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1 **Characteristics of submesoscale compensated/reinforced fronts in the**
2 **northern Bay of Bengal**

3

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11

12 **Key Points:**

- 13 • The submesoscale salinity (temperature) fronts are pronounced at surface
14 (subsurface), and they tend to be compensated.
- 15 • Subsurface layer is featured with more compensation than surface layer, and this
16 subsurface compensation is more submesoscale-selective.
- 17 • The slump of salinity-controlled compensated fronts will result in temperature
18 inversion and the retaining of barrier layer.

19
20
21 **ABSTRACT**

22
23 Fronts in the Bay of Bengal (BoB) are active and can potentially impact the regional
24 dynamics such as temperature variability, salinity distribution and oceanic circulation.
25 Based on the high resolution model output LLC4320, this study investigates the
26 characteristics of submesoscale fronts in the northern BoB and associated
27 compensation/reinforcement effects. At sea surface, horizontal gradients of salinity
28 and density are remarkable in the northern BoB, and they are nearly 3 times larger
29 than temperature gradients. As the depth deepens, temperature gradients increase and
30 become comparable to salinity gradients, while density gradients decrease a lot due to
31 the increasing effects of compensation at subsurface. Statistical results show the
32 dominance of salinity-controlled fronts over temperature-controlled fronts, and
33 compensated fronts over reinforced fronts. The surface cooling/heating results in
34 significant temporal variation of compensation at surface, but this variation is limited
35 at subsurface by the block of mixed layer base. The submesoscale-selective feature of
36 compensation is much more pronounced at subsurface layer than surface layer. From
37 statistical analysis and idealized numerical model, we found the slump of salinity-
38 controlled compensated fronts are important in generating temperature inversion and
39 maintaining barrier layer. This study validates the compensation theories originating
40 from observations, and further illustrates the importance of subsurface compensated
41 fronts with spatially continuous, regionally extended, and longer-term model output.
42 The subsurface-intensified submesoscale-selective compensation is proved for the
43 first time in this study.

Plain Language Summary

45

46 With cold, fresh water on the one side and warm, salty water on the other side, roles
47 of temperature and salinity in changing density are opposed across fronts, and they are
48 referred to as compensated fronts. Otherwise, the front is reinforced by temperature
49 and salinity. The strength of compensated fronts are thwarted to some extent
50 compared to reinforced fronts, thus the existence of compensation effects are not
51 favorable for forming a sharp front and associated instability processes. The statistics
52 of submesoscale compensated/reinforced fronts in the northern BoB are
53 comprehensively analyzed in this study. Concerning the amount of freshwater input,
54 fronts are dominated by salinity gradients instead of temperature gradients over the
55 northern BoB, and compensated fronts are more likely to form during winter with the
56 existence of both large salinity gradients and heat losses. Both statistical analysis and
57 idealized model simulation suggest that when the salinity front compensated by
58 temperature collapses, a reversed vertical temperature gradient (temperature inversion)
59 is favored to form.

60

61

62 1. Introduction

63 The Bay of Bengal (BoB) is a semi-enclosed basin in the northeastern Indian Ocean.
64 The thermohaline structure in the BoB is very unique among the world's ocean basins.
65 A freshwater plume exists in the northern Bay of Bengal (nBoB) due to freshwater
66 input from oceanic monsoon precipitation and associated continental river discharge
67 (Varkey et al., 1996, Sengupta et al., 2006; Papa et al., 2012). Freshwater input
68 creates a strong salinity stratification in the upper ocean of the nBoB, forming a
69 barrier layer (where halocline deeper than thermocline) and temperature inversion
70 layer (where warm water between colder water above and below) in this region
71 (Lucks and Lindstrom, 1991; Sprintall and Tomczak, 1992; Thadathil et al., 2002).
72 Temperature inversion layer and barrier layer usually coexist, and they are crucial in
73 modulating local air-sea momentum and heat exchange, and thus impacting climate
74 and post-monsoon tropical cyclones (Thadathil et al., 2016).

75
76 Fronts are ubiquitous in the ocean and are characterized by sharp horizontal variations
77 in temperature, salinity, density or other material concentrations, with horizontal
78 scales ranging from meters to kilometers (McWilliams, 2021). For example, the
79 Kuroshio, Gulf Stream, and Antarctic Circumpolar Current are known for their
80 prominent horizontal temperature gradients across their major axes (Wunsch, 1998;
81 Clayton et al., 2014; Wenegrat et al., 2020) and they are largely constrained by
82 Earth's rotation.

