaged mean sea surface currents from 1994 to 2003 for the model in February, May, August, and November.

transport was 3.59 Sv in October and the minimum was 1.67 Sv in January (Figure 5 with pluses). *Takikawa et al.* [2005] report transport variations for 5 years between February 1997 and August 2002, which includes the period of *Teague et al.* [2005]. Their data are obtained from an ADCP mounted on a ferryboat which makes round trips across the Korea Strait three times a week. The observed mean transport is 2.71 Sv from January 1999 to December 2000. The minimum and maximum monthly averaged transports are 1.73 Sv in January 2000, and 4.20 Sv in October 1999, respectively (Figure 5 with crosses). Compared with that of *Teague et al.* [2005], the maximum transport reported by *Takikawa et al.* [2005] is larger by about 0.61 Sv and the minimum transport is slightly larger.

[14] Given the uncertainty in the observed transports through the Korea Strait, the amplitude and phase of its seasonal variations are comparable in the simulation and observations (Figure 5). The simulated mean transport is 2.85 Sv between January 1999 and December 2000. Focusing on the period overlapping the observations [*Teague et al.*, 2005], the modeled transport is 2.95 Sv between May 1999 and March 2000. This is higher by 0.14 Sv than that of *Takikawa et al.* [2005] and higher by 0.30 Sv than that of *Teague et al.* [2005]. The correlation coefficients of the simulated transport with those of *Teague et al.* [2005] and *Takikawa et al.* [2005] are 0.60 and 0.86 for the overlapping period, respectively, while the correlation between two observed transports is 0.83 (Figure 6). This discrepancy between the simulated and the observed transports results partly from some uncertainty in the model forcing and the grid resolution.

[15] For the other three straits, only limited short-term transport data are available. The transport of the Taiwan Strait is 1.16–2.34 Sv between March and August with no persistent northward flow in winter [*Jan et al.*, 2006]. For the Tsugaru Strait, the observed transport is 1.1–2.1 Sv,

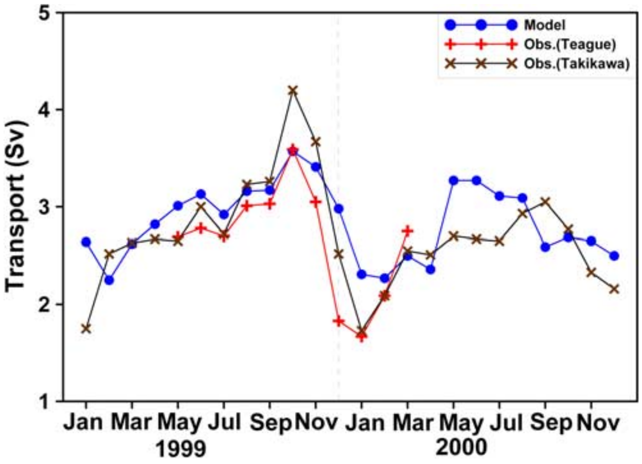

Figure 5. Comparison of modeled (dots) and observed (crosses [*Takikawa et al.*, 2005] and pluses [*Teague et al.*, 2005]) transports in the Korea Strait from 1999 to 2000.

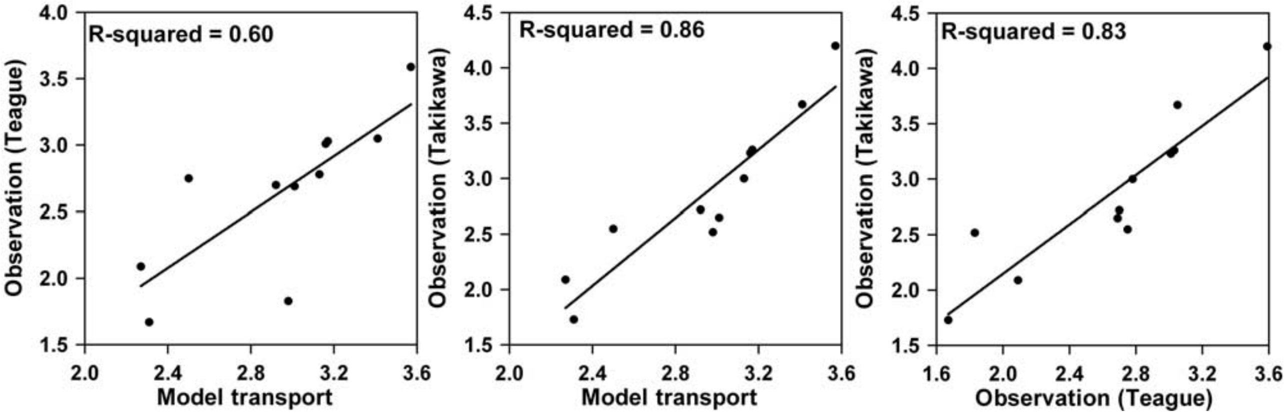

Figure 6. (left) Relationship of the model transports with the observations of *Teague et al.* [2005], (middle) relationship of the model transports with the observations of *Takikawa et al.* [2005], and (right) relationship of the two observations, in the Korea Strait from May 1999 to March 2000. Transports are in Sv.

