Continental Shelf Research 81 (2014) 7–18

Contents lists available at ScienceDirect

# Continental Shelf Research

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

Research papers

# Summer behavior of the Changjiang diluted water to the East/Japan Sea: A modeling study in 2003

Pil-Hun Chang[a,*], Atsuhiko Isobe[b], Ki-Ryong Kang[c], Sang-Boom Ryoo[d], Hyun-suk Kang[a], Young-Hwa Kim[a]

[a] National Institute of Meteorological Research, 16-Gil, Yeouidaebang-ro, Dongjak-gu, Seoul 156-720, Republic of Korea
[b] Center for Marine Environmental Studies, Ehime University, Bunkyo-cho 2-5, Matsuyama, Ehime 790-8577, Japan
[c] National Typhoon Center, 810 Seosung-ro, Seogwipo, Jeju 699-942, Republic of Korea
[d] Suwon Weather Station, 149 Seoho-ro, Gwonseon-gu, Suwon, Gyeonggi-do 441-856, Republic of Korea

ARTICLE INFO

*Article history:*
Received 22 August 2013
Received in revised form
7 March 2014
Accepted 7 March 2014
Available online 21 March 2014

*Keywords:*
Changjiang diluted water
Ekman dynamics
Plume extension
East China Sea

ABSTRACT

The summer behavior of Changjiang diluted water (CDW) toward the East/Japan Sea (EJS) is investigated by using a numerical ocean model. The present study focuses on the summer 2003, in which significant low salinity water is observed in the southwestern EJS in spite of similar amount of Changjiang discharge to the normal year. This paper mainly compares two experimental results for the summer 2003 (Exp. Y2003) and the normal year (Exp. NML). The simulated CDW in summer 2003 reveals remarkable changes in the pathway toward the Tsushima/Korea (T/K) Strait. The northeastward CDW behavior to the Jeju Strait, a major pathway in the normal year, is significantly reduced, while an intense southeastward extension to the along-shelf current (i.e., Taiwan–Tsushima Warm Current System) is dominant, similar to the field observation in July 2003. It is suggested that the Ekman dynamics plays an active role in remarkable changes of the CDW behavior. Namely, the reduction of northeastward behavior is associated with the dominance of strong northerly wind anomaly where the fresher bulge develops. On the other hand, the strengthened southwesterly wind over the southern region off the river mouth reinforces the extension to the along-shelf current. In consequence, the CDW below 28.0 psu joins the along-shelf current in the central East China Sea, and a passage of significant low salinity water is resulted at the T/K Strait in August 2003 due to the advection by along-shelf current. The additional experiment also exhibits that the strength of along-shelf current has an impact on the passage of CDW via the T/K Strait.


## 1. Introduction

The Yellow and East China Seas (YECS) are broad shelf regions connected with the East/Japan Sea (EJS) via Tsushima/Korea (T/K) Strait, and with South China Sea via the Taiwan Strait (Fig. 1). Prominent currents in the YECS are the Kuroshio, Taiwan Warm Current, and Tsushima Warm Current. The Kuroshio flows along the shelf edge of East China Sea (ECS), and supplies heat and salt to the shelf region. The Taiwan Warm Current flows over the shelf, and a part of it migrates into the relic river valley off the Changjiang mouth (Beardsley et al., 1985). The Tsushima Current plays an important role in the transport of heat and salinity from the East China Sea to the EJS. In addition, it is proposed that 'the Taiwan–Tsushima Warm Current (TTWC) System' exists over the shelf in the East China Sea (Fang et al., 1991; Isobe, 1999).

The surface water characteristics over the YECS shelf region are strongly influenced by the freshwater discharged from the Changjiang. It is considered that 'the Changjiang is the single most important freshwater source' in the YECS (Chen et al., 1994). The Changjiang is the largest river in terms of volume discharge with annual mean of about $30.0 \times 10^3\ m^3\ s^{-1}$ (Beardsley et al., 1985; Shen et al., 1988), which accounts for about 90 percents of the whole river discharge in this region (refer to Gao et al., 1992).

The freshwater from the Changjiang that debouches into the YECS forms Changjiang diluted water (CDW) mixing with ambient saline water. In general, the CDW is identified by 31.0 or 32.0 psu isohaline (Hu, 1994). Previous studies demonstrated that seasonal variation of the CDW behavior is strongly affected by the East Asian Monsoon system (e.g., Hu, 1994; Isobe et al., 2002; Lie et al., 2003). The CDW widely spreads east/northeastward over the ECS shelf region during summer when the southerly wind prevails, while it confines along the Chinese coast within narrow band in winter when the strong northerly wind is dominant. It is also noteworthy that the tidal forcing dominates the northeastward

* Corresponding author. Tel.: +82 70 7850 6709; fax: +82 2 841 2787.
*E-mail address:* phchang@korea.kr (P.-H. Chang).

http://dx.doi.org/10.1016/j.csr.2014.03.007
0278-4343/

and southeastward plume structure in the region around river mouth during summer (see Fig. 9 in Wu et al. (2011)).

It is widely accepted that the CDW is transported to the EJS via the T/k Strait during summer and autumn (e.g., Ogawa, 1983; Senjyu, 1999; Isobe et al., 2002). Based on a numerical experiment, Chang and Isobe (2003) also showed that the T/K Strait is a major outlet of the freshwater discharged from the Changjiang and at least 70% of the discharge flows into the EJS. The freshwater transport into the EJS reveals a clear seasonal variation, and its maximum appears in August. This inflow of the CDW largely influences on the physical and bio-chemical environment in the EJS (e.g., Nof, 2001; Yanagi, 2002).

There are several studies on the relationship between the Changjiang discharge and the salinity at the T/K Strait. Based on the EOF analysis of salinity at the T/K Strait, Senjyu et al. (2006) found that the time series of the first EOF mode in summer is largely correlated with the Changjiang discharge. Using a numerical ocean model, Chang and Isobe (2005) also showed that when river discharge increases (decreases) the freshwater transport at the T/K Strait also increases (decreases). In addition, the relationship between Changjiang discharge and less saline water is often detected in field observation over the southern EJS. For instance, abnormally low salinity water was observed in summer 1998 when the Changjiang discharge reaches its maximum of about $80.0 \times 10^3\ m^3\ s^{-1}$ (Kuroda and Hirai, 2000). Thus, it is considered that the CDW spreading toward the EJS is largely affected by the amount of Changjiang discharge.

It is also considered that the CDW transport toward the T/K Strait is strongly influenced by external forcings, such as wind fields and ambient ocean current. There are several numerical studies on the CDW transport based on an idealized forcing. For instance, Bang and Lie (1999) and Moon et al. (2010) pointed out that the spreading of CDW toward the T/K Strait is intensified when southerly wind becomes strong. According to Chang and Isobe (2003), it seems like that the advection by the ocean current has an important role on the eastward extension of the CDW when winds are negligible. In spite of their importance, a little effort considering a realistic circulation has been made so far in understanding forcings to affect the CDW transport toward the EJS.

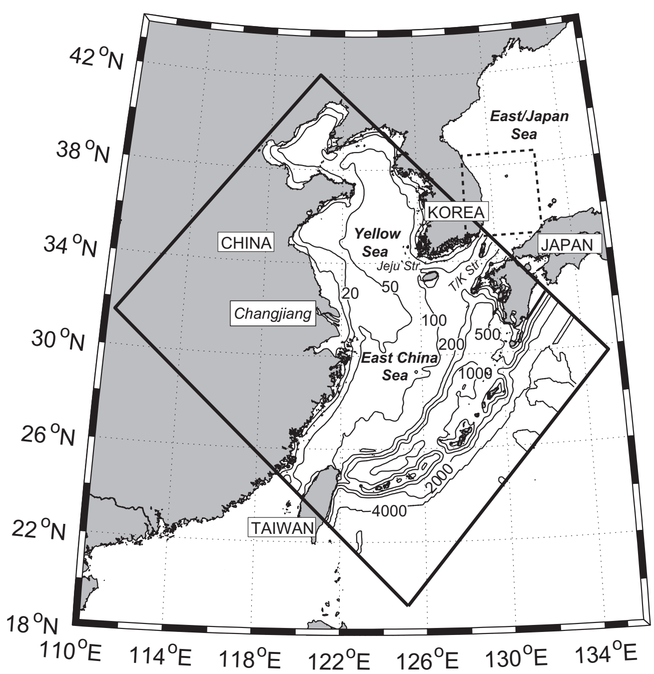


**Fig. 1.** Study region. Rotated square box indicates model domain. Also shown is bottom topography in meters.

In summer 2003, meridional band of significant low salinity water was observed in the southwestern EJS. Fig. 2a and b shows summer surface salinity distributions of 10-year mean and the year 2003, respectively. It is obvious that surface salinity in the southern EJS is strongly affected by the CDW, showing the inflow of less saline water around 32.5–33.0 psu through the T/K Strait (Fig. 2a). In recent observations from 2001 to 2012, low salinity waters below 32.0 psu are found in years of 2002, 2003, 2004, 2009 and 2012 with patch-like patterns (not shown; years of 2006 and 2010 are exclusive because of lack of data). During recent 10-year, the low salinity water over the southwestern EJS is substantial in August 2003 (Fig. 2b). Note that thick solid line in Fig. 2b indicates salinity anomaly of $-1.0$ psu to the 10-year averaged surface salinity.