83
84 Submesoscale fronts with horizontal scales of 0.1~10 km and time scales of hours ~
85 days are widely distributed over the global ocean (McWilliams, 2016). These fronts
86 are associated with relatively large Rossby numbers ($O \sim (1)$) and are thus less
87 constrained by the geostrophic effect (Thomas et al., 2008). The generation
88 mechanisms of submesoscale fronts and filaments (considered as dual fronts) are
89 illustrated by previous researchers: strain-induced frontogenesis (Hoskins and
90 Bretherton, 1972), mixed layer instability (Boccaletti et al., 2007), horizontal
91 convergence motion (Barkan et al., 2019) and boundary layer turbulence
92 (McWilliams et al., 2015). Vertical velocities around submesoscale fronts are
93 typically large due to the development of ageostrophic secondary circulation, making
94 them instrumental in influencing oceanic biogeochemical processes (Mahadevan,

95 2016; Lévy et al., 2018) and marine pollutant distributions (Poje et al., 2014). Besides,
96 submesoscale fronts provide a connection between mesoscale and small scale
97 processes for energy cascade (Barkan et al. 2021; Balwada et al., 2022; Naveira
98 Garabato et al., 2021).

99

100 Although the small spatiotemporal scale of submesoscale fronts makes them difficult
101 to resolve observationally, several studies have observed submesoscale fronts in the
102 BoB using advanced observational means. For example, Sengupta et al. (2016)
103 observed high-frequency salinity variations in the nBoB based on a long time series of
104 mooring observations. They suggested that a salinity jump with magnitude of 0.2-1.2
105 PSU occurs when submesoscale salinity fronts moving pass the mooring. Based on a
106 high-resolution radiator survey in the central BoB from the Air–Sea Interactions in the
107 Northern Indian Ocean (ASIRI) - Ocean Mixing and Monsoons (OMM) project
108 (Wijesekera et al., 2016), abundant submesoscale temperature and salinity fronts were
109 observed by Ramachandran et al. (2018). They believed that these submesoscale
110 fronts are important in modulating the ocean vertical stratification. More recently,
111 using the Monsoon Intraseasonal Oscillations in the Bay of Bengal (MISO-BOB)
112 observations, Mckie et al. (2024) suggested that the submesoscale frontal instability
113 and temperature inversion are closely related in the BoB.

114

115 High-resolution numerical modelling is a powerful tool for studying submesoscale
116 fronts. Based on outputs from a high-resolution air-ocean-wave coupled model,
117 Jensen et al. (2018) found that the submesoscale salinity front can evolve into
118 submesoscale currents in the mixed layer through frontal instabilities. Using Large
119 Eddy Simulation (LES) results, Sarkar et al. (2016) suggested that the submesoscale
120 salinity fronts in the nBoB are associated with a variety of instability processes (e.g.,
121 symmetric instability and Kelvin-Helmholtz shear instability), and further
122 development of the instability processes can alter the ocean stratification. Based on
123 LES, Pham and Sarkar (2019) found that strong salinity fronts are prone to shear
124 instability, which drives the generation of ageostrophic secondary circulations,
125 leading to the formation of barrier and temperature inversion layers on both sides of
126 the front, and enhancing local mixing.

127

128 Compensating/opposing (these two terms are used interchangeably in this study)
129 effects are common across oceanic fronts when the roles of salinity and temperature
130 in density variation are opposite (i.e., warm but salty water on one side and cold but
131 fresh water on the other) (Rudnick and Martin, 2002). Horizontal density fronts at ~ O
132 (10 km) scales tend to be compensated in many regions (Drushka et al., 2019), and the
133 universality of the compensation in the North Pacific Ocean (Rudnick and Ferrari,
134 1999) and the Gulf of Mexico (Barkan et al., 2017) has been captured by cruise
135 observations and model simulations, respectively. Lin et al. (2023) used towed
136 measurements to reveal the mechanism of scale-dependent compensation in the
137 Taiwan Strait. They suggested that the compensation effect at submesoscale is larger
138 (smaller) in salinity (temperature) dominated frontal zones compared to larger scales.
139 In the BoB, Spiro Jaeger and Mahadevan (2018) investigated the temperature-salinity
140 compensation effect across fronts using ship-based observations and model
141 simulations. They proposed that the restratification effect resulting from submesoscale
142 frontal instability could transform lateral gradients into mixed-layer stratification.
143 Consequently, when cooled by the atmosphere, the sea surface temperature (SST)
144 decreases more significantly on the restratified side of the salinity-controlled front
145 owing to the shallower mixed layer. This leads to the occurrence of temperature-
146 salinity compensation.

147

148 The above-mentioned studies of submesoscale fronts are based on either observations
149 or idealized numerical models. However, the spatial coverage (both horizontal and
150 vertical) and the time span of the observations are limited, and idealized models are
151 limited to describe the real oceanic fronts. Besides, a general conclusion on
152 temperature-salinity compensation or reinforcement across fronts is still lacking. In
153 this study, a comprehensive analysis of submesoscale fronts and the associated
154 compensation/reinforcement effect is performed in the BoB using a spatially
155 continuous, regionally extended, and longer-term model output.

156

157 The remainder of the manuscript is structured as follows: Data and methods are
158 described in Section 2. Model outputs are validated in Section 3. Statistics of
159 submesoscale fronts in the BoB are presented in Section 4. Compensation and
160 reinforcement effects across submesoscale fronts are illustrated in Section 5. The

161 relationship between compensated fronts and vertical stratification is shown in
162 Section 6. Discussion and conclusions are given in Section 7.

