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Dear Dr. John M. Huthnance,

Thanks very much for your comments and assistances in editing our joint manuscript. We have made all the related corrections on the manuscript according to your comments.

Appended to this letter is the “Response to the referee” and a “marked-up manuscript”. The “Response to the referee” contains our point-by-point responses to the comments raised by you. The “marked-up manuscript” tracks our changes.

Yours sincerely,

Jiliang Xuan, Daji Huang, Thomas Pohlmann, Jian Su, Bernhard Mayer, Ruibin Ding,  
Feng Zhou  
January 13, 2017

## **Response to the referee**

**Line 26. Better to omit “the” before “geostrophic”.**

**Author’s response:** Agree.

**Author’s changes in manuscript:** Line 26: “the geostrophic balance” was changed to “geostrophic balance”.

**Lines 89-90. “negative density anomalies” (line 89) does not seem to agree with “less low-density water was transported to . .” (line 90).**

**Author’s response:** Thanks. Apparently it is “more low-density water” which was transported to the ECS shelf and causes the negative density anomalies.

**Author’s changes in manuscript:** Line 90: “less low-density water” was changed to “more low-density water”.

**Line 124. “wintertime TWC synoptic . .” (I think you intended this anyway).**

**Author’s response:** Agree.

**Author's changes in manuscript:** Line 124: “wintertime synoptic fluctuations” was changed to “wintertime TWC synoptic fluctuations”.

**Lines 296-297. Better “. . resulting in an upward-increasing northeastward flow. The northeasterly . .”**

**Author's response:** Agree.

**Author's changes in manuscript:** Line 296-297: “resulting in an increasing of northeastward flow increasing upward” was changed to “resulting in an upward-increasing northeastward flow”.

**Line 299-300. Better “. . indicates weaker baroclinicity or stronger wind . .”**

**Author's response:** Agree.

**Author's changes in manuscript:** Line 300: “indicates that a weaker baroclinicity or a stronger wind friction” was changed to “indicates weaker baroclinicity or stronger wind friction”.

**Line 333. Better “. . magnitude that was sometimes larger . .”**

**Author's response:** Agree.

**Author's changes in manuscript:** Line 333: “a magnitude sometimes being larger than” was changed to “a magnitude that was sometimes larger than”.

**Line 336. “outside of the 100 m isobath”. Do you mean “out to the 100 m isobath”?**

**Author's response:** Thanks.

**Author's changes in manuscript:** Line 336: “outside of the 100 m isobath” was changed to “out to the 100 m isobath”.

**Line 337. I do not understand “low temperature”. The figures do not show temperature. You could omit it?**

**Author's response:** We have now revised the statement.

**Author's changes in manuscript:** Line 335: “Fig.4, high temperature” was changed to “Fig.4, red color”; Line 337: “Fig.4, low temperature” was changed to “Fig.4, blue color”.

**Figure 7 and caption (line 921). Current is a vector and its standard deviation has two components which can be represented by an ellipse but not fully by an arrow. Are the black arrows perhaps the ellipse (semi-) major axis?**

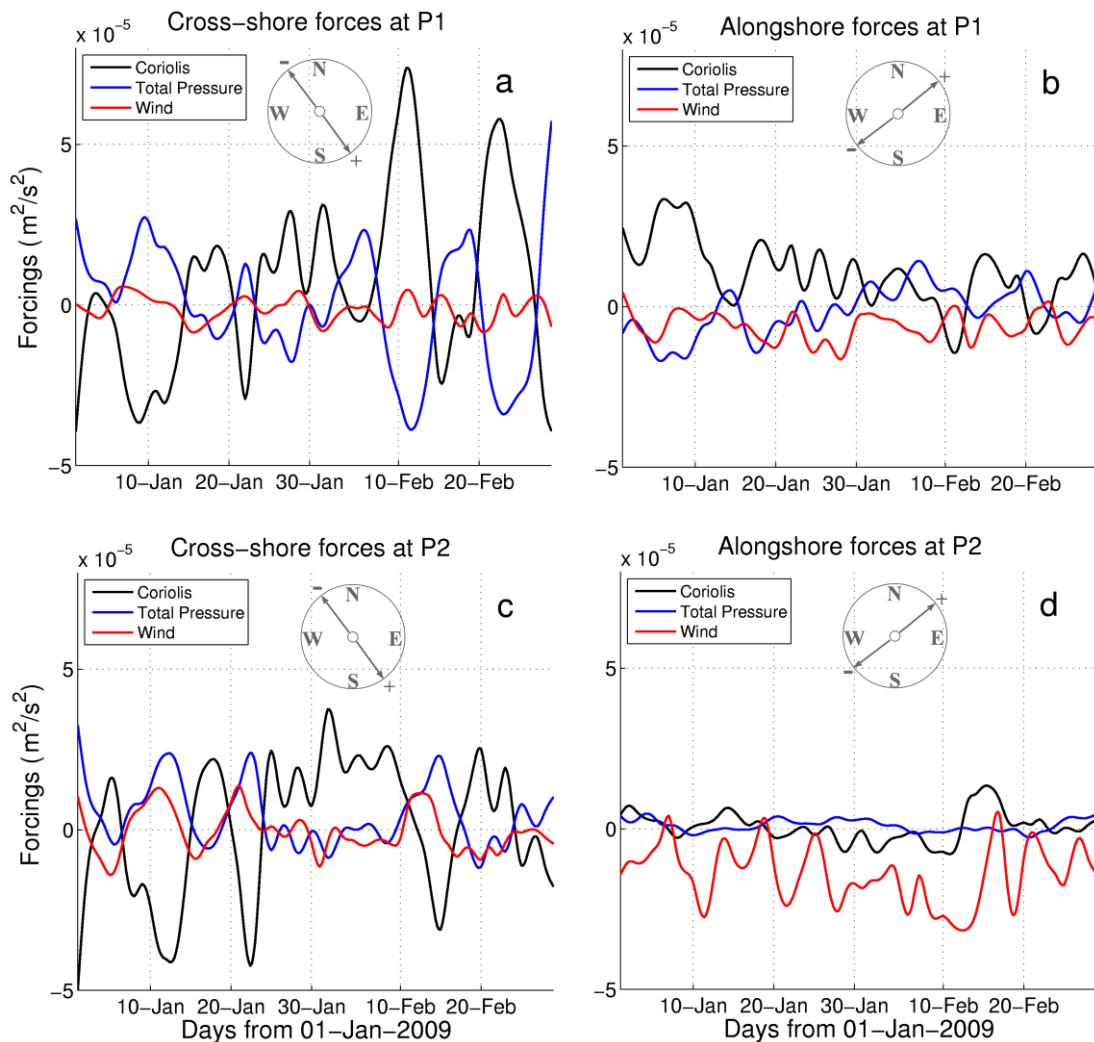
**Author's response:** Thanks. As you said, the black arrows indicate the major axis of the ellipse of the current standard deviation.

**Author's changes in manuscript:** Line 924-926 and 814-816: we revised the caption as following: “The black arrows indicate the major axis of the ellipse which represent the standard deviation of the current. The color shading shows the respective magnitude.”

**Figure 13 and caption (lines 960, 961). The main text line 430 refers to “northwestward” Coriolis force and seems correct but this is not the “alongshore” direction stated in the figure caption.**

**Author’s response:** Thanks. We have corrected the “alongshore” direction and the “cross-shore” direction in Figure 13 and changed the legends accordingly.

In addition, we added a pointer to indicate the alongshore and cross-shore directions in Figure 13 (marked in grey) in order to provide a better impression of dynamical effects in earth coordinate system, e.g., a negative value of the Coriolis force (Fig. 13c, black line) indicates a northwestward directed Coriolis force.



**Author’s changes in manuscript:**

Line 963: we added grey pointers in Figure 13.

Line 964-967 and 847-850: we switched the statements of “alongshore” and “cross-shore”. We also added a notation for the grey pointers: “The grey pointers indicate the alongshore and cross-shore directions of dynamical effects in the earth coordinate system.”

1 **Synoptic fluctuation of the Taiwan Warm Current in winter on the East China Sea shelf**

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3

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9 **Highlights**

- 10 ● Synoptic fluctuations of the wintertime Taiwan Warm Current appear mainly in two areas: north of  
11 Taiwan and the inshore area
- 12 ● Synoptic fluctuation is mainly driven by the Taiwan Strait Current north of Taiwan and by wind in  
13 the inshore area
- 14 ● Large Taiwan Strait Current intrusion generates a cross-shore transport from the coastal area to the  
15 offshore area
- 16 ● Winter monsoon affects the alongshore transport of Taiwan Warm Current water between the 30  
17 and 100 m isobaths
- 18 ● Winter monsoon affects the cross-shore transport of Taiwan Warm Current water at the latitudes  
19 26.5 °N and 28 °N

20

21 **Abstract.** The seasonal mean and synoptic fluctuation of the wintertime Taiwan Warm Current (TWC)  
22 were investigated using a well validated finite volume community ocean model. The spatial distribution  
23 and dynamics of the synoptic fluctuation were highlighted. The seasonal mean of the wintertime TWC  
24 has two branches: an inshore branch between the 30 and 100 m isobaths and an offshore branch between  
25 the 100 and 200 m isobaths. The Coriolis term is much larger than the inertia term and is almost balanced  
26 by the pressure gradient term in both branches, indicating ~~the~~ geostrophic balance of the mean current.  
27 Two areas with significant fluctuations of the TWC were identified during wintertime. One of the areas  
28 is located to the north of Taiwan with velocities varying in the cross-shore direction. These significant  
29 cross-shore fluctuations are driven by barotropic pressure gradients associated with the intrusion of the  
30 Taiwan Strait Current (TSC). When a strong TSC intrudes to north of Taiwan, the isobaric slope tilts  
31 downward from south to north, leading to a cross-shore current from the coastal area to the offshore area.  
32 When the TSC intrusion is weak, the cross-shore current to the north of Taiwan is directed from offshore  
33 to inshore. The other area of significant fluctuation is located in the inshore area between the 30 and 100  
34 m isobaths. The fluctuations are generally strong both in the alongshore and cross-shore directions, in  
35 particular at the latitudes 26.5° N and 28° N. Wind affects the synoptic fluctuation through episodic events.  
36 When the northeasterly monsoon prevails, the southwestward Zhe-Min Coastal Current dominates the  
37 inshore area associated with a deepening of the mixed layer. When the winter monsoon is weakened or  
38 the southwesterly wind prevails, the northeastward TWC dominates in the inshore area.

39

40 **Keywords:**

41 Synoptic fluctuation, East China Sea, Taiwan Warm Current, Taiwan Strait Current, Kuroshio

42

43 **1 Introduction**

44

45 On the East China Sea (ECS) shelf, the mean path of the Taiwan Warm Current (TWC) has two branches:  
46 the inshore branch along the 50 m isobath and the offshore branch along the 100 m isobath (Su and Pan,  
47 1987). The summer TWC has been well studied because the current is stationary and strong, with an  
48 average speed of 0.3 m/s (Guan, 1978; Fang et al., 1991; Isobe, 2008; Yang et al., 2011, 2012). The  
49 spatial structure and temporal variation of the wintertime (December to March) TWC are less known due  
50 to its weak mean surface velocity, according to a climatological structure of the surface current in the  
51 ECS mapped by Qiu and Imasato (1990).

52

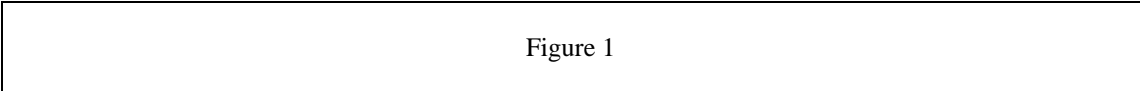
53 The wintertime TWC on the ECS shelf shows synoptic fluctuations (Cui et al., 2004; Zhu et al., 2004;  
54 Zeng et al., 2012; Huang et al., 2016). These synoptic fluctuations show some features common with  
55 those over other continental shelves, i.e., they have periods between 3 and 15 days and are associated  
56 with coastal sea level changes, which can be explained by local winds or by coastal trapped waves (Huyer,  
57 1990; Brink, 1991; Huthnance et al., 1986). Huang et al. (2016) have shown that the wind was a main  
58 physical factor which caused the temporal variation of the wintertime currents at the synoptic scale in  
59 the coastal area of the ECS. However, the dominant physical factors of the TWC fluctuations still lack  
60 study; the fluctuations on the whole shelf of the ECS may be complicated due to the complex bottom  
61 topography, alternating wind forcing and conjunction of several current systems such as the Kuroshio  
62 Current, the Taiwan Strait Current (TSC) and the Zhe-Min Coastal Current (ZMCC). These synoptic  
63 fluctuations are also known to influence the regional material transport, especially when the amplitude  
64 of the fluctuations is comparable to, or even larger than, the mean current. On the ECS shelf, some recent

65 observations have shown that the TWC has an episodic wintertime feature (Zhu et al., 2004) and the  
66 variations of the TWC in winter have an amplitude as large as 0.2 m/s (Zeng et al., 2012). Moreover, it  
67 has been observed that the variations of the TWC in winter cause a cross-shore current which is closely  
68 linked to the alongshore component (Huang et al., 2016). Therefore, we focus on studying the spatial  
69 patterns of synoptic fluctuations to better understand the role of the wintertime TWC on the cross-shore  
70 water exchange.

71

72 A comparison between the wintertime climatological density (Fig. 1a) and synoptic density distributions  
73 observed during two surveys (Figs. 1b and 1c) suggests that two distinct areas with significant synoptic  
74 fluctuations exist. The climatological density is taken from the Generalized Digital Environment Model  
75 (GDEM, Carnes, 2009) data, and the two surveys were carried out in February 2007 by two research  
76 vessels. Because the isopycnal lines are closely related to geostrophic currents, we can infer the strength  
77 of the TWC from the horizontal gradient of the isopycnals between  $24\text{-}\sigma_t$  and  $25\text{-}\sigma_t$  contours (Fig. 1a).  
78 This accounts for the fact that in winter the water mass of TWC is located in this density range [according  
79 to the hydrography analysis of Su et al. (1994)]. The two-branch structure of the TWC can be inferred  
80 from the wintertime climatological density. In this paper, we defined that the near-coast area is the area  
81 between the coast and 30 m isobath where the ZMCC occurs; the inshore area is the area between the 30  
82 and 100 m isobaths where the TWC inshore branch dominates; and the offshore area is the region between  
83 the 100 and 200 m isobaths where the TWC offshore branch prevails. According to the hydrographic  
84 data analysis and numerical interpretation by Su and Pan (1987), the TWC inshore and offshore branches  
85 mainly occur close to those specific isobaths. However, these two branches were missing during the two  
86 synoptic surveys (Figs. 1b and 1c), indicating strong synoptic fluctuations of the TWC on the ECS shelf.