The Changjiang discharge in 2003 is, however, very similar to the long-term averaged monthly values, implying that the river discharge is of no relevance to the significant low salinity water in August 2003 (shown later in Fig. 3). Hence, it is naturally anticipated that other external forcing can control the outflow of CDW to the EJS, by affecting on the CDW behavior over the ECS shelf region. The investigation of CDW in summer 2003, therefore, possibly can help us better understand other factors to control the CDW behavior, which can afford to affect largely on the CDW outflow toward the EJS.

In order to examine the CDW behavior in summer 2003, a numerical model is adopted in this study. Since it is difficult to observe the evolution of CDW, which spreads widely over the ECS

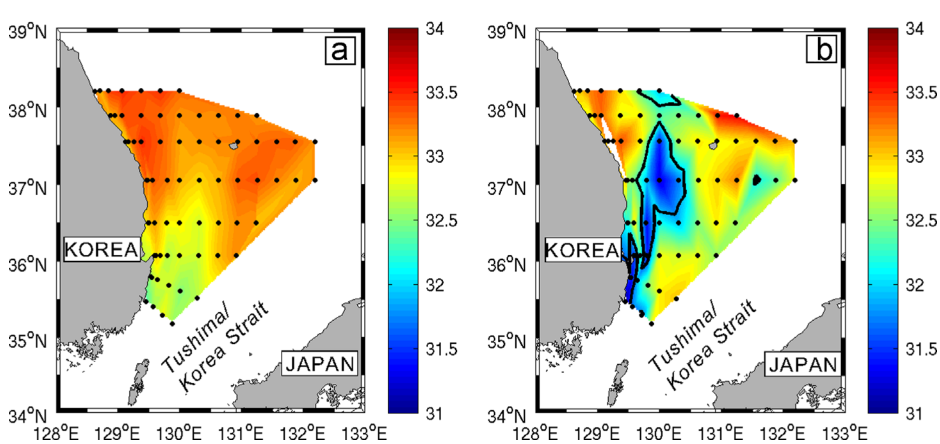


**Fig. 2.** Surface salinity distributions (at 10 m depth) in the southwestern East/Japan Sea (see dotted box in Fig. 1) in August: (a) 10-year mean and (b) year 2003. Units are psu, and the contour in (b) indicates $-1.0$ psu anomaly to the 10-year mean. The data are obtained from Korea Oceanographic Data Center.

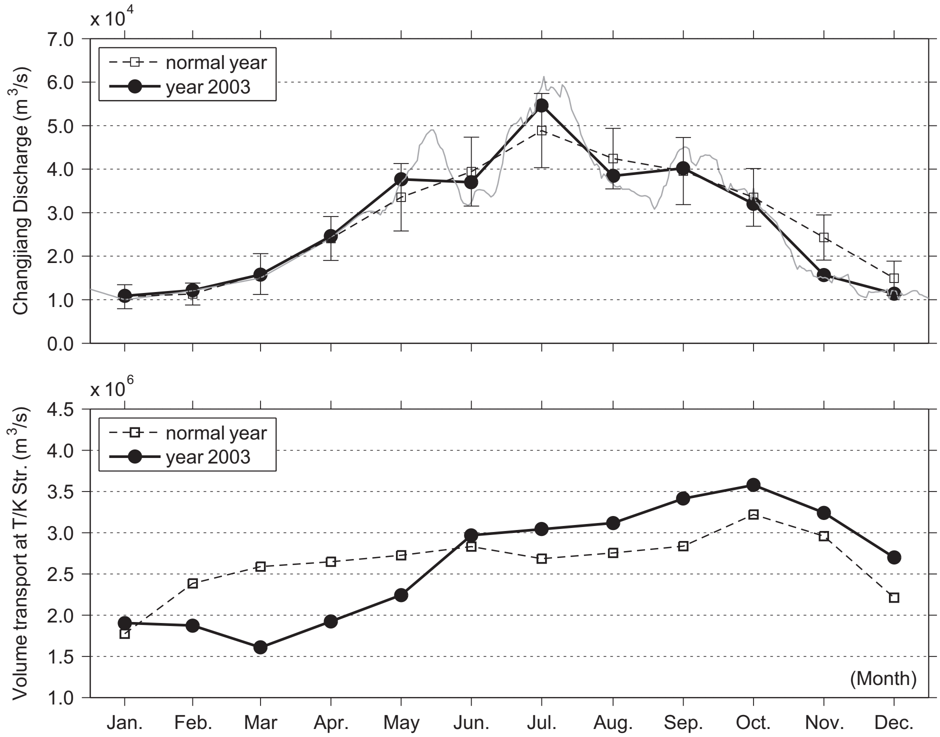


**Fig. 3.** Annual variations of (a) Changjiang discharge and (b) volume transport at the Tsushima/Korea (T/K) Strait. Thick solid lines with circles indicate monthly mean variations in 2003, and thin dotted lines with square are long-term mean variations. Also shown is daily discharge in 2003 with gray line. Note that daily variation of Changjiang discharge is used in the Exp. Y2003.

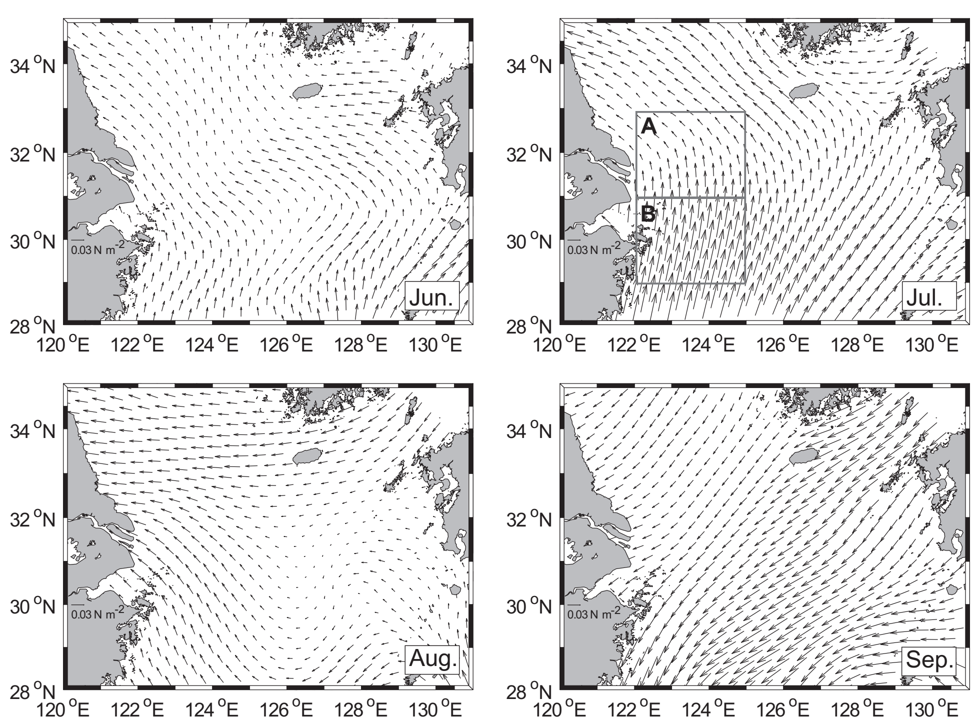


**Fig. 4.** Monthly mean wind stress in June, July, August, and September 2003, based on the QuickSCAT Mean Wind Fields dataset. Boxes of A and B shown in the July mean wind field are adopted for the comparison between variations in 2003 and long-term mean (see Figs. 10 and 11).

shelf region during summer, the numerical model approaches will be very useful. In the present study, we first reproduce the CDW in the normal year (i.e., climatology) and the year 2003 and then compare them with CTD observations conducted in the central East China Sea shelf region during mid-July 2003. When realistic distributions are reproduced in the model, the model results will be able to interpret the CDW behavior toward the T/K Strait. Thereafter, a responsible forcing for the CDW behavior in summer 2003 is discussed.

## 2. Descriptions of model and experiments

A numerical model adopted in this study is basically identical to the model used by Chang and Isobe (2003), in which the behavior of the CDW and freshwater transport process in the YECS are examined. For the present study, we enhance vertical resolution of the model and add $M_2$ tide to consider tidal mixing. Also, the volume transport at the T/K Strait observed during 5 and a half year is applied in the model (Takikawa et al., 2005). As details of the model description are given by Chang and Isobe (2003), only essential features are given here.

The numerical model is based on the primitive-equation, sigma-coordinate Princeton Ocean Model (POM; Blumberg and Mellor, 1987), which incorporates the level 2.5 of turbulence closure submodel (Mellor and Yamada, 1982). The horizontal viscosity and diffusivity are parameterized by the Smagorinsky diffusion formula. The model resolution is 1/12 degree in the horizontal and 16 sigma layers in the vertical. The bottom topography is interpolated from ETOPO5 with 5-min resolution. The area deeper than 4000 m is set to be flat with 4000 m depth.

