

**Site selection of ocean current power generation from drifter
measurements**

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Abstract

Site selection of ocean current power generation is usually based on numerical ocean calculation models. In this study however, the selection near the coast of East Asia is optimally from the Surface Velocity Program (SVP) data using the bin average method. Japan, Vietnam, Taiwan, and Philippines have suitable sites for the development of ocean current power generation. In these regions, the average current speeds reach 1.4, 1.2, 1.1, and 1.0 m s^{-1} , respectively. Vietnam has a better bottom topography to develop the current power generation. Taiwan and Philippines also have good conditions to build plants for generating ocean current power. Combined with the four factors of site selection (near coast, shallow seabed, stable flow velocity, and high flow speed), the waters near Vietnam is most suitable for the development of current power generation. Twelve suitable sites, located near coastlines of Vietnam, Japan, Taiwan, and Philippines, are indentified for ocean current power generation. After the Kuroshio power plant being successfully operated in Taiwan, more current power plants can be built in these waters.

Keywords: SVP drifter, ocean current, power generation, the East Asia, Kuroshio

1. Introduction

Ocean current power is generated from the kinetic energy of ocean currents with less uncertainty than the wind, wave and solar power, and has the high load capacity resulting from the high density of fluid (seawater) [1–3]. Electric power generation from global ocean currents has enormous potential. In 2000, Blue Energy, Inc., estimated that global ocean currents have capacity over 450 GW and represent a market of approximately US\$550 billion per annum (assuming purchase price per kWh = US\$0.1395) [4]. However, it is noted that devices which extract power from a fluid's momentum (e.g. a tidal turbine or wind turbine) can realistically reach an efficiency up to 50% (the Betz limit is a bit higher, but not by a great deal).

There are many world-wide sites with tidal velocities of 2.5 m s^{-1} and greater. Countries with an exceptionally high resource include the UK, Italy, Philippines, and Japan [4]. But strong tidal currents only last for a short time period, and cannot provide a stable power supply. The strong Florida Current and Gulf Stream move close to the shore of the United States [5-6] in areas of high demand for power [4]. Earlier studies [7–8] indicated that the westward recirculations steadily increase the transport of the Gulf Stream from approximately 30 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) in the Florida Current to approximately 150 Sv at 55°W . The transport is around 20–30 Sv for the Kuroshio near

Taiwan, and about 4–10 GW of ocean current power are generated with the flow velocity of 1 m s^{-1} [9].

In Taiwan, the Kuroshio power plant of 30MW was planned between Taitung and Green Island ($\sim 121.43^\circ\text{E}$, 22.70°N , see Fig. 1) [9]. The estimated annual net income of power plant is 488.58 million NTD (new Taiwan dollar, 1 USD $\sim$ 31 NTD). The payback period is only 6.2 years. The estimated power plant life is 20 years. Thus, the Kuroshio power plant in Taiwan will be operated successfully in the future. Questions arise: Are there other sites or locations in the East Asia suitable for the development of the (Kuroshio) current power generation? If yes, where are these sites? Ocean flow measurement data is an important factor in selecting the site of ocean current power generation. The purpose of this paper is to determine possible sites of current power plant for technical and economic feasibility, and to develop a complete map of strong currents in the East Asia using the Surface Velocity Program (SVP) drifter data of Global Drifter Program (GDP). The GDP is the principle component of the Global Surface Drifting Buoy Array, a branch of the NOAA Global Ocean Observing System (GOOS) and a scientific project of the Data Buoy Cooperation Panel (DBCP).

2. Data and Method

The NOAA Drifter Data Assembly Center (DAC) provides quality controlled data for velocity measurements. Upper ocean current velocities every 6 h can be obtained from the website: <http://www.aoml.noaa.gov/phod/dac/dacdata.php>. A total of 1,883 drifters in the northwestern Pacific (10° – 50° N, 100° – 150° E) during 1985–2009 are used for this study (see Fig. 2). There are 1,029,889 six-hourly velocity observations of SVP drifters in the study area. All drifters had a holey-sock drogue centered at a nominal depth of 15 m. The 6 hourly velocities are obtained via 12 h centered differencing of the kriged positions [10]. The estimated accuracy of the velocity measurements using SVP drifters is 0.01 m s^{-1} with surface winds of 10 m s^{-1} [11].

3. Site Selection

3.1 Four factors of site selection

Four factors related to the site selection of ocean current power generation [9] are (1) near coast, (2) shallow seabed, (3) stable flow velocity, and (4) high flow speed, respectively. Near-shore or shallow-water facilities require less cost of construction and maintenance. High and stable flow speeds can provide the great and steady power in comparison tidal current power generation (short period strong currents). The distance from shore (L) can be calculated from the coastline data of NOAA National Geophysical

95 Data Center (NGDC). The depth (D) data can also be obtained from the NOAA/NGDC.

96 The drifter locations and velocities can be downloaded online at the NOAA/DAC website.

97 The ensemble of the individual drifter locations is plotted in Fig. 2 with color coded in

98 accordance with the local instantaneous speed. The strongest current of the Northwestern

99 Pacific is the Kuroshio. Formed from branching of the North Equatorial Current, the

100 Kuroshio is intensified east of Luzon and Taiwan [12]. Figure 3 shows the numbers of

101 data point in $0.25^\circ \times 0.25^\circ$ bins and their standard deviation. The ensemble mean current

102 speed (Fig. 4) and velocity vectors (Fig. 5) are computed using the bin average method

103 [13–14] in $0.25^\circ \times 0.25^\circ$ bins and is shown only for bins with more than 7 observations.

104 The Kuroshio axis is along the east coast of Luzon, Taiwan and Japan. Drifter-measured

105 velocities (U) are often greater than 1.2 m s^{-1} in the Kuroshio axis (Fig. 2). Besides

106 Kuroshio, there is a strong current with a velocity of 1.2 m s^{-1} in the South China Sea

107 along the coast of Vietnam. Fig. 4 shows the average speeds of strong currents near Japan,

108 Vietnam, Taiwan, and Philippines, reaching 1.4, 1.2, 1.1, and 1.0 m s^{-1} , respectively. A

109 complete map of strong ocean currents is obtained from 25 years (1985–2009) of direct

110 velocity measurements for the site selection of ocean current power generation in the East

111 Asia. Thus, Japan, Vietnam, Taiwan, and Philippines (Figs. 4 and 5) have a good

112 condition ($U > 1.0 \text{ m s}^{-1}$) for developing the ocean current power generation.

Percentages of current speed greater than 1 m s^{-1} (i.e., percentage of good quality of power supply) in $0.25^\circ \times 0.25^\circ$ bins (Fig. 6) can reach 55–80% (~ 13.2 – 19.2 hours/day) in some locations near Japan, Taiwan, Vietnam, and Philippines. Fig. 7 shows the seasonal variation of current speeds with the mean current speeds in winter half-year (from October to March) and in summer half-year (from April to September). The locations of strong currents along the east coast of Luzon, Taiwan and Japan are almost the same in winter half-year as in summer half-year. But, the mean current speeds are 0.1 – 0.2 m s^{-1} greater in summer half-year than in winter half-year. Thus the power plant will generate more electricity in summer half-year. The observed current data near Vietnam is less in summer half-year, but strong currents ($>1.0 \text{ m s}^{-1}$) were measured along the east coast of Vietnam in both winter and summer half-years.