87 Furthermore, the density anomalies between the two surveys and the GDEM data (Figs. 1d and 1e)  
88 indicate that the most significant fluctuations are located north of Taiwan and in the inshore area. Both  
89 surveys show negative density anomalies north of Taiwan, indicating that the TWC was weak and that  
90 ~~less~~-more low-density coastal water was transported to the ECS shelf during the observational periods.  
91 The density anomalies in the inshore area show different patterns for the two synoptic surveys, with a  
92 positive anomaly in the first survey (Fig. 1d) and a negative anomaly in the second (Fig. 1e), indicating  
93 a strong synoptic fluctuation in the inshore area.



94  
95  
96  
97 Candidate factors for driving these synoptic fluctuations are local wind, surface cooling, and the upstream  
98 currents of the Kuroshio Current and the TSC. As discussed by Huyer (1990), wind is often considered  
99 as the major driving mechanism of synoptic fluctuations of the wintertime TWC. The northeasterly  
100 monsoon wind in winter blows against the northeastward TWC and produces a southwestward ZMCC  
101 (Chuang and Liang, 1994; Oey et al., 2010). Zhu et al. (2004) suggested that the occurrence and duration  
102 of the TWC are associated with the meandering of the Kuroshio Current north of Taiwan. The  
103 northeastward TSC, as an upstream flow of the TWC, also influences the synoptic fluctuation of the  
104 wintertime TWC. Hong et al. (2011) and Hu et al. (2010) summarized that the temporal and spatial  
105 variation of TSC is modulated by strong wind forcing, complex topography and circulation in the  
106 northern South China Sea as well as coastal water input and the Kuroshio intrusion. Guan and Fang (2006)  
107 showed evidence that the TSC and the TWC merge in the area between the Taiwan Strait and the Zhe-  
108 Min coastal region. Takahashi and Morimoto (2013) pointed out that the temporal variation of the TWC



109 is characterized by the propagation of vorticity anomalies originating from northeast of the Taiwan Strait,  
110 which further demonstrated that the fluctuations of TWC was associated with its upstream currents such  
111 as the TSC.

112

113 To explore the spatial distribution of synoptic fluctuations of the wintertime TWC on the ECS shelf,  
114 current data with high resolution in both space and time are required. Previous studies on the wintertime  
115 TWC were based on cruise surveys (Su and Pan, 1987; Chen et al., 1994; Chen and Wang, 1999),  
116 anchored mooring observations (Zhu et al., 2004; Zeng et al., 2012; Huang et al., 2016) and numerical  
117 simulations (Guo et al., 2003, 2006; Yang et al., 2011, 2012; Xuan et al., 2012, 2016). The observation  
118 data are limited in terms of temporal and spatial coverage; hence, they cannot fully reveal the synoptic  
119 fluctuations of the TWC and their regional differences. Numerical simulations provide a promising  
120 approach for studying the overall structure and driving mechanisms of synoptic fluctuations of the TWC  
121 in more detail.

122

123 In this study, the Finite Volume Coastal Ocean Model (FVCOM; Chen et al., 2003) is used to investigate  
124 wintertime TWC synoptic fluctuations and their mechanisms. The rest of this paper is organized as  
125 follows. In Sect. 2, we provide a description of methods and validation. The mean distribution, synoptic  
126 fluctuations, and dynamic diagnostics of the wintertime TWC are given in Sect. 3. The impact of synoptic  
127 fluctuation on water exchange is further discussed in Sect. 4, followed by conclusions in Sect. 5.

128

129 **2 Methods and validation**

130 **2.1 Model configuration**

131 To investigate the currents (TWC, Kuroshio Current, ZMCC, etc.) and their synoptic fluctuations on the  
132 ECS shelf, a 3-D unstructured-grid (Fig. 2, left panel) FVCOM is developed for the entire Bohai, Yellow,  
133 and East China Seas (part of the Japan/East Sea, and part of the Pacific Ocean). A regional refinement of  
134 the resolution (approximately 3 km) is specified around the ECS shelf break at the 200 m isobaths, where  
135 a strong excursion of the Kuroshio Current also occurs. The General Bathymetric Chart of the Oceans  
136 (GEBCO) provides high-resolution (approximately 1 km) bathymetric data (Smith and Sandwell, 1997).  
137 Twenty vertical layers with 76954 triangle cells were specified in the water column in a sigma-stretched  
138 coordinate system.

139

140 The driving forces of the numerical simulation include tides, river discharge, surface heat fluxes, wind,  
141 and open boundary conditions. Harmonic constants of 11 major tidal constituents ( $M_2$ ,  $S_2$ ,  $N_2$ ,  $K_2$ ,  $K_1$ ,  $O_1$ ,  
142  $P_1$ ,  $Q_1$ ,  $M_4$ ,  $MS_4$ , and  $MN_4$ ) were used; these are based on the Oregon State University global inverse  
143 tidal model TPXO.7.0 (Egbert et al., 1994; Egbert and Erofeeva, 2002). The daily-mean river discharge  
144 of the Changjiang and Huanghe were taken from publicly available observation data at the Datong  
145 hydrometric station (<http://yu-zhu.vicp.net/>). Other rivers were not included because of their small  
146 discharges, e.g., the Qiantang River, with the largest runoff from the Zhejiang coast, has a climatological  
147 mean discharge in winter of about  $230 \text{ m}^3/\text{s}$ , which is nearly negligible compared to the Changjiang  
148 winter discharge of about  $11500 \text{ m}^3/\text{s}$ . The daily-mean heat fluxes were from the objectively analyzed  
149 air-sea fluxes (Yu and Weller, 2007), and the 3-hourly wind stress and 10 m wind speed data was from  
150 the ERA-40 re-analysis (Uppala et al., 2005). The open boundary conditions, including daily temperature,

151 salinity, and fluxes at the Taiwan Strait, the western Pacific Ocean, and the Japan/East Sea, were obtained  
152 from the Hybrid Coordinate Ocean Model (Bleck, 2002) and interpolated onto the FVCOM model grid  
153 points. The temporal resolution of all the driving force fields is better than or equal to one day, which is  
154 essential to resolve synoptic fluctuations.

155

156 The hindcast outputs of sea surface height, temperature, salinity, and velocities for the five years of  
157 simulation from 2009 to 2013 are used, following three spin-up years (2006-2008) initiated with the  
158 temperature and salinity taken from the Hybrid Coordinate Ocean Model and velocity set to zero. The  
159 initial conditions are ramped-up over a period of 30 days and at the lateral boundaries a sponge layer was  
160 used with the same method as Chen et al. (2008). The model time step was 15 seconds for the 2-D  
161 barotropic mode and 90 seconds for the 3-D baroclinic mode. All of the output fields were processed  
162 with a tidal filter (Godin, 1972) to remove tidal oscillations (considering that the major time scale of  
163 synoptic fluctuations in this study area is 3–15 days).

164

165 Since the currents in 2009 could partly be validated by means of available observational data (see Sect.  
166 2.2), the currents from January 1 to February 28, 2009 were selected for analysis of the wintertime TWC.

167

## 168 **2.2 Validation of the mean currents and synoptic fluctuations**

169 The mean currents, e.g., the Kuroshio Current, the TWC, and the ZMCC, were calculated by averaging  
170 the outputs of January and February 2009. We validated the mean currents in terms of circulation  
171 structure, boundary fluxes, and coastal currents.

172

173 The FVCOM has reproduced almost all of the known circulation structure in the ECS in winter. The  
174 surface mean currents (Fig. 2) shows three major currents: the Kuroshio Current, the TWC, and the  
175 ZMCC. The Kuroshio Current, with a speed of about 1 m/s, enters the ECS just northeast of Taiwan and  
176 flows along the shelf break up to the northern area and ultimately leaves the ECS through the Tokara  
177 Strait. Both the route and strength of the Kuroshio are comparable with those reported in the literature  
178 (Guan, 1978; Qiu and Imasato, 1990). The TWC has two northeastward branches, one inshore (between  
179 the 30 and 100 m isobaths) and another offshore (between the 100 and 200 m isobaths), which is  
180 consistent with Su and Pan (1987). The southwestward directed ZMCC in the nearshore area from the  
181 Changjiang Estuary to the Taiwan Strait agrees well with that reported in previous studies (Guan and  
182 Mao, 1982; Zeng et al., 2012).

183

184 The simulated volume transports across the Taiwan Strait, the East Taiwan Channel, the Tsushima Strait,  
185 the Tokara Strait, and the shelf break of the 200 m isobath were validated using results from the literature  
186 (Table 1). The simulated transports were accurate enough to reproduce volume transport (1.22 Sv)  
187 through the Taiwan Strait which is closer to the observation value (1.20 Sv) from Isobe (2008) than  
188 former model results. The volume transports across the Taiwan Strait and the Tokara Strait, and the cross-  
189 shore exchange, affected the path and magnitude of the TWC. The annual mean transport across the 200  
190 m isobath toward the shelf is 1.66 Sv, which is balanced by the inflow from the Taiwan Strait (1.22 Sv)  
191 and the outflow through the Tsushima Strait (2.85 Sv).

192

193

Figure 2

194

Table 1

196

197 Figure 3 shows a comparison between simulation and observation results for the alongshore currents and  
198 the cross-shore currents on the ECS shelf. The observational data were obtained from four mooring  
199 surveys (Fig. 2, red stations) off the Zhe-Min coast (Zeng et al., 2012). The observed and simulated  
200 currents were both averaged for the observational period, which was from January 1 to February 28,  
201 2009. Using the same method as in Huang et al. (2016), we defined the positive alongshore current  
202 direction as from southwest ( $218^\circ$ ) to northeast ( $38^\circ$ ), which is the mean tangential direction of the  
203 isobaths on the southwestern shelf of the ECS. The positive cross-shore direction is from northwest ( $308^\circ$ )  
204 to southeast ( $128^\circ$ ), normal to the isobaths. The alongshore components (Figs. 3a and 3b) show that the  
205 ZMCC flows southwestward parallel to the coast in winter, with a maximum speed of 0.15 m/s along the  
206 30 m isobath. The TWC flows northeastward with a speed of 0.05 m/s, and the core is located in the  
207 lower layer at about 50 m at Station 4. The cross-shore component (Figs. 3c and 3d) is much weaker than  
208 the alongshore components, and it shows a complex spatial pattern. It flows offshore in the upper layer  
209 and onshore in the lower layer at Station 1. Moreover, it mainly flows onshore at Station 2, and it flows  
210 offshore in the entire water column at Stations 3 and 4. Altogether, the simulated pattern and magnitude  
211 both of the alongshore and cross-shore components are in good agreement with the observations.  
212 However, there are some differences between the observed and simulated results; for example, the  
213 simulated ZMCC occupies a broader space than that in the observations. This may have been caused by  
214 the relatively low number of observational stations.

215

Figure 3

217

218 Synoptic fluctuations of the TWC inshore branch during January and February 2009 were also validated  
219 against the mooring results (Fig. 4). Since the TWC shows a strong signature at Station 4, the time series  
220 of the alongshore currents and cross-shore currents in the whole water column of Station 4 were used for  
221 the validation. To eliminate the influence of local effects, the simulated currents were averaged in a  $10 \times$   
222  $10 \text{ km}^2$  area around Station 4. Both the observed and simulated results show that the TWC fluctuates  
223 with a period of 3–15 days. The simulated TWC (Fig. 4a, warm color) appeared stronger ( $> 0.1 \text{ m/s}$ ) on  
224 Jan. 7, Jan. 12, Jan. 18, Jan. 21, Jan. 26, Jan. 29, Feb. 10, Feb. 14, Feb. 19, Feb. 22, and Feb. 25, which  
225 agrees well with data from the observations (Fig. 4b). The time series of the simulated cross-shore  
226 component (Fig. 4c) are virtually in phase with the observations (Fig. 4d). The magnitude of the cross-  
227 shore fluctuations is comparable to the alongshore fluctuations. This is different to the anisotropic  
228 characteristic of the mean currents (Fig. 3), for which the alongshore component is nearly one order of  
229 magnitude larger than the cross-shore component.

230

231

Figure 4

232

### 233 **2.3 EOF analysis of synoptic fluctuations**

234 The Empirical Orthogonal Function (EOF) method (Emery and Thomson, 2001), as a statistical method,  
235 has been used to understand synoptic fluctuations of the wintertime TWC. The simulated currents from  
236 Jan. 1 to Feb. 28, 2009 were selected and their anomalies were calculated. Then, using the Matlab EOF-  
237 function, the current vectors were separated into several orthogonal modes to show the spatial and  
238 temporal variations. Because the first two leading modes explain 91 % of the total variance, only these

239 two modes were used for the analysis.

240

241 The spatial distributions of the two leading EOF modes were used to analyze the regional difference of  
242 the synoptic fluctuations. To investigate the driving force of the two EOF modes, the temporal variation  
243 was compared to the potential influence factors, such as wind, upstream currents, and net surface heat  
244 flux.

245

#### 246 **2.4 Momentum analysis**

247 The driving mechanisms of the synoptic fluctuations were further analyzed using the momentum  
248 equation. First, the momentum balance as implemented in FVCOM (Chen et al., 2003) is shown in Eq.  
249 (1). The three terms on the left hand side represent local acceleration, Coriolis acceleration, and advection,  
250 respectively, and the three terms on the right hand side represent pressure gradient, friction, and diffusion,  
251 respectively.

$$252 \quad \frac{\partial \bar{V}}{\partial t} - 2\bar{\Omega} \times \bar{V} + (\bar{V} \cdot \nabla) \bar{V} = -\frac{1}{\rho_0} \nabla P + \frac{\partial}{\partial z} (K_m \frac{\partial \bar{V}}{\partial z}) + \bar{F}, \quad (1)$$

253 where  $\bar{V}$  is velocity,  $\bar{\Omega}$  is the Earth's rotation angular velocity,  $\rho_0$  is the average density,  $P$  is  
254 pressure,  $K_m$  is the vertical eddy viscosity coefficient, and  $\bar{F}$  is horizontal diffusion.

255

256 Second, according to the hydrostatic approximation used in FVCOM [as shown in Eq. (2)], the pressure  
257 gradient is given as the product of density times the gravitational acceleration. This results in Eq. (3),  
258 which indicates that pressure gradient can be decomposed into the effects of the barotropic and baroclinic  
259 components, as shown in Eq. (4).

260 
$$\frac{\partial P}{\partial z} = \rho g, \quad (2)$$

261 
$$P_z = \int_z^\eta \rho g dz = \int_z^\eta (\rho_0 + \rho') g dz = \rho_0 g(z + \eta) + \int_z^\eta \rho' g dz, \quad (3)$$

262 
$$\nabla \bar{P} = \rho_0 g \nabla \eta + \nabla \left( \int_z^\eta \rho' g dz \right), \quad (4)$$

263 where  $\rho$  is density,  $\rho'$  is density anomaly,  $g$  is the gravitational acceleration, and  $\eta$  is sea surface  
264 height.