The model domain is depicted in Fig. 1 by rotated box, in which four ocean currents are considered by giving time-dependent volume transports, temperature and salinity. Geostrophically calculated volume transport at the T/K and Taiwan straits, and the Kuroshio inflow (i.e., east of Taiwan) are adjusted to observations by Takikawa et al. (2005), Zhao and Fang (1991), and Ichikawa and Chaen (2000), respectively. The Kuroshio outflow (e.g., east of Kyushu) is given by the difference of total inflow and outflow volume transport. Temperature and salinity at prescribed open boundaries are obtained from World Ocean Atlas 1994 (WOA94).

At the open boundary, tidal forcing due to $M_2$ tidal constituent, provide by Matsumoto et al. (2000), is also linearly superimposed on the sub-tidal fields. The normal velocity along the open boundary, $U_n$, is computed according to the Flather (1976) radiation condition, $U_n = U_O + U_T + \sqrt{g/H}(\eta - \eta_T)$, where $U_O$ represents ocean current. $U_T$ and $\eta_T$ denote the tidal flow and elevation computed using the harmonic constants of $M_2$ tidal component, provided by Matsumoto et al. (2000). $\eta$ denotes predicted sea elevation in the model, and $H$ is water depth along open boundary.

Spatially averaged precipitation and evaporation from Chen et al. (1994) is given at the model sea surface. For the heat flux, modeled temperature at the first layer is relaxed to the climatological temperature (i.e., WOA94) with 1-day time scale. Model sea surface is imposed by wind stress derived from Comprehensive Ocean-Atmosphere Data Set (COADS) with 1.0 degree resolution, using a drag coefficient of Large and Pond (1981). The present model also includes long-term averaged annual variation of Changjiang discharge (Shen et al., 1988).

The above model is integrated during 4-year until model becomes stable state. From the end of fourth year, we carried out two experiments in order to reproduce summer CDW in the normal year (Exp. NML) and in the year 2003 (Exp. Y2003). In the Exp. NML, the model is driven by the same forcings mentioned above. For the hindcast simulation in 2003 (i.e., Exp. Y2003), only the wind stress, the volume transport at the T/K Strait, and the Changjiang discharge in the Exp. NML are replaced by corresponding variations in 2003. Daily wind fields are obtained from QuikSCAT Mean Wind Fields (http://www.ifremer.fr/cersat/) with 0.5 degree resolution, and then wind stress fields are calculated by using drag coefficient of Large and Pond (1981). Volume transport at the T/K Strait in 2003 is estimated using an empirical formula suggested by Takikawa and Yoon (2005), in which sea level difference across the strait is applied. Also, daily variation of Changjiang discharge in 2003 is imposed on the model. Since our study focuses on the summer behavior of the CDW, all experiments are integrated until the end of September.

Figs. 3 and 4 show the Changjiang discharge, volume transport at the T/K Strait, and wind stress in 2003, which are applied in the Exp. Y2003. Also, corresponding values used in the Exp. NML are given there. As mentioned in Section 1, river discharge in 2003 is very similar to the long-term mean values. On the other hand, the estimated volume transport at the T/K Strait for the Exp. Y2003 shows relatively large difference with that used in the Exp. NML, showing about 0.3–0.4 Sv ($1\ \mathrm{Sv} = 10^6\ \mathrm{m}^3\ \mathrm{s}^{-1}$) during summer time. The monthly mean wind stress reveals that the southerly winds generally predominant in June and July. On the other hand, onset of northeasterly wind appears in September. The comparison of wind forcing with that in the normal year will be given in Figs. 9 and 10.

## 3. Results

### 3.1. Comparison of surface current fields between Exp. NML and Exp. Y2003

In this subsection, we compare modeled surface current field of Exp. NML with that of Exp. Y2003 (Fig. 5). Here, we adopt monthly mean current fields at 4 m depth in July when the CDW spreads widely over the ECS shelf region. In Fig. 5, isohaline of 31.0 psu at the same depth is also superimposed.

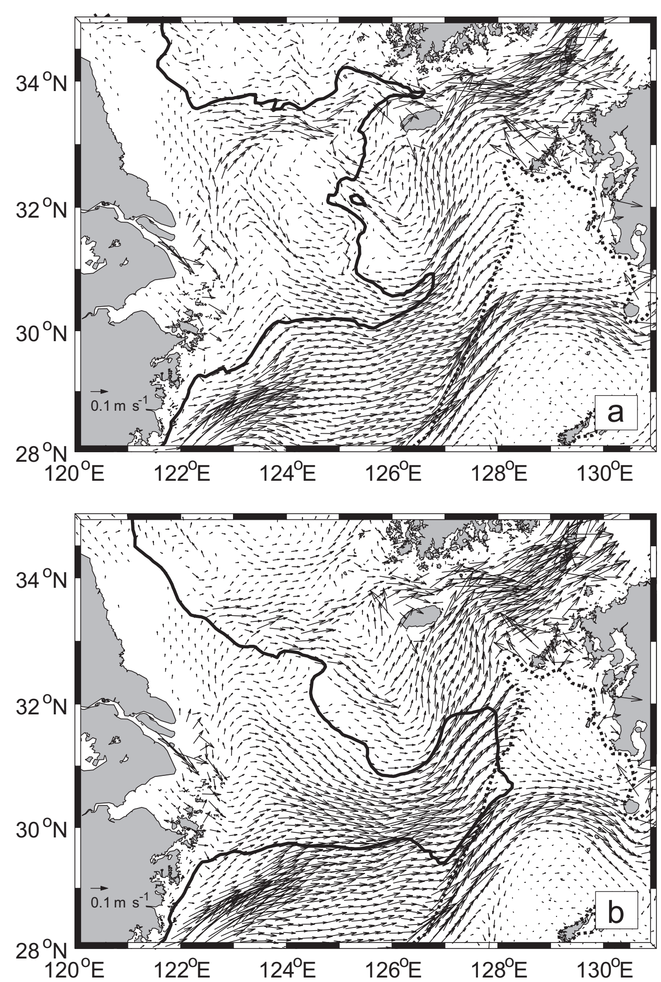


**Fig. 5.** Modeled surface current distributions in July (at 4 m depth) for (a) the normal year (i.e. Exp. NML) and (b) year 2003 (i.e., Exp. Y2003). Vectors in the area deeper than 200 m are rescaled by the factor of 0.25. The solid line denotes the isohaline of 31.0 psu at 4.0 m depth. Thick dotted line indicates 200 m isobaths.

The circulation pattern in the shallow shelf region obtained from the Exp. NML (Fig. 5a) is well consistent with a composite map of trajectories obtained from 16 surface drifters (see Fig. 10 of Lie et al. (2003)). In the vicinity of river mouth, the surface current flows mainly northward and then turns eastward sharply around 33–33.5°N. Between 123°E and 125°E of 33.5°N line, the narrow zonal current is found, and it continuously flows to the Jeju Strait.

There are three notable discrepancies between the surface current fields obtained from Exps. NML and Y2003: the Taiwan Warm Current, the southeastward flow, and north/northeastward flow off the Changjiang mouth (Fig. 5a and b). Both experiments exhibit the northeastward Taiwan Warm Current off the Chinese coast, which in turn deflects to the east and reaches near the Kuroshio frontal region, represented by 200 m isobaths (see the region of 28–30°N and 122–126°N). Thereafter, the current flows to the north toward the T/K Strait, implying that TTWC exists over the East China Sea shelf region during summer. In general, the simulated current system in the ECS shelf region well coincides with the observational result of Katoh et al. (2000). The main current speed (width) is, however, more rapid (narrow) during summer 2003 than the normal year.

In the central ECS shelf region, there is found a large difference in a southeastward surface current, which joins to the along-shelf current (i.e., TTWC; see the region of 30.0–32.0°N and 123.0–126.0°E). When comparing with Exp. NML, the southeastward current toward the along-shelf current is very strong and wide in July 2003, showing the current speeds of about 10.0 cm $s^{-1}$. In addition, we can see the difference in the north/northeastward flows near the river mouth, (see the region of 31.0–34.0°N and 122–124°E). In the Exp. NML, the relatively strong current about 5.0–10.0 cm $s^{-1}$ flows to the north and reaches where the eastward current flowing to the Jeju Strait is dominant (near the 33.5°E line), while this current pattern is relatively weak in July 2003.

It seems like that the difference of CDW distributions are closely related with the change of northeast and southeastward flows off the river mouth. In the Exp. NML, the outer boundary of CDW (see isohalines of 31.0 psu in Fig. 5) exhibits two pathways toward the T/K Strait, and they are confined to the aforementioned surface current patterns. It is, however, necessary to mention that the main pathway in the normal year is the northeastward extension (shown later in Fig. 6a). That is the modeled CDW in the normal year mostly moves to the Jeju Strait, as Lie et al. (2003) suggested. On the other hand, the northeastward spreading of CDW to the Jeju Strait is negligible in July 2003, while the intense southeastward extension relevant to the increase of southeastward current appears in the central ECS. In Sections 3.2 and 3.3, we will describe features of the CDW behavior in more detail.

### 3.2. Validation of modeled sea surface salinity

To assess the simulated result, here we compare modeled CDW distributions with a field observation. Fig. 6a and b shows simulated monthly mean surface salinity distributions in July obtained from Exp. NML and Exp. Y2003, respectively. Also, Fig. 6c indicates surface salinity at 4 m depth observed in July 2003. Observation line and schedule are shown in there.