163

164 **2. Data and Method**

165 **2.1 Numerical Model output**

166 A high resolution primitive equation model is used to provide high resolution
167 thermohaline data in the BoB (3°N-23°N, 76°E-99°E). This model is the
168 Massachusetts Institute of Technology General Circulation Model (MITgcm) on a
169 latitude-longitude polar cap (LLC) grid (Menemenlis et al., 2008) for a period of 14
170 months from September 13, 2011 to November 14, 2012. The model simulation used
171 here is the so-called LLC4320, which has a horizontal grid spacing of $1/48^\circ$ (~ 2 km
172 in BoB). The vertical resolution of this model is refined at surface layer: grid space
173 increases from 1 m at surface to 380 m at bottom, with 22 layers in the upper 100 m.
174 The temporal resolution of the model output is one hour, and the daily averaged data
175 are selected for analysis in order to remove the tidal signals.

176

177 The model is forced with six-hourly surface atmospheric fields (including momentum
178 and buoyancy flux) from the European Centre for Medium-Range Weather
179 Forecasting (ECMWF) atmospheric operational model analysis (with a horizontal
180 resolution of 0.14°). The climatological river discharge over the BoB is included in
181 the surface freshwater flux. Full luni-solar tidal constituents are also included in this
182 simulation as additional atmospheric pressure forcing. The vertical subgrid mixing
183 scheme used in the model is the K-Profile Parameterization (KPP). This model output
184 has been successfully used in submesoscale studies (e.g. Rocha et al. 2016; Su et al.,
185 2018; Dong et al., 2021; Cheng et al., 2023; Zhou et al., 2024). In this study, a period
186 of one full year (October 1, 2011 ~ September 30, 2012) is chosen for the analysis.

187

188 **2.2 Multisource Data**

189 We use several observational data sets to validate the numerical model. Sea surface
190 salinity (SSS) and temperature (SST) data with a 7-day interval are obtained from Soil
191 Moisture and Ocean Salinity SMOS/SMAP OI L4 maps product (SMOS for short)
192 provided and supported by the CNES CATDS and CNES TOSCA SMOS OCEAN
193 projects (Kolodziejczyk et al., 2021). Daily SST data are from the Group of High-

194 Resolution Sea Surface Temperature (GHRSSST) product with a 0.01°×0.01° resolution
 195 (Dash et al., 2012). We also use SST data from Aqua Moderate Resolution Imaging
 196 Spectroradiometer (MODIS, Savtchenko et al., 2004) with a resolution of 4 km. The
 197 World Ocean Atlas 2018 (WOA18) provides vertical thermohaline data (Locarnini et
 198 al., 2018; Zweng et al., 2018). The time period for all data is from October 2011 to
 199 September 2012, except that WOA18 is monthly climatology. Detailed information
 200 about these data can be found in Table 1.

201 **Table 1. Observations and reanalysis data used in this study**

Data	Time Resolution	Spatial Resolution	Variable
SMOS	7 Days	0.25°×0.25°	SSS
GHRSSST	Daily	0.01°×0.01°	SST
MODIS	Daily	4 km	SST
WOA18	Monthly	0.25°×0.25°	Salinity, Temperature

202

203

204 2.3 Idealized numerical model

205 The Coastal and Regional Ocean COMMunity model (CROCO, Auclair et al., 2022),
 206 is used to set up frontal experiments to corroborate the findings from statistical
 207 analysis (see Section 6 for detail). The fronts we set are in a channel measuring 60 km
 208 (along front) × 60 km (cross front) and 25 m (vertically), with a horizontal resolution
 209 of 2 km and a vertical resolution of 1 m. The frontal axes are along the y-direction
 210 with a hyperbolic function along the x-direction. Temperature and salinity across the
 211 fronts are set to be similar with that of Pham and Sarkar (2019) by:

$$\begin{aligned}
 T(x, z) &= \frac{\nabla T_x|_{max} L}{60\alpha g} \left\{ T_0 \right. \\
 &\quad \left. + 0.25 \left[1 + \tanh \tanh \left(x - \frac{L}{2} \right) \frac{12}{L} \right] \left[1 + \tanh \tanh \left(\frac{z+H}{2} \right) \right] \right\} \\
 &\quad - \frac{0.5}{\alpha g} \left\{ [N_{m,T}^2 + N_{p,T}^2] z + 2(N_{m,T}^2 - N_{p,T}^2) \log \left[\frac{\cosh((z+H)/2)}{\cosh(H/2)} \right] \right\} \\
 S(x, z) &= \frac{-\nabla S_x|_{max} L}{60\beta g} \left\{ S_0 \right. \\
 &\quad \left. + 0.25 \left[1 + \text{Sgn} * \tanh \tanh \left(x - \frac{L}{2} \right) \frac{12}{L} \right] \left[1 + \right. \right. \\
 &\quad \left. \left. \tanh \tanh \left(\frac{z+H}{2} \right) \right] \right\} \\
 &\quad - \frac{0.5}{\beta g} \left\{ [N_{m,S}^2 + N_{p,S}^2] z + 2(N_{m,S}^2 - N_{p,S}^2) \log \left[\frac{\cosh((z+H)/2)}{\cosh(H/2)} \right] \right\}
 \end{aligned}$$