with a mean value of 1.5 Sv between November 1999 and March 2000 [*Ito et al.*, 2003]. The observed transport of the Soya Warm Current by *Matsuyama et al.* [2006] is 1.2–1.3 Sv in August 1998 and 1.5 Sv in July 2000. The simulated transports are generally close to the observations with some discrepancies. The simulated seasonal maximum and the minimum are comparable to those observed in the Taiwan Strait, but are larger by 0.17 Sv and 0.72 Sv than those observed in the Tsugaru Strait. For the Soya Strait, the model outputs of 1.12 Sv in August 1998 and 1.09 Sv in July 2000 are reasonably close to the August 1998 observations (1.2–1.3 Sv), but smaller than the July 2000 observation (1.5 Sv).

4. Transport Variation Through the Straits

[16] Modeled transports in the straits for 10 years (Figure 7) show not only the seasonal variation but also the interannual variation. A positive transport value represents northward flow in the Taiwan Strait, northeastward flow in the Korea Strait and eastward flows in the Tsugaru Strait and the Soya Strait. The transports of the Taiwan Strait and the Soya Strait are negative in several winters when winter monsoon winds are strong (Figure 10). For the Taiwan Strait during winter, southward flow has been frequently observed [*Ko et al.*, 2003; *Lin et al.*, 2005]. In the model simulation, the flow of the Taiwan Strait is southward in December 1999 and November 2000, and the flow of the Soya Strait is westward in February 1994 and January 2001. Although the seasonal variations occur simultaneously in all straits over the 10-year period, the absolute maxima and minima occur in slightly different months for each strait.

[17] Except for the Tsugaru Strait, the monthly mean transports averaged over 10 years show strong seasonal variation (Figure 8). The maximum transports for all straits except for the Taiwan Strait occur in October or November and the minimum in February. The Taiwan Strait has its maximum and minimum in July and January, respectively,

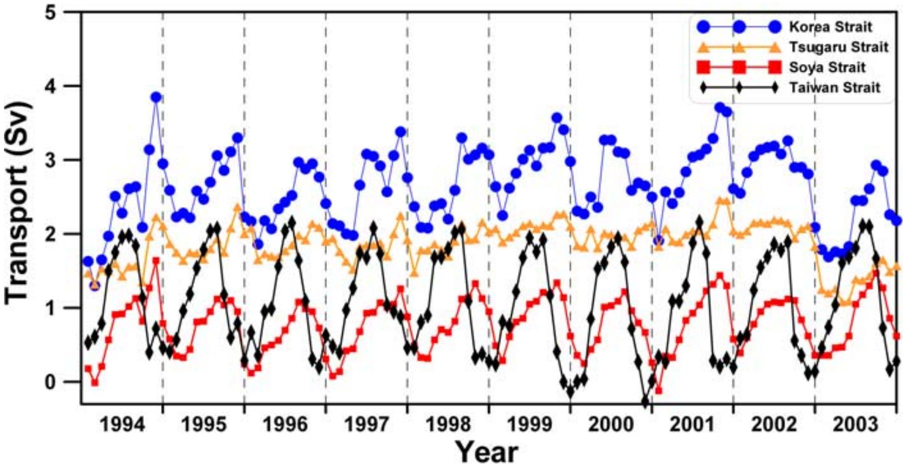

Figure 7. Monthly mean transports calculated by model through the Korea, Taiwan, Tsugaru, and Soya straits from 1994 to 2003.

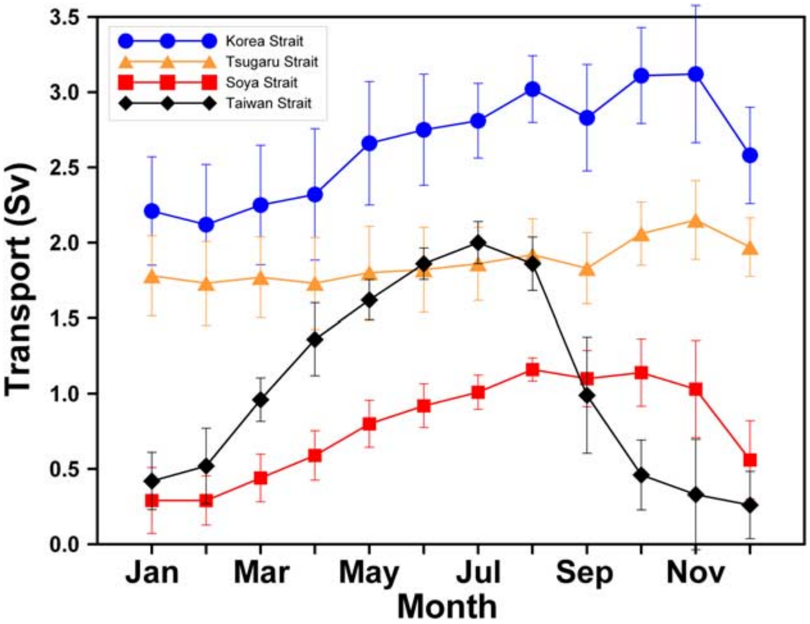

Figure 8. Monthly mean transports and standard deviations in the Korea, Taiwan, Tsugaru, and Soya straits from 1994 to 2003. The vertical lines represent standard deviations in each month.

