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1 Relative contributions of external forcing factors to circulation and hydrographic properties
2 in a micro-tidal bay

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14

15 Abstract

16

17 The dominant external forcing factors influencing estuarine circulation differ among coastal
18 environments. A three-dimensional regional circulation model was developed to estimate
19 external influence indices and relative contributions of external forcing factors such as
20 external oceanic forcing, surface heat flux, wind stress, and river discharge to circulation and
21 hydrographic properties in Tango Bay, Japan. Model results show that in Tango Bay, where
22 the Tsushima Warm Current passes offshore of the bay, under conditions of strong seasonal
23 winds and river discharge, the water temperature and salinity are strongly influenced by
24 surface heat flux and river discharge in the surface layer, respectively, while in the middle
25 and bottom layers both are mainly controlled by open boundary conditions. The estuarine

26 circulation is comparably influenced by all external forcing factors, the strong current,
27 surface heat flux, wind stress, and river discharge. However, the influence degree of each
28 forcing factor varies with temporal variations in external forcing factors as: the influence of
29 open boundary conditions is higher in spring and early summer when the stronger current
30 passes offshore of the bay, that of surface heat flux reflects the absolute value of surface heat
31 flux, that of wind stress is higher in late fall and winter due to strong seasonal winds, and that
32 of river discharge is higher in early spring due to snow-melting and summer and early fall
33 due to flood events.

34

35 Keywords:

36 Estuarine circulation; External forcing factor; External influence index; Regional circulation
37 model; Wakasa Bay; Tango Bay

38

39 1. Introduction

40

41 Regions of freshwater influence (ROFI; [Simpson et al., 1993](#)) form transition zones
42 between oceanic and riverine environments and are one of the most productive marine
43 ecosystems ([McLusky and Elliott, 2004](#)). ROFI ecosystems are driven by complex
44 interactions of physical and biochemical processes, and the physical processes such as
45 estuarine circulation have a major influence on the biochemical processes through the
46 transport of nutrients and organisms ([Mann and Lazier, 2005](#)). The physical processes are
47 under the combined influences of external forcing: oceanic (such as tides, waves, and the
48 intrusion of high salinity water), atmospheric (such as surface heat flux and wind stress), and
49 riverine (such as river discharge) forcing (reviewed by [Uncles, 2002](#)). Extensive studies on
50 the influences of external forcing on ROFIs have shown that they are dominated by forcing

51 factors such as tides (e.g., [Sylaios et al., 2006](#)), wind stress (e.g., [Geyer, 1997](#); [Cariniello et](#)
52 [al., 2011](#)), and river discharge (e.g., [Liu et al., 1997](#)), or a balance between/among these
53 forcing factors (e.g., [Niedda and Greppi, 2007](#)). The dominant forcing factor changes in
54 different ROFI environments, and the degree of influence of each forcing factor varies with
55 temporal variations in external forcing factors (reviewed by [Llebot et al., 2014](#)).

56

57 Wakasa Bay ([Fig. 1](#)), located in western Honshu Island, Japan, is one of the largest bays
58 along the Japanese coast of the Sea of Japan. The bottom depth is 50 to 100 m over a large
59 section of the bay, being deepest in the mouth of the bay. It is well known that the tide is
60 small in the Sea of Japan, and the tidal range is less than 50 cm at the Maizuru tidal station of
61 the Japan Meteorological Agency. The Tsushima Warm Current enters the Sea of Japan
62 through the Tsushima Straits and flows at depths shallower than 200 m offshore of Wakasa
63 Bay ([Hase et al., 1999](#)). Strong northwesterly winds prevail in late fall and winter, whereas in
64 summer winds are weak except during sporadic events such as typhoons. Two large rivers,
65 the Yura River and the Kita River, flow into the bay. The ROFI of the Yura River (Tango Bay;
66 [Fig. 1c](#)) is located in the southwestern part of Wakasa Bay and is connected through two
67 passages, the northern (NP) and eastern (EP) passages, which are east and south of the
68 Kammuri Island (ca. 22 km from the river mouth), respectively. This ROFI is an important
69 spawning and nursery ground for several fishes such as seabass (*Lateolabrax japonicus*) and
70 flounder (*Paralichthys olivaceus*), and the estuarine circulation plays an important role in the
71 transport of eggs and larvae ([Fuji et al., 2010](#); [Fuji et al., 2014](#); [Watanabe et al., 2014](#)).

72

73 Several physical oceanographic surveys in and around Wakasa Bay have been conducted.
74 [Yamagata et al. \(1984\)](#) and [Umatani et al. \(1986\)](#) reported the intrusion of a warmer and less
75 saline water mass, derived from the Tsushima Warm Current, into Wakasa Bay in summer.

76 Hashimoto (1982) and Hara et al. (1992) reported the occurrence of anticyclonic circulation
77 in Wakasa Bay in summer caused by the Tsushima Warm Current. Kumaki et al. (2005) and
78 Kumaki et al. (2012) reported the occurrence of a strong coastal current related to the
79 increase and decrease in water temperature around the Tango Peninsula after and before the
80 passage of a typhoon, respectively. Although previous studies mainly focused on short-term
81 fluctuations, Itoh et al. (2016) conducted a long-term mooring and hydrographic survey at
82 four stations (corresponding to St. 1–4 shown in Fig. 1c) between 2012 and 2014 in order to
83 clarify the seasonal circulation pattern in Tango Bay and the forces driving this flow. As their
84 results show, the anticyclonic circulation flows across the bay with the inflow and outflow at
85 the eastern and northern openings, respectively, and this flow intensifies in winter. They
86 carried out correlation analysis between mooring data (velocity and salinity) and forcing
87 factors (river discharge, wind speed and direction, and Tsushima Warm Current index), and
88 concluded that the circulation in the bay is strongly affected by seasonal winds and the
89 Tsushima Warm Current.

90

91 Numerical simulations also have been conducted in coastal regions including Wakasa Bay.
92 Igeta et al. (2007) and Kumaki et al. (2012) used a three-dimensional hydrodynamic model
93 with a horizontal resolution of 1 km to explain the generation mechanism of the strong
94 coastal current around the Tango Peninsula before and after the passage of a typhoon. The
95 model results showed that the “before” current was generated by continuous strong easterly
96 winds (Kumaki et al., 2012), and the “after” one was caused by the backwash from waves
97 breaking in the swash zone (Igeta et al., 2007). While both previous models considered only
98 wind stress as forcing, Hirose et al. (2016) developed a three-dimensional coastal ocean
99 model (called DR_C) with a horizontal resolution of 1.5 km considering a realistic open
100 boundary condition obtained from a regional data assimilation system (Hirose et al., 2013),

101 surface heat flux, wind stress, and river discharges. The polygon in Fig. 1a indicates the
102 DR_C model domain. The DR_C simulated rapid changes in the coastal current mostly
103 associated with strong wind events, and the model results showed good agreement with in-
104 situ velocity observations. The model also simulated the anticyclonic circulation in Wakasa
105 Bay, which was developed from a vortex separated from the Tango Peninsula.

106

107 Physical processes in an open bay, which is influenced by river water, are generally
108 complex and highly localized (Simpson, 1997; Itoh et al., 2016). Although previous studies
109 reported that Wakasa Bay is significantly influenced by the Tsushima Warm Current and wind
110 stress, the relative contribution of each forcing factor has not been evaluated as compared
111 with the other factors such as surface heat flux and river discharge. In this study using a
112 three-dimensional regional circulation model, therefore, we evaluated the relative
113 contributions of external forcing factors such as external oceanic forcing, surface heat flux,
114 wind stress, and river discharge to circulation and hydrographic properties (i.e., water
115 temperature, salinity, and velocity) in Tango Bay on a monthly and annual time scale.

116

117 2. Model configuration

118

119 The Princeton Ocean Model (POM), which is a three-dimensional numerical ocean model
120 (Mellor, 2002), has been widely applied to coastal areas and estuaries (e.g., Oey et al., 1985;
121 Xue et al., 2000; Wong et al., 2003; Yoon et al., 2013). The sigma coordinate system, in
122 which the vertical coordinate is scaled on the water column depth, is useful to simulate
123 significant topographical variabilities in estuaries and over continental shelf breaks and
124 slopes (Mellor, 2002).

125

126 In this study, the model (POM) was configured for Wakasa Bay. The model domain is
127 shown in Fig. 1b (100 km × 63 km). The horizontal grid was discretized by 199 × 125 lattice
128 points with a resolution of 500 m, and there were 20 non-uniform vertical layers with a finer
129 resolution near the surface being $\sigma = 0.000, -0.007, -0.017, -0.027, -0.041, -0.061, -0.088,$
130 $-0.116, -0.150, -0.190, -0.245, -0.306, -0.374, -0.442, -0.510, -0.578, -0.646, -0.714,$
131 $-0.796, -0.891$, and -1.000 . Time steps were 1 second for the external mode and 30 seconds
132 for the internal mode. Main parameter values of the POM are given in Table 1.