3.2 Index *I*

In the recent study [4], the mid-water energy production units (EPUs) with a retention–transmission cable system will lie 6–37 km offshore of southeast Florida in about 100–500 m of water. In Taiwan, the anchor system for the deep water of more than 500 m is also being developed for Kuroshio power plant near Taitung [9]. The sea depth near Taitung is often more than 500 m. Thus the anchor chain length must be over

a thousand meter. The relay platform is a flexible structure floating in the deep sea [15]. Existing turbines with vertical axis may be suitable for the Kuroshio plant [9]. Because its construction and maintenance cost is lowest for deep-sea engineering. Thus turbine generators and anchor system for the deep water may be able to work successfully in the next few years. In order to objectively consider four factors of site selection, an index I related to the site selecting of current power generation is designed as

$$I = \sum_{i=1}^4 I_i w_i, \quad (1)$$

$$I_1 = [1 - (L/50 \text{ km})], I_2 = [1 + (D/1000 \text{ m})], I_3 = P/100\%, I_4 = U/1.4 \text{ m s}^{-1}.$$

Here, P is the percentage of current speed greater than 1 m s^{-1} ; U is the current speed. The choice of constants ($L = 50 \text{ km}$, $D = 1000 \text{ m}$, and $U = 1.4 \text{ m s}^{-1}$) is based on the aforementioned studies [4] [9] and a maximum of mean speeds in Fig. 4. Each of these indices was weighted to reflect their impact on revenue, capital costs, and maintenance costs, etc. According to the recent study [9], the plant engineering of a 30 MW pilot plant needs a total investment fund of 2.3 billion NTD. The operation expenses, include maintenance costs, personnel costs, insurance, etc., is 0.12 billion NTD dollars a year. If the plant life is 20 years, the operation expenses of 20 years is 2.4 billion NTD. Thus the capital and maintenance costs of 20 years are about 4.7 billion NTD. The sales income of a 30 MW plant is $30,000 \text{ kW} \times 20 \text{ (years)} \times 365 \text{ (day/year)} \times 24 \text{ (h/day)} \times$

149 0.7 (assuming capacity = 70%) $\times$ 2.8 (NTD/kWh, purchase price per kWh= 2.8 NTD) =
150 10.3 billion NTD [9]. Thus, percentages of expenditure and income were 31% (4.7 billion
151 NTD) and 69% (10.3 billion NTD), respectively. I_1 and I_2 reflect their impact on
152 expenditure. I_3 and I_4 reflect their impact on revenue. Hence w_1 and w_2 are set to be
153 15.5%, then w_3 and w_4 are set to be 34.5%. Each index of site selection ranged from 0 to
154 1. The variations of I_1 , I_2 , I_3 , and I_4 are shown in the Fig. 8. The variation of the index I
155 is shown in the Fig. 9. The higher the index value is, the more suitable the site of ocean
156 current power generation selects. The recent study [9] suggests the four factors of site
157 selection in priority order: (1) near coast (I_1), (2) shallow seabed (I_2), (3) stable flow
158 velocity (I_3), and (4) high flow speed (I_4). Thus the ranges of four factors (or four indexes,
159 $I_1 - I_4$) were limited to select suitable sites of ocean current power generation in the
160 following paragraph. Firstly, 76 sites, which meet initial conditions ($L < 100$ km ($I_1 > -1$),
161 $D < 2000$ m ($I_2 > -1$), $P > 30\%$ ($I_3 > 0.3$), and $U > 0.7$ m s⁻¹ ($I_4 > 0.5$)), and their I values are
162 shown in Fig. 10a. These sites located in the east of Vietnam, northeast of Luzon, east of
163 Taiwan and south of Japan (in red boxes of Fig. 10a). The site of Kuroshio power plant
164 near Green Island in the recent study [9] is also selected in these conditions. If L is
165 reduced to 50 km ($L < 50$ km; $I_1 > 0$), the selected sites become less in amount (46 sites), as
166 shown in Fig. 10b. Shorter L will significantly reduce engineering and maintenance costs.

167 The site of Kuroshio power plant near Green Island is still one of selected sites. If D is
 168 reduced from 2000 m to 1000 m ($D < 1000$ m; $I_2 > 0$), only 21 sites are selected, as shown
 169 in Fig. 10c. Selecting a site in shallower waters will greatly increase the chances of
 170 successful operation, because developing an anchor system for the shallower water is
 171 easier. As $D < 1000$ m, the site of Kuroshio power plant near Green Island is not selected.
 172 Finally, if P and U are increased to 50% and 1 m s^{-1} ($I_3 > 0.5$, and $I_4 > 0.714$), respectively,
 173 income and power generation of plant will greatly increase. In Fig. 10d, the most suitable
 174 sites are selected for the development of ocean current power generation in the East Asia.
 175 There are 12 sites are selected according to the conditions of $L < 50$ km, $D < 1000$ m,
 176 $P > 50\%$, and $U > 1.0 \text{ m s}^{-1}$. The information of the 12 sites is listed in Table 1. There are
 177 seven sites (V1—V7) near Vietnam, three sites (J1—J3) near Japan, and 2 sites near
 178 Taiwan (T1) and Philippines (P1). Their index I values are 0.539—0.726 (V1—V7,
 179 Vietnam), 0.518—0.607 (J1—J3, Japan), 0.540 (T1, Taiwan), and 0.538 (P1, Philippines),
 180 respectively. This suggests that the most suitable region to develop the ocean current
 181 power generation is the shallow coastal water near Vietnam, and then is followed by
 182 Japan, Taiwan and the Philippines. The detail descriptions for each index are listed in
 183 Table 2.

184 In order to show clearly the correct position of 12 sites with strong currents,

185 enlargements of mean current speed from Fig. 4 with the isobaths near Japan, Taiwan,
 186 Vietnam, and Philippines, respectively, are plotted in Fig. 11. Sites V1 (109.5°E, 14.0°N),
 187 V6 (109.5°E, 11.75°N) and V7 (109.5°E, 11.5°N) are selected approximately 30 km east of
 188 Vietnam on the shelf (Table 1 and Fig. 11a). Water depths at V1, V6, and V7 are only 160,
 189 120, and 100 m, respectively (see Table 1). The three sites have higher I_2 values (0.84,
 190 0.88, and 0.90), which are much greater than those of other sites. Then, V6, V1, and V7
 191 have three highest I values (see Table 2). Thus the shallow seabed ($D < 200$ m) is an
 192 important parameter to influence the choice Vietnam over the others. Mid-water EPU's
 193 can work in approximately 100—500 m of water in recent study [4]. Thus it is easier to
 194 build a current power plant near Vietnam in the future. Sites V2—V5 are selected about
 195 40 km east of Vietnam with the current speeds of about 1.2 m s^{-1} (U), and depths (D) of
 196 700—900 m (see Table 1, and Fig. 11a). At these sites, there are stronger current speeds
 197 and deeper depths. Approximately 60% of observed speeds are greater than 1 m s^{-1} at
 198 these sites. Sites J1, J2, and J3 are selected about 40 km south of Shikoku, Japan with the
 199 U of 1.1 m s^{-1} , and D of 560—850 m (Fig. 11b). Site T1 is selected about 29 km east of
 200 Yilan, Taiwan (122.25°E, 24.5°N) with an average current speed of 1.0 m s^{-1} on the slope
 201 ($D \sim 650$ m) (Fig. 11c). About 50% of all measured currents speeds are greater than 1 m
 202 s^{-1} . Finally, site P1 near Philippines is selected about 30 km northeast of Palau Island

(122.5°E, 18.75°N) with an average current speed of 1.0 m s^{-1} (Fig. 11d). Approximately 55% of all observed speeds are greater than 1 m s^{-1} . Sites T1 and P1 located in the Kuroshio axis (see Figs. 11c and 11d). In Taiwan, the Kuroshio power generation was planned to build in the waters between Taitung and Green Island [9]. After the Kuroshio power plant is operated successfully in the near future, more current power plants can be built in the 12 suitable sites near Vietnam, Japan, Taiwan, and Philippines.

4. Summary

The charts of mean current speeds and 12 suitable sites in the East Asia are provided for the development of ocean current power generation from analyzing the SVP drifter current data (1985–2009). In the future, current power plants can be built in the regions of Vietnam, Japan, Taiwan, and Philippines. The United Nations Intergovernmental Panel on Climate Change (IPCC) has released its synthesis report, which can be obtained from http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_LONGERREPORT.pdf.

The report warns that greenhouse gas levels are at their highest in at least 800,000 years, and continued emission of greenhouse gases will cause irreversible impacts for people and ecosystems. The application of ocean current power generation will help to reduce greenhouse gas emissions.