owing to the strong influence of the TWC. The amplitudes of seasonal cycles through the Taiwan Strait, the Korea Strait, the Soya Strait, and the Tsugaru Strait are 1.74, 1.00, 0.87, and 0.42 Sv, respectively. The amplitude of the seasonal variation is the largest in the Taiwan Strait and smallest in the Tsugaru Strait. The seasonal variation through the Tsugaru Strait is remarkably weak compared to other straits. This result is consistent with findings from *Chu et al.* [2001] using observational data. They find seasonal amplitudes of variation of 1.0, 0.9 and 0.4 Sv for the Korea Strait, the Soya Strait, and the Tsugaru Strait, respectively.

[18] R-squared correlation values for the transport show that the seasonal variation of the Korea Strait is more closely related to that of Soya Strait than of the Tsugaru Strait (Figure 9). As the transport of the Korea Strait increases, the transport of the Soya Strait increases rapidly while the transport of the Tsugaru Strait increases slowly (Figure 8). This could be due to the differences in distance from the Korea Strait and the relative cross-sectional area of the straits. The Tsugaru Strait is relatively close to the Korea Strait. The cross-sectional area of the Tsugaru Strait (20 km wide, 170–200 m deep) is larger than that of the Soya Strait (40 km wide, 20–40 m deep).

[19] The seasonal variations in straits transports appear to be related to wind forcing. Seasonal changes in the wind fields are plotted in Figure 10 using monthly mean winds representing each season. In winter, there are strong northwesterly winds in the JES and east of Japan, and northeasterly winds in the ECS and the SCS. The winds become weak and change direction in spring. The southerly wind becomes dominant in summer. The winds are southwesterly in the SCS and southeasterly south of Japan. The southerly winds disappear in autumn. Northeasterly winds are dominant in the SCS and the ECS.

[20] The correlation of the transport through the Korea Strait to wind stress was examined using the wind stress averaged over the whole model area. Long-term mean monthly transport and wind stress were calculated from 10 years of data. The range of meridional wind stress is larger than that of the zonal wind stress. The transport has a negative correlation with the zonal wind stress and positive correlation with meridional wind stress. We the find max-

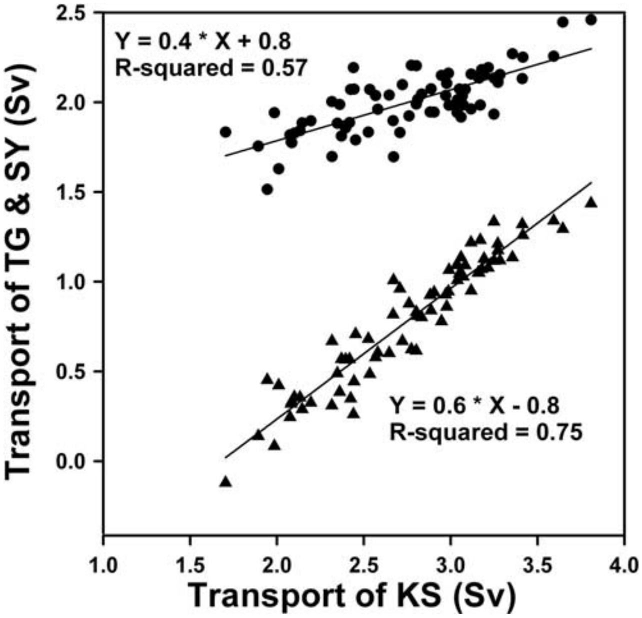

Figure 9. Monthly mean transport correlation between the Korea Strait (KS) and the Tsugaru Strait (TG) (triangles) and between KS and the Soya Strait (SY) (dots).