212 where $\nabla T_x|_{max} = 2 \times 10^{-6} s^{-2}$ are the maximum values of the lateral gradients of
 213 temperature; $L = 60 km$ is the frontal width; $\alpha = 2 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$ is the thermal
 214 expansion coefficient and $\beta = 8 \times 10^{-4} psu^{-1}$ is the haline contraction coefficient;
 215 $T_0 = 26$ is a parameter to make the temperature close to reality; $N_{m,T}^2 = -2 \times$
 216 $10^{-5} s^{-2}$ and $N_{p,T}^2 = -2 \times 10^{-4} s^{-2}$ are the temperature stratification in the mixed
 217 layer and the pycnocline; $N_{m,S}^2 = 4 \times 10^{-4} s^{-2}$ and $N_{p,S}^2 = 2 \times 10^{-3} s^{-2}$ are the
 218 salinity stratification in the mixed layer and pycnocline. These values are set to
 219 constant, so that the temperature structure is the same for all fronts (see first column
 220 in Fig. 13).

221

222 On the other hand, we change the following parameters according to the values of the
 223 Turner angle (see Section 5 for detailed definition): 1) the maximum values of the
 224 lateral gradients of temperature ($\nabla S_x|_{max}$); 2) parameter to adjust the salinity close to
 225 reality (S_0); and 3) a sign function (Sgn). This results in different salinity structures
 226 for different fronts (see second column in Fig. 13). The values of these parameters are
 227 listed in Table 2, and the way to classify a front (TCSR, SCTR, SCTO and TCSO) is
 228 described in Section 5.

229

Table 2. Parameter setups for different fronts

Parameter	TCSR	SCTR	SCTO	TCSO
$\nabla S_x _{max}$	$1 \times 10^{-6} s^{-2}$	$6 \times 10^{-6} s^{-2}$	$6 \times 10^{-6} s^{-2}$	$1 \times 10^{-6} s^{-2}$
S_0	-230	-39	-39	-230
Sgn	1	1	-1	-1