221

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227

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List of Tables

Table 1. Twelve suitable locations ($L < 50$ km, $D < 1000$ m, $P > 50\%$, and $U > 1$ m s⁻¹) for development of ocean current power generation

Site	Country	Location	Distance, L (km)	Depth, D (m)	Percentage, P (%)	Speed, U (m s ⁻¹)
V1	Vietnam	109.50 ° E, 14.00°N	19 km	-160 m	55% (> 1 m s ⁻¹)	1.05 m s ⁻¹
V2	Vietnam	109.75 ° E, 12.75°N	33 km	-960 m	62%	1.26 m s ⁻¹
V3	Vietnam	109.75 ° E, 12.50°N	33 km	-890 m	60%	1.20 m s ⁻¹
V4	Vietnam	109.75 ° E, 12.25°N	39 km	-790 m	51%	1.20 m s ⁻¹
V5	Vietnam	109.75 ° E, 12.00°N	46 km	-680 m	58%	1.25 m s ⁻¹

SITE SELECTION OF CURRENT POWER GENERATION

V6	Vietnam	109.50 ° E, 11.75°N	28 km	-120 m	63%	1.23 m s ⁻¹
V7	Vietnam	109.50 ° E, 11.50°N	38 km	-100 m	58%	1.12 m s ⁻¹
J1	Japan	134.75 ° E, 33.25°N	41 km	-850 m	64%	1.15 m s ⁻¹
J2	Japan	133.50 ° E, 32.75°N	41 km	-710 m	54%	1.05 m s ⁻¹
J3	Japan	133.25 ° E, 33.50°N	38 km	-560 m	64%	1.13 m s ⁻¹
T1	Taiwan	122.25 ° E, 24.50°N	29 km	-650 m	50%	1.01 m s ⁻¹
P1	Philippines	122.25 ° E, 18.75°N	23 km	-960 m	55%	1.05 m s ⁻¹

268

269 Table 2. Index I for selecting the site of ocean current power generation

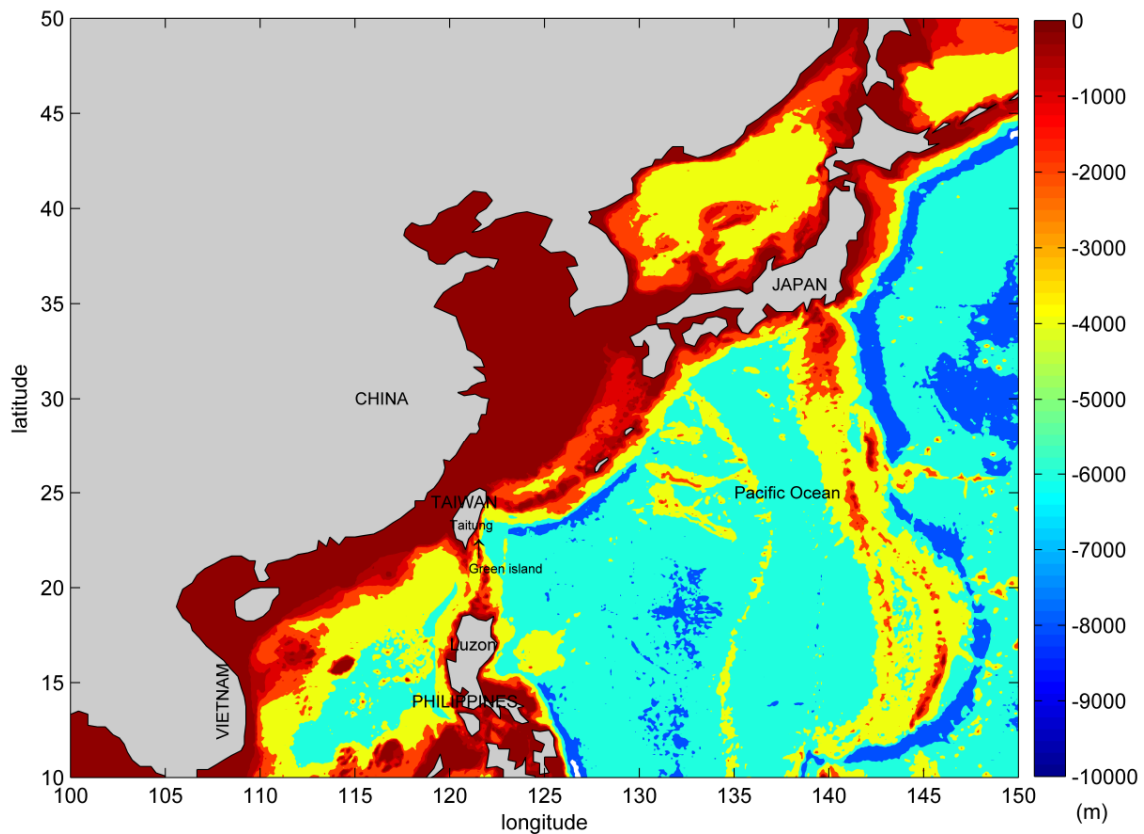
No.	Site	I_1 [1-L/50 km]	I_2 [1+D/1000 m]	I_3 [P/100%]	I_4 [U/1.4 m s ⁻¹]	I
1	V6	0.44	0.88	0.63	0.88	0.726
2	V1	0.62	0.84	0.55	0.75	0.675
3	V7	0.24	0.90	0.58	0.80	0.653
4	J3	0.25	0.44	0.64	0.81	0.607
5	V2	0.34	0.04	0.62	0.90	0.583
6	V3	0.34	0.11	0.60	0.86	0.574
7	V5	0.09	0.32	0.58	0.89	0.571

SITE SELECTION OF CURRENT POWER GENERATION

8	J1	0.18	0.15	0.64	0.82	0.555
9	T1	0.42	0.35	0.50	0.72	0.540
10	V4	0.22	0.21	0.51	0.86	0.539
11	P1	0.54	0.04	0.55	0.75	0.538
12	J2	0.18	0.29	0.54	0.75	0.518

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271 List of Figures



272

273 Figure 1. Geography and bottom topography of the East Asia.

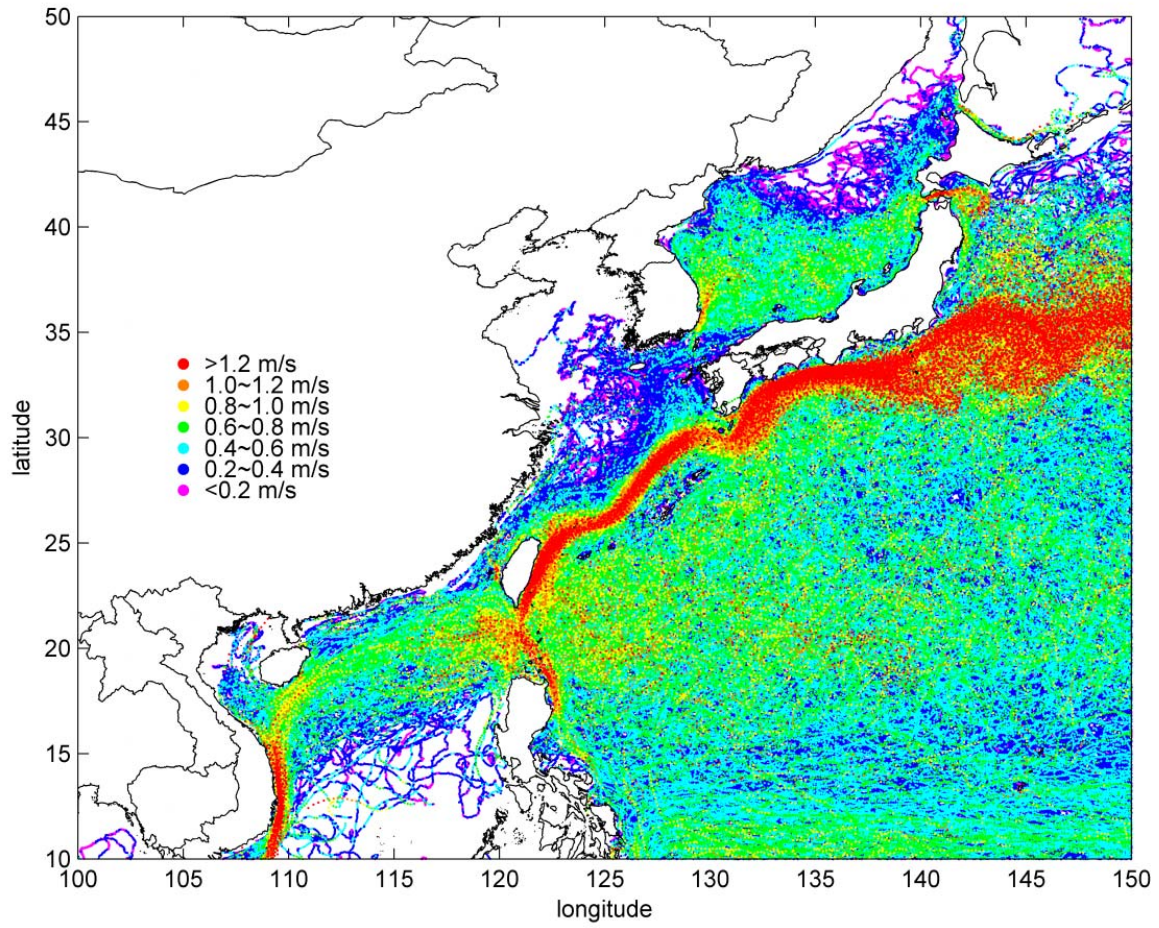


Figure 2. Locations of drifters with color-coded in accordance with their 6-hourly instantaneous speed.