265

266 Finally, the momentum equation is vertically integrated to estimate momentum balance for the water  
267 column. Since the horizontal diffusion is a comparatively small term, it is neglected for simplicity.

268 
$$\int_{-H}^0 \frac{\partial \bar{V}}{\partial t} + \underbrace{\int_{-H}^0 -2\bar{\Omega} \times \bar{V}}_{\text{Coriolis}} + \underbrace{\int_{-H}^0 (V \cdot \nabla \bar{V})}_{\text{Advection}} = \underbrace{-gH \nabla \eta}_{\text{Barotropic}} - \underbrace{\int_{-H}^0 \nabla \left( \int_z^\eta \rho' g dz \right)}_{\text{Baroclinic}} + \underbrace{\rho_a C_D |\bar{U}| \bar{U}}_{\tau_a} - \underbrace{k_b |\bar{V}_b| \bar{V}_b}_{\tau_b}, \quad (5)$$
  
*Acceleration* *Total Pressure*

269 where  $\tau_a$  is wind stress and  $\tau_b$  is bottom stress,  $\rho_a$  is the density of air,  $\bar{U}$  is the wind speed at 10 m  
270 above sea surface,  $C_D$  is a drag coefficient at the sea surface (which varies with wind speed  $\bar{U}$ ),  $k_b$   
271 is a bottom friction coefficient ( $k_b = 0.005$ ), and  $\bar{V}_b$  is the simulated velocity at the bottom.

272

### 273 3 Results

#### 274 3.1 Mean distribution of TWC in winter

275 Since the observational results (Su and Pan, 1987; Zeng et al., 2012) show that both branches of the  
276 wintertime TWC are flowing in the subsurface, we use the vertical maximum velocity (VMV) and its  
277 corresponding depth as two indices to quantify the strength of the subsurface currents (Fig. 5).

278

279 As stated above, the distribution of the VMV shows two branches of the TWC (Fig. 5a). The inshore



280 branch (Fig. 5a, blue arrow of IB), which was located between the 30 and 100 m isobaths, followed a  
281 straight route from the northwest of Taiwan to the northern ECS shelf. The offshore branch (Fig. 5a, blue  
282 arrow of OB) existed near the 100 m isobath and had two meanders. The two meanders turn to the cross-  
283 shore direction along latitudes 26.5°N and 28°N. These two branches are further illustrated in the  
284 distributions of current speed along the six cross-TWC sections (S1-S6), which were located at critical  
285 points in the two meanders (Fig. 6). From the VMV structure, it can be inferred that the intrusions of the  
286 TSC and the Kuroshio Current both affected the origin of the offshore branch (Fig. 6, S1-S3).

287

288 We further examined the subsurface current core using the depth of the VMV (Fig. 5b). We found that  
289 the VMV of the TWC was located 40–60 m below the surface at the inshore branch and 20–40 m below  
290 the surface at the offshore branch. Figure 6 shows the VMV positions in the subsurface layer; it also  
291 illustrates that the depth of the subsurface VMV in the inshore branch was deeper than that in the offshore  
292 branch. The difference can be explained by the combined effects of baroclinicity and wind friction.  
293 Assuming a relatively spatially homogeneous heat loss, different cooling occurs, due to the smaller heat  
294 capacity of the shallow coastal water compared to the deeper offshore waters; hence generating a  
295 northwestward horizontal density gradient leading to a northeastward thermal current (vertical current  
296 shear) according to the thermal wind relationship, resulting in an upward-increasing ~~of~~-northeastward  
297 flow ~~increasing upward~~. The northeasterly wind in winter weakens the northeastward TWC, particularly  
298 in the upper layer, which leads to the formation of the subsurface VMV. Therefore, the fact that the depth  
299 of the subsurface current core in the inshore branch is greater than that in the offshore branch indicates  
300 ~~that a~~-weaker baroclinicity or ~~a~~-stronger wind friction on the inshore branch than on the offshore branch.

301

302 The magnitude of the wintertime TWC was obtained by flux analysis. Two dividing lines (Fig. 5a, red  
303 lines) were defined as the boundaries for the ZMCC, the TWC inshore branch, and the TWC offshore  
304 branch, which had the weakest flows. The flux of each branch (Fig. 5c) was calculated using the  
305 horizontal integration between the boundaries and the vertical integration in the water column. The  
306 inshore branch intensifies along its way and becomes significant north of 26.5 °N, showing particularly  
307 strong flow velocities between 27.5 and 28.0 °N. In this area, the subsurface current was much stronger  
308 from S4 to S5 than in the other areas (Fig. 6). The flux in the entire offshore branch was large, particularly  
309 north of Taiwan.

310

311  Figure 5

312

313  Figure 6

314

### 315 **3.2 Synoptic fluctuations**

316 The observations (Fig. 4) have demonstrated that the synoptic fluctuation in the TWC inshore branch  
317 (near 121.5 °E, 27.0 °N) is significant. We further investigated the regional difference of fluctuations in  
318 the two TWC branches in winter 2009 using the following three steps: (i) two regions with significant  
319 fluctuations are identified by the current standard deviations of the VMV (Fig. 7) and the corresponding  
320 temporal variation of vertical structures at their extremes (Fig. 8); (ii) each of the two significant  
321 fluctuations is decomposed into EOF components (Fig. 9), and (iii) the influence factors, such as wind,  
322 upstream currents, and net surface heat flux, are investigated by examining their correlations with the  
323 first two leading EOF components (Figs. 10 and 11).

324

325 The current standard deviations (Fig. 7) shows that prominent fluctuations occurred in two regions: north  
326 of Taiwan and the inshore area. The standard deviations of VMV at the two regions were larger than 0.1  
327 m/s (comparable to the mean currents). In the area north of Taiwan, the fluctuation was located in the  
328 origin area of the TWC offshore branch. The fluctuation in this region was in phase with the fluctuation  
329 in the Taiwan Strait, indicating that the TSC played an important role in generating the fluctuation north  
330 of Taiwan (to a greater extent than did the Kuroshio intrusion). The TWC fluctuation had a strong cross-  
331 shore component, which means the fluctuation transported the water north of Taiwan to both the inshore  
332 and offshore branches. In the inshore area, the fluctuations were influencing a wide region between the  
333 30 and 100 m isobaths, with a magnitude that was sometimes ~~being~~ larger than the mean flow (Fig. 5a).  
334 These strong fluctuations led to an episodic occurrence of the TWC inshore branch, as observed at the  
335 site off the Zhe-Min coast (Fig. 4, ~~high temperature~~red color). When the TWC inshore branch was  
336 weakened due to these fluctuations, the ZMCC might even dominate a wide region ~~outside of~~ to the 100  
337 m isobath, especially at the surface (Fig. 4, ~~low temperature~~blue color).

338

339

Figure 7

340

341 The vertical structures of the fluctuations north of Taiwan and in the inshore area at two representative  
342 points and their relation with upper mixed layer depth are further analyzed (Fig. 8). The major component  
343 (the alongshore current) of the TWC in each of the two regions (P1 and P2, Fig. 7) is used to show the  
344 vertical structure of the fluctuation. The depths of the upper mixed layer were determined by a  
345 Richardson number criterion (Mellor and Durbin, 1975; Grachev et al., 2013; Richardson et al., 2013),

346 i.e., where the critical Richardson number equals 0.25 in this paper [as in Xuan et al. (2012)]. The mean  
347 depth of the upper mixed layer north of Taiwan (20 m) was much shallower than the mean depth in the  
348 inshore area (42 m). However, the TWC (Fig. 8, warm color) fluctuated with significant variations of the  
349 upper mixed layer depth (Fig. 8, gray lines) in both areas. When the upper mixed layer deepened, the  
350 northeastward TWC (Fig. 8, warm color) was weakened or even replaced by the southwestward ZMCC,  
351 and vice versa. Wind and surface cooling, which both drive the mixed layer depth, can affect the TWC  
352 fluctuation.

353

354

Figure 8

355

356 The TWC fluctuations were further decomposed into EOF modes. The first two leading EOF modes  
357 account for 54% and 37% of the total variances (Fig. 9), associated with the two prominent fluctuations  
358 north of Taiwan and in the inshore area (Fig. 7). Both EOF modes had a maximum fluctuation larger than  
359 0.2 m/s (comparable to the mean currents). The spatial pattern of the first EOF mode (EOF1, Fig. 9a)  
360 shows that the fluctuation continued from the Taiwan Strait to the area north of Taiwan, indicating that  
361 the fluctuation north of Taiwan was related to the TSC and not to the Kuroshio Current. The alongshore  
362 component also showed a strong fluctuation in the Taiwan Strait, which means that the TSC episodically  
363 intruded the shelf. The cross-shore component revealed a fluctuation north of Taiwan that was larger than  
364 0.1 m/s. This cross-shore fluctuation impacted on the trajectory of the TWS water, synoptically flowing  
365 into the TWC inshore branch, offshore branch, or Kuroshio Current.

366

367 The spatial pattern of the second EOF mode (EOF2, Fig. 9b) shows a synoptic fluctuation in the inshore

368 area. The area with alongshore fluctuation (Fig. 9d) larger than 0.1 m/s was located between the 30 and  
369 100 m isobaths, which demonstrates that the TWC could episodically affect this area. In addition, there  
370 were cross-shore fluctuations in the inshore area (Fig. 9f), mostly along the latitudes 26.5 °N and 28 °N.  
371 The latitudes of larger cross-shore fluctuations agreed well with the latitudes where the TWC offshore  
372 branch of the mean currents (Fig. 5a) turned to the cross-shore direction. This indicated that the cross-  
373 shore transports were most significant at the latitudes 26.5 °N and 28 °N, according to both the mean  
374 currents and the synoptic fluctuations.

375

376 Figure 10 shows the temporal variation of EOF1 and its relation with north-south component of wind  
377 speed, net surface heat flux, the TSC, and the Kuroshio Current. We found a close correlation between  
378 EOF1 and TSC ( $R = 0.86$ ), demonstrating that the TSC played the most important role in generating the  
379 TWC fluctuation north of Taiwan. The EOF1 and TSC were positively correlated, meaning that a larger  
380 TSC intrusion north of Taiwan leads to a cross-shore current from the coastal area to the offshore area  
381 and that a weak TSC intrusion causes a cross-shore current from offshore to inshore north of Taiwan.

382

383 Figure 11 shows the temporal variation of EOF2 and its relation with the north-south component of wind  
384 speed, net surface heat flux, the TSC, and the Kuroshio Current. It can be seen that EOF2 and wind are  
385 well correlated ( $R = 0.89$ ), indicating the important role of wind in generating the TWC fluctuation in  
386 the inshore area. The northeasterly monsoon would greatly enhance the southwestward ZMCC, which  
387 would then replace the northeastward TWC in the inshore area.

388

389

Figure 9

390

391

Figure 10

392

393

Figure 11

394

### 395 **3.3 Dynamic diagnostics**

396 The wintertime (January and February 2009) mean of the water column momentum balance (Fig. 12) is

397 used to show the overall distribution of the fundamental forces over the ECS shelf. The Coriolis force

398 (Fig. 12a) is mainly balanced by the total pressure (Fig. 12b) in both branches, indicating the dominant

399 role of geostrophic balance in the wintertime TWC. However, the wind-induced surface friction plays an

400 important role in the TWC, especially in the inshore area and the Taiwan Strait (Fig. 12c). The bottom

401 friction has an impact north of Taiwan and in the shallow Taiwan Strait, in particular when significant

402 Kuroshio intrusion enhances the bottom flow (Fig. 12d). The effects of advection and acceleration are

403 predominantly local indicated by mostly incoherent small scale distributions (Figs. 12e, 12f), so they can

404 be ignored when studying the large-scale current of the wintertime TWC.

405

406

Figure 12

407

408 The variation of the driving forces at two representative points P1 and P2 were used to analyze the

409 dynamics of synoptic fluctuations north of Taiwan and in the inshore area. Regarding the results from

410 the EOF analysis, the three force terms, namely Coriolis, total pressure, and wind (Fig. 13), were selected

411 to investigate the effect of the TSC on the fluctuation north of Taiwan (Fig. 9a) and the effect of wind on  
412 the fluctuation in the inshore area (Fig. 9b).

413

414 In the area north of Taiwan, the cross-shore fluctuations were induced by the TSC intrusion. The variation  
415 of alongshore Coriolis force (Fig. 13a, black line) was much greater than the cross-shore Coriolis force  
416 (Fig. 13b, black line), which means that the fluctuation north of Taiwan was mainly in the cross-shore  
417 direction. The Coriolis force (Fig. 13a, black line) was mainly balanced by the total pressure (Fig. 13a,  
418 blue line), which means the currents fluctuations north of Taiwan are dominated by geostrophic balance.

419 As mentioned in Sect. 3.2, the TWC fluctuation north of Taiwan was associated with the TSC rather than  
420 with the Kuroshio Current. Therefore, in the shallow coastal area the TSC mainly caused variations in  
421 the depth-independent barotropic pressure gradients, which further generated the cross-shore fluctuation.  
422 The mechanism can be interpreted as follows. When a larger TSC intrusion occurred, the isobaric slope  
423 tilted downward from south to north, generating a cross-shore current from the coastal area to the offshore  
424 area. On the contrary, when the TSC intrusion was weak, the Kuroshio intrusion from offshore to inshore  
425 dominated north of Taiwan.

426

427 Wind friction (Figs. 13c and 13d) was a fundamental factor in generating the fluctuations in the inshore  
428 area. Although the geostrophic balance dominated in the inshore branch for most of the time, the  
429 episodically strong winter monsoon had an important role in generating the TWC fluctuations. The  
430 northwestward direction Coriolis force (Fig. 13c, black line) shows that the southwestward ZMCC  
431 occurred on Jan. 12, Jan. 22, and Feb. 14, 2009 and was associated with a northeasterly wind (Fig. 13c,  
432 red line). It indicates that strong northeasterly monsoon in winter can reduce or even stop the

433 northeastward TWC in the inshore area, causing the intermittency of the TWC inshore branch.

434

435

Figure 13

436

#### 437 **4 Discussion**

438 Simulated results in the winters (December-March) of the years 2010 to 2013 (Fig. 14) show that general

439 structures of the TWC in the other winters were similar to that in winter 2009 (Fig. 5 and Fig. 9), which

440 indicates that the results from the winter 2009 can be regarded as representative for the winter situation.

441 The two TWC branches and the two areas of strong fluctuations were present in all winters from 2009 to

442 2013, although their strength showed a certain inter- annual variability in accordance with the changing

443 surface forcing and boundary fluxes.