133

134 The bottom topography was obtained from the J-EGG500 (JODC-Expert Grid data for
135 Geography-500 m) provided by the Japan Oceanographic Data Center (JODC). In addition, a
136 high-resolution (100 m in horizontal resolution) topographic survey was conducted in and
137 around Tango Bay to define the topography.

138

139 The open boundary conditions were obtained from the DR_C. The hourly surface elevation,
140 water temperature, salinity, and horizontal velocities of the DR_C were transferred to the
141 open boundary of the POM after linear interpolation in time and space.

142

143 The surface meteorological conditions were obtained from the NCEP/DOE Reanalysis
144 with a resolution of 250 km and the operational meso-scale model (MSM) with a resolution
145 of 5 km of the Japan Meteorological Agency. The hourly solar radiation at the sea surface,
146 converted from the daily downward solar radiation flux of the NCEP/DOE Reanalysis using
147 the NOAA Solar Calculator, and the hourly air temperature, cloud cover, relative humidity,
148 and wind vector of the MSM were linearly interpolated in time and space into the resolutions
149 of the POM.

150

151 The surface heat flux (Q), i.e., total downward flux of heat across the ocean surface, was
 152 estimated based on [Haney \(1971\)](#) as $Q = QS - (QB + QH + QE)$. The QS is the downward
 153 flux of solar radiation which penetrates the sea surface as $QS = G(1 - \alpha)$, where G is the
 154 solar radiation at the sea surface and α is the albedo of the sea surface. The QB , QH , and QE
 155 are the net upward flux of longwave radiation, sensible heat, and latent heat, respectively, as
 156 $QB = Q^* \sigma_{sb} T_s^4$, $QH = \rho_a C_d |\vec{U}_{wind}| C_p (T_s - T_a)$, and $QE = \rho_a C_d |\vec{U}_{wind}| L (q_s - q_a)$, where Q^*
 157 is an empirical function of air temperature, cloud cover, and relative humidity, σ_{sb} is the
 158 Stefan-Boltzmann constant, T_s is the sea surface temperature, ρ_a is the air density, C_d is the
 159 variable drag coefficient proposed by [Deacon and Webb \(1962\)](#) as
 160 $C_d = (1 + 0.07 |\vec{U}_{wind}|) \times 10^{-3}$, \vec{U}_{wind} is the wind velocity vector, C_p is the specific heat of air
 161 at constant pressure, L is the latent heat of vaporization, q_s is the saturation specific humidity,
 162 and q_a is the specific humidity. The eastward and northward wind stress components were
 163 estimated as $\tau_x = \rho_a C_d W_x |W_x|$ and $\tau_y = \rho_a C_d W_y |W_y|$, respectively, where W_x and W_y are
 164 the eastward and northward wind speed, respectively.

165
 166 The river stage (H_{riv}) and discharge (Q_{riv}) of the Yura River and the Kita River have been
 167 monitored by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan.
 168 The H_{riv} is expressed relative to the mean sea level of Tokyo Bay, Japan. The hourly river
 169 discharge was estimated from the hourly river stage based on the relationship between H_{riv}
 170 (m) and Q_{riv} ($m^3 s^{-1}$), obtained from the MLIT, as $Q_{riv} = 80.76 \times (H_{riv} + 2.19)^2$ when
 171 $H_{riv} \leq 0.00$, $Q_{riv} = 22.44 \times (H_{riv} + 4.15)^2$ when $0.00 < H_{riv} \leq 3.27$, and
 172 $Q_{riv} = 77.09 \times (H_{riv} + 0.73)^2$ when $3.27 < H_{riv}$ for the Yura River, and

173 $Q_{\text{riv}} = 37.14 \times (H_{\text{riv}} - 2.75)^2$ for the Kita River. The river discharge was assumed as the
174 downward vertical velocity at the surface layer of each river inflow grid cell in the POM
175 based on [Oey \(1996\)](#) with linear interpolation in time. The water temperature of river water
176 was estimated as a function of air temperature based on the observation in the Yura River
177 from April 2006 to March 2008 (unpublished data), and the salinity was set to zero.

178

179 The simulation was started from 00:00 January 1, 2012 under the initial condition
180 interpolated from the DR_C, and run for three years (to 24:00 December 31, 2014). For
181 model stabilization, the year of 2012 was run twice. For model validation, the model was
182 compared with observations obtained from mooring systems, which were deployed at stations
183 1–4 ([Fig. 1c](#)) between 2012 and 2014 ([Itoh et al., 2016](#)). The water temperature and salinity,
184 measured using the conductivity-temperature (CT) sensor at the depth of 0.5, 1.5, 3.5, and 28
185 m of St. 1 (bottom depth of 29 m), 54 m of St. 2 (61 m), 62 m of St. 3 (70 m), and 72.5 m of
186 St. 4 (76 m), and the velocity, measured using the ADCP on the seabed at Sts. 3 and 4, were
187 used. Sigma coordinate model results were interpolated to the observation depths.

188

189 To evaluate the seasonal relative contributions of external forcing factors such as open
190 boundary conditions (BC), surface heat flux (HF), wind stress (WS), and river discharge (RD)
191 to the circulation and hydrographic properties in Tango Bay, five climatological control
192 scenarios were designed as [Table 2](#). We used climatological values for external forcing
193 factors during the period 2012 to 2014. The CLIM was defined as a standard scenario
194 modeled under four climatological external forcing conditions, BC, HF, WS, and RD, and the
195 other four CTRLs ([Table 2](#)) were simulated under the conditions of CLIM without a specific
196 external forcing as: the CTRL_BC without the BC (i.e., sponge boundary conditions), the
197 CTRL_HF without the HF, the CTRL_WS without the WS, and the CTRL_RD without the

198 RD. The control scenarios were run for two years, and the first year was used as the spin-up
199 period. From the monthly mean model results in Tango Bay bounded by the NP and EP lines
200 shown in Fig. 1c, the external influence index (EII) of an external forcing (F) was calculated
201 as:

202

$$203 EII_F = \sqrt{\frac{\sum_{i=1}^N (X_i - Y_i)^2}{N - 1}},$$

204

205 where subscript F indicates the open boundary conditions (BC), surface heat flux (HF), wind
206 stress (WS), or river discharge (RD), X_i and Y_i are the monthly mean model results of CTRL
207 and CLIM in the “wet” grid cells, respectively, and N is the number of the model results. The
208 number of “wet” grid cells was 1129 horizontally and 20 vertically (totally 22580), in which
209 there were 22580 water temperature data points, 22580 salinity data points, and 41900
210 horizontal velocity data points. For example, the EII of BC, EII_{BC} , on water temperature was
211 calculated using the water temperatures of CTRL_BC (X_i) and CLIM (Y_i) with the number
212 of the model results of 22580. For example, when the water temperature decreases (or
213 increases) 1 °C uniformly over Tango Bay under the condition without the BC compared with
214 that of CLIM, the EII_{BC} on water temperature is approximately equal to 1. In this study, the
215 relative contribution of an external forcing factor (F) was defined as “the percentage of EII_F
216 in the summation of all EIIs” and symbolized as % EII_F :

217

$$218 \%EII_F = \frac{EII_F}{EII_{BC} + EII_{HF} + EII_{WS} + EII_{RD}} \times 100.$$

219

220 3. External forcing factors

221

222 [Figure 2](#) shows the four major external forcing factors, the Tsushima Warm Current,
223 surface heat flux and wind stress averaged over the entire model domain, and river discharges
224 of the Yura River and Kita River in Wakasa Bay. The Tsushima Warm Current Index (TWCI)
225 is represented as the volume flux through the Oki Strait (OS shown in [Fig. 1a](#)) simulated by
226 the DR_C. The Tsushima Warm Current flows into the Sea of Japan through the Tsushima
227 Straits, and the nearshore branch passes the Oki Strait before reaching Wakasa Bay. The
228 TWCI exhibits a seasonal change with an increasing trend from winter to summer and
229 sharply decreases in fall. This trend corresponds to the sea level difference between the
230 extreme edges of the Oki Strait ([Itoh et al., 2016](#)). The surface heat flux fluctuates
231 sinusoidally with a maximum in June and a minimum in December. The wind stress is strong
232 in late fall and winter due to the strong northwesterly seasonal winds, while weak in summer.
233 Especially the northerly wind dominated in the beginning of 2014. The river discharges
234 fluctuate with high annual and interannual variability, due to rainfall and snowfall. The early
235 spring peaks are associated with the melting of snow, and the two extreme peaks in
236 September 2013 and August 2014 are attributed to heavy rainfall due to typhoons. The annual
237 mean discharges of the Yura River and Kita River were $57 \text{ m}^3 \text{ s}^{-1}$ and $15 \text{ m}^3 \text{ s}^{-1}$, respectively.