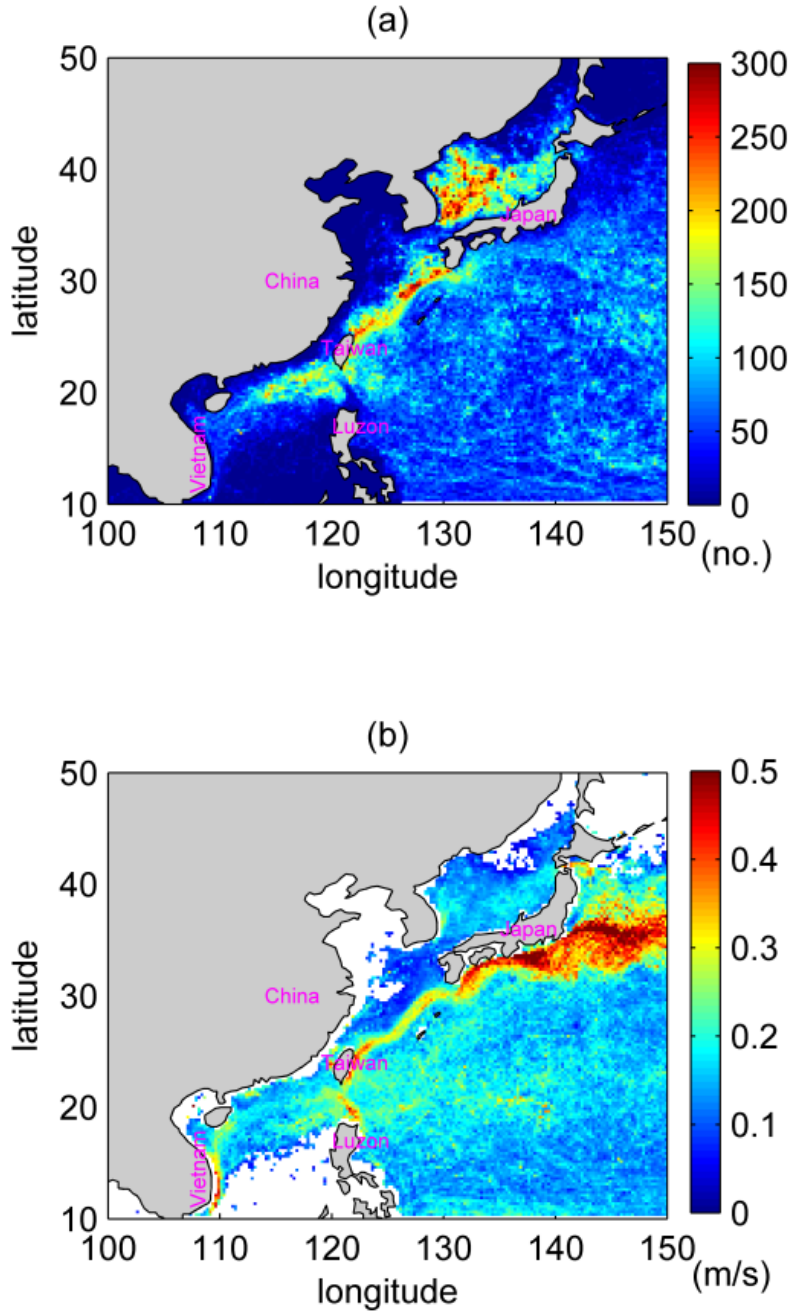
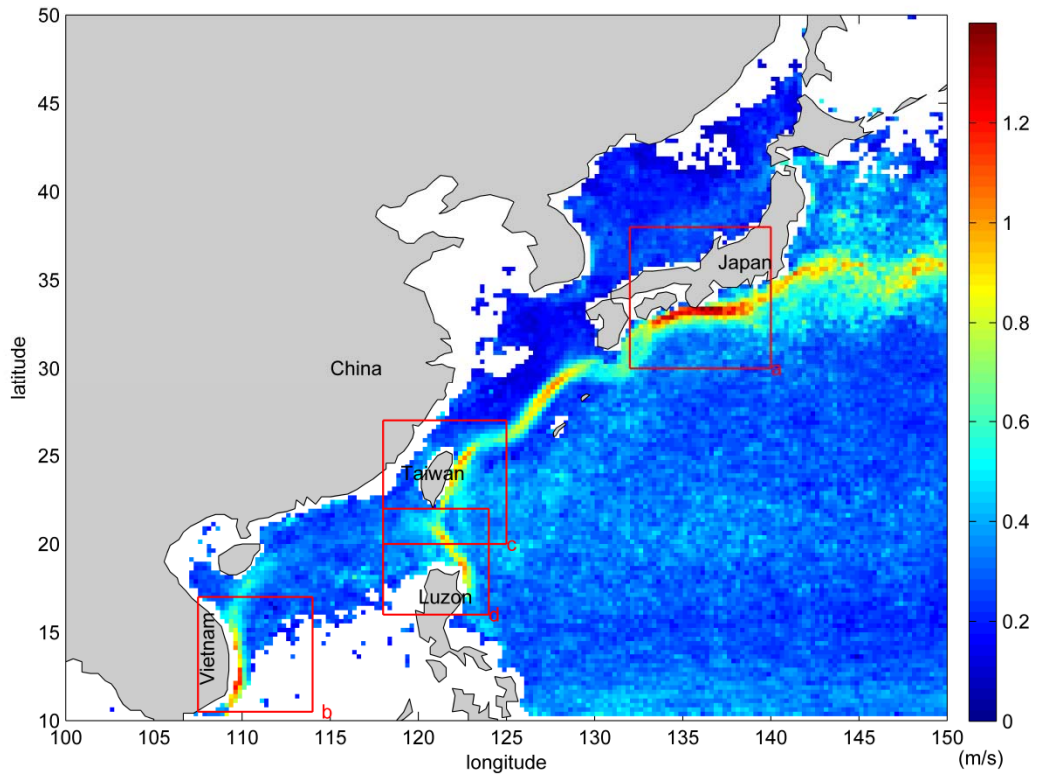


Figure 3. (a) Numbers of data point in $0.25^\circ \times 0.25^\circ$ bins and (b) their standard deviation
(m s^{-1}).