444

445

Figure 14

446

447 The wintertime TWC, which is manifested by two subsurface branches and significant synoptic

448 fluctuations, has a very different structure when compared with the stationary and surface summertime

449 TWC reported in previous studies (Guan, 1978; Fang et al., 1991; Isobe, 2008). The synoptic events,

450 with time scales of 3-15 days, play a dominant role on the horizontal advective transports. According to

451 Ledwell et al. (1998) synoptic variations are much more effective on the horizontal transport than

452 variations on shorter time scales. The synoptic fluctuations modulate the spatial structure of the

453 wintertime TWC, especially when their magnitudes are comparable with that of the mean currents, such

454 as the two prominent fluctuations north of Taiwan and in the inshore area (Fig. 7). Therefore, the two



455 prominent fluctuations will be discussed next in terms of their contributions to the alongshore and cross-  
456 shore transports.

457

#### 458 **4.1 Cross-shore transport north of Taiwan induced by the TSC**

459 In the area north of Taiwan, the TSC intrusion generated strong fluctuations of the TWC in the cross-  
460 shore direction (Fig. 9a). When a larger TSC intrusion occurred, the isobaric slope tilted downward from  
461 south to north, generating a cross-shore current from the coastal area to the offshore area. Compared to  
462 the reported summer route that transports Taiwan Strait water to the inshore area between the 30 and 100  
463 m isobaths (Guan, 1978; Fang et al., 1991; Isobe, 2008; Yang et al., 2011, 2012), our results showed that  
464 most Taiwan Strait water was transported to the TWC offshore branch and to the Kuroshio area as a result  
465 of the cross-shore fluctuations induced by the synoptic TSC intrusion.

466

467 A numerical tracer simulation was used to analyze the role of the cross-shore fluctuation in the transport  
468 of the TSC water and the Kuroshio water north of Taiwan. In order to demonstrate the characteristics of  
469 the flow patterns more clearly, artificial tracers are released in the model domain and transported by the  
470 velocity field provided by the FVCOM simulation. The tracer running was part of the FVCOM simulation;  
471 therefore, all the above mentioned dynamics were involved, e.g., tide, wind, and boundary forces. The  
472 release location and start date of the particles were configured as follows. Two sections, one in the Taiwan  
473 Strait (Fig. 15a, black dots) and another in the East Taiwan Channel (Fig. 15b, black dots), were selected  
474 as the source locations for the water masses of the TSC and the Kuroshio, respectively. The particles  
475 were released on January 1, 2009 and tracked until March 31, 2009 (a total of 90 days).

476

477 Figure 15a shows the traces originating from the TSC area. Unlike the traditional route, where the TSC  
478 water flows from the Taiwan Strait to the inshore area between the 30 and 100 m isobaths, most particles  
479 (Fig. 15a, gray lines) were concentrated in the offshore branch under the effect of cross-shore fluctuation.  
480 Two particles were selected to show the inshore route (Fig. 15a, red line) and offshore route (Fig. 15a,  
481 blue line), with both passing the area north of Taiwan. When the two particles arrived at the area north  
482 of Taiwan, the behavior of the tracers, according to specific velocity conditions (Fig. 15c), was very  
483 different: a northwestward transport occurred on Jan. 25 for the inshore particles (Fig. 15c) and a  
484 northeastward transport occurred on Feb. 12 for the offshore particles (Fig. 15c). The velocity conditions  
485 in the area north of Taiwan corresponded to the variation of the Taiwan Strait flux (Fig. 10), which shows  
486 that the Taiwan Strait flux on Feb. 12 was much greater than on Jan. 25. Therefore, it can be concluded  
487 that the TSC intrusion induced an offshore transport north of Taiwan.

488

489 Figure 15b shows the traces originating from the Kuroshio area. In the same way as the TSC water, the  
490 Kuroshio water was also transported to the northern shelf via both the inshore branch and the offshore  
491 branch. The separation of the two branches north of Taiwan was caused by cross-shore fluctuations of  
492 the currents. When the two particles arrived at the area north of Taiwan, a northwestward transport  
493 occurred on Feb. 2 for the inshore particles (Fig. 15c) and a northeastward transport occurred on Feb. 12  
494 for the offshore particles (Fig. 15c). This means that the offshore transport induced by the TSC also had  
495 an effect on the distribution of Kuroshio water north of Taiwan. Liu et al. (2016) showed that the winter  
496 TSC originated from a small branch of Kuroshio intrusion into the Luzon Strait. Our results complement  
497 this picture, since they show that most TSC particles flow into the TWC offshore branch under the  
498 influence of cross-shore fluctuation.

499

500

Figure 15

501

502 Our results may underestimate the impact of Kuroshio intrusion on the fluctuation of the TWC northeast  
503 of Taiwan, especially at the seasonal and interannual time scales. Wei et al. (2013) demonstrated that the  
504 annual and interannual variations of the Kuroshio volume transport are large. In addition, Zhou et al.  
505 (2015) pointed out that the annual and interannual variations of the Kuroshio intrusion northeast of  
506 Taiwan are prominent. Liu et al. (2014b) presented supportive evidence that the Kuroshio intrusion, from  
507 east of Taiwan to the onshore area north of Taiwan, is closely related to the Kuroshio volume transport.  
508 This relation between the Kuroshio intrusion and the Kuroshio volume transport had been interpreted by  
509 Su and Pan (1987) as the  $\beta$ -effect because of the sudden change in topography northeast of Taiwan. Our  
510 results show that the intra-seasonal variation of the Kuroshio intrusion and the Kuroshio volume transport  
511 was negligible compared with the TSC variation at the same time scale, indicating that the synoptic  
512 fluctuation of TWC north of Taiwan is mainly induced by the TSC. However, because FVCOM uses  
513 sigma co-ordinates in the vertical which are prone to errors in regions of steep topography, our results  
514 may underestimate the fluctuations at the shelf break, in particular to the northeast of Taiwan where  
515 Kuroshio intrusion occurs.

516

#### 517 **4.2 Water exchange in the inshore area induced by wind**

518 In the inshore area, the synoptic fluctuations of the TWC (Fig. 9b) caused by wind were generally strong  
519 in the alongshore direction and regionally important (along the latitudes 26.5°N and 28°N) in the cross-  
520 shore direction. The alongshore fluctuations showed that the TWC inshore branch occurred episodically.

521 This episodic occurrence of the TWC agrees with the results from a previous study based on four mooring  
522 surveys off the Zhe-Min coast (Zeng et al., 2012). The mechanism of the episodic occurrence of the TWC  
523 was mainly associated with the winter monsoon, which agrees with the analysis of observational data by  
524 Huang et al. (2016). However, the overall magnitude of the TWC fluctuation, and its role on the cross-  
525 shore flux, are still not fully understood due to the short-term nature of the observational data.

526

527 We investigated the magnitude of TWC fluctuation, and its role on the water exchange, in the inshore  
528 area. Previous studies (Su and Pan, 1987; Zeng et al., 2012) show that the TWC flows between the 50  
529 and 100 m isobaths, whereas the ZMCC water dominates the coastal area west of the 50 m isobath in the  
530 surface layer. As mentioned when discussing Figure 9d, the strongest TWC could reach the coastal area  
531 as close as the 30 m isobath, being stronger than those reported in the literature. Moreover, the area with  
532 large fluctuations spanned the area between the 30 and 100 m isobaths (Fig. 9b), indicating that water  
533 between the 30 and 100 m isobaths may be either ZMCC or TWC water.

534

535 The episodic occurrence of the TWC inshore branch is directly related to the relative importance of the  
536 southwestward ZMCC (Fig. 16, blue arrows) and the northeastward TWC (Fig. 16, red arrows). In this  
537 paper, only wind-induced synoptic fluctuations are considered, not short-term extreme storm events.

538 When the winter monsoon (the northeasterly wind) prevails, the ZMCC occupies most of the inshore  
539 area and the TWC inshore branch weakens (Fig. 16a). On the contrary, the TWC inshore branch can  
540 intrude into the near-coast area under southwesterly wind conditions (Fig. 16b). The boundary between  
541 the coastal current and the TWC may shift from the 100 m isobaths to the 30 m isobath in the cross-shore  
542 direction, covering the entire area of the TWC inshore branch.

543

544 Our results further reveal that strong wind-induced cross-shore fluctuations occur in the inshore area (Fig.  
545 9f). This cross-shore fluctuation has a significant ecological impact because of the connected nutrient  
546 transport (Zhao and Guo, 2011). Ren et al. (2015) observed a cross-shore flux in the inshore area, which  
547 was triggered by the transition of northeasterly to southwesterly winds. Their observed features can be  
548 further interpreted with our result that wind-induced fluctuations can affect the cross-shore water  
549 transport in the inshore area.

550

551 Largest cross-shore fluctuations were located at the latitudes 26.5 °N and 28 °N (Fig. 9f), which agreed  
552 well with the latitudes where the TWC offshore meanders occurred in the mean currents (Fig. 5a). Thus  
553 the offshore transports were most significant along the latitudes 26.5 °N and 28 °N according to both the  
554 mean currents and the synoptic fluctuations. The offshore transport may be associated with the offshore-  
555 penetrating fronts of coastal water in the ECS. Many remote-sensing images (He et al. 2010; Bai et al.  
556 2013) have exhibited offshore-penetrating fronts that crossed the 70 m isobath and played an important  
557 role in cross-shore material exchange, but the mechanisms of the offshore-penetrating fronts are still  
558 under debate. Yuan and Qiao (2005) pointed out that both downwelling- and upwelling-favorable winds  
559 are associated with the occurrence of the offshore-penetrating front. Ren et al. (2015) suggested that the  
560 penetrating front is generated by the transition of northeasterly to southwesterly winds. Wu (2015)  
561 suggested that the offshore-penetrating front is the response of buoyant coastal water to an along-isobath  
562 undulation of the ambient pycnocline, which is controlled by a temperature stratification of the water  
563 column. Our study offers a new interpretation, i.e., that the penetrating front is generated through the  
564 wind-induced fluctuations and the TWC offshore meanders.

565

566

567

Figure 16

568

## 569 **5 Conclusions**

570 The FVCOM model was able to reproduce the wintertime TWC in 2009 reasonably well, as shown by a  
571 validation in terms of the overall structure of the surface mean currents, the ECS boundary fluxes, and  
572 data from four mooring stations. The validation showed that the simulated TWC was comparable to the  
573 observed results, not only in terms of the mean currents but also in terms of the synoptic fluctuations.

574

575 The wintertime TWC showed two branches: one inshore and another offshore. The inshore branch  
576 covered an area between the 30 and 100 m isobaths and flowed northeastward via a straight route. The  
577 offshore branch was located between the 100 and 200 m isobaths and showed two prominent meanders.  
578 It was shown that the Coriolis force was nearly balanced by the pressure gradient in both branches,  
579 indicating the dominant role of the geostrophic balance for the mean current in both branches.

580

581 Two regions with significant synoptic fluctuations, north of Taiwan and the inshore area, were  
582 investigated using the EOF method. The first two leading modes explained 91% of the total variance.  
583 EOF1 showed that fluctuations occurred in the cross-shore direction south of 26°N. These fluctuations  
584 were mainly associated with variation of the TSC flux. EOF2 showed significant fluctuation between the  
585 30 and 100 m isobaths. These fluctuations caused the episodic existence of the TWC inshore branch in  
586 the alongshore direction and cross-shore fluctuations mainly at latitudes 26.5°N and 28°N, which were

587 mainly associated with the variation of wind speed.

588

589 We also studied the different dynamic reasons for the fluctuations in the two regions. In the area north of  
590 Taiwan, the TSC and Kuroshio converged to initiate the TWC. A barotropic pressure anomaly was  
591 generated by TSC intrusion from the Taiwan Strait causing a barotropic pressure gradient in the  
592 alongshore direction; this explains why the synoptic fluctuations in this area occurred in the cross-shore  
593 direction. Additionally, the wind had a strong effect on the synoptic fluctuations in the inshore area. The  
594 northeasterly monsoon enhanced the southwestward ZMCC and replaced the TWC in the inshore area.  
595 This situation is reversed during the southwesterly wind.

596

597 The synoptic fluctuations north of Taiwan and in the inshore area are important for both the alongshore  
598 and cross-shore transports. Due to the fluctuation north of Taiwan, the mixed water of the TSC and the  
599 Kuroshio was transported to both the inshore area and the offshore area, whereas most Taiwan Strait  
600 water was transported to the offshore area in winter. The inshore fluctuation not only caused an episodic  
601 occurrence of the TWC in the alongshore direction, which affected the alongshore transport of ZMCC  
602 water and TWC water between the 30 and 100 m isobaths, but also impacted the cross-shore transports  
603 along latitudes 26.5°N and 28°N.

604

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613

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771 **Table Captions**

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774

775 **Figure Captions**

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789

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798 period as the observation data.

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803 line DL1 represents the dividing line between the coastal current and inshore branch, and the red line  
804 DL2 separates the two TWC branches. b) Depth (m) of flow axes in the ECS, shown by color. Sections  
805 S1–S6 were selected to study the wintertime TWC. c) Flux of inshore branch (blue) and offshore branch  
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809 Figure 6: Distributions of current speed along the six sections S1–S6 in winter. The blue arrow on the  
810 left indicates the inshore branch according to the velocity cores from section S3 to S6. The blue arrow  
811 on the right indicates the offshore branch according to the velocity cores from section S2 to S6. TSC is  
812 the Taiwan Strait Warm Current.

813

814 Figure 7: Current standard deviation (~~black arrows~~) in the layer of the VMV. The black arrows indicate  
815 the major axis of the ellipse which represent the standard deviation of the current. The color shading  
816 shows the respective ~~magnitude-of-the-current-standard-deviation~~. The two blue arrows indicate the two  
817 TWC branches. The red curve indicate the area where the current standard deviation is larger than 0.1  
818 m/s and the branches' representative points (P1 and P2) are selected for later analysis.

819

820 Figure 8: Variation of alongshore currents (m/s, shown by color scale) for the entire water column north  
821 of Taiwan (P1) and in the inshore area (P2) and their relation with upper mixed layer depth. The positive  
822 velocity (warm color) indicates the occurrence of the TWC. The gray solid lines show the depth of the  
823 upper mixed layer.

824

825 Figure 9: The spatial pattern of the first (EOF1; left) and second (EOF2; right) leading modes of the  
826 VMV in the ECS: (a) EOF1 currents, (b) EOF2 currents, (c) EOF1 alongshore component, (d) EOF2  
827 alongshore component, (e) EOF1 cross-shore component, and (f) EOF2 cross-shore component (all  
828 shown by black arrows with the color representing the magnitude). The 30, 50, 70, 100 and 200 m  
829 isobaths are indicated with grey lines.

830

831 Figure 10: Temporal variation of EOF1, north-south component of wind speed, surface net heat flux, and  
832 TSC flux across the TWS section, and Kuroshio flux across the ET section. Their linear correlation  
833 coefficients  $R$  and time-lags are also indicated in each panel. The  $p$  value is a declining indicator which  
834 indicates the impact significance of the linear correlation coefficients  $R$  whereby  $R$  has statistical  
835 significance and the confidence level is larger than 95% when the  $p$  value is less than 0.05.