The modeled CDW distribution calculated in Exp. NML well coincides with climatology presented by previous studies (e.g., Isobe et al., 2002; Lie et al., 2003). The CDW distributes widely over the ECS shelf region, forming a wide fresher tongue (Fig. 6a). The CDW extends mainly to the northeast toward Jeju Strait, and also it reveals weak southeastward spreading toward along-shelf current (refer to Fig. 5a). When forcings in 2003 are imposed on the model (i.e., Exp. 2003), however, the CDW distribution is dramatically changed (Fig. 6b). When comparing with Exp. NML,

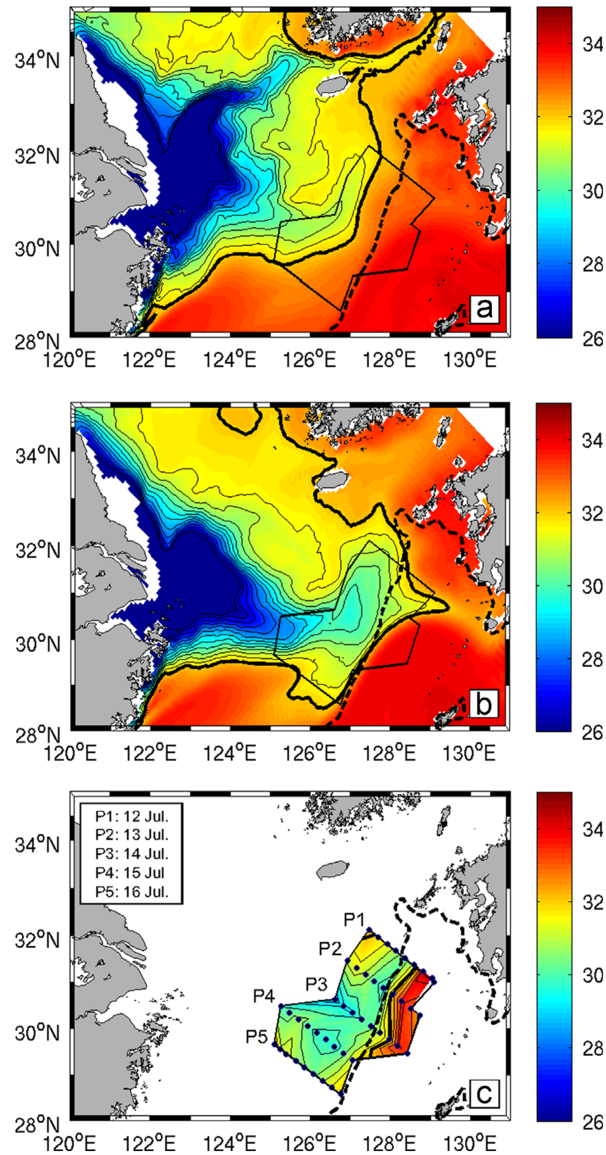


**Fig. 6.** Surface salinity distributions in July: (a) Exp. NML, (b) Exp. Y2003, and (c) observational results in July 2003. Thick solid lines indicate isohalines of 32.0 psu. Salinity below 26.0 psu is omitted because of over-crowding, and the contour interval is 0.5 psu. The circles in the lower panel denote CTD stations. Also shown are isobaths of 200 m with thick dashed line.

the southeastward spreading to the along-shelf current is enhanced, while the northeastward extension of CDW is significantly reduced.

The surface salinity observed in mid-July 2003 indicates that the less saline water below 32.0 psu (i.e., CDW) is distributed widely over the observational area (Fig. 6c). The CDW reaches the Kuroshio frontal area around the 200 m isobaths (see thick dotted line), and waters below 30.0 psu intrude along the line of P3. The thickness of less saline water below 32.0 psu reaches around 20.0 m depth at P3 line (not shown).

The Exp. Y2003 captures well these observational features. Since all forcings, except for the wind stress, Changjiang discharge, and volume transport at the T/K Strait, are the same as those of Exp. NML, two maps cannot be compared directly. Nevertheless, the model reproduces well characteristics of surface salinity distribution in July 2003. Although the location is a little different, both salinity distributions exhibit the intrusion of less saline water below 30.0 psu into the observational region. Also, less saline water below 32.0 psu is largely diffused near the Kuroshio frontal region. On the other hand, Exp. NML does not illustrate those features observed in summer 2003.

### *3.3. Behavior of the Changjiang diluted water toward the East/Japan Sea*

Based on the results obtained from both experiments, here, we describe the evolution of CDW during summer. Figs. 7 and 8 display daily mean surface salinity distributions from June 16 to August 25 with 14-day interval obtained from Exp. NML and Exp. 2003, respectively. In the normal year, the CDW reveals the northeastward extension off the river mouth from mid-June (Fig. 7). In addition, a fresher filament is directed to the southeast, which is also captured by field observations (e.g., Isobe et al., 2002). In subsequence, the CDW extends further northeastward and reaches at the Jeju Strait around July, and then it flows out through the T/K Strait. From the late August, a part of CDW begins to flow southward, hugging the Chinese coast.

Fig. 8 illustrates that the behavior of CDW in summer 2003 was very different from that in the normal year. Comparing with the CDW in the normal year, the fresher water distributes widely off the southern coast of river mouth in mid-June, and the northeastward extension toward the Jeju Strait becomes negligible. On the other hand, the eastward spreading of the CDW near 30°N develops from late June to early July, and it continuously moves to the Kuroshio frontal region around mid-July. Thereafter, the strong along-shelf current carries the CDW rapidly to the T/K Strait, and the CDW finally passes via the T/K Strait from early August. In connection with the CDW outflow to the EJS, the large salinity difference between Exp. Y2003 and Exp. NML is also found near the T/K Strait (see the region around 31°N, 128°E). In addition, it should be mentioned that the northeastward plume structure exists within a fresher bulge near the region of river mouth (around the region of 32°N and 123°E) on June 30 when the southerly wind is weak (not shown). This result may indicate that the northeastward extension near the river mouth is an intrinsic property of the Changjiang plume, as suggested by Wu et al. (2011).

To investigate the outflow of CDW through the T/K Strait, here we show the time variations of surface salinity at 10 m depth across the T/K Strait (Fig. 9). In the normal year, the less saline water begins to pass through the T/K Strait from early July to the end of September. Also, waters below 31.5 psu appear from mid-August to mid-September (Fig. 9a). On the other hand, the CDW outflow during July 2003 is negligible in the Exp. Y2003, but the low salinity water below 31.5 psu passes through the strait from early August. The difference of surface salinity between Exp. Y2003 and Exp. NML reaches about 1.0 psu at the strait during

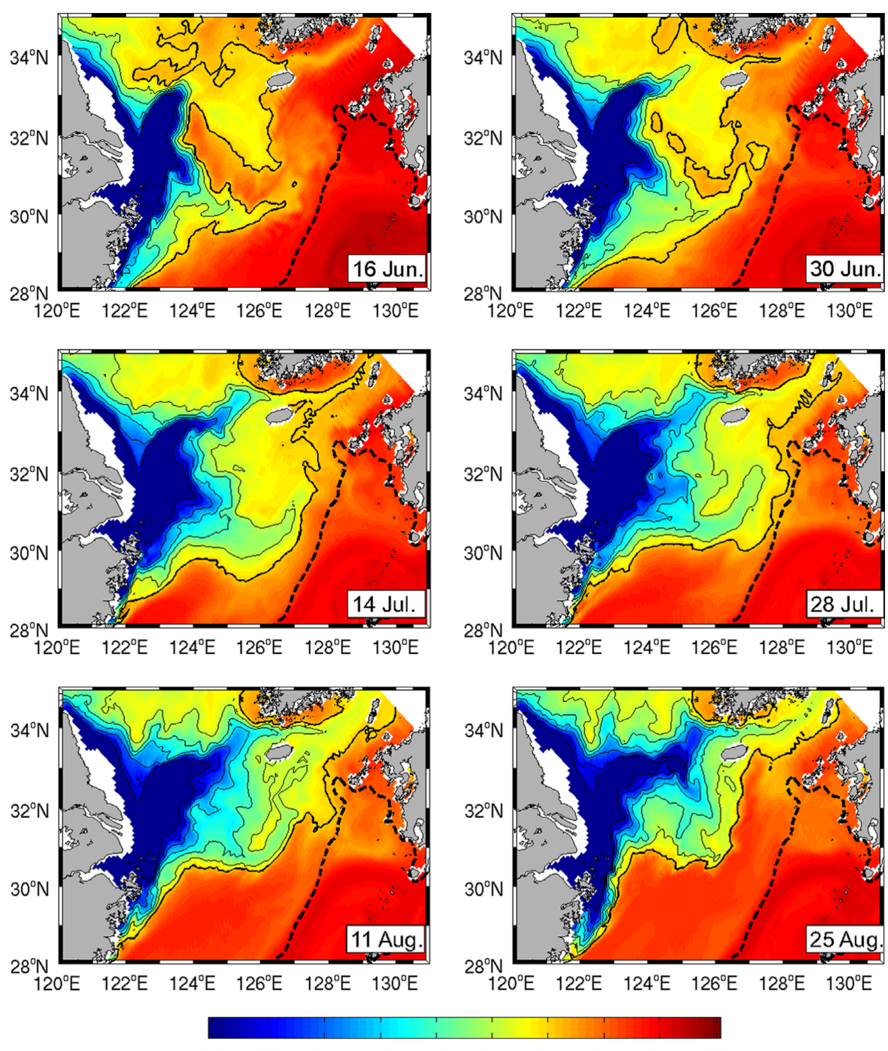


**Fig. 7.** Simulated daily mean surface salinity distributions (at 4 m depth) for the normal year (i.e., Exp. NML) from mid-June to early August with 14-day interval. Thick solid lines denote isohalines of 32.0 psu, and the contour interval is 1.0 psu.