283

284 Figure 4. Averaged drifter speeds (unit: m s^{-1}) in $0.25^\circ \times 0.25^\circ$ bins.

285

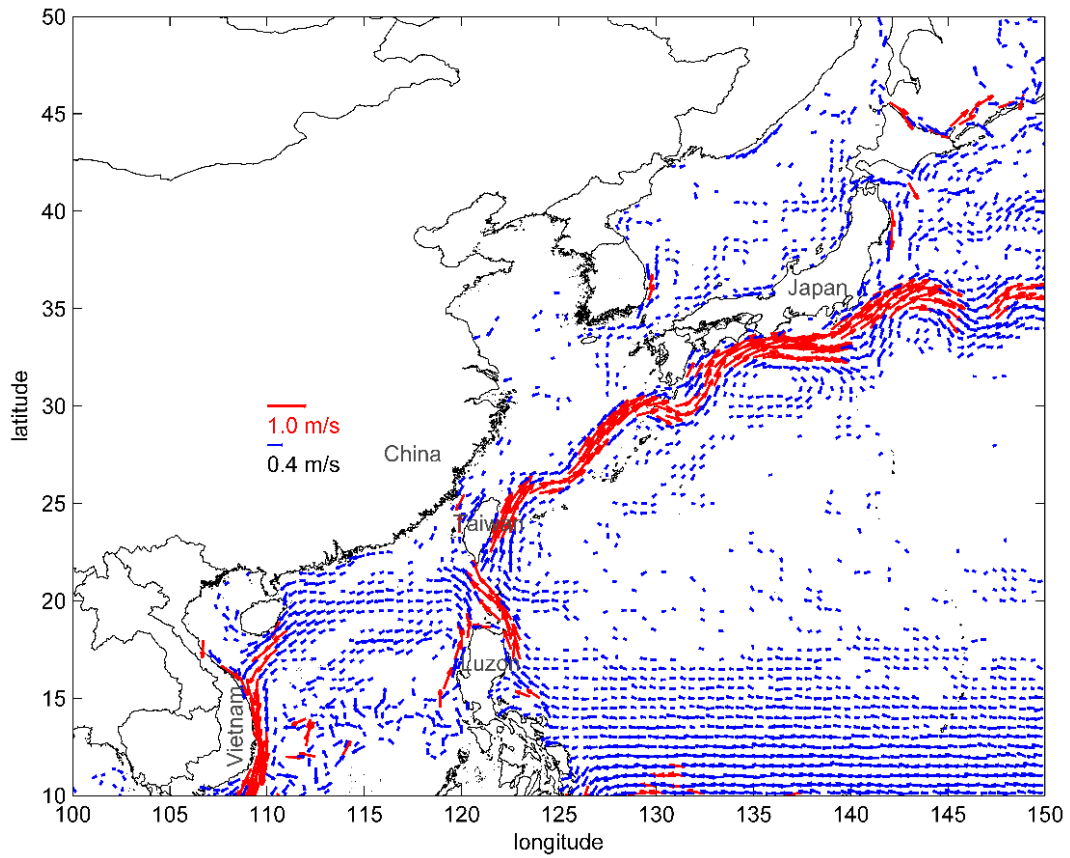
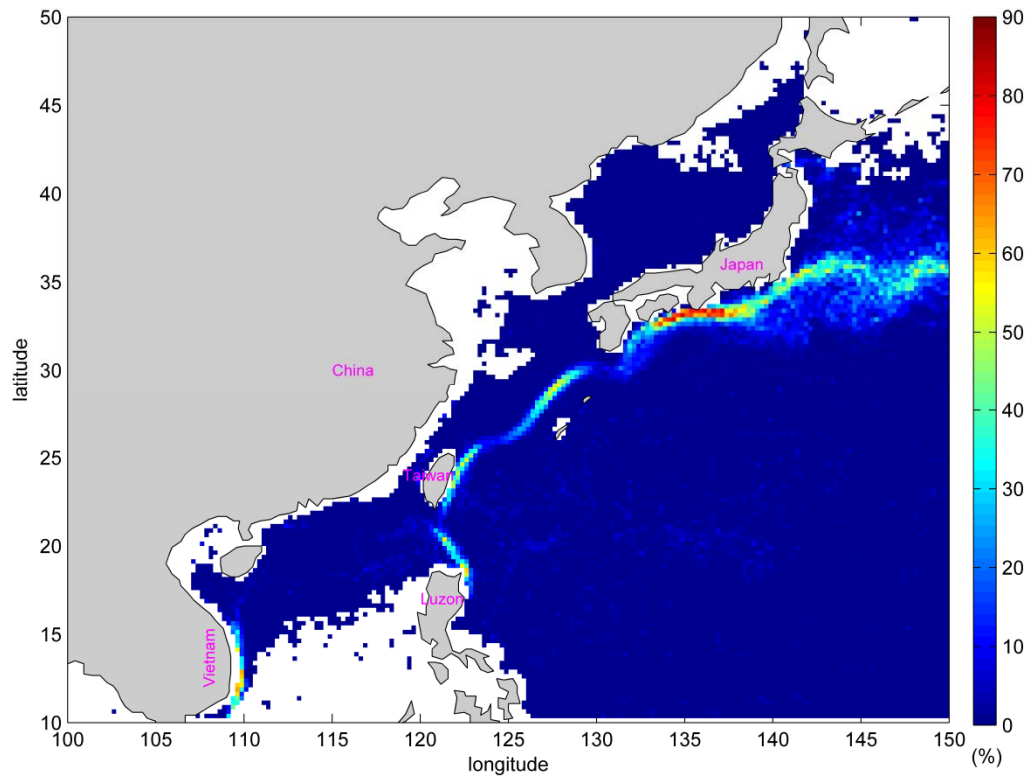


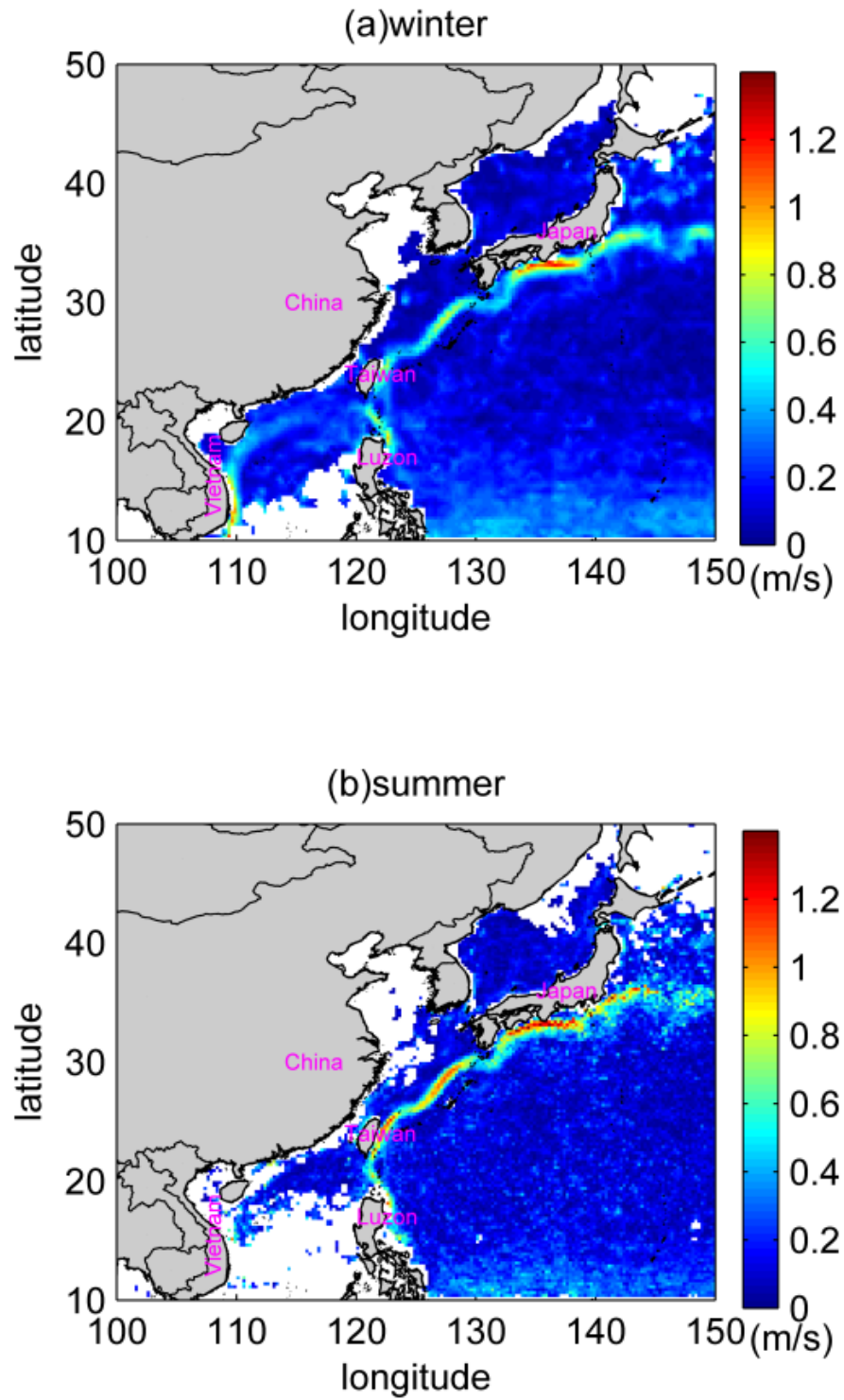
Figure 5. Averaged drifter velocities. Speeds higher and lower than 0.4 m s^{-1} are shown in red and blue, respectively.