836

837 Figure 11: Temporal variation of EOF2, north-south component of wind speed, surface net heat flux, and  
838 TSC flux across the TWS section, and Kuroshio flux across the ET section. Their linear correlation  
839 coefficients and time-lags are also indicated in each panel.

840

841 Figure 12: The effects of Coriolis force (a), total pressure (b), surface friction (c), bottom friction (d),  
842 advection (e), and local acceleration (f) for water column in winter according to Eq. (5) (shown by black  
843 arrows with the color representing the magnitude; units:  $10^{-4} \text{ m}^2/\text{s}^2$ ). The two blue arrows indicate the  
844 two TWC branches. The two triangles indicate the two regions with significant fluctuation north of  
845 Taiwan (P1) and in the inshore area (P2).

846

847 Figure 13: Variations in Coriolis force, total pressure, and wind in the alongshore-cross-shore direction  
848 at P1 (a), the cross-alongshore direction at P1 (b), the alongshore-cross-shore direction at P2 (c), and the  
849 cross-alongshore direction at P2 (d) according to Eq. (5). The grey pointers indicate the alongshore and  
850 cross-shore directions of dynamical effects in the earth coordinate system.

851

852 Figure 14: Mean currents (upper panels) and synoptic fluctuations (EOF1 in middle panels and EOF2 in  
853 bottom panels) in winters of 2010-2013. The black arrows in the upper panels show the velocity (m/s) in  
854 the layer of VMV with the color representing the current speed. The two blue arrows with label IB and  
855 OB represent the flow axes of the inshore branch and offshore branch, respectively. The black arrows in  
856 the middle panels and bottom panels represent the EOF components (m/s) with their magnitude  
857 represented by color scales.

858

859 Figure 15: Traces of TSC water (a) and Kuroshio water (b) in winter, with the variation of surface currents  
860 north of Taiwan (c). The green lines L1 and L2 indicate the starting latitude of the tracers ( $24.5^\circ \text{N}$ ) and  
861 the latitude which is representative for synoptic fluctuations north of Taiwan ( $25.8^\circ \text{N}$ ), respectively. The  
862 black dots represent the release locations of tracers originated from line L1. The gray lines show the

863 entire trajectories of the tracers. The red lines and blue lines are selected trajectories, which are close to  
864 the inshore branch and offshore branch, respectively. The dates show the times when selected tracers  
865 cross the latitude indicated by line L2. The numbers are the depths of the tracers, which are labeled at an  
866 interval of six days. The two black arrows represent the two TWC branches.

867

868 Figure 16: The VMV under the northerly wind (a) and southerly wind (b). Panel (c) shows the variation  
869 of wind in winter. Blue vectors and red vectors show the southwestward coastal current and the  
870 northeastward TWC, respectively. Gray contours indicate the 30, 50, 70, and 100 m isobaths. The two  
871 black arrows represent the two TWC branches. The green ellipse indicates the inshore area with  
872 significant fluctuation.

873

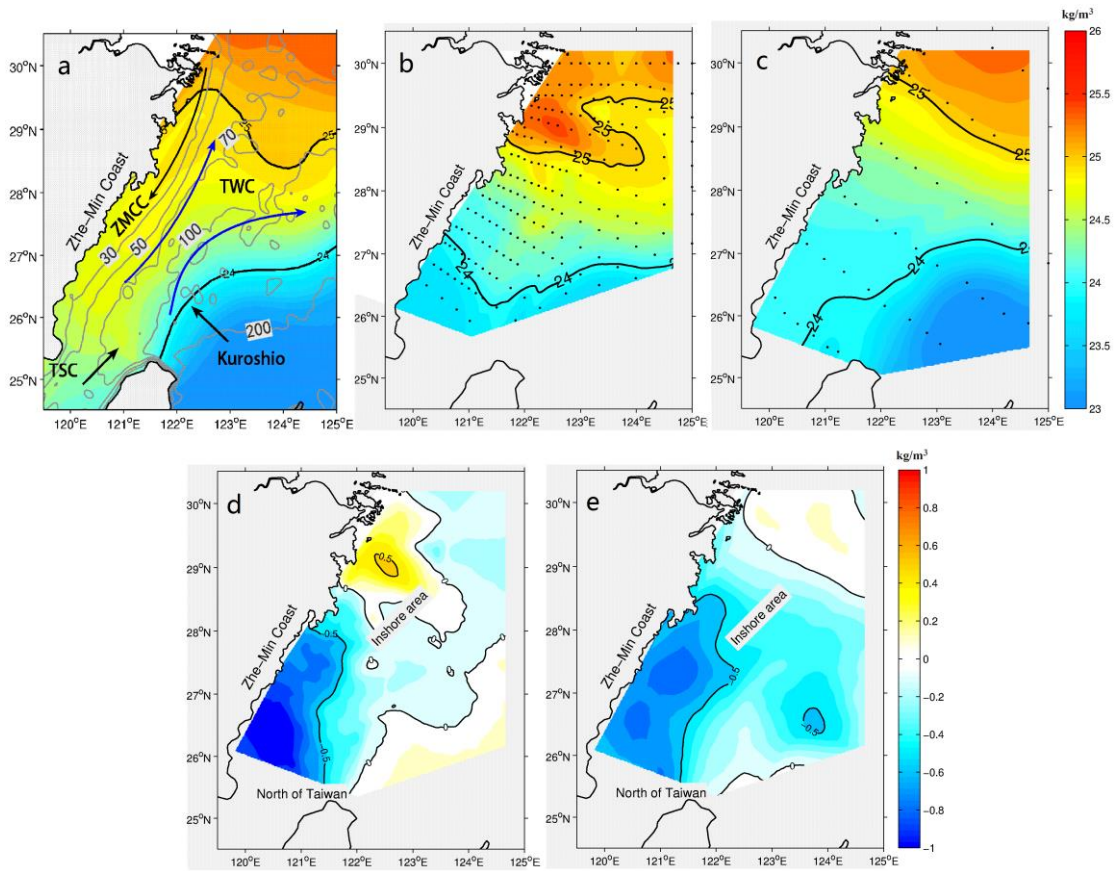


874 Table 1: Annual-mean volume transports ( $S_v = 10^6 \text{ m}^3/\text{s}$ ) through various sections. The sections are  
 875 shown in Figure 2 using blue dashed lines.

Section	Present model	Previous estimates
<b>Taiwan Strait</b>	1.22	1.2 (Isobe, 2008)
		1.8 (Wang et al., 2003)
		1.09 (Wu and Hsin, 2005)
		1.03 (Yang et al., 2011)
		1.72 (Guo et al., 2006)
		0.5 (Hung et al., 2003)
		1.10 (Liu et al., 2014b)
<b>Tsushima Strait</b>	2.85	2.65 (Isobe, 2008)
		3.03 (Guo et al., 2006)
		2.70 (Yang et al., 2011)
		2.52 (Liu et al., 2014b)
<b>200m isobath</b>	1.66	1.46 (Guo et al., 2006)
		0.87 (Liu et al., 2014a)
		3.0 (Teague et al., 2003)
		2.74 (Lee and Matsuno, 2007)
<b>East Taiwan Channel</b>	22.71	21.50 (Johns et al., 2001)
		23.00 (Teague et al., 2003)
		23.83 (Guo et al., 2006)
		28.4 (Hsin et al., 2013)
		21.37 (Yang et al., 2011)
		20.74 (Liu et al., 2014b)
<b>Tokara Strait</b>	23.20	23.4 (Feng et al., 2000)
		20.00 (Teague et al., 2003)
		20.66 (Yang et al., 2011)
		24.42 (Liu et al., 2014b)

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877



879

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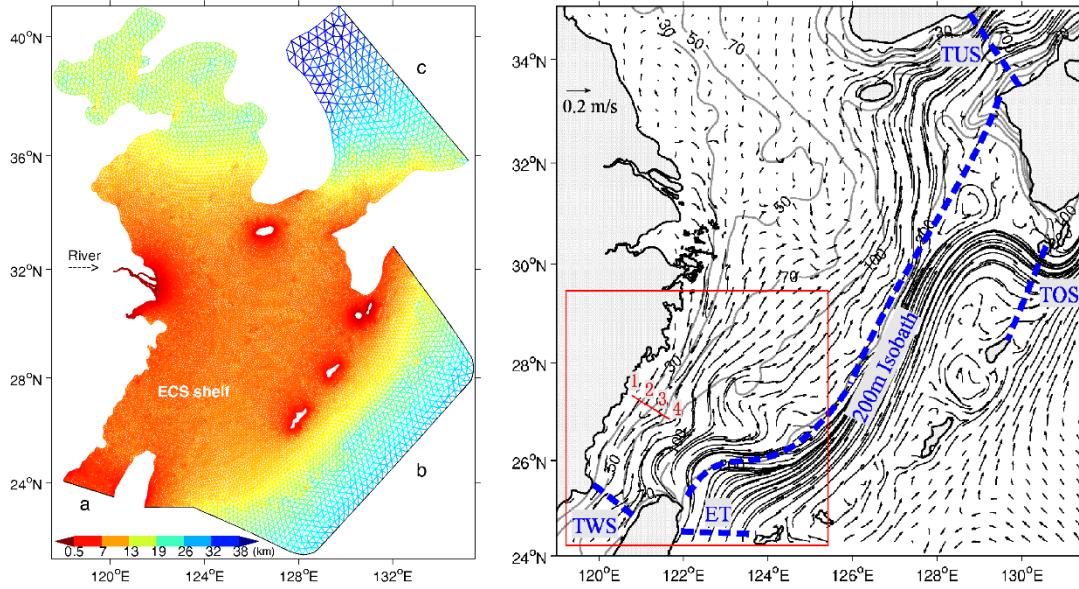
881 February (a), an ocean survey from Feb. 1–27, 2007 (b), and an ocean survey from Feb. 3–16, 2007 (c),

882 with the density anomalies between the GDEM data and the two surveys (d and e). The two blue arrows

883 indicate the two TWC branches in winter. The 30, 50, 70, 100 and 200 m isobaths are indicated with grey

884 lines in panel a.

885



886

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888 colors in the left panel show the grid length (km). The letters a, b, and c indicate the three open boundaries

889 at the Taiwan Strait, the northwest Pacific Ocean, and the Japan/East Sea, respectively. The blue dashed

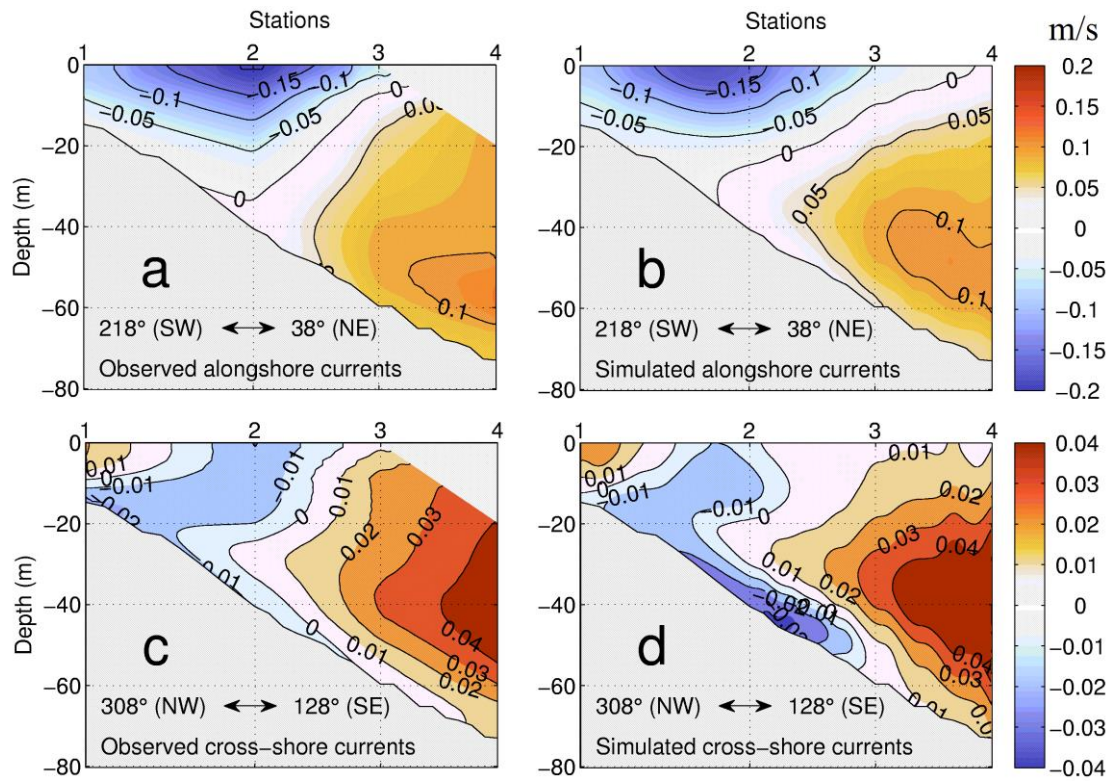
890 lines (right) show some important straits around shelf boundary, including the Taiwan Strait (TWS), the

891 East Taiwan Channel (ET), the Tsushima Strait (TUS), the Tokara Strait (TOS), and shelf break at the

892 200 m isobath. The red rectangle shows the study area of the wintertime TWC. The four red numbers off

893 the Zhe-Min coast shows the four mooring sites observed from Jan. 5 to Feb. 28, 2009.