230

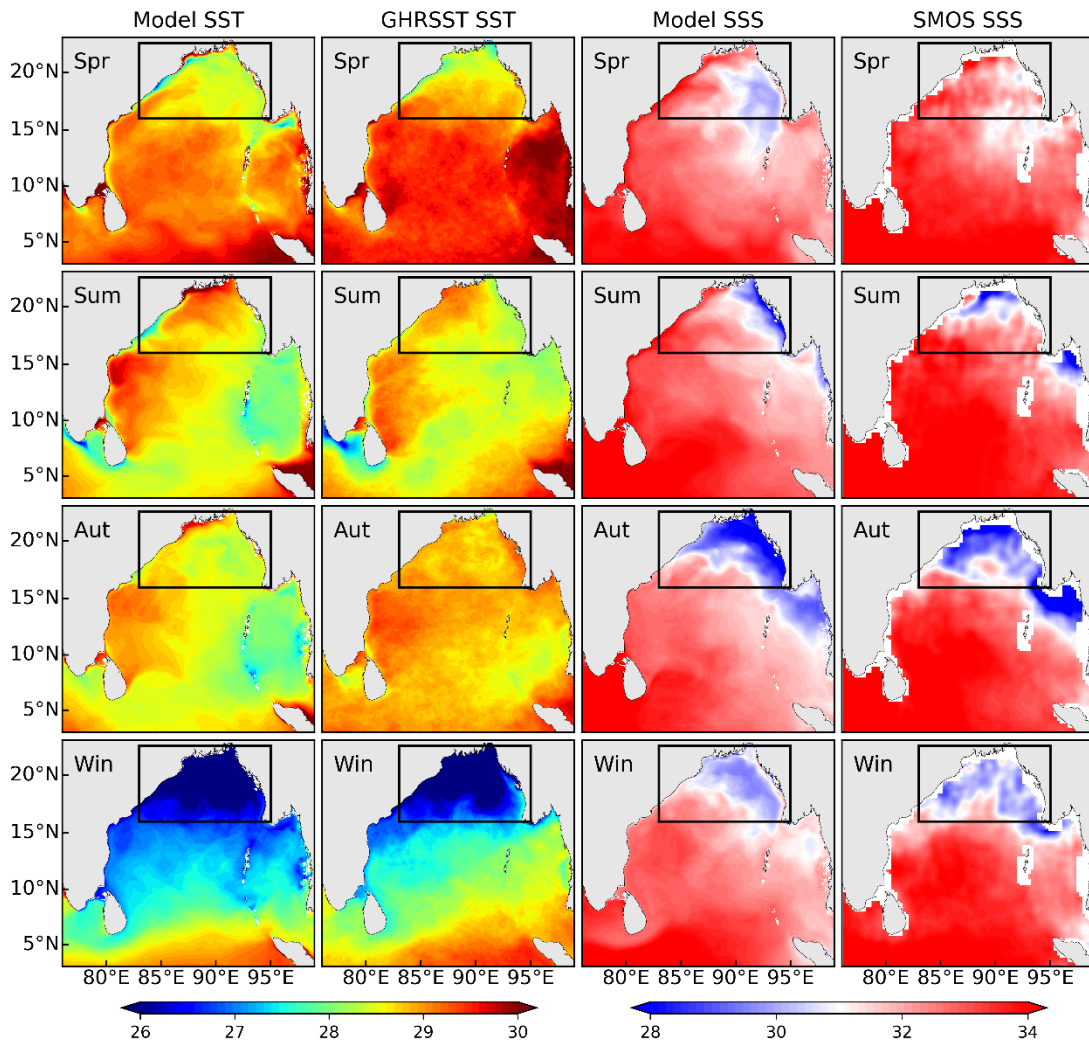
231

232 3. Model validation

233 (a) Surface temperature/salinity

234 We first validate the ability of the LLC4320 to simulate oceanic properties in the BoB.
 235 Although there are small discrepancies, the seasonal cycles of SSS and SST in
 236 LLC4320 agree quite well with the observed SSS (from SMOS) and SST (from
 237 GHRSSST) (Fig. 1). The spatio-temporal distribution of hydrological properties in the
 238 BoB is well represented in this simulation. The largest variations in SST/SSS are
 239 located in the northern bay (boxes in Fig. 1, 16°N - 22.5°N , 83°E - 95°E , hereafter
 240 region R1), partly due to the large input and/or variations in heat/freshwater fluxes in

241 this region (Fig. S1).



242

243 **Fig. 1.** Geographical distribution of model seasonal SST (first column, °C), GHRSSST
244 seasonal SST (second column, °C), model seasonal SSS (third column, PSU), and
245 SMOS seasonal SSS (last column, PSU) during October 2011-September 2012. Black
246 boxes refer to region R1.

247

248 *(b) Vertical thermohaline*

249 The vertical thermohaline distribution of the model is evaluated through comparing it
250 with observations. We focus on region R1, which is subject to the largest SSS/SST
251 variability (Fig. S1). The model reproduces the seasonal cycles of the subsurface
252 thermohaline distribution well compared with the WOA18 monthly climatology data
253 (Figs. 2a-2d). In particular, both model and observations capture the strong surface
254 layer cooling in winter and warming in spring/summer (Fig. 2e). In addition, the
255 upper ocean freshening event due to the increasing freshwater flux in late summer and

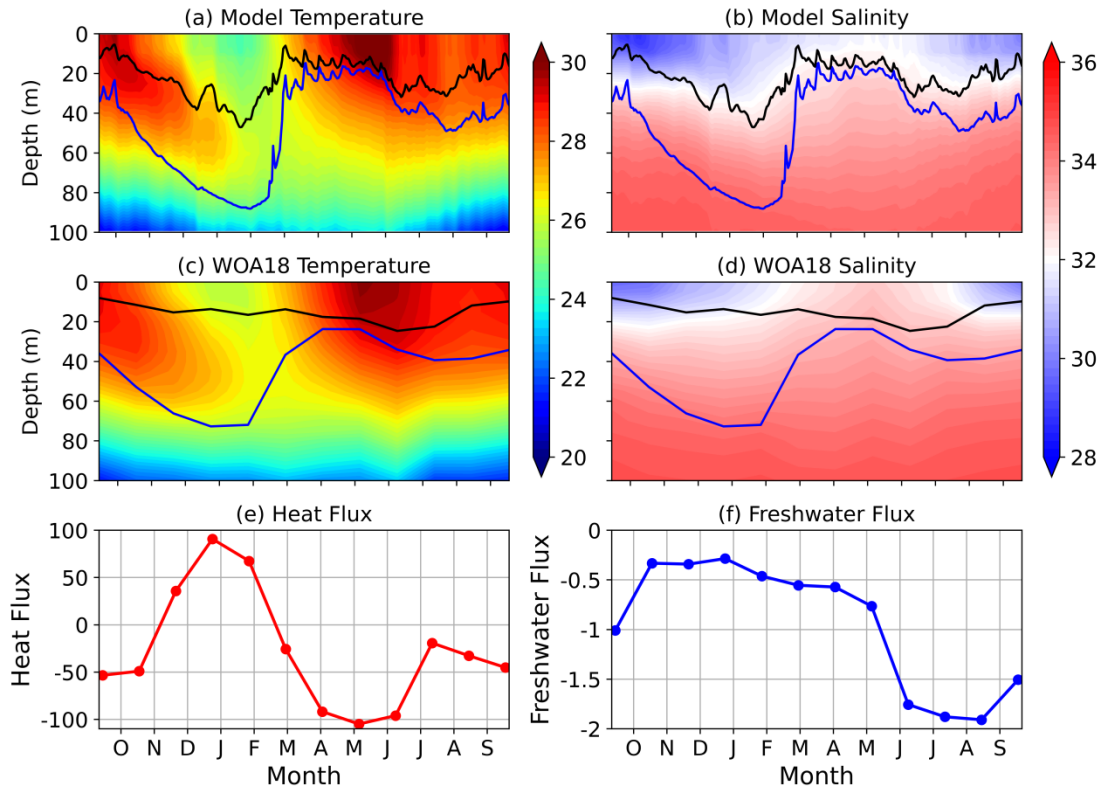
256 autumn (Fig. 2f) is well captured by the model.