290

291 Figure 6. Percentages of current speed greater than 1 m s^{-1} in $0.25^\circ \times 0.25^\circ$ bins.

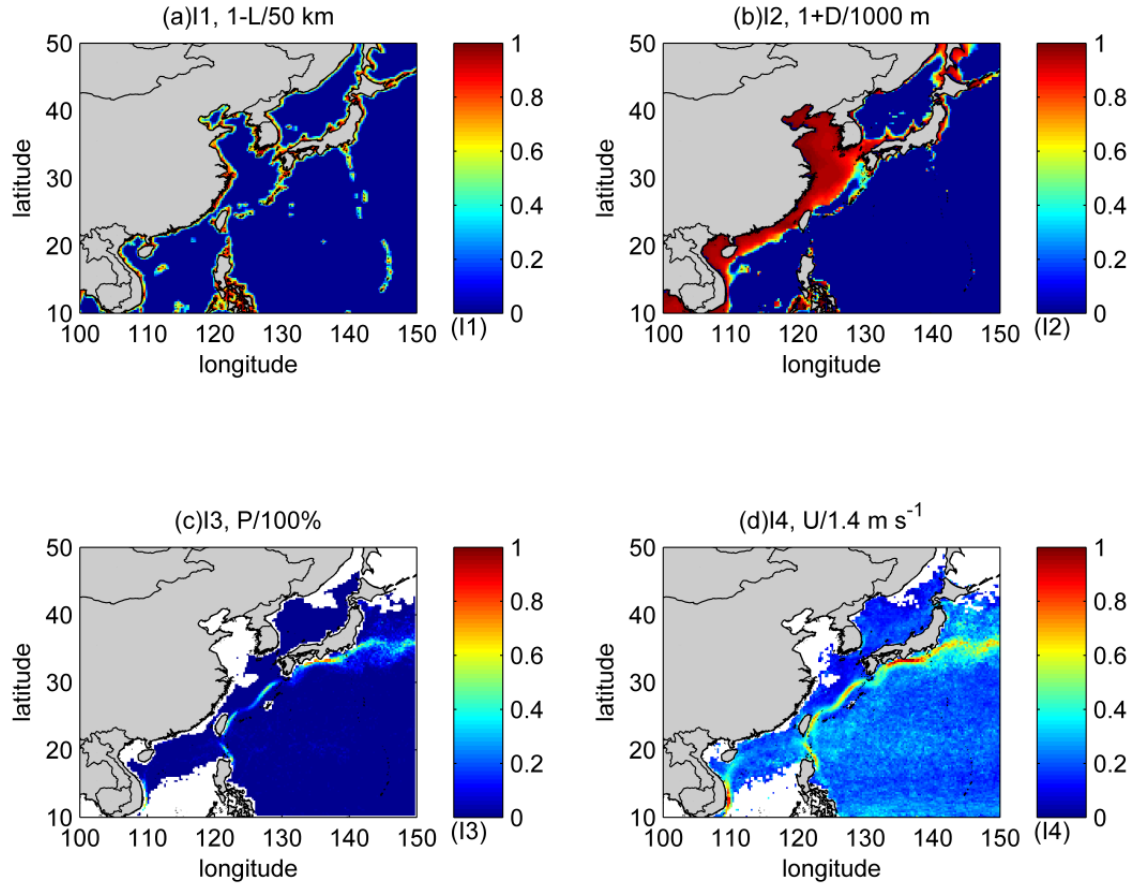
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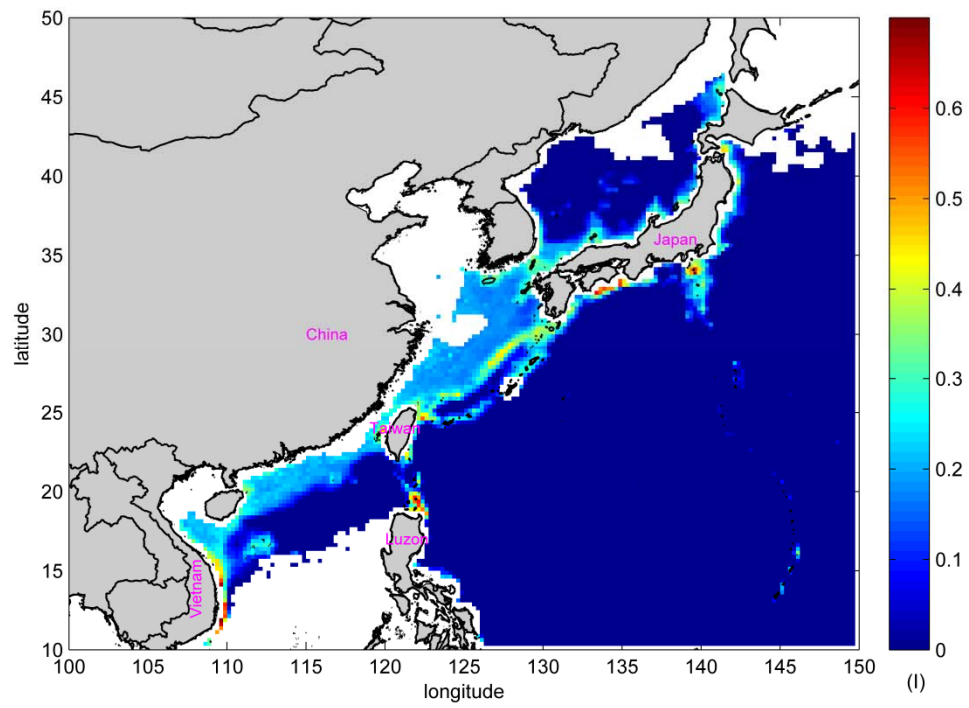
294 Figure 7. Averaged drifter speeds (unit: m s^{-1}) (a) in winter half-year and (b) in summer

295 half-year.



296

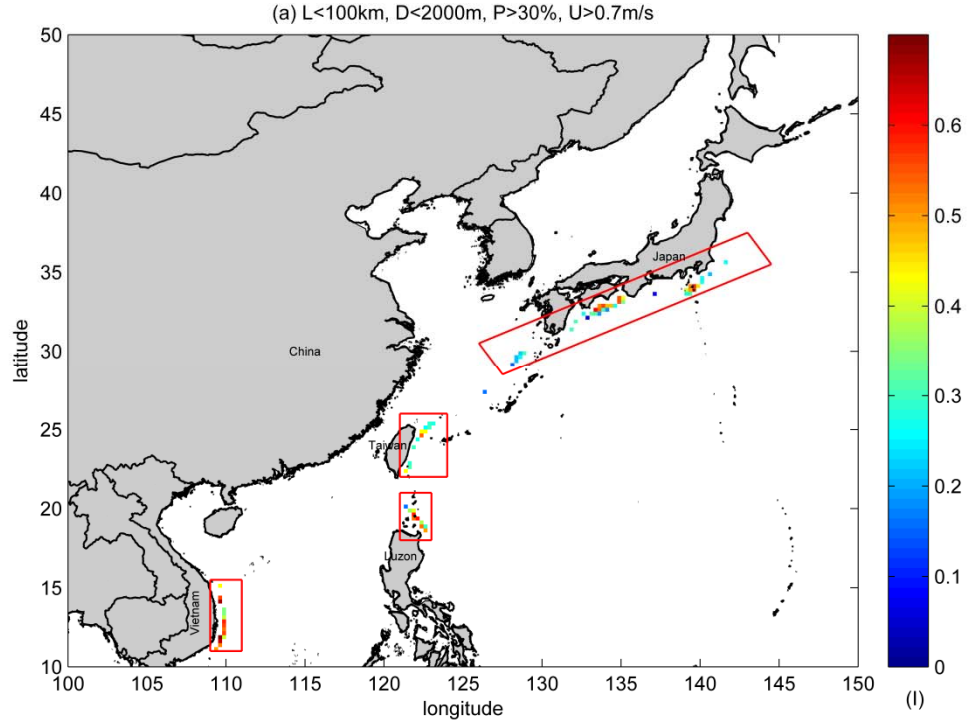
297 Figure 8. Distributions of index I_1 , I_2 , I_3 , and I_4 in the East Asia