894

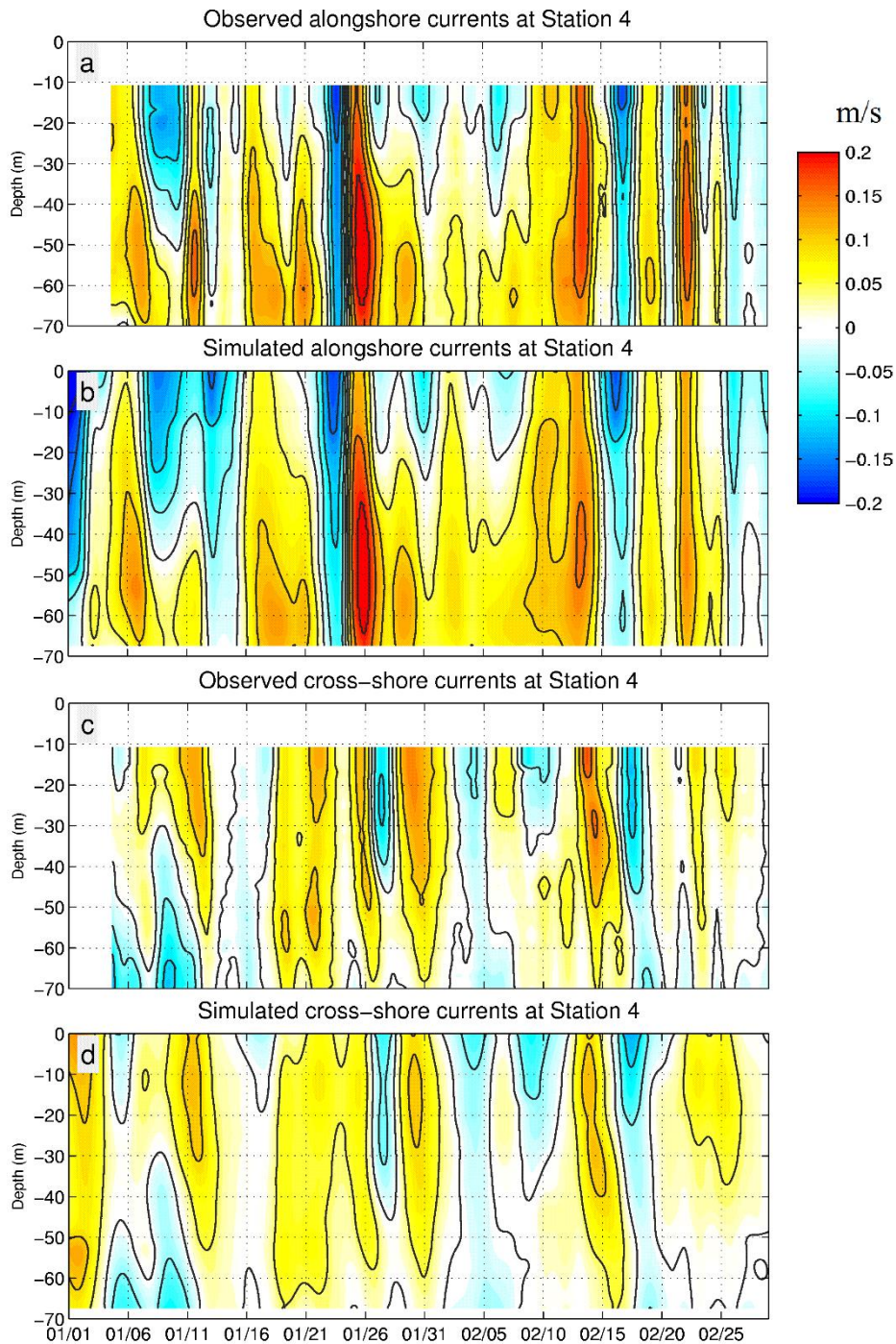


895

896 Figure 3: Validations of the wintertime TWC (warm color) along the section off the Zhe-Min coast (the  
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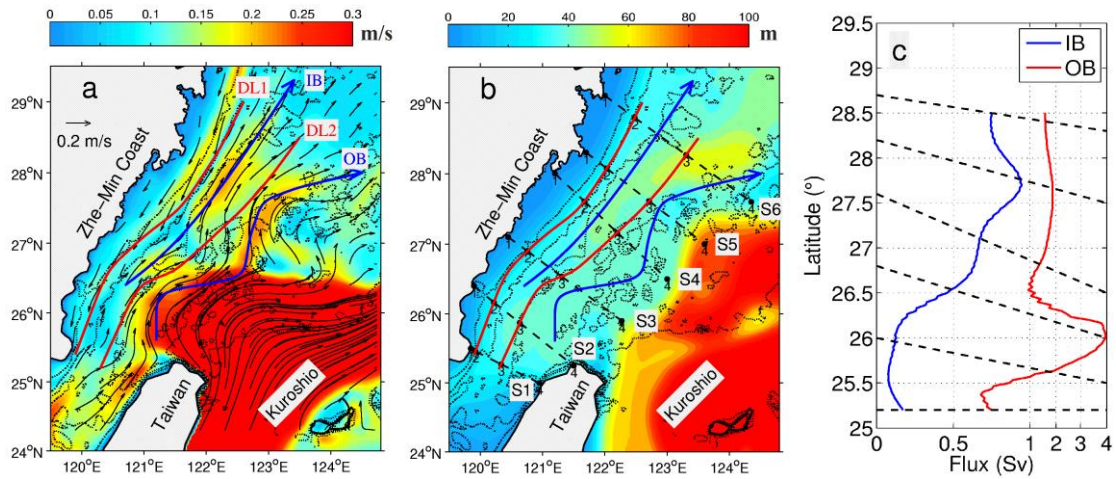
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904 cross-shore currents. The observation data comes from Station 4 in Figure 1 and the simulated data has

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911 line DL1 represents the dividing line between the coastal current and inshore branch, and the red line

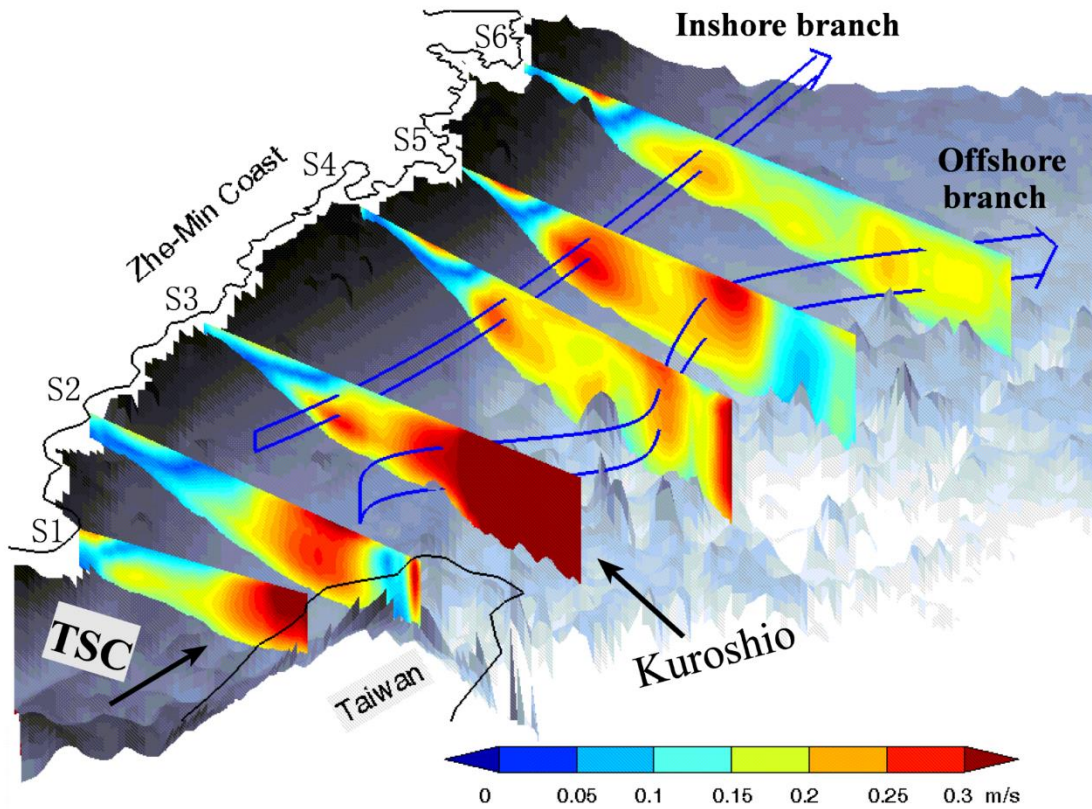
912 DL2 separates the two TWC branches. b) Depth (m) of flow axes in the ECS, shown by color. Sections

913 S1–S6 were selected to study the wintertime TWC. c) Flux of inshore branch (blue) and offshore branch

914 (red) at different latitudes. Dashed lines show the positions of Sections. S1–S6. Note, the scale is not

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916



917

918 Figure 6: Distributions of current speed along the six sections S1–S6 in winter. The blue arrow on the

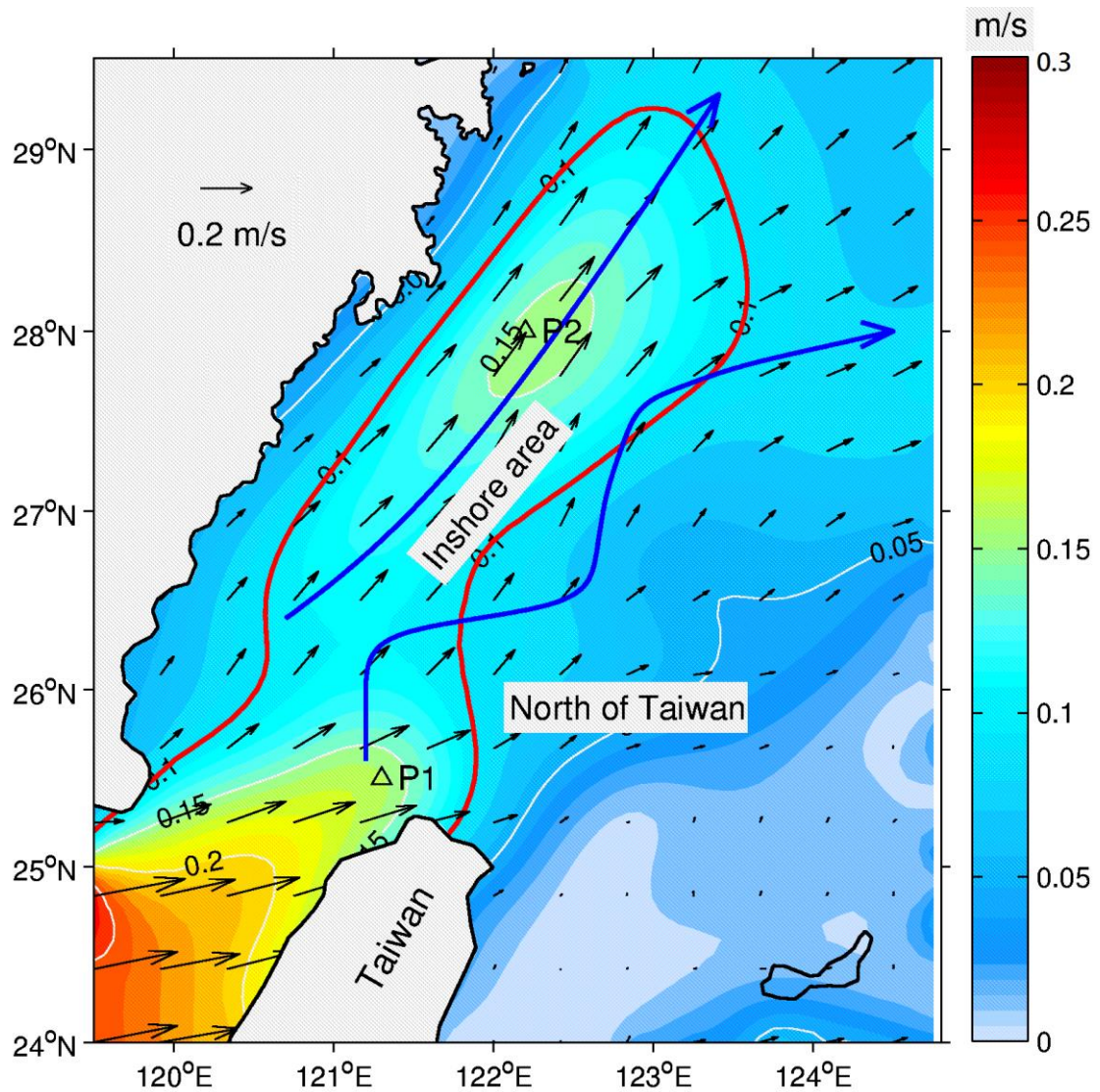
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920 on the right indicates the offshore branch according to the velocity cores from section S2 to S6. TSC is

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924 Figure 7: Current standard deviation (black arrows) in the layer of the VMV. The black arrows indicate

925 the major axis of the ellipse which represent the standard deviation of the current. The color shading

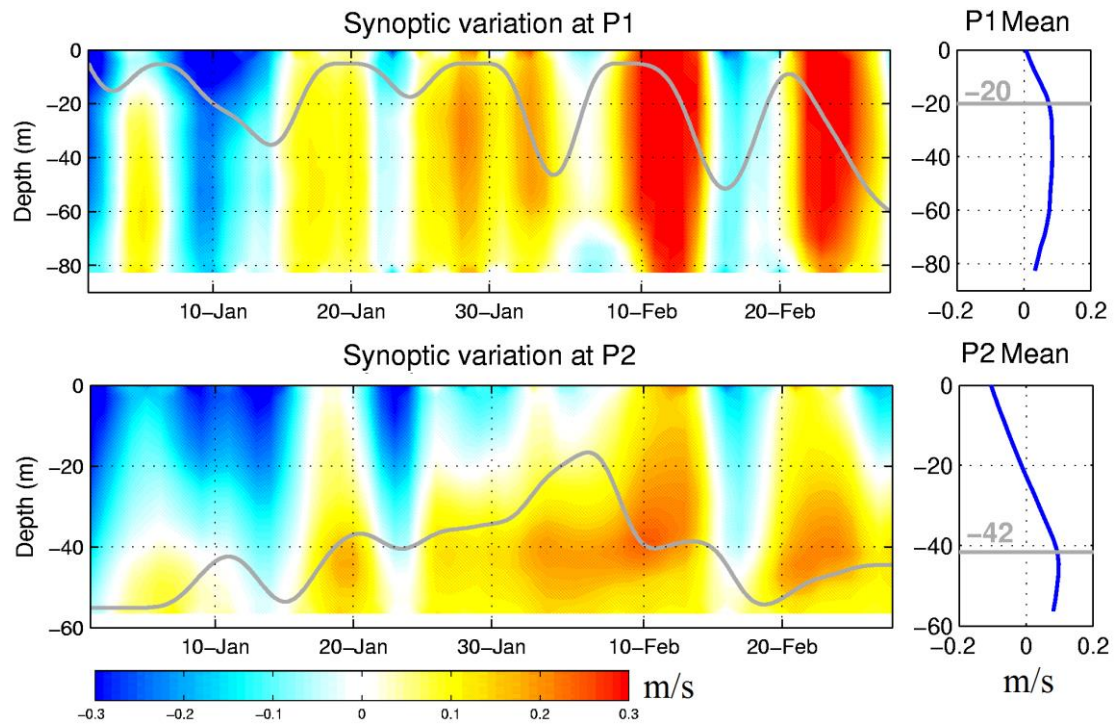
926 shows the respective magnitude ~~of the current standard deviation~~. The two blue arrows indicate the two

927 TWC branches. The red curve indicate the area where the current standard deviation is larger than 0.1

928 m/s and the branches' representative points (P1 and P2) are selected for later analysis.