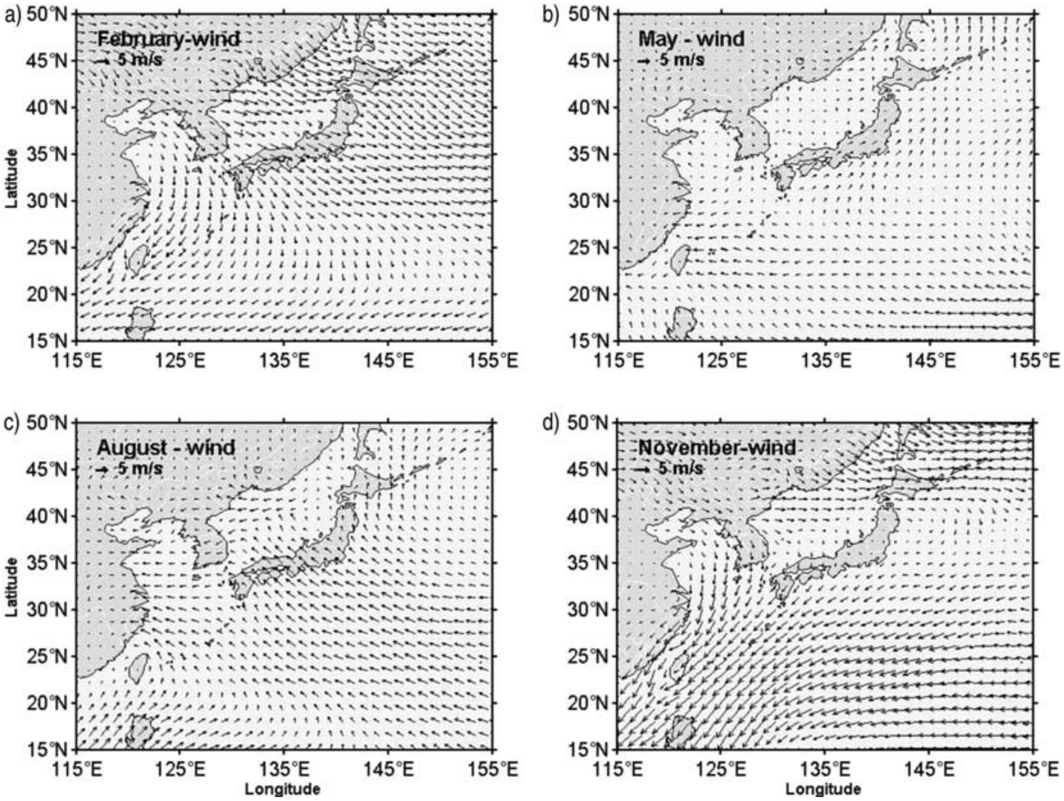

Figure 10. Mean surface wind in (a) February, (b) May, (c) August, and (d) November from January 1994 to December 2003.

imum correlation of the wind with the Korea Strait transport occurs when the wind direction 20° is rotated counterclockwise. The R-squared correlation coefficient between the Korea Strait transport and cross-strait wind stress is 0.64 while that with along-strait wind stress is 0.01 (Figure 11).

5. Connectivity of the Straits

[21] The monthly mean transports in all the straits and the ratios of the transports from the Taiwan Strait, the Tsugaru Strait, and the Soya Strait relative to the Korea Strait are calculated to examine the connectivity among the straits (Tables 1 and 2). The monthly mean transport of the Korea Strait changes from 2.12 to 3.12 Sv with the mean of 2.65 Sv (Table 1).

[22] The ratio of the transport to the Korea Strait enables us to understand the connectivity to the Korea Strait in each month (Table 2). The mean transport ratios to the Korea Strait are 40%, 71%, and 28% in the Taiwan Strait, the Tsugaru Strait, and the Soya Strait, respectively. The trans-

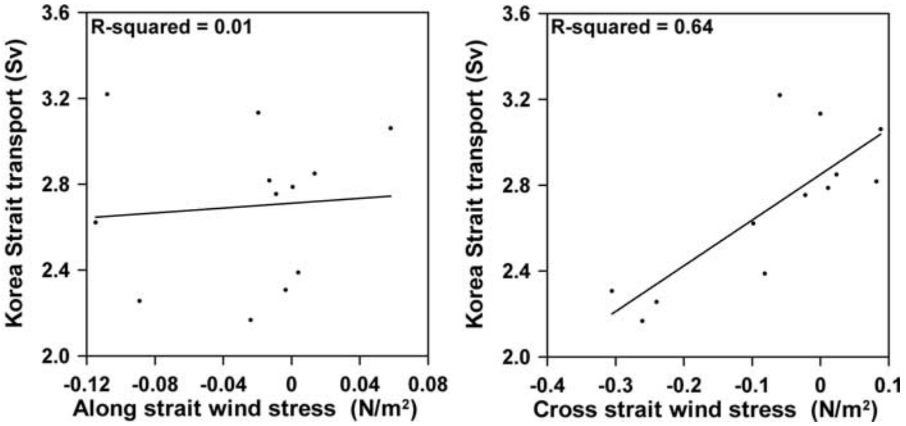

Figure 11. Relationship of the Korea Strait transport to (left) along-strait wind stress and (right) cross-strait wind stress. Long-term mean monthly data for 10 years from 1994 to 2003 were used. The wind direction is rotated 20° counterclockwise.