238

239 The western open boundary (WOB shown in [Fig. 1b](#)) is the main route of inflow of the
240 Tsushima Warm Current, because the nearshore branch flows eastward or northeastward
241 along the Japanese coast. Therefore, the water temperature and salinity averaged between
242 0–100 m on the WOB ([Figs. 3a–b](#)) are expected to reflect those of the Tsushima Warm
243 Current. The water temperature fluctuates sinusoidally with a maximum in September and a
244 minimum in March. The water temperature was lower in 2014 (September mean of 21.8°C)
245 compared with the other years (23.8°C in 2012 and 23.5°C in 2013). The interannual

246 variation in the water temperature is due to the surface heat flux (August mean of 160 W m^{-2}
247 in 2012, 174 W m^{-2} in 2013, and 133 W m^{-2} in 2014) ([Fig. 2b](#)) and is influenced by the
248 original water temperature of the Tsushima Warm Current. The salinity exhibits high
249 seasonality with a maximum in May (monthly mean of 34.5 in 2012 and 2013, and 34.7 in
250 2014) and a minimum in November (33.5 in all three years). The marked decrease in salinity
251 after June is mainly due to the Changjiang Diluted Water entrained into the Tsushima Warm
252 Current ([Itoh et al., 2016](#)). The seasonal variation in the eastward velocity averaged between
253 0–100 m on the WOB ([Fig. 3c](#)) corresponds to that in the TWCI ([Fig. 2a](#)). The offshore
254 oceanic water entered through the WOB (i.e., the positive eastward velocity shown in [Fig. 3c](#))
255 flows out through the northern open boundary that is the positive northward velocity (the
256 summation of both velocities) shown in [Fig. 3d](#). The northern open boundary is divided into
257 two equal-width parts, the northwestern (NWOB) and northeastern (NEOB) open boundaries.
258 The northward velocities averaged between 0–100 m on the NWOB and NEOB shown in [Fig.](#)
259 [3d](#) represent the main path of the Tsushima Warm Current from WOB to NEOB (i.e., the
260 speed is faster on NEOB) in spring and early summer and to NWOB (i.e., faster on NWOB)
261 in late summer.

262

263 4. Model validation

264

265 [Figure 4](#) shows the simulated salinities with horizontal velocity vectors at the depths of 1
266 and 50 m in Wakasa Bay in January (representing winter), June (representing high salinity
267 early summer), and August (representing low salinity late summer) 2013. The Tsushima
268 Warm Current flows to the north of the bay, being weak in winter and strong in summer ([Fig.](#)
269 [3c](#)). In summer, the strong offshore current generates an anticyclonic circulation in the bay,
270 and the modeled circulation corresponds to the circulation observed by [Hashimoto \(1982\)](#) and

271 Hara et al. (1992). The main path of the Tsushima Warm Current in June is different from that
272 in August, and this leads to the different circulation pattern in the bay. The anticyclonic
273 circulation is generated in the center of the bay in June, but it shifts to the northeastern part in
274 August, when the cyclonic circulation is remarkable in the southern part of the bay. The
275 circulation pattern at the depth of 50 m in Tango Bay as the inflow and outflow at the eastern
276 and northern passages, respectively, corresponds to the observed circulation reported by Itoh
277 et al. (2016). The circulation strengthens in winter, especially in the lower layers, while it
278 weakens in summer (see detail in section 5.1). Freshwater from the Yura River generates a
279 salinity gradient eastward along the coast near the surface. At the depth of 50 m, the river-
280 induced salinity gradient is indistinctive, and the salinity exhibits a gradual gradient from the
281 coast to the open sea. The intrusion of the less saline water mass into Wakasa Bay reported by
282 Yamagata et al. (1984) and Umatani et al. (1986) is clearly shown in late summer, after the
283 marked decrease in the offshore salinity (Fig. 3b).

284

285 The model results were compared with observational data at stations 1–4 (shown in Fig. 1c)
286 obtained from Itoh et al. (2016). Figure 5 shows the comparison between daily mean model
287 results and observations for water temperature and salinity at the depths of 0.5, 1.5, 3.5, and
288 28 m of St. 1, 54 m at St. 2, 62 m of St. 3, and 72.5 m of St. 4 throughout the observation
289 periods. The modeled water temperature and salinity show a fairly good agreement with
290 observed values, although the salinity data scatter increases in the low salinity range (< 30).
291 The temporal variations in water temperature, salinity, and velocity at representative positions
292 were also compared between the model results and observations. Time series data derived
293 from the model results and observational data for water temperature and salinity in the
294 surface layer (at the depth of 0.5 m) at St. 1 (the shallowest and nearest observation station to
295 the mouth of the Yura River) and in the bottom layer (72.5 m) at St. 4 (the deepest

observation station) are shown in Fig. 6, and those for velocity in the surface (0.5 m), middle (29 m), and bottom (59 m) layers at Sts. 3 (nearly the central point of the northern passage of Tango Bay) and 4 (nearly the central point of the eastern passage of the bay) are shown in Fig. 7. As well as water temperature and salinity, the modeled velocities also showed good agreement with the observations, although there is a trivial discrepancy during summer. These results indicate our model can represent the real hydrographic conditions fairly well in Tango Bay. Therefore, it is appropriate to evaluate the relative contributions of the external forcing factors to the circulation and hydrographic properties in the bay, using this model. Details of the circulation and hydrographic properties in Tango Bay are described in section 5.1.

306

307 5. Model results

308

309 5.1. Circulation and hydrographic properties in Tango Bay

310

311 The water temperature and salinity in Tango Bay fluctuate seasonally (Fig. 6). The
312 seasonal variation in water temperature in the bottom layer is almost the same as the offshore
313 water temperature (Fig. 3a). The water temperature fluctuates sinusoidally with a maximum
314 in August to September and a minimum in February to March. The maximum and minimum
315 occur slightly earlier at St. 1 than those on the WOB under the influence of the surface heat
316 flux and river discharge (i.e., the shallow area is easy to heat/cool). The seasonal variation in
317 salinity shows a different pattern between the surface and bottom layers. The surface salinity
318 responds sensitively to the Yura River discharge and fluctuates dramatically during the spring
319 snow-melting and flood periods. The maximum occurs in May to June in the low river
320 discharge season, and the minimum occurs during the highest Yura River discharge in each

321 year (i.e., in March 2012, September 2013, and August 2014). However, the bottom salinity
322 follows almost the same fluctuation as the offshore salinity ([Fig. 3b](#)). Two minima occurred
323 in September and November every year. The peaks are not the influence of the Yura River
324 discharge, but the intrusion of less saline offshore water. The maximum and minimum occur
325 in May to June and in November, respectively, corresponding to the offshore salinity.

326

327 The velocities in the surface layer show a different behavior from velocities in the middle
328 and bottom layers at Sts. 3 and 4 ([Fig. 7](#)). In the surface layer, the flow speed varies
329 irregularly, whereas the flow direction changes seasonally as: the predominant direction is
330 northeastward at St. 3 and southwestward at St. 4 in winter, and southwestward at St. 3 and
331 eastward at St. 4 in summer. On the other hand, in the middle and bottom layers, the flow
332 speed varies seasonally with a maximum in winter and a minimum in late spring/early
333 summer, whereas the flow direction is almost constant as the predominant direction is
334 northward (i.e., out away from the bay) at St. 3 and westward (i.e., into the bay) at St. 4. This
335 indicates that the offshore water enters Tango Bay from the eastern passage and exits to the
336 northern passage. The circulation is stronger in winter and weaker in late spring/early summer,
337 as shown in [Fig. 4](#).

338

339 5.2. Relative contributions of external forcing factors to the hydrographic conditions in Tango
340 Bay

341

342 [Table 3](#) shows the external influence indices (EII_s) and relative contributions (%EII_s) of
343 external forcing factors in Tango Bay bounded by the NP and EP lines shown in [Fig. 1c](#) on an
344 annual time scale. The bay is divided into six sub-domains as: two horizontally (areas the
345 bottom depth (D) is ≤ 50 m near the shore and > 50 m further from the shore) and three

346 vertically (the surface (the first; $\sigma = -0.003$), middle (the 14th; $\sigma = -0.476$), and bottom (the
347 20th; $\sigma = -0.946$) layers), consequently as: (1) $D \leq 50$ m and $\sigma = -0.003$, (2) $D \leq 50$ m and σ
348 = -0.476 , (3) $D \leq 50$ m and $\sigma = -0.946$, (4) $D > 50$ m and $\sigma = -0.003$, (5) $D > 50$ m and $\sigma =$
349 -0.476 , and (6) $D > 50$ m and $\sigma = -0.946$.