929

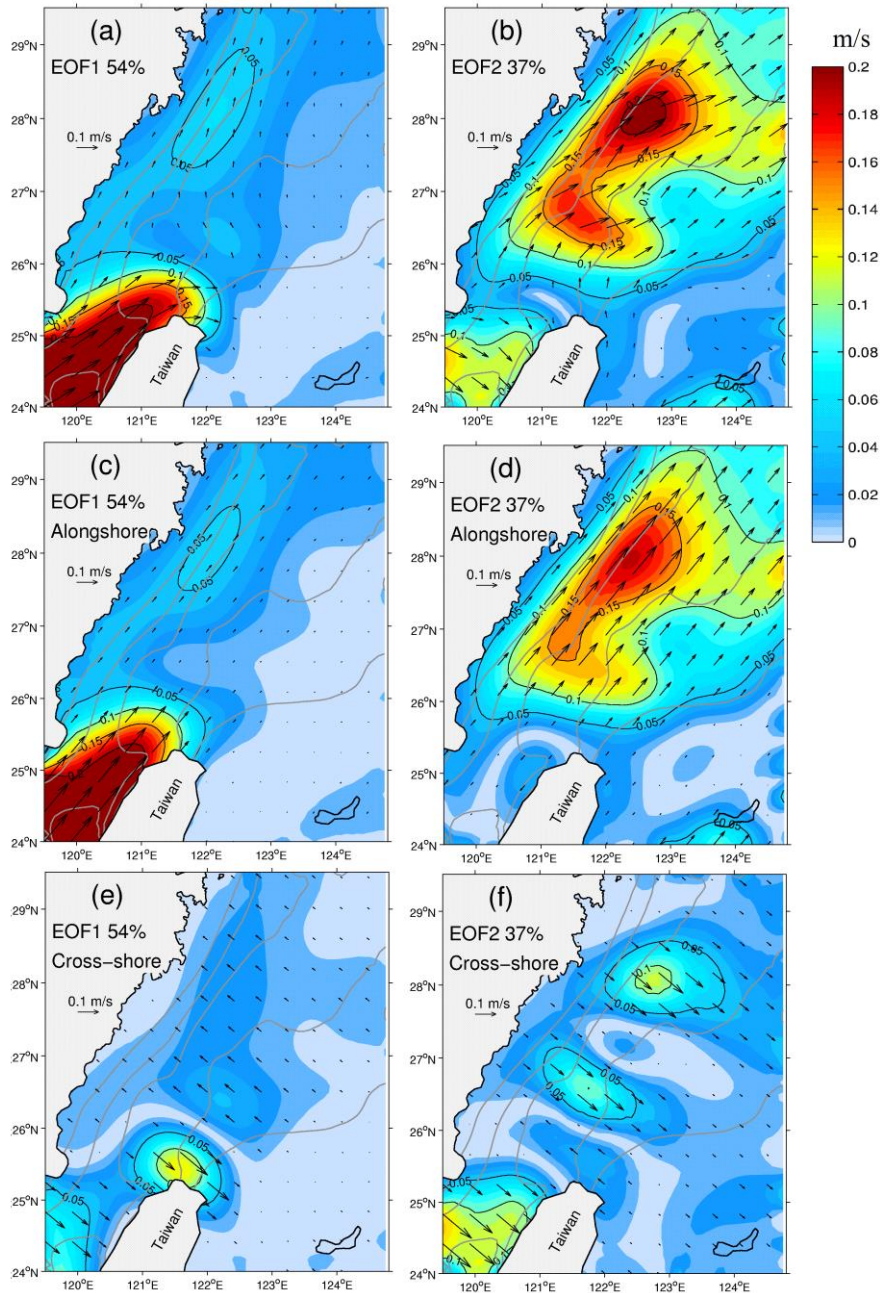




930

931 Figure 8: Variation of alongshore currents (m/s, shown by color scale) for the entire water column north  
 932 of Taiwan (P1) and in the inshore area (P2) and their relation with upper mixed layer depth. The positive  
 933 velocity (warm color) indicates the occurrence of the TWC. The gray solid lines show the depth of the  
 934 upper mixed layer.

935



936

937 Figure 9: The spatial pattern of the first (EOF1; left) and second (EOF2; right) leading modes of the

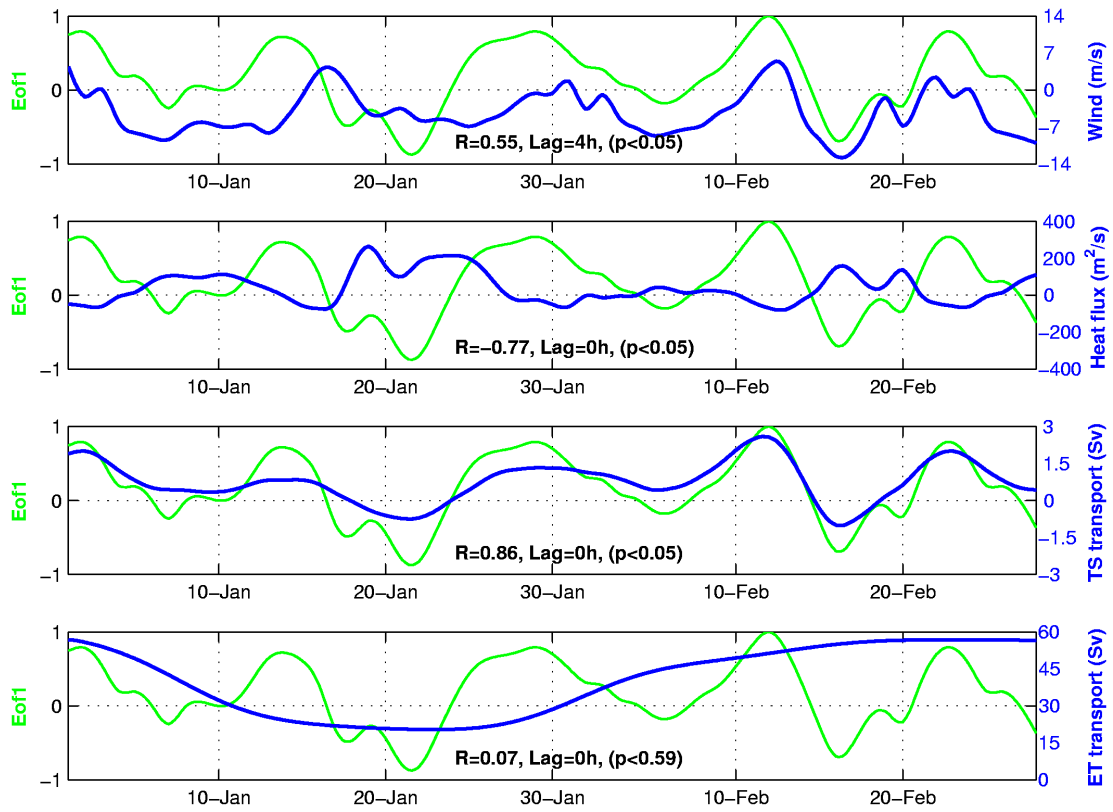
938 VMV in the ECS: (a) EOF1 currents, (b) EOF2 currents, (c) EOF1 alongshore component, (d) EOF2

939 alongshore component, (e) EOF1 cross-shore component, and (f) EOF2 cross-shore component (all

940 shown by black arrows with the color representing the magnitude). The 30, 50, 70, 100 and 200 m

941 isobaths are indicated with grey lines.

942



943

944 Figure 10: Temporal variation of EOF1, north-south component of wind speed, surface net heat flux, and

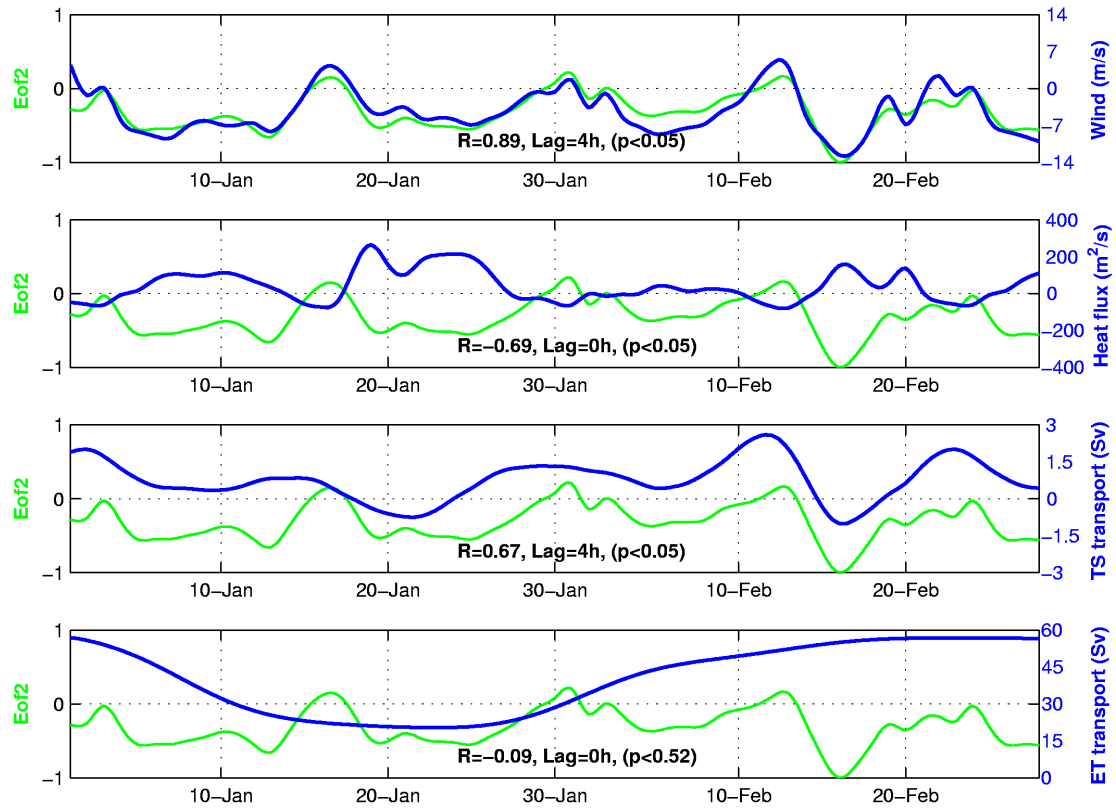
945 TSC flux across the TWS section, and Kuroshio flux across the ET section. Their linear correlation

946 coefficients R and time-lags are also indicated in each panel. The p value is a declining indicator which

947 indicates the impact significance of the linear correlation coefficients R whereby R has statistical

948 significance and the confidence level is larger than 95% when the p value is less than 0.05.

949



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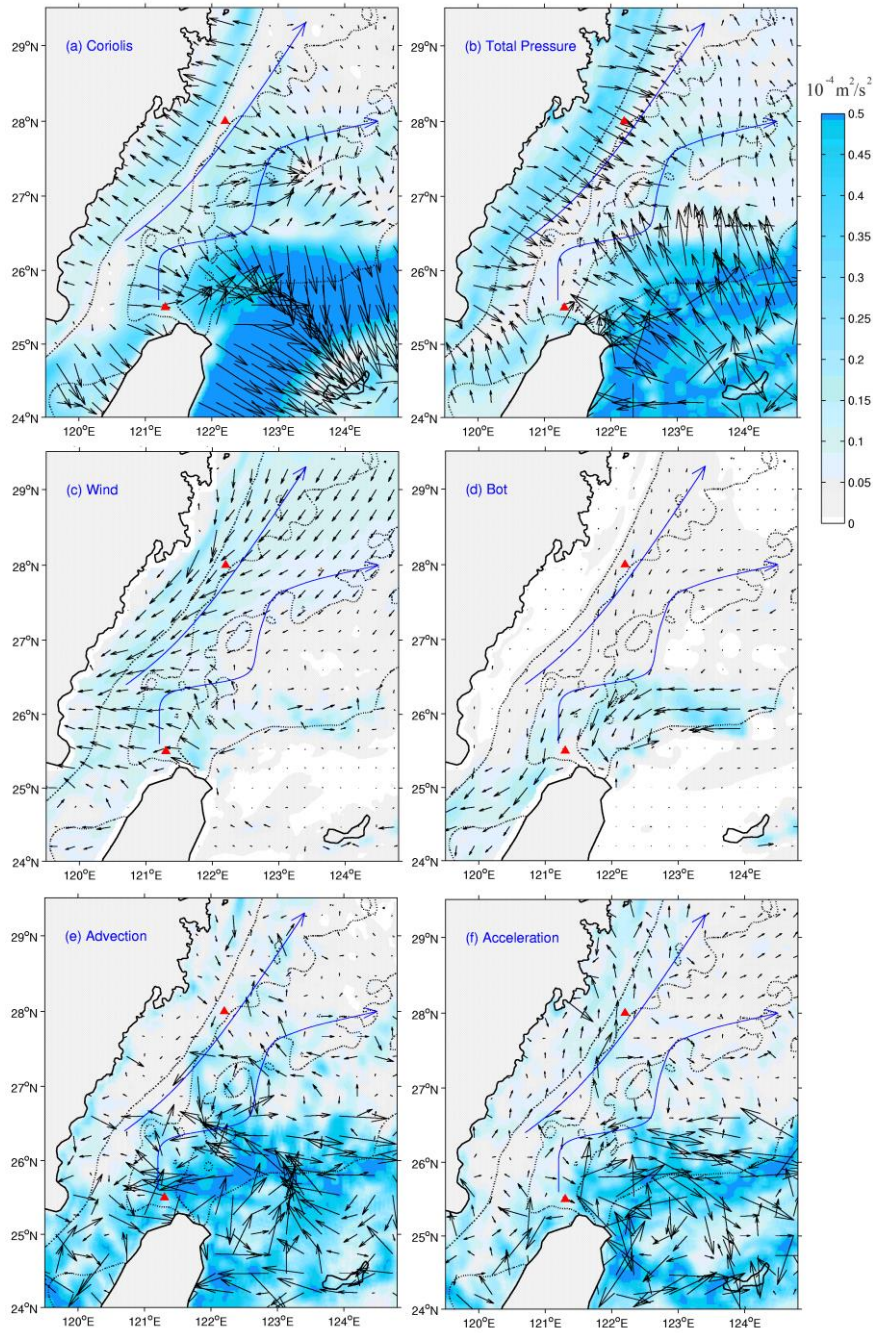
951 Figure 11: Temporal variation of EOF2, north-south component of wind speed, surface net heat flux, and

952 TSC flux across the TWS section, and Kuroshio flux across the ET section. Their linear correlation

953 coefficients and time-lags are also indicated in each panel.