Table 1. Monthly Mean Transport in Each Strait[a]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Korea	2.21	2.12	2.25	2.32	2.66	2.75	2.81	3.02	2.83	3.11	3.12	2.58	2.65
Taiwan	0.42	0.52	0.96	1.36	1.62	1.86	2.00	1.86	0.99	0.46	0.33	0.26	1.05
Tsugaru	1.78	1.73	1.77	1.73	1.80	1.82	1.86	1.92	1.83	2.06	2.15	1.97	1.87
Soya	0.29	0.29	0.44	0.59	0.80	0.92	1.01	1.16	1.10	1.14	1.03	0.56	0.78

[a] In Sv (106 m^3/s).

port ratio of the Taiwan Strait relative to the Korea Strait is no more than to 20% from October to January and more than 50% from April to August. This implies little connection between the Taiwan Strait and the Korea Strait in winter but high connection in summer. Our model results suggest that more than half of the water volume passing the Korea Strait could come from the Taiwan Strait in summer but that the major source of water passing the Korea Strait in winter is the Kuroshio.

[23] Some of the mass passing through the Taiwan Strait might not enter into the Korea Strait. To further examine the connectivity between the Taiwan Strait and the Korea Strait we conducted numerical drifter experiments (Figure 12). Twenty drifters were released at the surface along the Taiwan Strait line of the every month from February to July and their trajectories were traced for 6 months in 2000. We chose this period on the basis of the consistency of the model Korea Strait transport with the observed data from February to December 2000 (Figure 5).

[24] Most drifters traveled into the JES through the Korea Strait during spring, summer and fall. However, two drifters deployed in April traveled out to the Pacific. The travel time from the Taiwan Strait to the Korea Strait is about 4 months and from the Taiwan Strait to the Tsugaru Strait and the Soya Strait more than 6 months. The drifter trajectories are highly affected by wind direction in winter when the strong northeasterly wind forces ocean currents to flow into the Taiwan Strait (Figure 10d). The flow through the Taiwan Strait in the winters of 1999–2000 and 2000–2001 is negative owing to the strong northeasterly wind (Figure 7). The southwestward flow in winter may be weak in mild winter years when the northeasterly wind is weak over the ECS and the Taiwan Strait. This implies that the travel time from the Taiwan Strait to the Korea Strait may be shorter than 4 months in mild winter years when no flow reversal occurs.

[25] On the basis of the model calculation, we can quantitatively understand the connectivity of the straits as shown in Figure 13. The connectivity between the Taiwan Strait and the Korea Strait is high in summer but low in winter. Transport ratio of the Taiwan Strait to the Korea Strait in winter and summer are 17% and 66%, respectively. Drifter experiments suggest the possibility that some water volume passing the Taiwan Strait may join the Kuroshio in spring and summer.

6. Summary and Concluding Remarks

[26] The model study shows that the simulations for the mean and seasonal variations of temperature and transport are comparable to those of satellite-observed sea surface temperature and measured transports in the straits. Model results in the JES showed high seasonality of the transport in the Korea Strait and the Soya Strait, but relatively low seasonality in the Tsugaru Strait. Observed transports [*Teague et al.*, 2003; *Takikawa et al.*, 2005] have also characterized the seasonality in the Korea Strait. The amplitudes of observed seasonal variations are successfully simulated by the model.

[27] The mean transports of the Korea Strait, the Tsugaru Strait, the Taiwan Strait, and the Soya Strait are 2.65, 1.87, 1.05, and 0.78 Sv, respectively. The seasonal transport amplitudes of the Taiwan Strait, the Korea Strait, the Soya Strait, and the Tsugaru Strait are 1.74, 1.00, 0.87, and 0.42 Sv, respectively. The downstream mean transport ratios relative to the Korea Strait are 40, 71, and 28% in the Taiwan Strait, the Tsugaru Strait, and the Soya Strait, respectively. Surface drifter experiments show that most drifters from the Taiwan Strait enter into the JES through the Korea Strait. It takes about 4 months from the Taiwan Strait to the Korea Strait and more than 6 months from the Taiwan Strait to the Tsugaru Strait or the Soya Strait. This implies that the average velocity of drifters is about 13 km/d from the Taiwan Strait to the Korea Strait.

[28] The seasonality of transports through the Korea Strait is positively related to the meridional wind stress and negatively to zonal wind stress. Transports in the straits are large in summer when the wind is southeasterly and small in winter when it is northeasterly. Strong northeasterly wind over the ECS and the Taiwan Strait in winter sometimes reverses the transport in the Taiwan Strait.

[29] Numerical modeling of the ocean circulation in the northwest Pacific for 10 years enables us to understand the connectivity of the current systems among the marginal seas, which has been debated [*Uda*, 1934; *Nitani*, 1972; *Beardsley et al.*, 1985; *Fang et al.*, 1991; *Zhu et al.*, 2004].