350

351 The influence of external forcing factors on the water temperature is higher in order of BC
352 (%EII_{BC} = 47%), HF (%EII_{HF} = 37%), RD (%EII_{RD} = 12%), and WS (%EII_{WS} = 4%) in the
353 entire domain of Tango Bay. This indicates BC and HF are the most important external
354 forcing factors to determine the water temperature in the bay. While %EII_{BC} is higher in the
355 middle and bottom layers than in the surface layer, %EII_{HF}, %EII_{WS}, and %EII_{RD} are higher
356 in the surface layer. In the surface layer of the inshore area ($D \leq 50$ m), the most influential
357 external forcing factor is HF (%EII_{HF} = 50), while BC in the middle and bottom layers
358 (%EII_{BC} is 46 and 51, respectively). In the surface layer of the nearshore area ($D > 50$ m),
359 both BC (%EII_{BC} = 43%) and HF (%EII_{HF} = 42%) are influential, and the influence of BC is
360 most marked (%EII_{BC} > 80%) in the middle and bottom layers.

361

362 The influence of external forcing factors on the salinity is higher for RD (%EII_{RD} = 68%),
363 BC (%EII_{BC} = 17%), HF (%EII_{HF} = 8.3%), and WS (%EII_{WS} = 7.6%) in the entire domain.
364 RD is the most important external forcing factor to determine the salinity in the inshore area
365 (%EII_{RD} ≥ 60%) and the surface layer of the nearshore area (%EII_{RD} = 42%), while in the
366 middle and bottom layers BC is the most important factor (%EII_{BC} ≥ 70%).

367

368 The influence of external forcing factors on the velocity is higher for BC (%EII_{BC} = 36%),
369 RD (%EII_{RD} = 22%), WS (%EII_{WS} = 21%), and HF (%EII_{HF} = 20%) in the entire domain.
370 The differences among the four external forcing factors are relatively small compared with

371 the water temperature and salinity. In the six sub-domains, %EII ranges from 12 to 45%,
372 smaller than those of the water temperature (2 to 88%) and salinity (3 to 79%). While the
373 water temperature and salinity are mainly affected by one or two external forcing factors, the
374 velocity is affected by all external forcing factors, even if the influence of the HF seems weak
375 intuitively. The influences of RD and BC are relatively predominant in the inshore and
376 nearshore areas, respectively.

377

378 [Figure 8](#) shows time series of relative contributions (%EII_s) of external forcing factors in
379 the entire domain of Tango Bay on a monthly time scale. %EII for the water temperature
380 fluctuates considerably depending on the BC and HF. %EII_{BC} fluctuates with two peaks in
381 early spring and late summer, when the offshore water temperature is at a minimum and a
382 maximum, respectively ([Fig. 3a](#)). The influence of HF is smaller than that of BC except in
383 December to January and May to June, when HF is at a minimum and a maximum,
384 respectively ([Fig. 2b](#)). This indicates that the offshore water plays a more important role in
385 the cooling and heating of the water in the bay except when the absolute value of HF is close
386 to its maximum. %EII_{WS} increases in winter due to the strong seasonal wind, but is weak and
387 stable throughout the year relatively to that of the other factors. %EII_{RD} is higher
388 than %EII_{HF} in February and March, when the cold freshwater flows into the bay due to the
389 melting of snow.

390

391 %EII for the salinity is directly related to %EII_{RD} throughout the year. %EII_{RD} is lower
392 from May to June, corresponding to the low river discharge season ([Fig. 2d](#)). Although the
393 river discharge is higher in summer and fall, %EII_{RD} is slightly higher in spring. The reason
394 is that the offshore salinity is higher in spring than in summer and fall ([Fig. 3b](#)), and the
395 influence of RD is larger when the river (the salinity is zero) flows into the higher salinity

396 bay. %EII_{BC} fluctuates with two peaks in late spring and late fall, when the offshore salinity
397 is the maximum and the minimum, respectively (Fig. 3b). %EII_{WS} and %EII_{HF} are higher in
398 winter and summer, respectively, but both are smaller than %EII_{BC} throughout the year.

399

400 %EII for the velocity is distributed evenly among the four external forcing factors,
401 compared with that to the water temperature and salinity. %EII_{BC} is higher from March to
402 July, when the inward velocity on the WOB is faster compared with other months (i.e., the
403 Tsushima Warm Current is stronger), and the offshore velocity is faster on the NEOB than on
404 the NWOB (i.e., the main path of the Tsushima Warm Current is toward NEOB) (Figs. 3c–d,
405 e.g. Figs. 4c–d). On the other hand, %EII_{BC} is lower in August although the inward velocity
406 on the WOB is also faster in August, because the outward velocity is faster on the NWOB
407 than on the NEOB (e.g., Fig. 4e–f). In other words, when the open ocean seawater entering
408 through the WOB flows out through the NWOB, the influence on the nearshore circulation is
409 larger than that when it flows out through the NEOB. %EII_{HF} is at the maximum in June,
410 when HF is the maximum, and at minima in March and October, when the absolute value of
411 HF is close to 0 (Fig. 2b). %EII_{WS} is at its maximum in February, when the southward wind
412 stress is the maximum. (Fig. 2c). Although the eastward wind stress is at its maximum in
413 December (which value is higher than in February), %EII_{WS} is not high. This indicates that
414 the influence of wind on the nearshore circulation is affected by the wind direction as: the
415 southward wind has greater influence than the eastward wind. %EII_{RD} is above 20% except
416 during the low river discharge season in May and June.

417

418 6. Discussion and conclusions

419

420 While Itoh et al. (2016) concluded that the circulation in Tango Bay is strongly influenced

421 by the Tsushima Warm Current and seasonal winds, our model results showed that the
422 relative contributions of open boundary conditions, surface heat flux, wind stress, and river
423 discharge to the velocity field are comparable in the bay, although that of open boundary
424 conditions is slightly higher than those of the other factors. Itoh et al. (2016) considered three
425 forcing factors of the Tsushima Warm Current, wind, and river and conducted correlation
426 analysis between the three forcing factors and the salinity and velocity observed in the bay.
427 The water temperature and surface heat flux were not taken into consideration, and thus the
428 influence of surface heat flux was omitted. The surface heat flux generating a thermal
429 gradient plays an important role in estuarine circulation (Simpson, 1997; Burchard and
430 Hofmeister, 2008). The influence of surface heat flux has been overlooked when external
431 forcing factors are evaluated (e.g., Geyer, 1997; Liu et al., 1997; Sylaios et al., 2006; Itoh et
432 al., 2016), because it intuitively seems weaker than the other external forcing factors, such as
433 tides, wind stress, and river discharge. In this study, we considered the open boundary
434 conditions as an external oceanic forcing factor. The open boundary conditions such as water
435 temperature, salinity, and velocity obtained from the DR_C (Hirose et al., 2016) contain not
436 only the Tsushima Warm Current but also atmospheric forcing factors, such as surface heat
437 flux and wind stress in the open sea. Consequently, the relative contribution of open boundary
438 conditions is likely to have been overestimated compared with that of the Tsushima Warm
439 Current, while those of surface heat flux and wind stress are likely to have been
440 underestimated, because the influence of surface heat flux and wind stress in the open sea
441 was included in that of open boundary conditions. Despite of the possibility of
442 underestimation, the relative contribution of surface heat flux was only slightly lower than
443 that of open boundary conditions. This indicates that the surface heat flux is as influential as
444 open boundary conditions and wind stress on the estuarine circulation in Tango Bay.

445

446 Itoh et al. (2016) reported that the influence of river discharge on the velocity field is only
447 observed at St. 1 (inshore station) and is weaker than those of the Tsushima Warm Currents
448 and seasonal winds in the entire domain of Tango Bay. However, our model results showed
449 that the relative contribution of river discharge to the velocity in the bay ($\%EII_{RD} = 22\%$) is
450 similar to that of wind stress ($\%EII_{WS} = 21\%$). Freshwater from the Yura River flows
451 eastward along the coast near the surface (e.g., Fig. 4a), and thus the influence of river
452 discharge is small at Sts. 2–4 (nearshore stations). Therefore, the riverine influence reported
453 by Itoh et al. (2016) would be underestimated compared with our model results, because the
454 ratio of the number of inshore ($D \leq 50$ m) data to the number of nearshore ($D > 50$ m) data
455 for correlation analysis (1/3) is smaller than that in this study (> 1/ 1.8).

456

457 Offshore oceanic currents have an important influence on the inshore circulation
458 (Huthnance, 1992; Sánchez-Arcilla and Simpson, 2002). The Tsushima Warm Current
459 passing offshore of Wakasa Bay plays an important role in the circulation and hydrographic
460 properties in Tango Bay (Itoh et al., 2016) as well as in Wakasa Bay (Hashimoto, 1982;
461 Yamagata et al., 1984; Umatani et al., 1986; Hara et al., 1992). Our model results showed that
462 open boundary conditions play the most important role in the circulation and hydrographic
463 properties in Tango Bay. Although the relative contribution of open boundary conditions is
464 likely to be higher than that of the Tsushima Warm Current because the influence of surface
465 heat flux and wind stress in the open sea was included in that of open boundary conditions,
466 the influence of open boundary conditions is likely to reflect that of the Tsushima Warm
467 Current because open boundary conditions reflect the Tsushima Warm Current (see detail in
468 section 3).