298

299 Figure 9. Distribution of index I in the East Asia

300

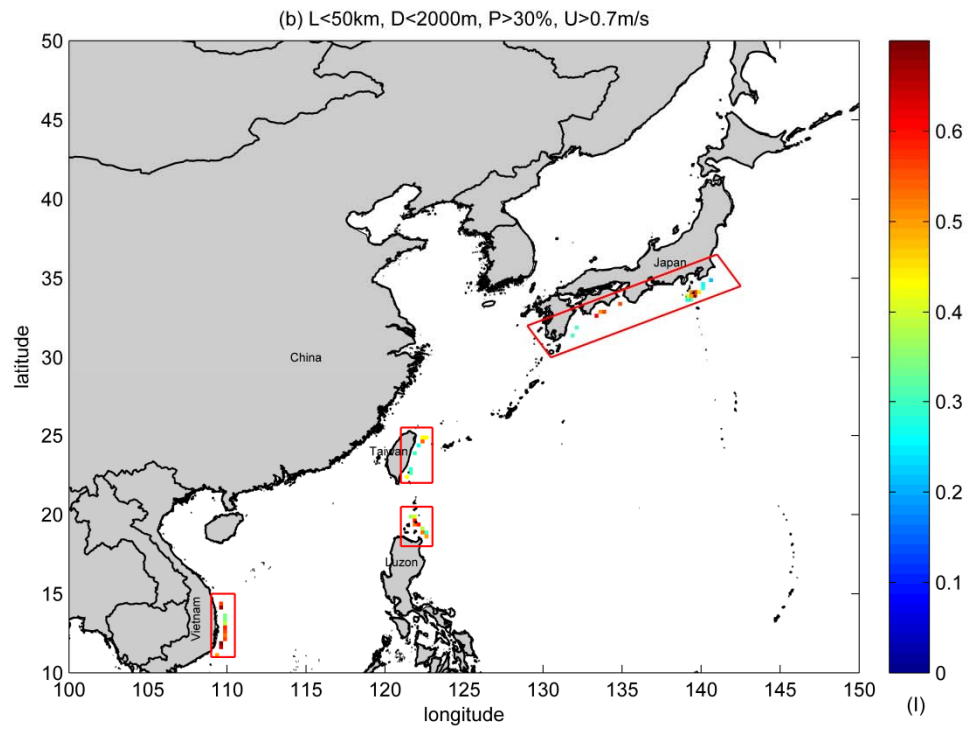


301

302 Figure 10. Selected sites in conditions of (a) $L < 100 \text{ km}$, $D < 2000 \text{ m}$, $P > 30\%$, $U > 0.7 \text{ m s}^{-1}$,

303 (b) $L < 50 \text{ km}$, $D < 2000 \text{ m}$, $P > 30\%$, $U > 0.7 \text{ m s}^{-1}$, (c) $L < 50 \text{ km}$, $D < 1000 \text{ m}$, $P > 30\%$, $U > 0.7$

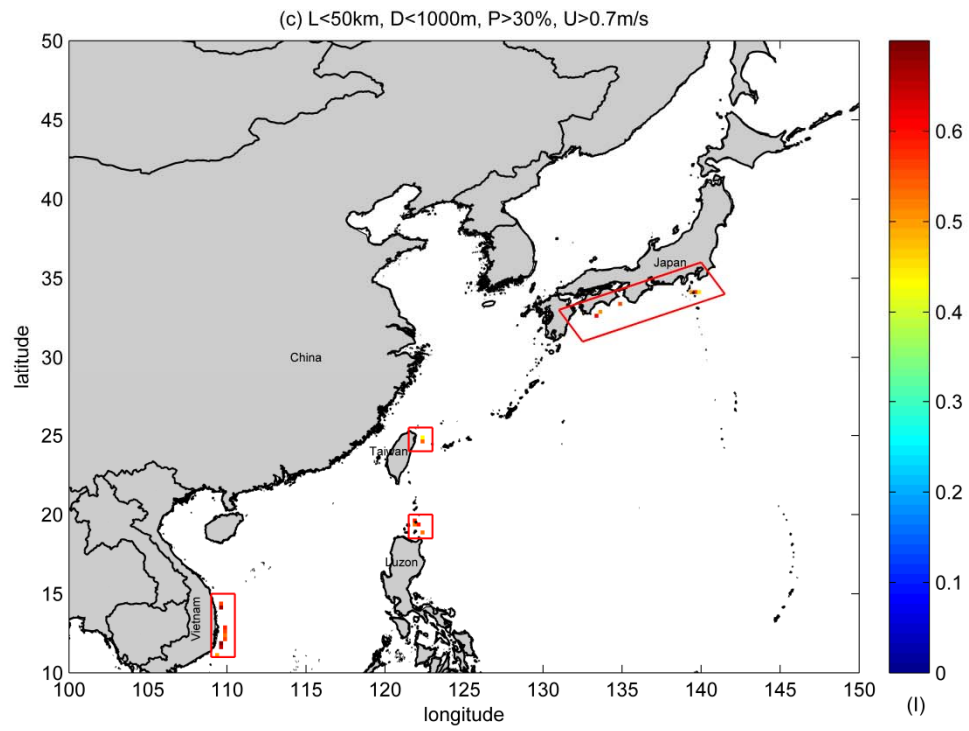
304 m s^{-1} , and (d) $L < 50 \text{ km}$, $D < 1000 \text{ m}$, $P > 50\%$, $U > 1.0 \text{ m s}^{-1}$.