Table 2. Transport Ratios in Percent of the Taiwan, Tsugaru, and Soya Straits Relative to the Korea Strait

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Taiwan	19	25	42	59	61	68	71	62	35	15	11	10	40
Tsugaru	81	81	78	74	68	66	66	64	65	66	69	76	71
Soya	13	13	19	25	30	33	36	38	39	37	33	22	28

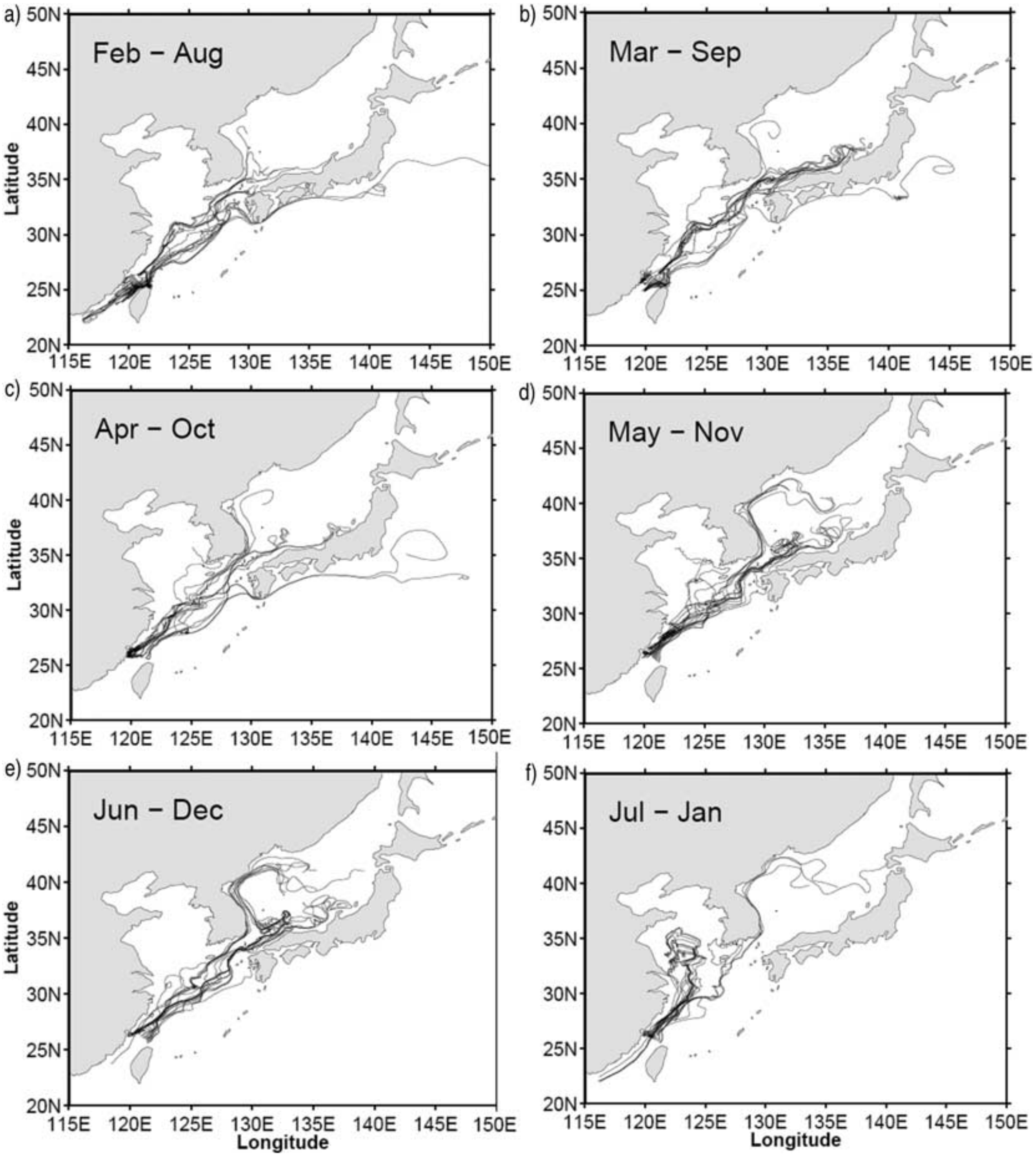

Figure 12. (a–f) Trajectories of surface drifters simulated by the numerical model. Twenty drifters were deployed from February 2000 to July 2000 and tracked for 6 months in each experiment. In Figure 12a (February to August), surface drifters were deployed in February and were carried by currents until August.

In particular, the model sheds light on the source of water flowing through the Korea Strait. Previous competing opinions suggest the source of water through the Korea Strait is the Kuroshio [*Uda*, 1934; *Nitani*, 1972] or the TWC [*Beardsley et al.*, 1985; *Fang et al.*, 1991; *Zhu et al.*, 2004]. Our work reconciles these opinions by suggesting that the TWC is more important in summer while the Kuroshio dominates in winter.