469

470 This study evaluated the relative contributions of the four major external forcing factors of

471 the external oceanic forcing, surface heat flux, wind stress, and river discharge to circulation
472 and hydrographic properties (i.e., water temperature, salinity, and velocity) in Tango Bay
473 using a three-dimensional regional circulation model. The dominant external forcing factor
474 influencing estuarine circulation changes in different estuarine environments. In an extremely
475 shallow lagoon with a mean depth of 0.7 m, the dominant forcing factor is tide even in the
476 micro-tidal regime with a tidal range of 0.1 to 0.4 m ([Sylaios et al., 2006](#)). In shallow micro-
477 tidal estuaries with a depth < 4 m and a tidal range < 0.5 m, the dominant forcing factor is
478 wind stress due to strong wind forcing ([Geyer, 1997](#)) or river discharge due to strong and
479 episodic freshwater inflow ([Liu et al., 1997](#)). We conclude that in Tango Bay, a micro-tidal
480 ROFI with a mean depth of 50 m and a tidal range < 0.2 m, where a strong current (i.e.,
481 Tsushima Warm Current) passes offshore of the bay, under conditions of strong seasonal
482 winds and river discharge, the estuarine circulation (i.e., the circulation in Tango Bay
483 bounded by the NP and EP lines shown in [Fig. 1c](#)) is comparably influenced by all external
484 forcing factors, i.e., the offshore current, surface heat flux, wind stress, and river discharge.
485 The degree of influence of each forcing factor varies with temporal variations in external
486 forcing factors. The influence of open boundary conditions is higher in spring and early
487 summer when the stronger current passes offshore of the bay; the surface heat flux reflects
488 the absolute value of surface heat flux; wind stress is higher in late fall and winter due to the
489 strong seasonal winds; and river discharge is higher in early spring due to the snow-melt and
490 summer and early fall due to flood events.

491

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493

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499

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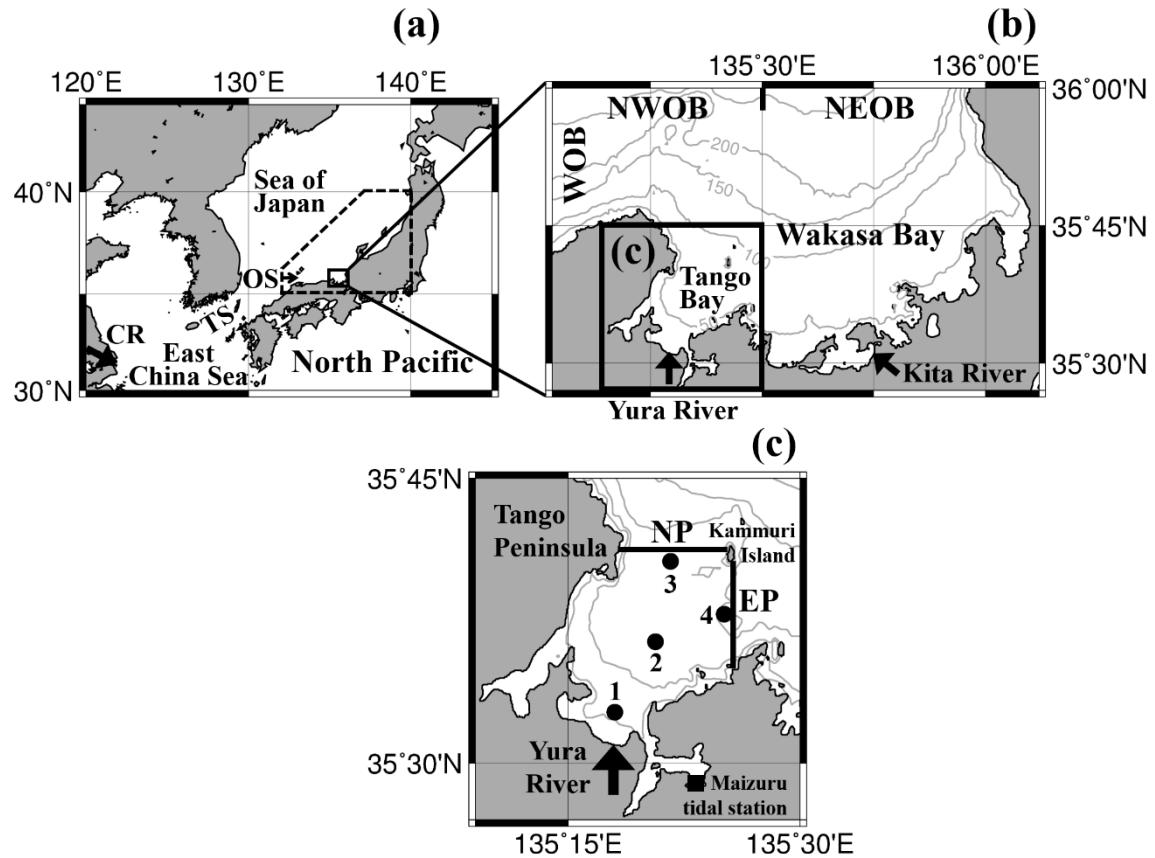
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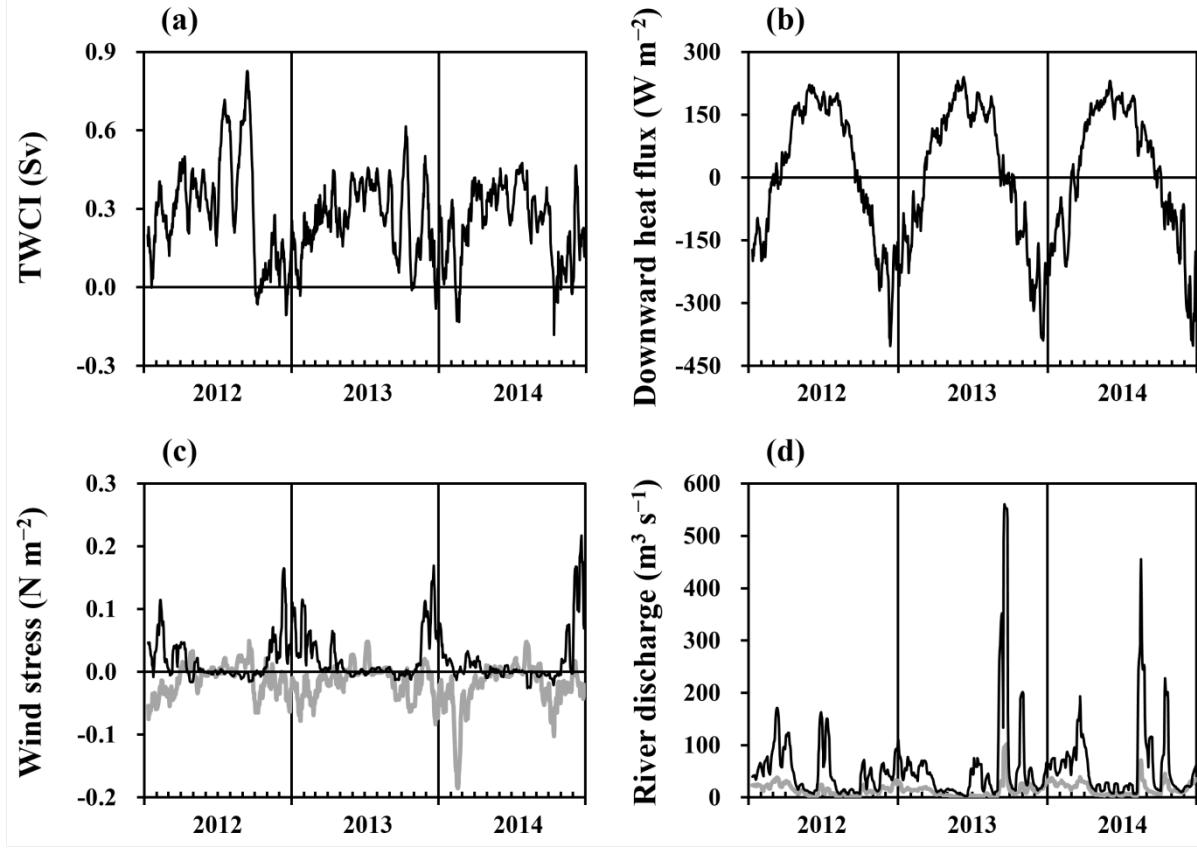
1 Figures



2

3 Fig. 1. (a) Location of the study area. CR, TS, and OS indicate Changjiang River, Tsushima
4 Straits, and Oki Strait, respectively, and the dashed polygon indicates the domain of the
5 DR_C model develop by [Hirose et al. \(2016\)](#). (b) Model domain and bathymetry with a
6 contour interval of 50 m. WOB, NWOB, and NEOB indicate the western, northwestern, and
7 northeastern open boundary, respectively. (c) Observation stations with bathymetry with a
8 contour interval of 25 m. Lines NP and EP indicate the northern and eastern passage of Tango
9 Bay, respectively. Numbers represent station numbers.