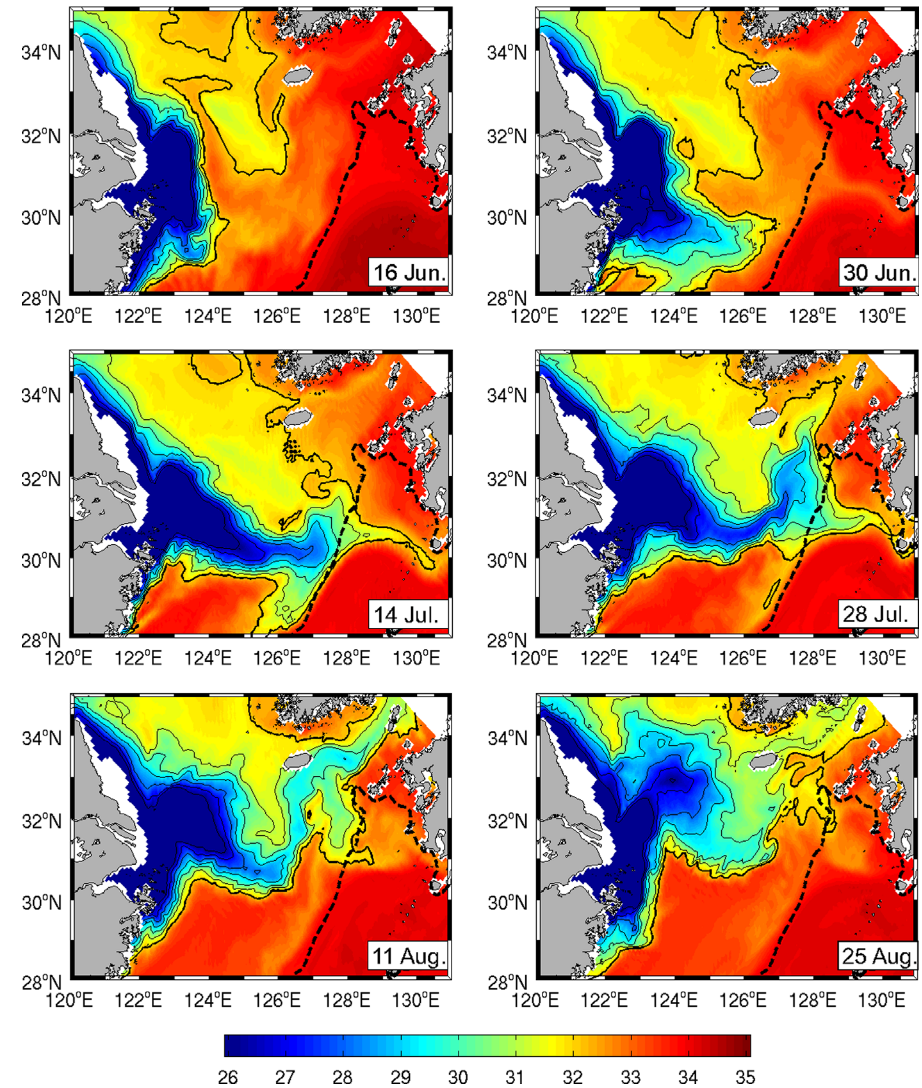


**Fig. 8.** Same as Fig. 7, but for simulation for the year 2003 (i.e., Exp. Y2003).

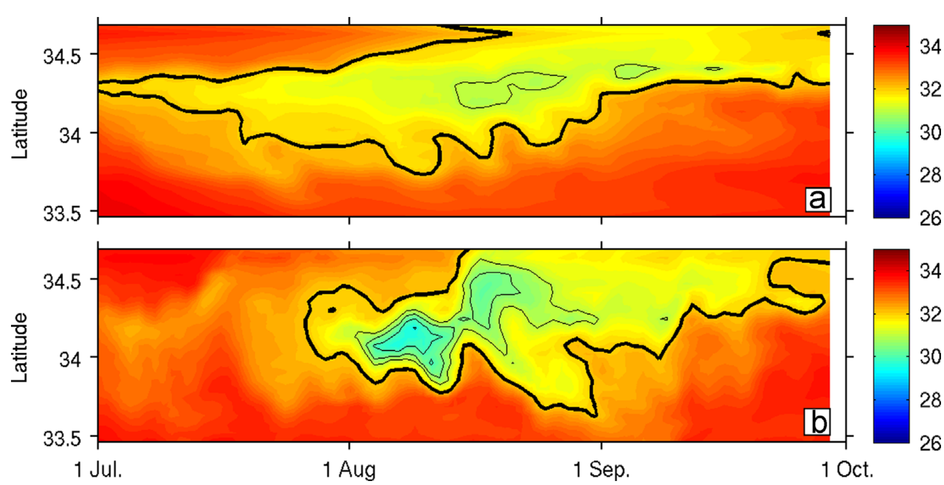


**Fig. 9.** Time variations of surface salinity (at 10 m depth) across the Tsushima/Korea (T/K) Strait: (a) Exp. NML and (b) Exp. Y2003. Thick solid lines indicate isohalines of 32.0 psu, and the contour interval is 0.5 psu.

August. The simulated surface salinity through the T/K Strait corresponds well with the significant low salinity waters observed in the southwestern EJS (Fig. 2b).

The comparison between experimental results represents that the main pathway of the CDW to the T/K Strait is significantly changed in summer 2003 without regard to the Changjiang discharge. Since the CDW outflow via the T/K Strait in summer 2003 is mostly done by the advection due to the along-shelf current, it is considered that the intense extension of CDW to the along-shelf current is closely related with a passage of lower surface salinity water via the strait. During mid-July, it is seen that low salinity water ( $<28.0$ psu) is directed to the southeast, and it joins the strong along-shelf current flowing out via the T/K strait (Fig. 8). The observation also reveals a similar tendency during mid-July (Fig. 6). In addition, the vertical mixing in the surface layer obtained from Exp. Y2003 is generally stronger than that from the Exp. NML, indicating that the vertical mixing makes a negative contribution to the passage of low surface salinity water in summer 2003 (not shown). In the next subsection, therefore, we will examine possible mechanisms for the change of CDW behavior in summer 2003.

### 3.4. Roles of wind forcing to change the pathway of CDW

Two remarkable differences are found in the CDW behavior between Exps. NML and Y2003: the northeastward extension to the Jeju Strait and the southeastward behavior to the along-shelf current (i.e., TTWC). Since only the wind stress, Changjiang discharge, and volume transport at the T/K Strait in 2003 are replaced in the Exp. Y2003, it is naturally anticipated that there is a responsible forcing among these forcings. Thus, we carried out three experiments, in which each forcing is changed into that in the normal year (Exp. NML). Consequently, the model forced by a long-term mean wind stress reveals a similar behavior to the Exp. NML, implying that wind forcing in 2003 causes a remarkable difference in the CDW behavior (shown later in Section 4). Therefore, we here focus on the wind forcing to investigate how the wind forcing changes the CDW behavior in summer 2003.

Fig. 10 illustrates time series of spatially averaged wind stress off the river mouth in which fresher bulge is formed (see the region A in Fig. 4). In the normal year, southerly wind gradually increases from early June and reveals the maximum of about 0.025 N $\mathrm{m}^{-2}$ in mid-July (see the solid lines). Thereafter, northerly wind stress develops from late August. Also, the easterly stress of about 0.01–0.02 N $\mathrm{m}^{-2}$ continues from June to late September. On the other hand, the meridional stress in 2003 reveals frequently strong negative anomalies from June to mid-August, indicating that the southerly stress becomes very weak off the river mouth during summer 2003. In addition, the easterly wind stress generally becomes weak in 2003.

It is widely accepted that the northeastward extension of CDW is mainly due to the southerly wind during summer (e.g., Isobe et al., 2002; Lie et al., 2003). Based on the numerical simulation, Bang and Lie (1999) and Moon et al. (2010) also pointed out that the strength of southerly winds has a large influence on the CDW transport toward the Jeju and T/K Straits. Also, Wu et al. (2011) showed that the northeastward plume structure in the region around river mouth produced by the tidal forcing extends to the far fields when the southerly wind acts on the model (see their Figs. 9 and 14). Indeed, in our experiment, the offshore extension to the Jeju Strait is negligible throughout summer 2003 during which weak southerly winds prevail off the river mouth. Thus, it is intuitively obvious that the weakened Ekman transport due to the northerly wind anomalies is responsible for the reduction of northeastward spreading in summer 2003.

In the similar fashion, the cause of southeastward extension of the CDW toward the along-shelf current is investigated by the comparison of wind stress spatially averaged over southern region off the river mouth (Fig. 11). When comparing with stresses in the normal year, we can see that positive anomalies are dominant in the meridional and zonal components from mid-June to late July, during which the eastward extension is intensified (refer to Fig. 8). Thus, it is expected that the wind-induced advection is relevant to the southeastward movement of the CDW toward the Kuroshio frontal region. The effect of strong southwesterly winds are also revealed in the core of CDW ( $<26.0$ psu), which is generally directed to the southeast (see Fig. 8).