305

306 Figure 10. (continue)

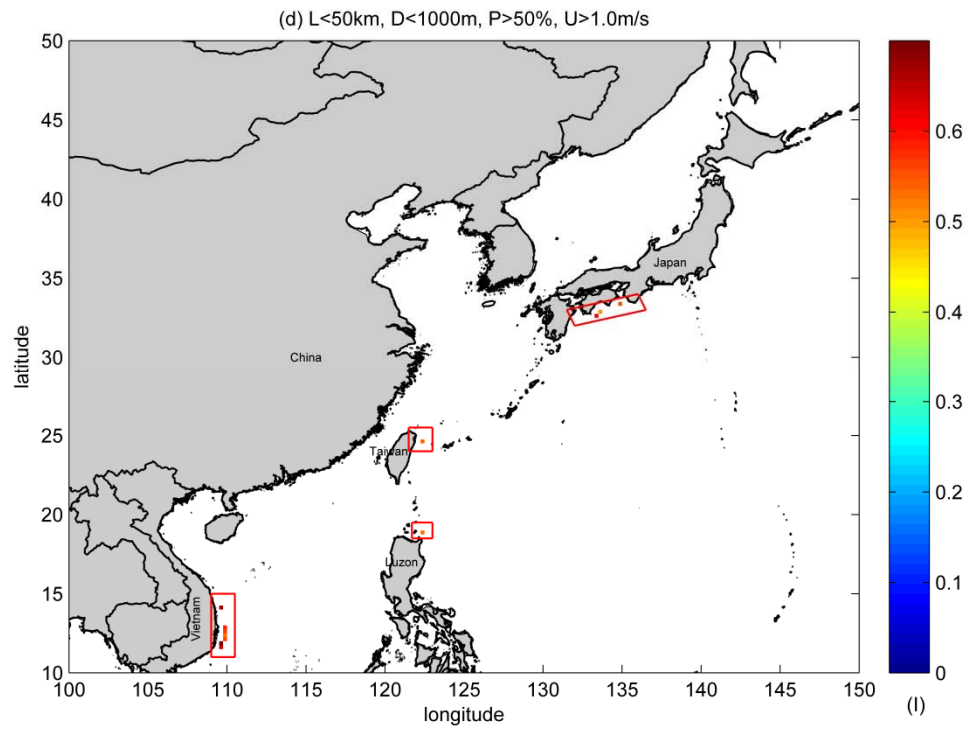
307



308

309 Figure 10. (continue)

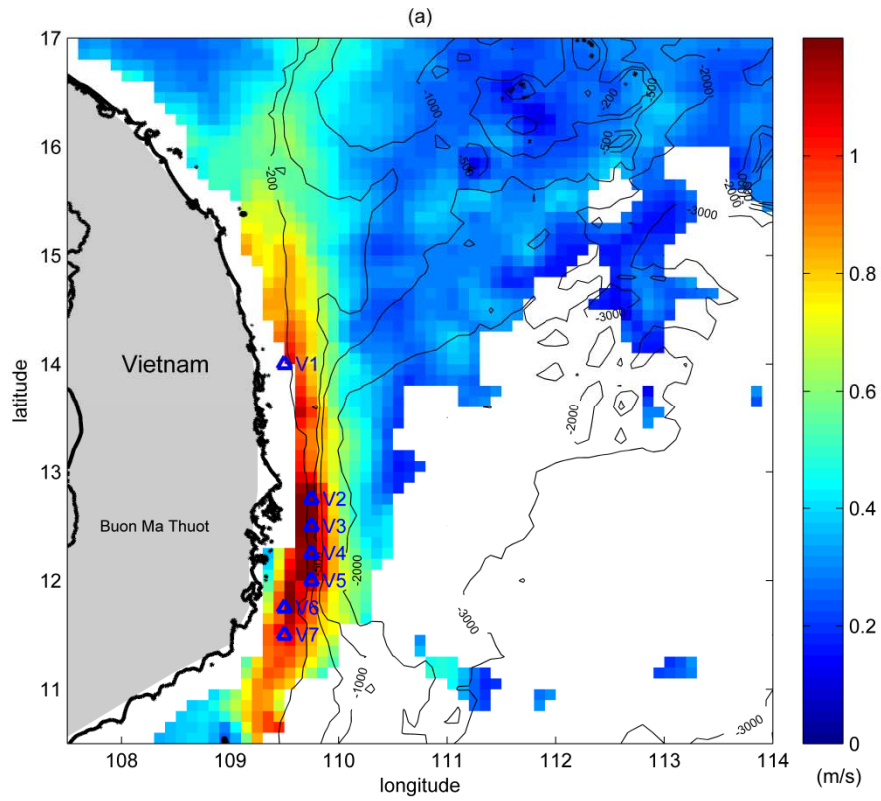
310



311

312 Figure 10. (continue)

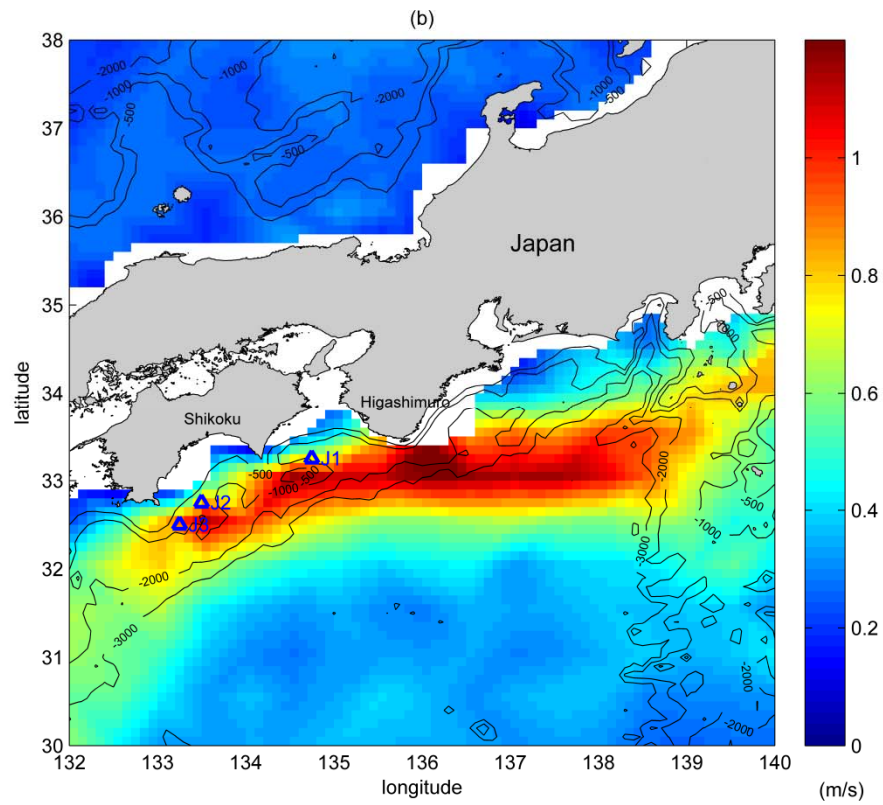
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314

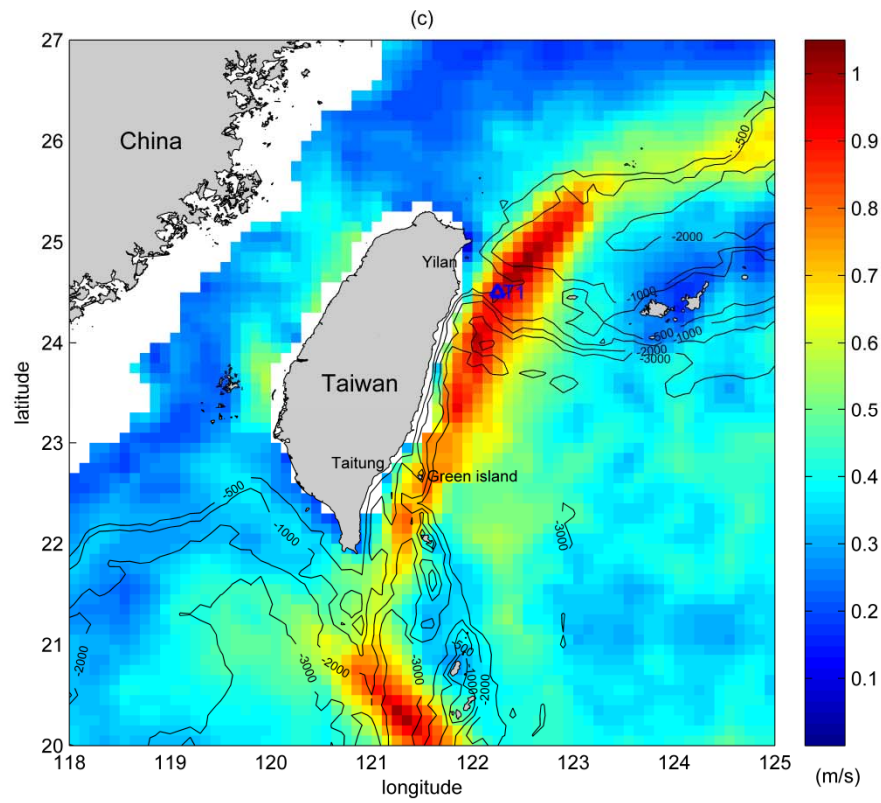
315 Figure 11. Enlargement of bin-averaged speed (a) east of Vietnam, (b) south of Japan, (c)

316 east of Taiwan, and (d) northeast of Philippines. The contour line is an isobath (unit: m).



317

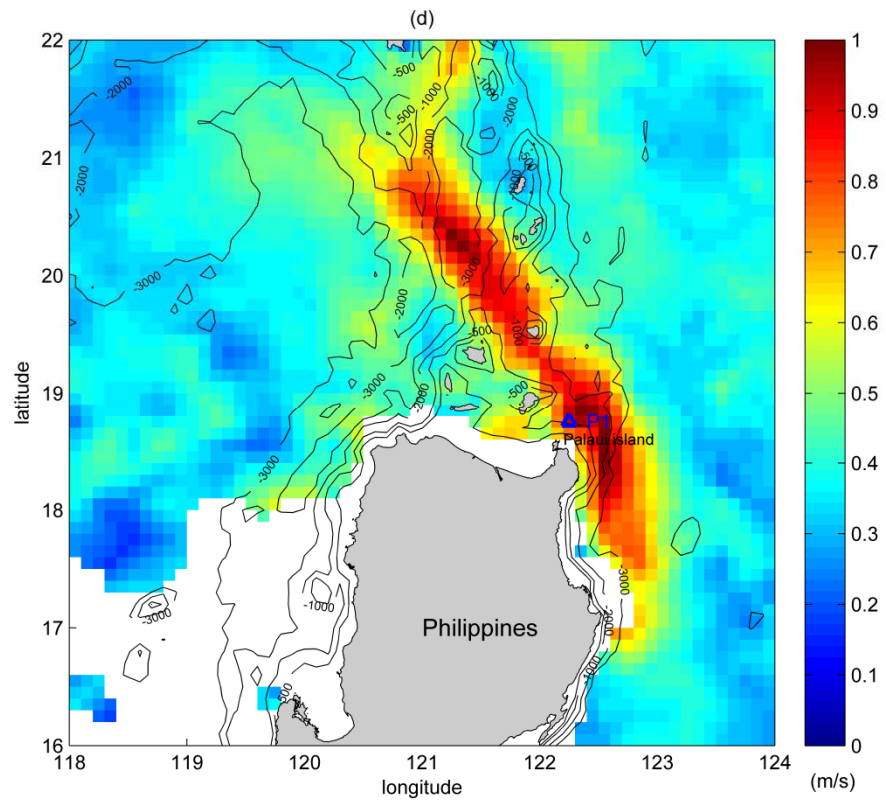
318 Figure 11. (continue)



319

320 Figure 11. (continue)

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322

323 Figure 11. (continue)

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