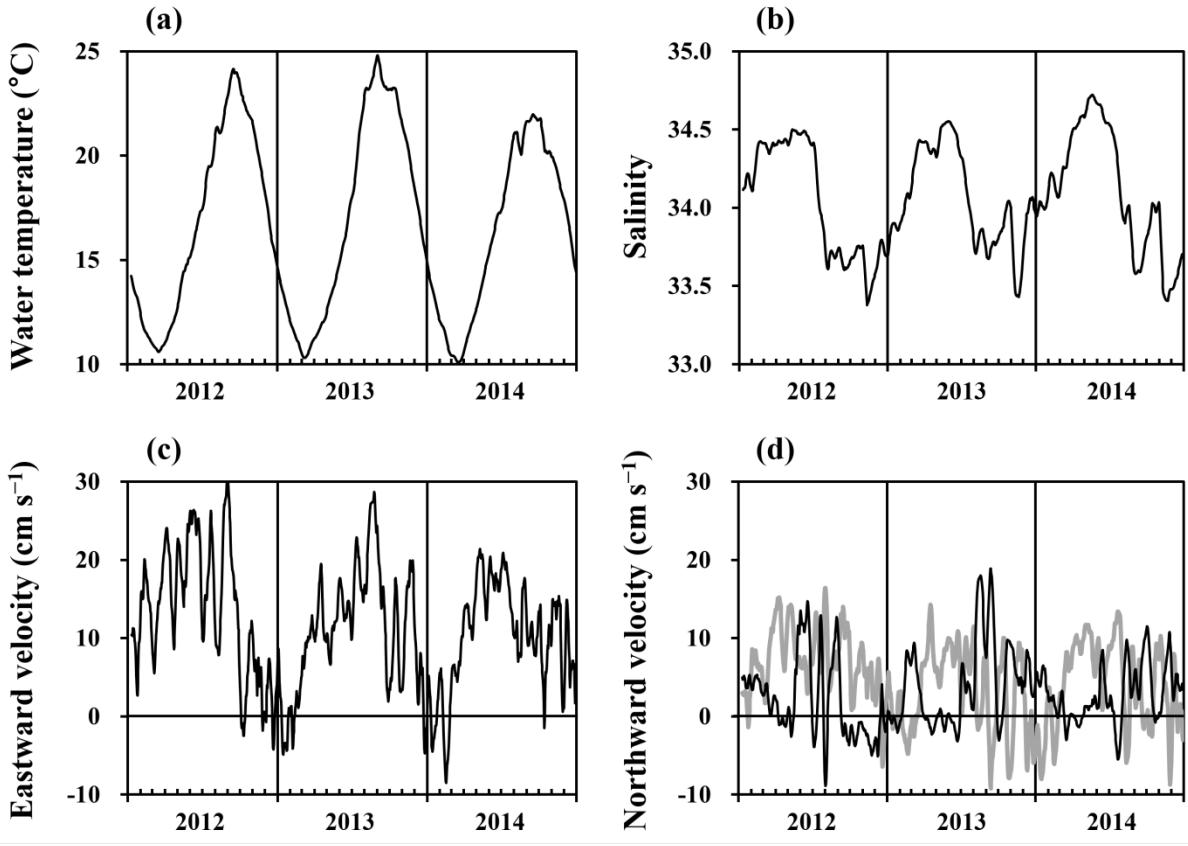
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11

12 Fig. 2. 10-day moving average time series of (a) Tsushima Warm Current Index (TWCI) (see
 13 details in section 3), (b) downward surface heat flux, (c) eastward (black line) and northward
 14 (grey line) wind stress averaged over the entire model domain, and (d) the river discharges of
 15 the Yura River (black line) and the Kita River (grey line).

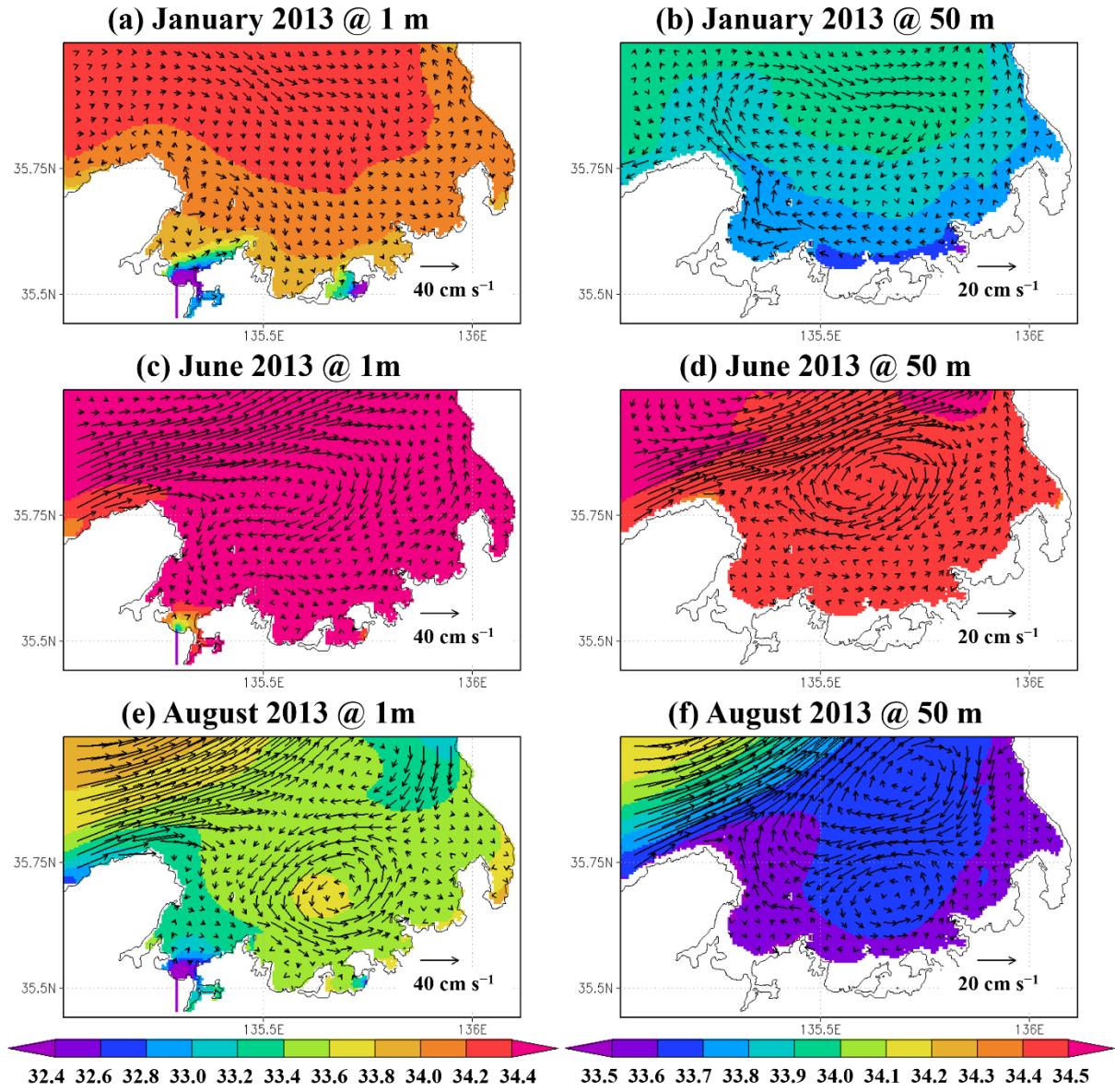
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Fig. 3. 10-day moving average time series of (a) water temperature, (b) salinity, and (c)
 19 eastward velocity vertically averaged between 0–100 m on the western open boundary (WOB
 20 shown in Fig. 1b), and (d) northward velocities on the northwestern (NWOB; black line) and
 21 northeastern (NEOB; grey line) open boundary.