In order to quantify the dominance of Ekman dynamics for the southeastward extension of CDW, a momentum balance along the section from 28–32°N at 124°E line is examined. Here, we simply consider a two-layer system, which consists of the layer for the CDW and that below the CDW. If the Ekman balance is dominant in the along-shore momentum equation, we can simplify the equation for the upper layer (i.e., CDW layer) as $fu_p = \tau(y)/\rho h$. Here, $f$ indicates the Coriolis parameter, and $u_p$ is across shore velocity within the CDW. Also, $\tau(y)$ and $h$ indicate the meridional wind stress and thickness of CDW, respectively. In addition, we consider a shear momentum equation to better quantify the Ekman dynamics for the CDW, following Fong et al. (1997); see Eq. (5) in their paper. Then, the Ekman balance for a shear momentum equation could be

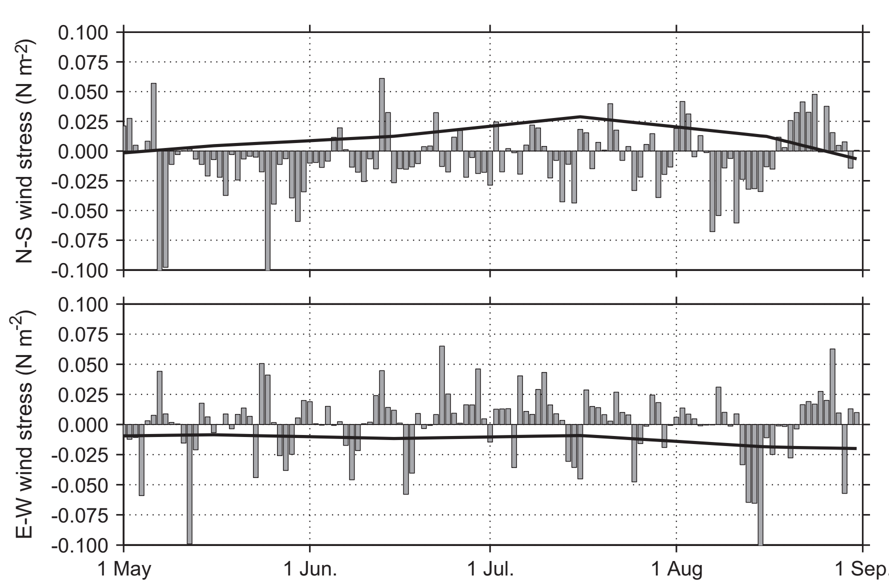


**Fig. 10.** Time variations of (a) meridional and (b) zonal wind stress, spatially averaged in the east/northern region off the Changjiang mouth (see region A in Fig. 4). Thick solid lines indicate climatological wind stress (i.e., COADS), and bars are the wind stress anomaly to the climatology.

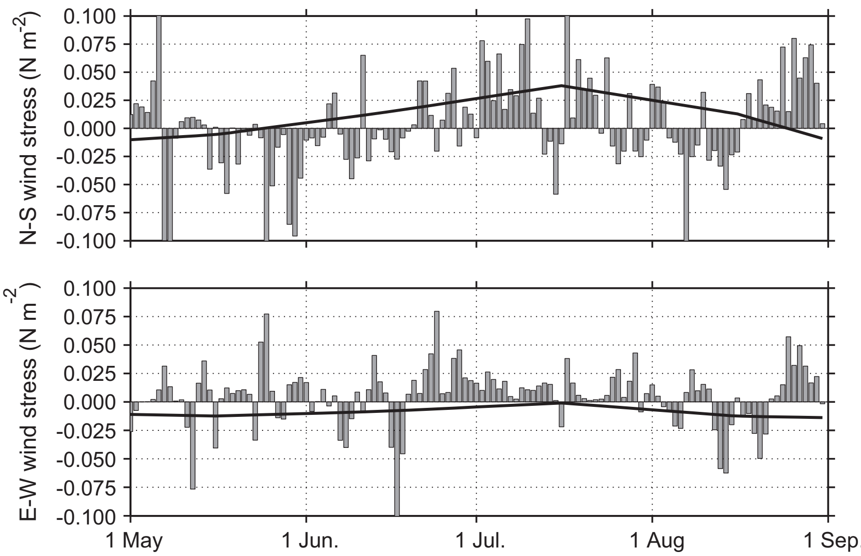


**Fig. 11.** Same as Fig. 10, but for the spatial average in the southern region off the Changjiang mouth (see region B in Fig. 4).

expressed as $f(u_p - u_o) = \tau(y)/\rho h$, where $u_o$ indicates vertically averaged velocity below the CDW.

Fig. 12 shows time variations of Coriolis and wind stress terms from mid-June to the end of July. Also, a shear Coriolis term, $f(u_p - u_o)$, is given by thick gray line there. Although relatively large difference between both terms is found around late June, they reveal generally high correlation. The correlation coefficient is about 0.78. The large difference in late June is mostly caused by the contribution of along-shelf current which advects parts of the CDW to the east (see Fig. 8; the CDW below 30°N at 124°N line in 30 June). When we consider a shear Coriolis term (see thick gray line), the correlation coefficient reaches about 0.93. Therefore, it is concluded that the Ekman dynamics play an active role in the intense offshore extension of CDW toward the along-shelf current.

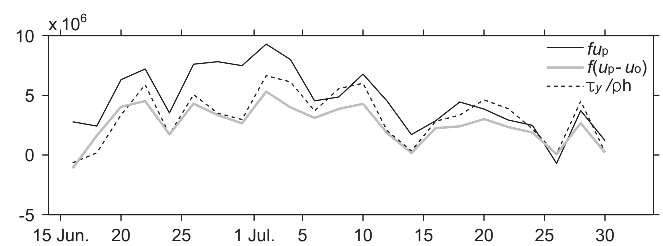


**Fig. 12.** Time series of Coriolis and meridional wind stress terms in the alongshore momentum equation. Also, shown is a shear Coriolis term with thick gray line. Units are $m^2\ s^{-2}$.

## 4. Discussion

In the Exp. Y2003, forcings of wind stress, the Changjiang discharge and the volume transport at the T/K Strait in 2003 are only considered to reproduce the CDW behavior in summer 2003. Therefore, again we can simply verify the roles of wind stress on the change of CDW's pathway by replacing wind forcing in Exp. Y2003 with that in the normal year. Also, it is necessary to examine the sensitivity of CDW behavior to the daily river discharge and volume transport at the T/K Strait. For instance, the daily discharge, which is imposed in Exp. Y2003 (see gray line in Fig. 3), exhibits somewhat large fluctuations, though its monthly variation is similar to that used in the Exp. NML. In addition, the volume transport at the T/K Strait during summer 2003 reveals larger values of about 0.3–0.4 Sv to the normal year. It is expected that the increased volume transport induces the stronger along-shelf current in Exp. Y2003 (refer to Fig. 5).

To elucidate the effects of each forcing to the CDW behavior, here, we performed additional three experiments of CWSa, CCDa and CVTa. The method of each experiment is as follows. All experimental conditions are the same with Exp. Y2003, but each experiment of CWSa, CCDa, and CVTa is forced by wind stress, the Changjiang discharge, and the volume transport at the T/K Strait in the normal year, respectively.

The outer boundary of CDW (here, isohaline of 31.0 psu) in July obtained from each experiment is compared in Fig. 13. Also, the corresponding result from Exp. Y2003 is depicted by thick gray line there. It is shown that the outer boundary obtained from Exp. CWSa, in which the wind stress in the normal year is adopted, exhibits nearly same pattern with that of Exp. NML. Thus, it is reconfirmed that the CDW behavior in July 2003 is mostly determined by the wind forcing as mentioned in Section 3.4. On the other hand, both experiments of CCDa and CVTa exhibit similar pattern to the Exp. Y2003, showing the strong southeastward extension to the Kuroshio frontal region. However, a difference between Exp. CVTa and Exp. Y2003 appears in the region where the CDW flows northward to the T/K Strait (see the boxed region C). The outer boundary of CDW in the Exp. CVTa is located some more southern side (about 0.5°) than that in the Exp. Y2003, implying that the passage of CDW through the T/K Strait could be delayed.

To examine the effect of each forcing to the CDW outflow via the T/K Strait, we investigate the time variations of surface salinity at the strait (Fig. 14). Comparing to the Exp. NML, the CDW passing through the T/K Strait has lower surface salinity during August in all cases. Although the surface salinity in the Exp. CWSa reveals relatively lower values than the Exp. NML, the pattern is very similar to the Exp. NML (Fig. 14a). It is considered that the passage of lower salinity water in the Exp. CWSa is related with the increase of volume transport at the strait. On the other hand, the result of Exp. CCDa is very similar to Exp. Y2003, though the daily fluctuation of discharge is somewhat large (refer to Fig. 3). When volume transport at the T/K Strait is changed (i.e., Exp. CVTa), however, the delay of CDW passage through the strait is distinct as expected from outer boundary of CDW in July (Fig. 14c).