257

258 The barrier layer is well known in the ocean, especially in the BoB, for its climatic
259 effect, and the barrier layer thickness (BLT) is a good indicator to describe the ocean
260 salinity stratification. The BLT is calculated based on the variable density threshold
261 method following De Boyer Montegut et al. (2004): First, we define a reference depth
262 ($Z_{ref} = 0\text{ m}$) and find the depth at which the temperature decreases by 0.5°C
263 compared to the temperature at Z_{ref} , which gives us the isothermal layer depth (ILD).
264 Then we calculate the density variation from Z_{ref} with a constant salinity and a 0.5°C
265 temperature decrease ($\delta\rho$). Finally, we search for the depth at which the density
266 increase from Z_{ref} is equal to $\delta\rho$, and this depth is defined as the mixed layer depth
267 (MLD). The layer between the MLD and the ILD is defined as the BLT.

268

269 The BLT corresponds to the layer between the black line (MLD) and the blue line
270 (ILD) in Figs. 2a-2d. The seasonal variation of the BLT in the model agrees well with
271 the WOA18 data, with a maximum in winter and a minimum in spring. During winter,
272 when the barrier layer is thickest and heat exchange between the surface and
273 subsurface layers is blocked, both WOA18 and LLC4320 capture a subsurface
274 temperature inversion at a depth of 40-60 m. These validations confirm the robust
275 thermohaline representation of the model and provide substantial credibility for
276 conducting further analyses.



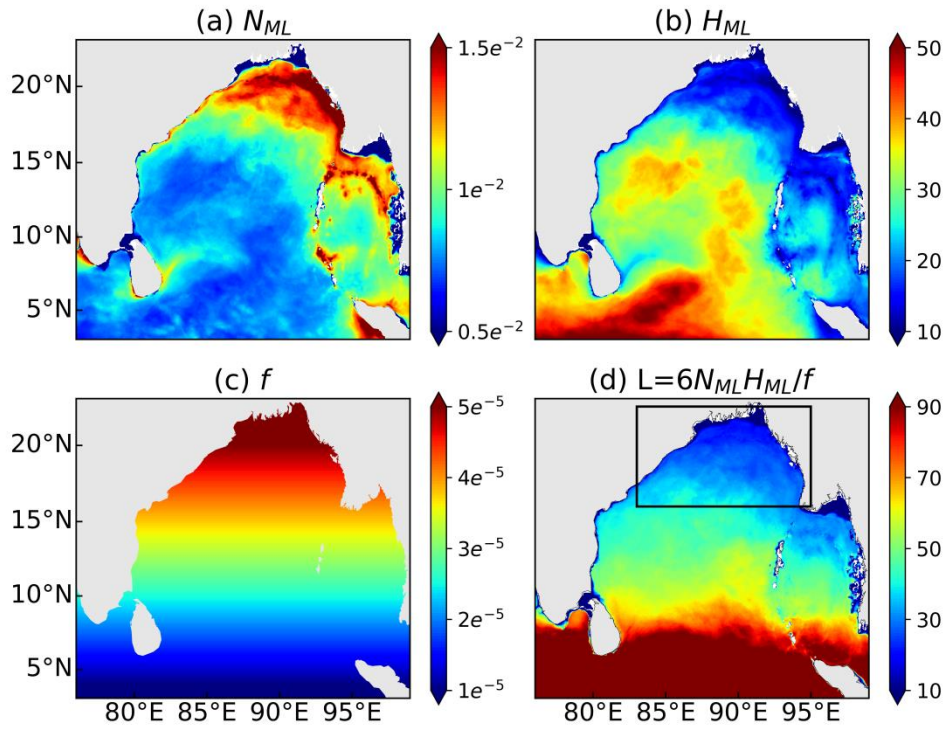
277

278 **Fig. 2.** Depth-time plot of (a) temperature (°C) and (b) salinity (PSU) averaged over
 279 region R1 based on LLC4320 during October 2011-September 2012. (c) and (d) are
 280 the thermohaline structure from WOA18 monthly climatology data. (e) Regional
 281 mean heat flux in the model (upward, positive value means surface cooling, W/m^2). (f)
 282 Regional mean freshwater flux in the model (upward, positive value means losing
 283 freshwater, cm/day). Black lines in (a-d) represent the MLD and blue lines in (a-d)
 284 represent the ILLD. The layer in between is the barrier layer.