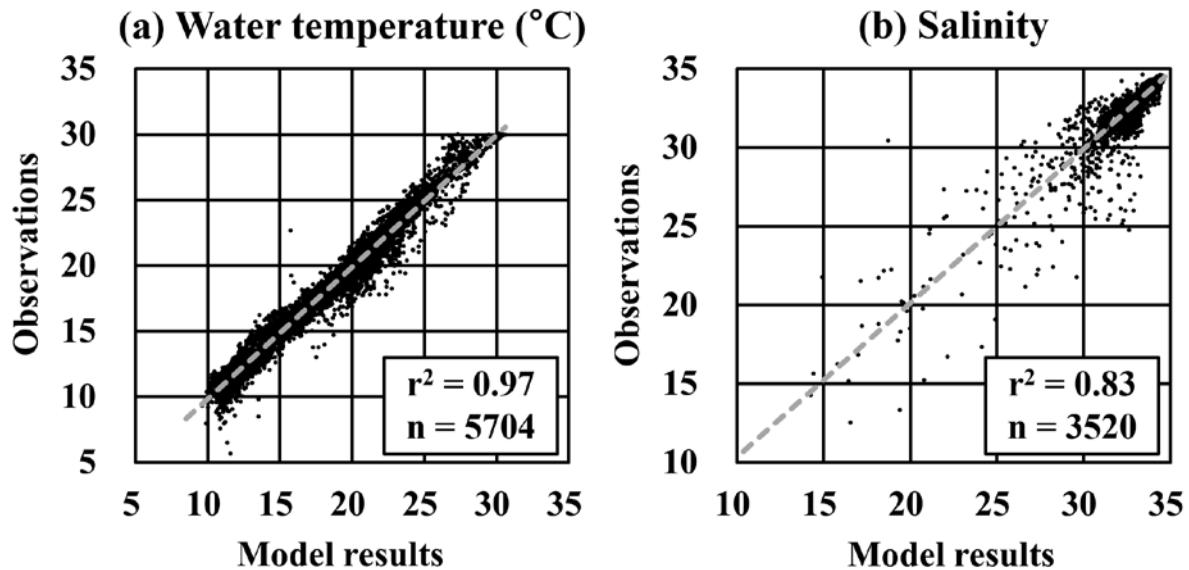
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24 Fig. 4. Simulated monthly mean salinities with horizontal velocity vectors at the depths of 1
 25 and 50 m in Wakasa Bay in January, June, and August 2013. Note the difference of color
 26 levels and vector scales between the depths of 1 and 50 m.

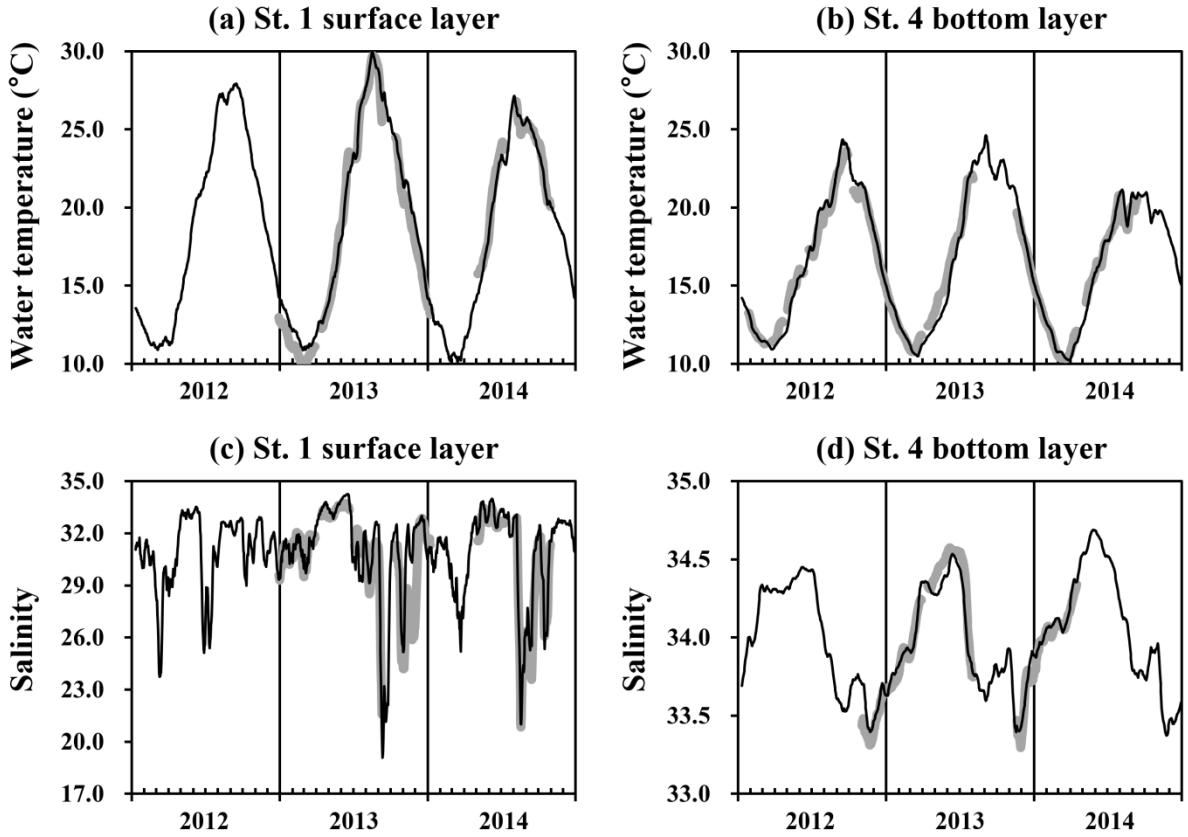
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29 Fig. 5. Scatter plots between model results and observations for water temperature and
 30 salinity at the depth of 0.5, 1.5, 3.5, and 28 m at St. 1, 54 m at St. 2, 62 m at St. 3, and 72.5 m
 31 at St. 4. These values are expressed as daily mean values. Grey dashed lines indicate the
 32 regression lines.

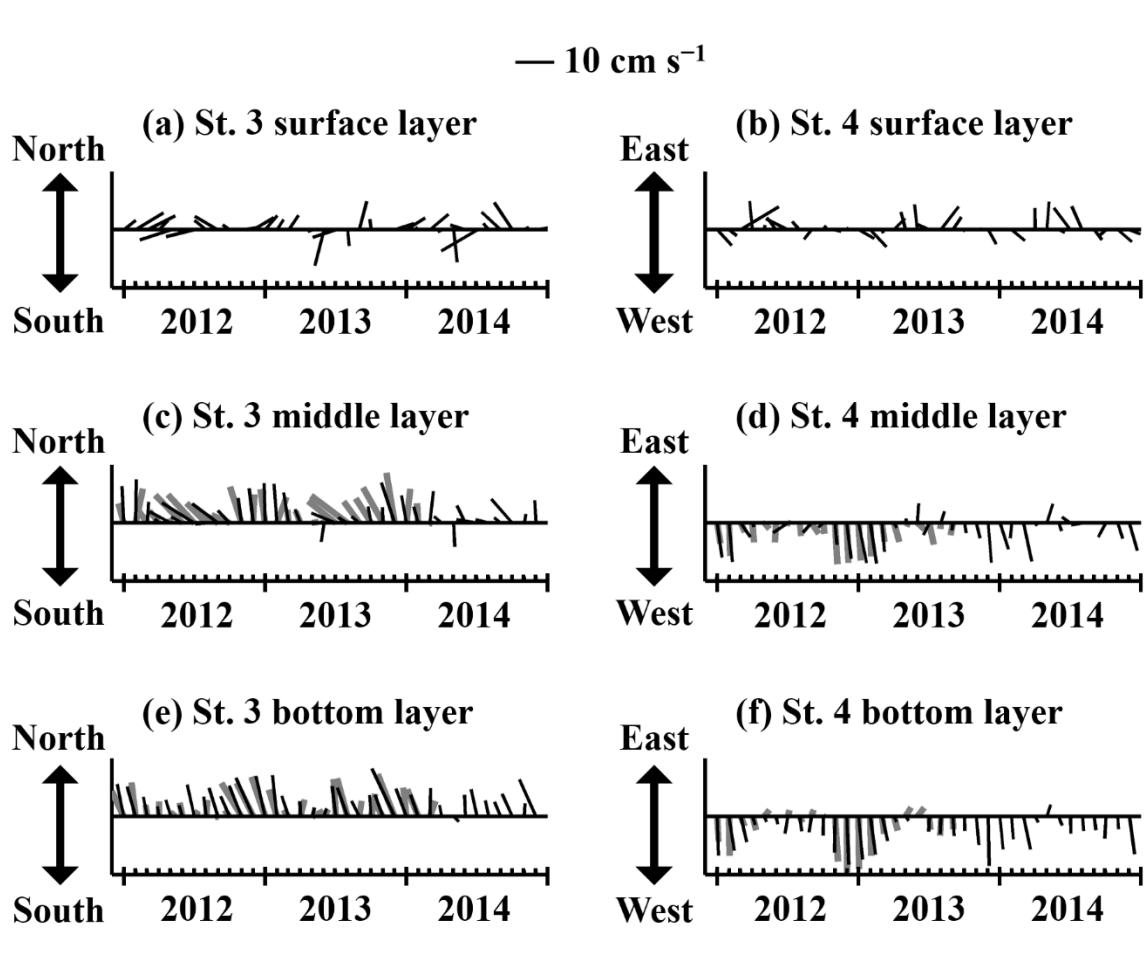
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35 Fig. 6. 10-day moving average time series of model results (black lines)
 36 and observations (grey lines) for water temperature and salinity in the surface layer
 37 (at the depth of 0.5 m) at St. 1 and the bottom layer (72.5 m) at St. 4 between 2012 and 2014.