Fig. 15 illustrates difference of spatially averaged surface current in region C (see Fig. 13) between Exp. Y2003 and Exp. CVTa and temporal

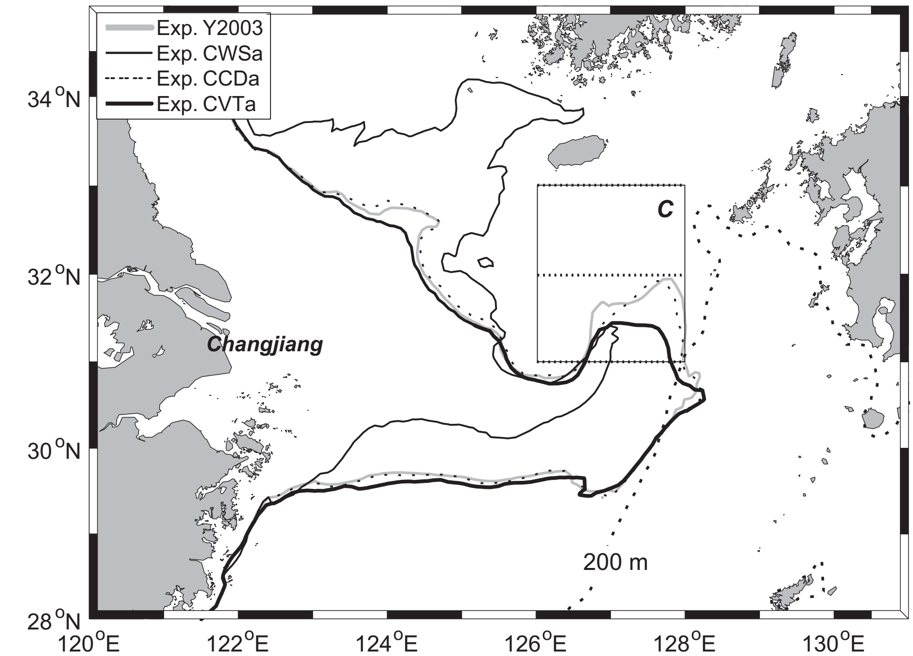


**Fig. 13.** Isohalines of 31.0 psu at 4 m depth in July for experiments of CWSa, CCDa, and CVTa. Also, shown is corresponding results obtained from Exp. Y2003 (see thick gray line). Boxed region C and dotted lines are adopted for the comparison of surface current and salinity between Exp. Y2003 and Exp. CVTa (see Fig. 15).

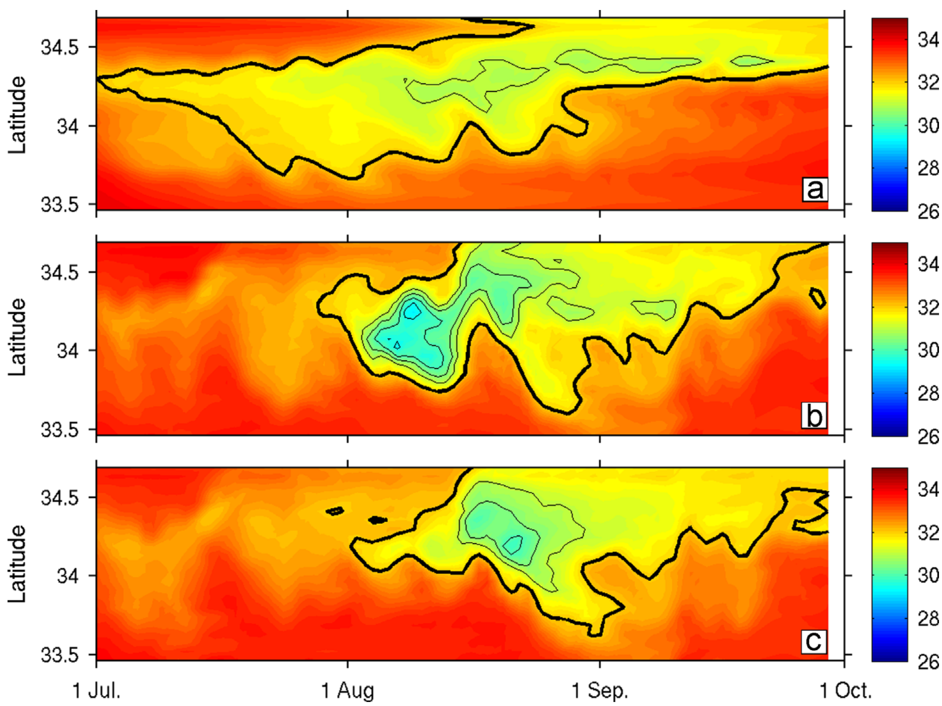


**Fig. 14.** Time variations of surface salinity (at 10 m depth) across the Tsushima/Korea (T/K) Strait: (a) Exp. CWSa, (b) Exp. CCDa, and (c) Exp. CVTa. Thick solid lines indicate isohalines of 32.0 psu, and the contour interval is 0.5 psu.

variations of surface salinity at lines of 31°N, 32°N and 33°N. Variations at 4 m and 10 m depth are depicted by black and gray lines, respectively. As Fig. 15 indicates, the difference of northward surface current (i.e., Exp. Y2003–Exp. CVTa) increases from June and shows a maximum of about 3.0 cm $s^{-1}$ around mid-July. Also, the variations of current difference at each depth are analogous with each other.

The variations of surface salinity exhibit the northward propagation of the CDW and a distinct phase lag between both experiments. The phase lag at 31°N line is relatively small, while it becomes large at the higher latitude as the CDW flows northward. This implies that the increased along-shelf current carries rapidly the CDW toward the T/K Strait. According to Chang and Isobe (2003), the CDW behavior toward the T/K Strait is partially impeded by the northerly wind over the ECS from autumn. When we consider the onset of northeasterly wind from September, thus, the strength of along-shelf current will be important to the CDW outflow to the EJS, especially when the CDW's main pathway is changed into the along-shelf current.

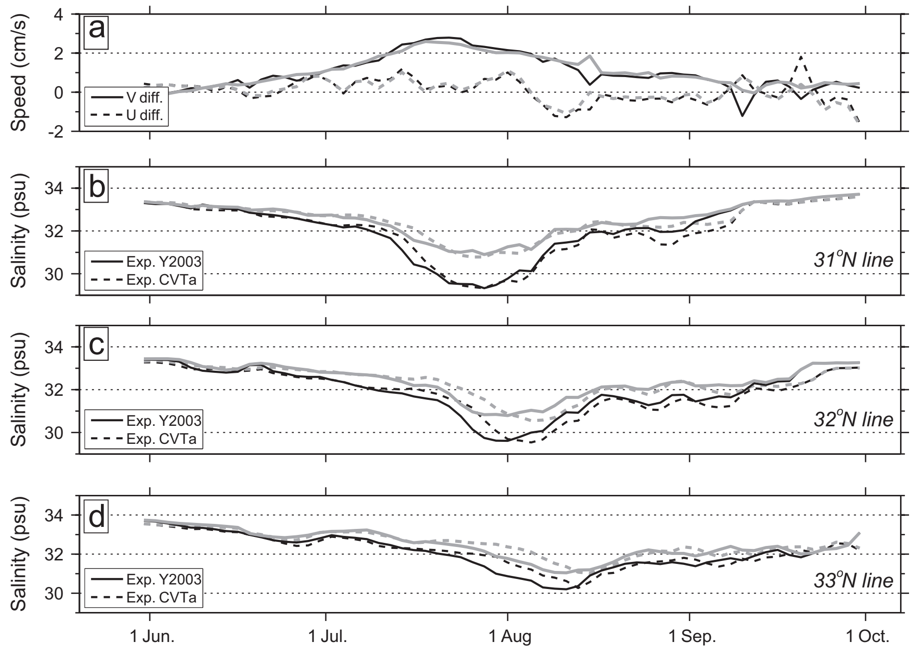


**Fig. 15.** Comparisons of surface current and salinity between Exp. Y2003 and Exp. CVTa. (a) Difference of surface current spatially averaged in region C (i.e., Exp. Y2003–Exp. CVTa), and (b), (c) and (d) surface salinity at 31°N, 32 °N, and 33°N lines. Note that black and gray lines denote results at 4 m and 10 m depth, respectively. Region C and adopted lines for the comparison are shown in Fig. 13.

## 5. Summary

The summer behavior of the CDW toward the EJS is investigated by using a numerical ocean model. In order to exclude the effect of river discharge, the present study focuses on the CDW in summer 2003, during which significant less saline water below 32.0 psu is observed in the southwestern EJS in spite of similar Changjinag discharge to the normal year. Two numerical experiments for the summer 2003 (Exp. Y2003) and the normal year (Exp. NML) are carried out, and both simulated results are compared with each other.