285

286 *(c) Typical length of submesoscale*

287 Based on the theory of baroclinic instability (Boccaletti et al., 2007; Dong et al.,
 288 2020), the upper bound of the mixed layer baroclinic instability wavelength is $L =$
 289 $6 \frac{N_{ML} H_{ML}}{f}$, where N_{ML} is the mixed layer stratification, H_{ML} is the mixed layer depth,
 290 and f is the Coriolis parameter. The value of L in the study area is within the range of
 291 15~50 km (Fig. 3), so the submesoscale fronts can be at least partially resolved by
 292 LLC4320 with its grid resolution of O (~2 km). The regional mean L over the nBoB is
 293 about 28 km, so hereafter the submesoscale fronts are defined as fronts with scales ~O
 294 (10-30 km).



295

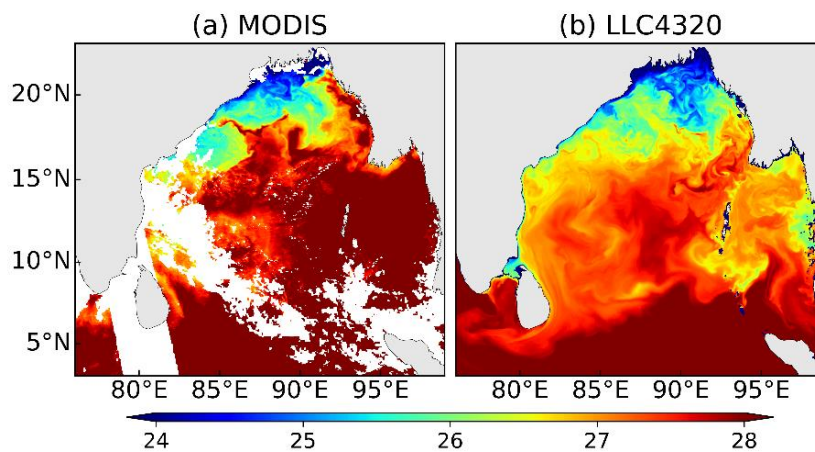
296 **Fig. 3.** Spatial distribution of annual mean (a) mixed layer stratification (s^{-1}), (b)
 297 mixed layer depth (m), (c) Coriolis parameter (s^{-1}) and (d) upper bound of mixed
 298 layer baroclinic instability wavelength (km). Black box in (d) refers to region R1.

299

300 4. Statistics of submesoscale fronts in the BoB

301 (a) Observed submesoscale fronts

302 Ocean fronts are characterized by large horizontal gradients of tracers. A snapshot of
 303 SST from MODIS (Fig. 4a) on a typical winter day shows amounts of temperature
 304 fronts in the Bay of Bengal with horizontal scales of $\sim O(1)$ km, which can be
 305 considered as submesoscale fronts (Sengupta et al., 2016; Li et al, 2022). These
 306 submesoscale fronts are also obvious in LLC4320 (Fig. 4b).



307

308 **Fig. 4.** Snapshots of SST (°C) on December 31, 2011 from (a) MODIS and (b)
 309 LLC4320 over the BoB region. Missing data in (a) are cloud covered regions.

310

311 (b) *Lateral gradients for tracers*

312 To represent the frontal characteristics in the BoB, the zonal and meridional gradients
 313 of temperature, salinity and density scaled by their respective coefficients are
 314 calculated as:

$$315 \quad \nabla T_x = -g\alpha \partial T / \partial x; \quad \nabla T_y = -g\alpha \partial T / \partial y \quad (3.1)$$

$$316 \quad \nabla S_x = g\beta \partial S / \partial x; \quad \nabla S_y = g\beta \partial S / \partial y \quad (3.2)$$

$$317 \quad \nabla \rho_x = \nabla T_x + \nabla S_x; \quad \nabla \rho_y = \nabla T_y + \nabla S_y \quad (3.3)$$

318 where T , S and ρ are temperature, salinity and density, respectively. α is the thermal
 319 expansion coefficient and β is the haline contraction coefficient. x and y are the zonal
 320 and meridional direction, respectively. These scaled gradients are adjusted to have the
 321 same unit (s^{-2}), facilitating easier comparison. Hereafter we will simply refer to the
 322 “scaled gradients” of temperature, salinity, and density as “gradients”.