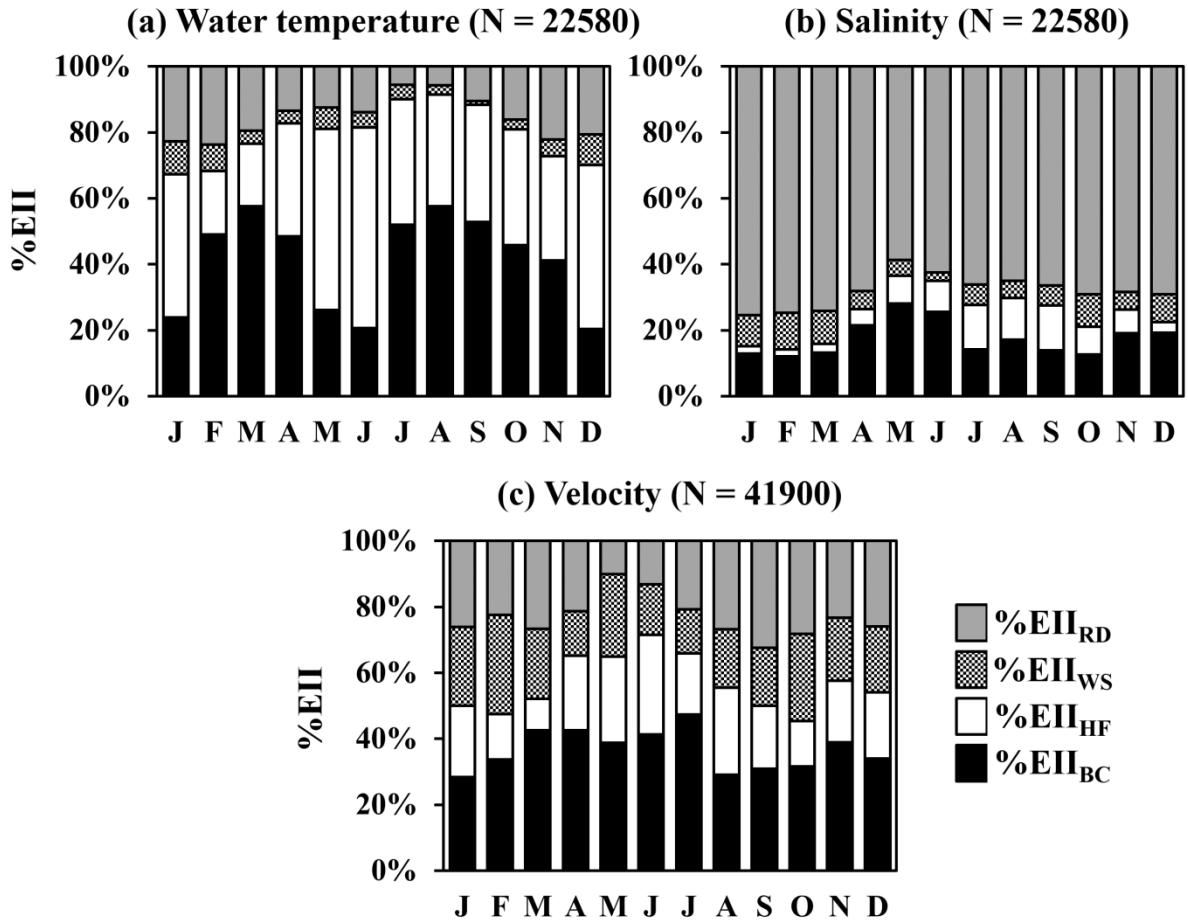
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40 Fig. 7. Stick plots for the modeled (black thin lines) and observed (grey thick lines) velocities
 41 in the surface (at the depth of 0.5 m), middle (at the depth of 29 m), and bottom (59 m) layers
 42 at Sts. 3 and 4 between 2012 and 2014. The length and direction of each stick represent the
 43 speed and direction of the monthly mean velocity. Note the difference of y-axis direction
 44 between the two stations: north-south at St. 3 and east-west at St. 4.

45



46

47 Fig. 8. Monthly relative contributions (%EII)s of open boundary conditions (%EII_{BC}), surface
 48 heat flux (%EII_{HF}), river discharge (%EII_{RD}), and wind stress (%EII_{WS}) to (a) water
 49 temperature, (b) salinity, and (c) velocity in the entire model domain of Tango Bay bounded
 50 by the NP and EP lines shown in Fig. 1c.

51

52 Tables

53 Table 1 Main parameter values of the Princeton Ocean Model (Mellor, 2002).

Symbol	Parameter description	Value	Unit
nadv	Advection scheme	2	-
nitera	Number of iterations for Smolarkiewicz iterative upstream scheme	2	-
sw	Smoothing parameter for Smolarkiewicz iterative upstream scheme	0.5	-
rheref	Rerefence density	1025	kg m^{-3}
grav	gravity constant	9.806	m s^{-2}
kappa	von Karman's constant	0.4	-
z0b	Bottom roughness	0.01	m
cbcmin	Minimum bottom friction coefficient	0.0025	-
cbcmax	Maximum bottom friction coefficient	1	-
horcon	Smagorinsky diffusivity coefficient	0.1	-
tprni	Inverse horizontal turbulent Prandtl number	0.1	-
umol	Background vertical diffusivity	0.00002	$\text{m}^2 \text{s}^{-1}$
ntp	Water type	2	-
nbct	Surface temperature boundary condition	2	-
nbcS	Surface salinity boundary condition	1	-
ispadv	Step interval during which external mode advective terms are not updated	5	-
smoth	Constant in temporal filter used to prevent solution splitting	0.1	-
alpha	Weight used for surface slope term in external dynamic equation	0.225	-

54

55

56 Table 2 Climatological control scenarios. “Clim.” indicates a climatological value from 2012
57 to 2014.

Case ID	Open boundary conditions	Heat flux	Wind stress	River discharge
CLIM	Clim.	Clim.	Clim.	Clim.
CTRL_BC	Sponge boundary conditions	Clim.	Clim.	Clim.
CTRL_HF	Clim.	0 W m^{-2}	Clim.	Clim.
CTRL_WS	Clim.	Clim.	0 N m^{-2}	Clim.
CTRL_RD	Clim.	Clim.	Clim.	$0 \text{ m}^3 \text{ s}^{-1}$

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60 Table 3 External influence indices (EIIs) and relative contributions (%EIIs) of external
 61 forcing factors, open boundary conditions (BC), surface heat flux (HF), wind stress (WS),
 62 and river discharge (RD) to water temperature (T), salinity (S), and velocity (V) in the surface
 63 (Sur), middle (Mid), and bottom (Bot) layers of bottom depth (D) \leq 50 m and $>$ 50 m in
 64 Tango Bay bounded by the NP and EP lines shown in Fig. 1c on an annual time scale.
 65 Numbers in parentheses indicate %EIIs. The number of data is 5556 for T and S in a layer of
 66 D \leq 50 m, 7992 for T and S in a layer of D $>$ 50 m, 9252 for V in a layer of D \leq 50 m, and
 67 15888 for V in a layer of D $>$ 50 m.

Compartment	External forcing	Entire	D \leq 50 m			D $>$ 50 m		
			Sur	Mid	Bot	Sur	Mid	Bot
Temperature	BC	2.47 (47)	2.04 (27)	2.70 (46)	2.79 (51)	1.83 (43)	2.76 (82)	2.60 (88)
	HF	1.93 (37)	3.73 (50)	2.11 (36)	1.80 (33)	1.76 (42)	0.41 (12)	0.18 (6)
	WS	0.22 (4)	0.46 (6)	0.18 (3)	0.13 (2)	0.43 (10)	0.09 (3)	0.11 (4)
	RD	0.64 (12)	1.22 (16)	0.85 (15)	0.75 (14)	0.20 (5)	0.11 (3)	0.06 (2)
Salinity	BC	0.52 (17)	0.60 (10)	0.74 (20)	0.84 (25)	0.36 (23)	0.32 (70)	0.30 (79)
	HF	0.26 (8)	0.45 (7)	0.35 (9)	0.31 (9)	0.14 (9)	0.06 (13)	0.05 (13)
	WS	0.24 (8)	0.63 (10)	0.27 (7)	0.18 (5)	0.39 (25)	0.04 (9)	0.02 (5)
	RD	2.12 (68)	4.49 (73)	2.39 (64)	1.99 (60)	0.65 (42)	0.04 (9)	0.01 (3)
Velocity	BC	3.42 (36)	1.78 (15)	1.24 (28)	0.66 (27)	5.42 (37)	3.44 (45)	1.77 (45)
	HF	1.90 (20)	1.80 (15)	0.95 (22)	0.84 (35)	3.12 (21)	1.59 (21)	0.92 (23)
	WS	1.95 (21)	3.05 (26)	0.90 (21)	0.36 (15)	3.48 (24)	1.49 (20)	0.77 (20)
	RD	2.10 (22)	5.25 (44)	1.30 (30)	0.55 (23)	2.61 (18)	1.05 (14)	0.48 (12)