The simulated CDW behavior in summer 2003 very much differs from that in the normal year. Namely, the northeastward spreading to the Jeju Strait is significantly reduced, while the intense southeastward extension to the along-shelf current is found. The model result is well consistent with the field observations conducted in the central ECS shelf region during July 2003. It is concluded that the pathway change of the CDW in summer 2003 is mostly due to the local wind forcing. The weakened southerly wind stress off the Changjiang mouth causes the significant reduction of the northeastward extension, while increased southwesterly stress over the southern region off the river mouth reinforces the southeastward extension. The alongshore momentum balance demonstrates that the Ekman dynamics is predominant in the intense eastward extension of the CDW toward the along-shelf current. Indeed, additional experiment (i.e., Exp. CWSa), in which wind forcing in Exp. Y2003 is replaced by climatological values, exhibits that wind forcing determines the change of CDW pathway toward the T/K Strait. The CDW joined to the along-shelf current then rapidly moves to the T/K Strait due to the advection by the strong current system (i.e., TTWC).

The changes in the surface salinity through the T/K Strait are also remarkable, showing the passage of significant low salinity waters ( > 31.0 psu) via the strait during August 2003. On the whole, the difference of surface salinity between Exp. Y2003 and Exp. NML reaches below −1.0 psu at the T/K Strait during August, and this corresponds well with the observation over the southwestern EJS (see Fig. 2). It is considered that the passage of lower salinity water is associated with an intense extension of CDW to the along-shelf current in July, during which the CDW with below 28.0 psu joins to the along-shelf current. The strong along-shelf current then advects the CDW to the T/K Strait. Although it is difficult to examine precisely the roles of along-shelf current due to the limitation of model's open boundary condition for the Taiwan Warm Current and/or the Kuroshio inflow (i.e. Exp. Y2003), the result of Exp. CVTa suggests that the along-shelf current is able to modulate the CDW transport to the EJS, especially when the main pathway of CDW is changed into the along-shelf current.

The present study suggests that the local wind forcing off the Changjiang mouth can alter the main pathway of CDW toward the T/K Strait. Based on the ERA-40 reanalysis data from 1957 to 2002, Huang et al. (2008) showed that the decline of East Asian Summer Monsoon due to northerly wind anomaly is prominent in the Yellow Sea and the northern ECS (see Fig. 9 in their paper). If the increase of northerly wind anomaly continues, it is expected that the main pathway of the CDW is changed in the future, similar to the result of Exp. Y2003. Thus, the local climate change of wind forcing associated with the CDW behavior could be an important issue in the physical and/or biochemical environment in the ECS and/or EJS. The investigation on the effect of the local climate change of summer winds on the CDW behavior will be a subject deserving further study.


## Acknowledgments

The authors express their sincere thanks to two anonymous reviewers for their suggestions on improving the manuscripts. The authors also would like to thank Dr. Jianrong Zhu of the East China Normal University for providing the Changjiang discharge data in 2003. This study is carried out as part of the "Research for Meteorological and Earthquake Observation Technology and Its Application" research project supported by NIMR/KMA.

## References


Bang, I., Lie, H.-J., 1999. A numerical experiment on the dispersion of the Changjiang river plume. J Korean Soc Oceanogr. 34, 873–883.
Beardsley, R.C., Limeburner, R., Yu, H., Cannon, G.A., 1985. Discharge of the Changjiang (Yangtze River) into the East China Sea. Cont. Shelf Res. 4, 57–76.
Blumberg, A.F., Mellor, G.L., 1987. A description of a three-dimensional coastal ocean circulation model. In: Heaps, N.S. (Ed.), Three-Dimensional Coastal Ocean Models, Coastal Estuarine Science 4. AGU, Washington, DC, pp. 1–16.
Chang, P.-H., Isobe, A., 2003. A numerical study on the Changjiang diluted water in the Yellow and East China Seas. J. Geophys. Res. 108 (C9), 3299, http://dx.doi.org/10.1029/2002JC001749.
Chang, P.-H., Isobe, A., 2005. Interannual variation of freshwater in the Yellow and East China Seas: roles of the Changjiang discharge and wind forcing. J. Oceanogr. 61, 817–834.
Chen, C., Beardsley, R.C., Limeburner, R., Kim, K., 1994. Comparison of winter and summer hydrographic observations in the Yellow and East China Sea and adjacent Kuroshio during 1986. Cont. Shelf Res. 14, 909–929.
Fang, G., Zhao, B., Zhu, Y., 1991. Water volume transport through the Taiwan Strait and the continental shelf of the East China Sea measured with current meters. In: Takano, K. (Ed.), Oceanography of Asian Marginal Seas. Elsevier Science, New York, pp. 345–358.
Flather, R.A., 1976. A tidal model of the north-west European continental shelf. Mem. Soc. R. Sci. Liege 10, 141–164.
Fong, D.A., Geyer, W.R., Signell, R.P., 1997. The wind-forced response on a buoyant coastal current: observations of the western Gulf of Maine plume. J. Mar. Syst. 12, 69–81.
Gao, Y., Arimoto, R., Duce, R.A., Lee, D.S., Zhou, M., 1992. Input of atmospheric trace elements and mineral matter to the Yellow Sea during the spring of a low-dust year. J. Geophys. Res. 97, 3767–3777.
Hu, D.X., 1994. Some striking features of circulation in Huanghai Sea and East China Sea. In: Di, Z. (Ed.), Oceanology of China Seas, vol. 1. Kluwer Academic Publishers, Dordrecht, pp. 27–38.
Huang, Y., Baoshu, Y., Perrie, W., Yijun, H., 2008. Responses of summertime extreme wave heights to local climate variations in the East China Sea. J. Geophys. Res. 113, C09031, http://dx.doi.org/10.1029/2008JC004732.
Ichikawa, H., Chaen, M., 2000. Seasonal variation of heat and freshwater transports by the Kuroshio in the East China Sea. J. Mar. Syst. 24, 119–129.
Isobe, A., 1999. The Taiwan–Tsushima warm current system: its path and the transformation of the water mass in the East China Sea. J. Oceanogr. 55, 185–195.
Isobe, A., Ando, M., Watanabe, T., Senjyu, T., Sugihara, S., Manda, A., 2002. Freshwater and temperature transports through the Tsushima–Korea Straits. J. Geophys. Res. 107 (C7), 3065, http://dx.doi.org/10.1029/2000JC000702.
Katoh, O., Morinaga, K., Nakagawa, N., 2000. Current distributions in the southern East China Sea in summer. J. Geophys. Res. 105, 8565–8573.
Kuroda, K., Hirai, M., 2000. Abnormal low-salinity phenomenon occurred in the Japan Sea in 1998. JAMARC, Japan Marine Fishery Resources Research Center 54, 17–31 (in Japanese).
Large, W.G., Pond, S., 1981. Open ocean momentum flux measurement in moderate to strong winds. J. Phys. Oceanogr. 11, 324–336.
Lie, H.-J., Cho, C.-H., Lee, J.-H., Lee, S., 2003. Structure and eastward extension of the Changjiang River plume in the East China Sea. J. Geophys. Res. 108 (C3), 3077, http://dx.doi.org/10.1029/2001JC001194.
Matsumoto, K., Takanezawa, T., Ooe, M., 2000. Ocean tide models developed by assimilating TOPEX/POSEIDON altimeter data into hydrodynamical model: a global model and a regional model around Japan. J. Oceanogr. 56, 567–581.
Mellor, G.L., Yamada, T., 1982. Development of a turbulence closure model for geophysical fluid problems. Rev. Geophys. 20, 851–875.
Moon, J.H., Hirose, N., Yoon, J.H., Pang, I.C., 2010. Offshore detachment process of the low-salinity water around Changjiang Bank in the East China Seas. J. Phys. Oceanogr. 40, 1035–1053, http://dx.doi.org/10.1175/2010JPO4167.1.
Nof, D., 2001. China's development could lead to bottom water formation in the Japan/East Sea. Bull. Am. Meteorol. Soc. 82, 609–618.
Ogawa, Y., 1983. Seasonal changes in temperature and salinity of water flowing into the Japan Sea through the Tsushima Strait. Bull. Jpn. Soc. Fish. Oceanogr. 43, 1–8 (in Japanese).
Senjyu, T., 1999. The Japan sea intermediate water; its characteristics and circulation. J. Oceanogr. 55, 111–122.
Senjyu, T., Enomoto, H., Matsuno, T., Matsui, S., 2006. Interannual salinity variations in the Tsushima Strait and its relation to the Changjiang discharge. J. Oceanogr. 62, 681–692.
Shen, H., Zhang, C., Xiao, C., Zhu, J., 1998. Change of the discharge and sediment flux to estuary in Changjiang River. In: Hong, G.H., Zhang, J., Park, B.K. (Eds.), Health of the Yellow Sea. The Earth Love Publication Association, Seoul, pp. 129–148.
Takikawa, T., Yoon, J.H., Cho, K.D., 2005. The Tsushima warm current through Tsushima Straits estimated from ferryboat ADCP data. J. Phys. Oceanogr. 35, 1154–1168.
Takikawa, T., Yoon, J.H., 2005. Volume transport through the Tsushima Straits estimated from sea level difference. J. Oceanogr. 61, 699–708.
Wu, H., Zhu, J., Shen, J., Wang, H., 2011. Tidal modulation on the Changjiang River plume in summer. J. Geophys. Res. 116, C08017, http://dx.doi.org/10.1029/2011JC007209.
Yanagi, T., 2002. Water, salt, phosphorus and nitrogen budgets of the Japan Sea. J. Oceanogr. 58, 797–804.
Zhao, B.R., Fang, G.H., 1991. The estimate of transport of the main water route in the East China Sea. Acta Ocenol. Sin. 13 (2), 169–178.