[30] Our result is consistent with the previous studies on the origin of the TC obtained by numerical experiments [*Isobe*, 1999; *Guo et al.*, 2006], current observations [*Teague et al.*, 2003], and oxygen isotope analysis [*Kim et al.*, 2005]. Water passing the Taiwan Strait enters the JES through the Korea Strait and returns to the Pacific through the Tsugaru Strait and the Soya Strait. The transport ratios passing the Tsugaru Strait are 79% and 65% in winter and summer. The rest of the water passes through the Soya Strait to the Pacific.

[31] Although the model experiment has many limitations, the transport variability in each strait of the northwest Pacific marginal seas is well simulated. A more accurate model with higher resolution and over a longer time period calculation will reveal more detailed circulation structure and interannual variations in this area. The dynamical mechanism that induces variability of transport in each strait will be investigated in a future study.

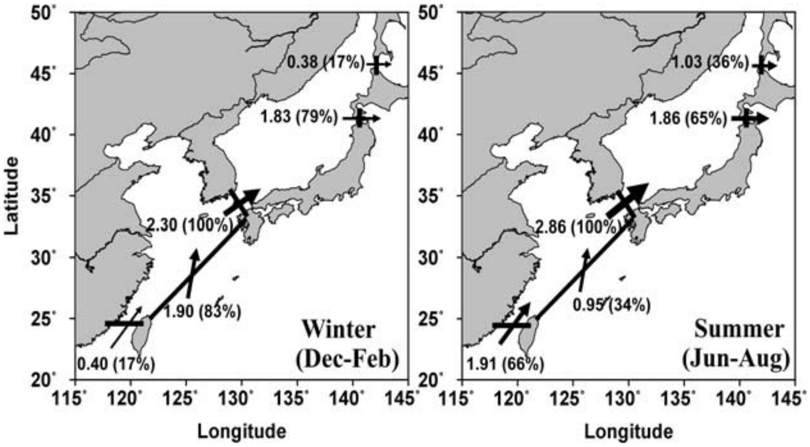

Figure 13. Calculated mean volume transports in the straits and inferred volume transport in the section between Taiwan and Kyushu in (left) winter and (right) summer. Units are Sv (10^6 m^3/s). Numbers in parentheses represent relative transport percentage relative to the Korea Strait transport.

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References

Beardsley, R. C., R. Limeburner, H. Yu, and G. A. Cannon (1985), Discharge of the Changjiang (Yangtze River) into the East China Sea, *Cont. Shelf Res.*, *4*, 57–76, doi:10.1016/0278-4343(85)90022-6.

Cho, Y.-K., and K. Kim (2000), Branching mechanism of the Tsushima Current in the Korea Strait, *J. Phys. Oceanogr.*, *30*, 2788–2797, doi:10.1175/1520-0485(2000)030<2788:BMOTTC>2.0.CO;2.

Chu, P. C., J. Lan, and C. Fan (2001), Japan Sea thermohaline structure and circulation. part II: A variational P-vector method, *J. Phys. Oceanogr.*, *31*, 2886–2902, doi:10.1175/1520-0485(2001)031<2886:JSTSAC>2.0.CO;2.

Curchitser, E. N., D. B. Haidvogel, A. J. Hermann, E. L. Dobbins, T. M. Powell, and A. Kaplan (2005), Multi-scale modeling of the North Pacific Ocean: Assessment and analysis of simulated basin-scale variability (1996–2003), *J. Geophys. Res.*, *110*, C11021, doi:10.1029/2005JC002902.

Egbert, G. D., and S. Y. Erofeeva (2002), Efficient inverse modeling of barotropic ocean tides, *J. Atmos. Oceanic Technol.*, *19*(2), 183–204, doi:10.1175/1520-0426(2002)019<0183:EIMOBO>2.0.CO;2.

Fairall, C. W., E. F. Bradley, D. P. Rogers, J. B. Edson, and G. S. Young (1996), Bulk parameterization of air-sea fluxes for tropical ocean-global atmosphere Coupled-Ocean Atmosphere Response Experiment, *J. Geophys. Res.*, *101*, 3747–3764, doi:10.1029/95JC03205.

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, in *Oceanography of Asian Marginal Seas*, edited by K. Takano, pp. 345–348, Elsevier, Amsterdam.

Guo, X., Y. Miyazawa, and T. Yamagata (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*, 2205–2231, doi:10.1175/JPO2976.1.

Haidvogel, D. B., and A. Beckmann (1999), *Numerical Ocean Circulation Modeling*, Imperial Coll. Press, London.

Isobe, A. (1999), On the origin of the Tsushima Warm Current and its seasonality, *Cont. Shelf Res.*, *19*, 117–133, doi:10.1016/S0278-4343(98)00065-X.