954

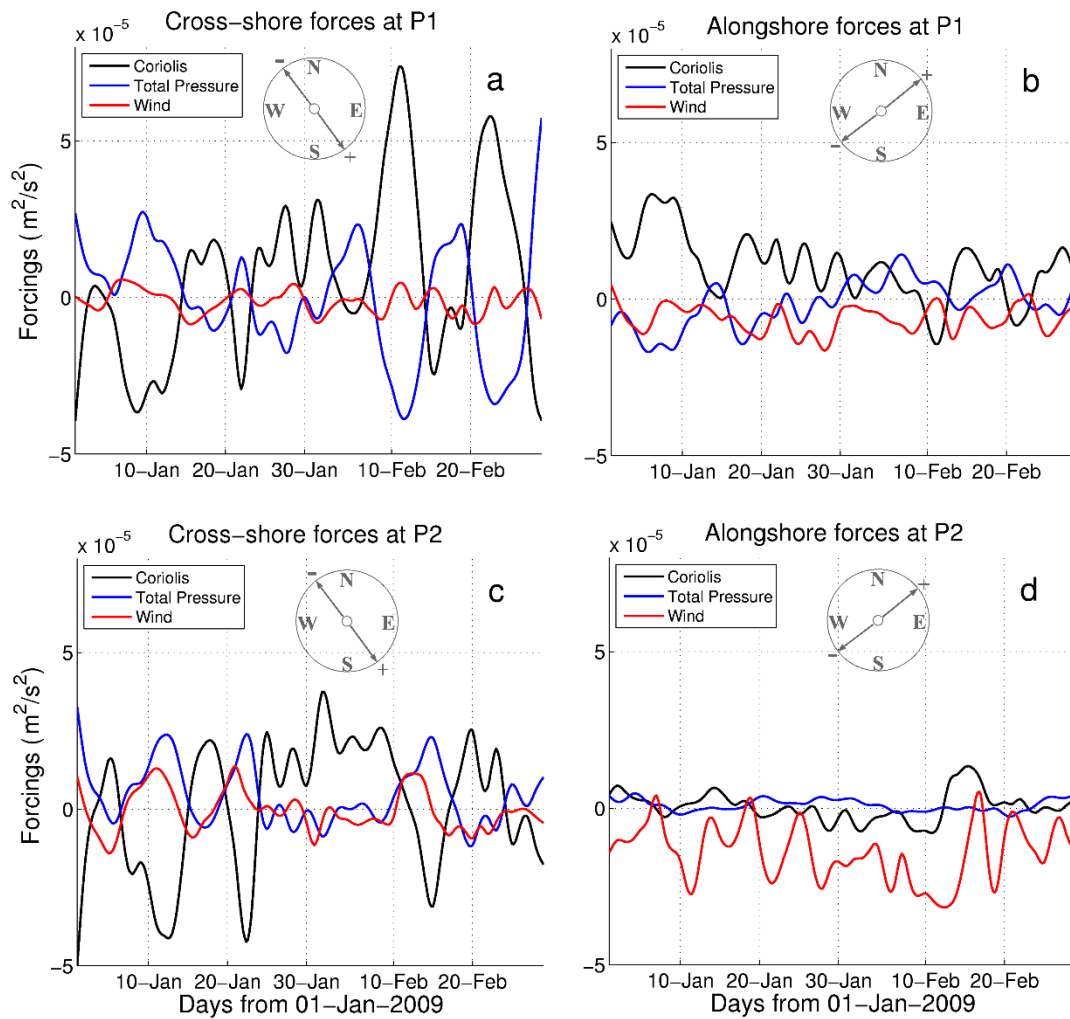




955

956 Figure 12: The effects of Coriolis force (a), total pressure (b), surface friction (c), bottom friction (d),  
 957 advection (e), and local acceleration (f) for water column in winter according to Eq. (5) (shown by black  
 958 arrows with the color representing the magnitude; units:  $10^{-4} \text{ m}^2/\text{s}^2$ ). The two blue arrows indicate the  
 959 two TWC branches. The two triangles indicate the two regions with significant fluctuation north of  
 960 Taiwan (P1) and in the inshore area (P2).

961

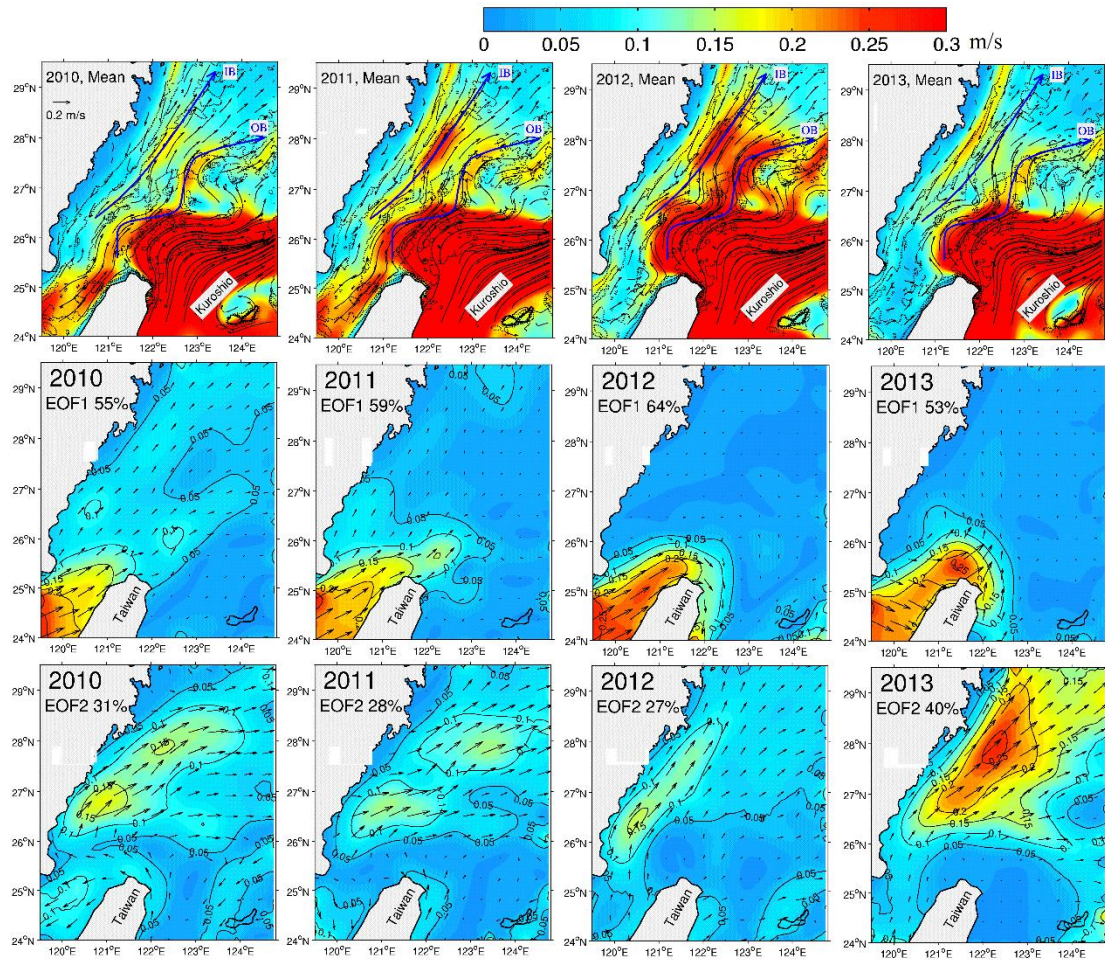


963

964 Figure 13: Variations in Coriolis force, total pressure, and wind in the alongshore-cross-shore direction  
 965 at P1 (a), the cross-alongshore direction at P1 (b), the alongshore-cross-shore direction at P2 (c), and the  
 966 cross-alongshore direction at P2 (d) according to Eq. (5). The grey pointers indicate the alongshore and  
 967 cross-shore directions of dynamical effects in the earth coordinate system.

968

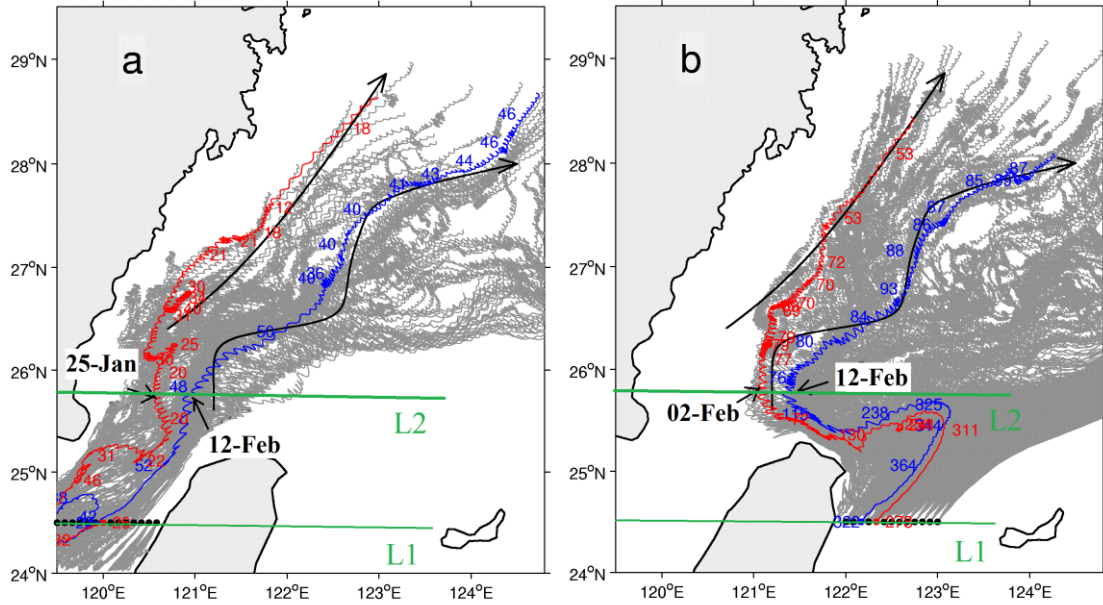




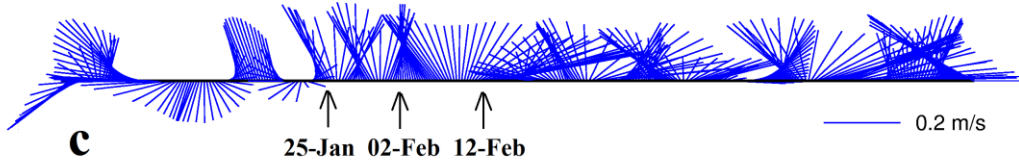
969

970 Figure 14: Mean currents (upper panels) and synoptic fluctuations (EOF1 in middle panels and EOF2 in  
 971 bottom panels) in winters of 2010-2013. The black arrows in the upper panels show the velocity (m/s) in  
 972 the layer of VMV with the color representing the current speed. The two blue arrows with label IB and  
 973 OB represent the flow axes of the inshore branch and offshore branch, respectively. The black arrows in  
 974 the middle panels and bottom panels represent the EOF components (m/s) with their magnitude  
 975 represented by color scales.

976



### Variation of currents north of Taiwan



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01-Jan 15-Jan 01-Feb 15-Feb 01-Mar 15-Mar 30-Mar

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Figure 15: Traces of TSC water (a) and Kuroshio water (b) in winter, with the variation of surface currents

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north of Taiwan (c). The green lines L1 and L2 indicate the starting latitude of the tracers (24.5°N) and

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the latitude which is representative for synoptic fluctuations north of Taiwan (25.8°N), respectively. The

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black dots represent the release locations of tracers originated from line L1. The gray lines show the

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entire trajectories of the tracers. The red lines and blue lines are selected trajectories, which are close to

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the inshore branch and offshore branch, respectively. The dates show the times when selected tracers

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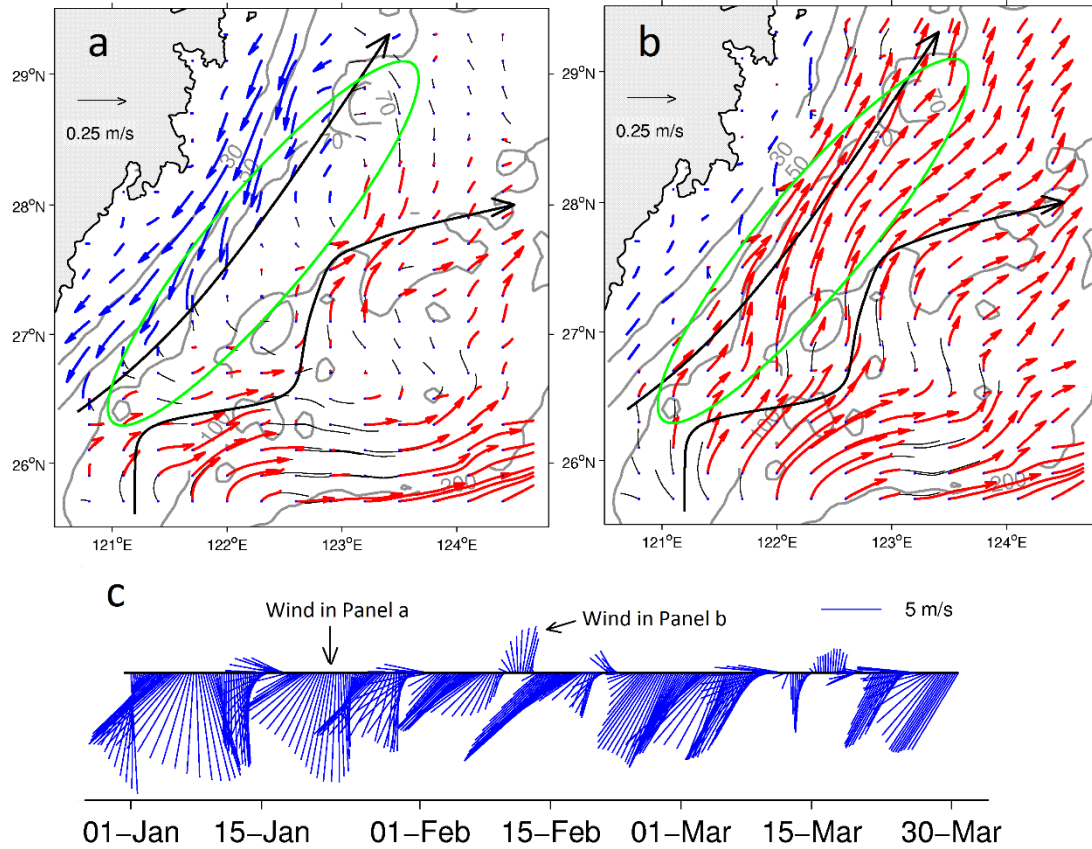
cross the latitude indicated by line L2. The numbers are the depths of the tracers, which are labeled at an

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interval of six days. The two black arrows represent the two TWC branches.

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988 Figure 16: The VMV under the northeasterly wind (a) and southwesterly wind (b). Panel (c) shows the  
 989 variation of wind in winter. Blue vectors and red vectors show the southwestward coastal current and the  
 990 northeastward TWC, respectively. Gray contours indicate the 30, 50, 70, and 100 m isobaths. The two  
 991 black arrows represent the two TWC branches. The green ellipse indicates the inshore area with  
 992 significant fluctuation.

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