Ito, T., O. Togawa, M. Ohnishi, Y. Isoda, T. Nakayama, S. Shima, H. Kuroda, M. Iwahashi, and C. Sato (2003), Variation of velocity of volume transport of the Tsugaru Warm Current in the winter of 1999–2000, *Geophys. Res. Lett.*, *30*(13), 1678, doi:10.1029/2003GL017522.

Jan, S., D. D. D. Sheu, and H.-M. Kuo (2006), Water mass and throughflow transport variability in the Taiwan Strait, *J. Geophys. Res.*, *111*, C12012, doi:10.1029/2006JC003656.

Kim, K.-R., Y.-K. Cho, D.-J. Kang, and J.-H. Ki (2005), The origin of the Tsushima Current based on oxygen isotope measurement, *Geophys. Res. Lett.*, *32*, L03602, doi:10.1029/2004GL021211.

Ko, D. S., R. H. Preller, G. A. Jacobs, T. Y. Tang, and S. F. Lin (2003), Transport reversals at Taiwan Strait during October and November 1999, *J. Geophys. Res.*, *108*(C11), 3370, doi:10.1029/2003JC001836.

Large, W. G., J. C. McWilliams, and S. C. Doney (1994), Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization, *Rev. Geophys.*, *32*, 363–403, doi:10.1029/94RG01872.

Lie, H.-J., C.-H. Cho, J.-H. Lee, P. Niller, and J.-H. Hu (1998), Separation of the Kuroshio water and its penetration onto the continental shelf west of Kyushu, *J. Geophys. Res.*, *103*, 2963–2976, doi:10.1029/97JC03288.

Lin, S. F., T. Y. Tang, S. Jan, and C. J. Chen (2005), Taiwan Strait current in winter, *Cont. Shelf Res.*, *25*, 1023–1042, doi:10.1016/j.csr.2004.12.008.

Marchesiello, P., J. McWilliams, and A. Shchepetkin (2001), Open boundary conditions for long-term integration of regional oceanic models, *Ocean Modell.*, *3*, 1–20, doi:10.1016/S1463-5003(00)00013-5.

Matsuyama, M., M. Wadaka, T. Abe, M. Aota, and Y. Koike (2006), Current structure and volume transport of Soya Warm Current in summer, *J. Oceanogr.*, *62*, 197–205, doi:10.1007/s10872-006-0044-8.

Moriyasu, S. (1972), The Tsushima Current, in *Kuroshio: Its Physical Aspects*, edited by H. Stommel and K. Yoshida, pp. 353–369, Univ. of Tokyo Press, Tokyo.

Nitani, H. (1972), Beginning of the Kuroshio, in *Kuroshio: Its Physical Aspects*, edited by H. Stommel and K. Yoshida, pp. 129–163, Univ. of Tokyo Press, Tokyo.

Senjyu, T., H. Enomoto, T. Matsuno, and S. Matsui (2006), Interannual salinity variation in the Tsushima Strait and its relation to the Changjiang discharge, *J. Oceanogr.*, *62*, 681–692, doi:10.1007/s10872-006-0086-y.

Seo, G.-H., S. Kim, B.-J. Choi, Y.-K. Cho, and Y.-H. Kim (2009), Implementation of the ensemble Kalman filter into a Northwest Pacific Ocean circulation model, in *Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications*, edited by S. K. Park and L. Xu, pp. 341–352, Springer, Berlin.

Takikawa, T., J.-H. Yoon, and K.-D. Cho (2005), The Tsushima Warm Current through Tsushima Straits estimated from ferryboat ADCP data, *J. Phys. Oceanogr.*, *35*, 1154–1168, doi:10.1175/JPO2742.1.

Teague, W. J., G. A. Jacobs, H. T. Perkins, and J. W. Book (2002), Low-frequency current observations in the Korea Tsushima Strait, *J. Phys. Oceanogr.*, *32*, 1621–1641, doi:10.1175/1520-0485(2002)032<1621:LFCOIT>2.0.CO;2.

Teague, W. J., G. A. Jacobs, D. S. Ko, T. Y. Tang, K.-I. Chang, and M.-S. Suk (2003), Connectivity of the Taiwan, Cheju, and Korea straits, *Cont. Shelf Res.*, *23*, 63–77, doi:10.1016/S0278-4343(02)00150-4.

Teague, W. J., P. A. Hwang, G. A. Jacobs, J. W. Book, and H. T. Perkins (2005), Transport variability across the Korea/Tsushima and the Tsushima Island wake, *Deep Sea Res., Part II*, *52*, 1784–1801, doi:10.1016/j.dsr2.2003.07.021.

Uda, M. (1934), The results of simultaneous oceanographical investigations in the Japan Sea and its adjacent waters in May and June, *J. Imp. Fish. Exp. Stn.*, *5*, 57–190.

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.

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