323

324 Spice is a passive tracer that combines the gradients of temperature and salinity on
 325 isopycnal surfaces (Spiro Jaeger et al., 2020). BoB region is a typical “*spicy sea*”
 326 suggested by MacKinnon et al. (2016), which represents a region in which there is
 327 significant temperature salinity (T-S) variability along an isopycnal. The scaled spice
 328 gradients are calculated as:

$$329 \quad \nabla \gamma_x = \nabla S_x - \nabla T_x; \quad \nabla \gamma_y = \nabla S_y - \nabla T_y \quad (3.4)$$

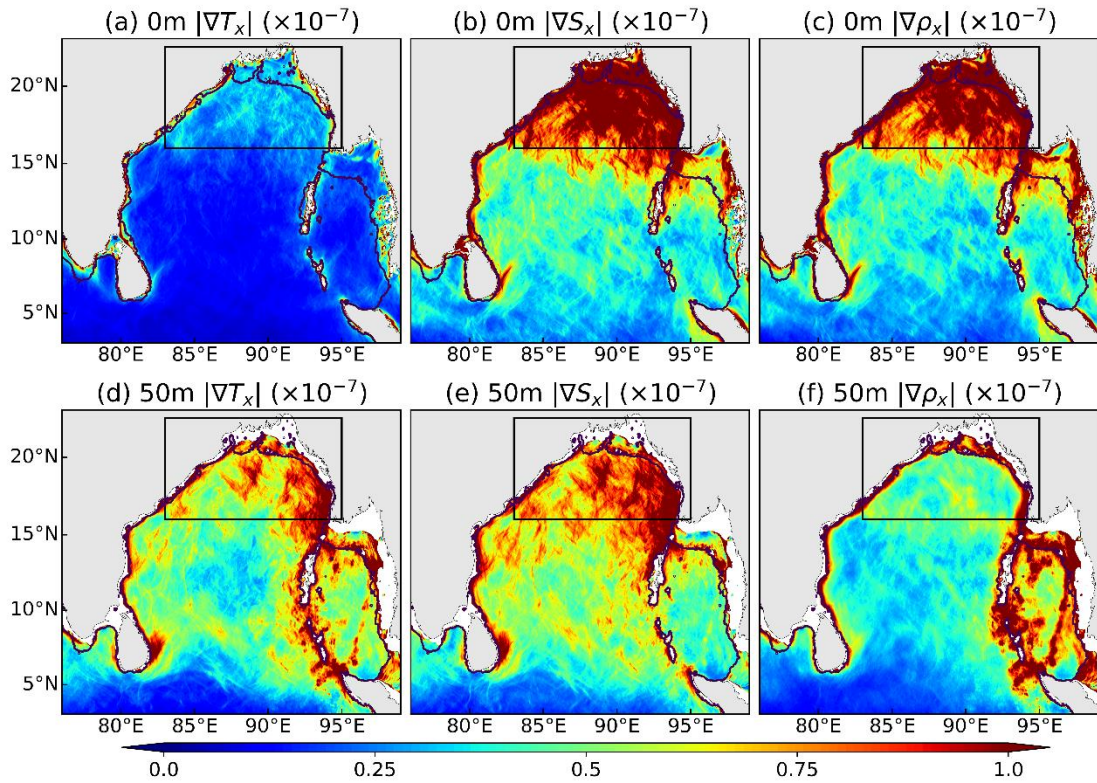
330

331 The results that will be discussed below are based on the zonal (x direction) gradients,
 332 while the results based on meridional (y direction) gradients are shown in
 333 Supplementary Materials for comparison. It can be seen that most of the results are
 334 statistically independent of direction. Hereafter we use “gradients” as a shortening for
 335 “scaled zonal gradients”.

336

337 The annual mean amplitude of gradients at the sea surface for temperature, salinity,
 338 and density in the BoB are shown in Figures 5a-5c. Spatially, the largest gradients of
 339 salinity and density are visible in region R1 (black boxes). The region receives large
 340 amounts of freshwater from precipitation and river runoff (Fig. S1), and large

341 gradients are formed by the stirring of ocean currents. Large salinity and density
 342 gradients are also visible in the coastal regions (i.e., east coast of India, coast of Sri
 343 Lanka, west coast of Myanmar, Andaman Islands, and southern part of Sumatra).
 344 These regions have very shallow water depths (shoreward of the 200 m isobaths in
 345 Fig. 5), so the ocean-land interaction can induce large gradients. The surface
 346 temperature gradients are much smaller compared to that of salinity and density. (Fig.
 347 5a). From Eq (3.3), the horizontal density gradients are exactly the sum of the
 348 temperature gradients and the salinity gradients, so that at sea surface most of the
 349 density gradients are caused by salinity rather than temperature. This salinity-
 350 controlled feature is also obvious in the surface temperature-salinity diagram (Fig.
 351 S2a).



352

353 **Fig. 5.** Spatial distribution of annual mean (October 2011-September 2012) sea
 354 surface (0 m) (a) $|\nabla T_x|$, (b) $|\nabla S_x|$ and (c) $|\nabla \rho_x|$ in the BoB, multiplied by 10^{-7} . (d-f)
 355 are subsurface (50 m) values. Units are s^{-2} . The black boxes refer to region R1 and
 356 the black contours indicate the 200 m isobaths from ETOPO2.

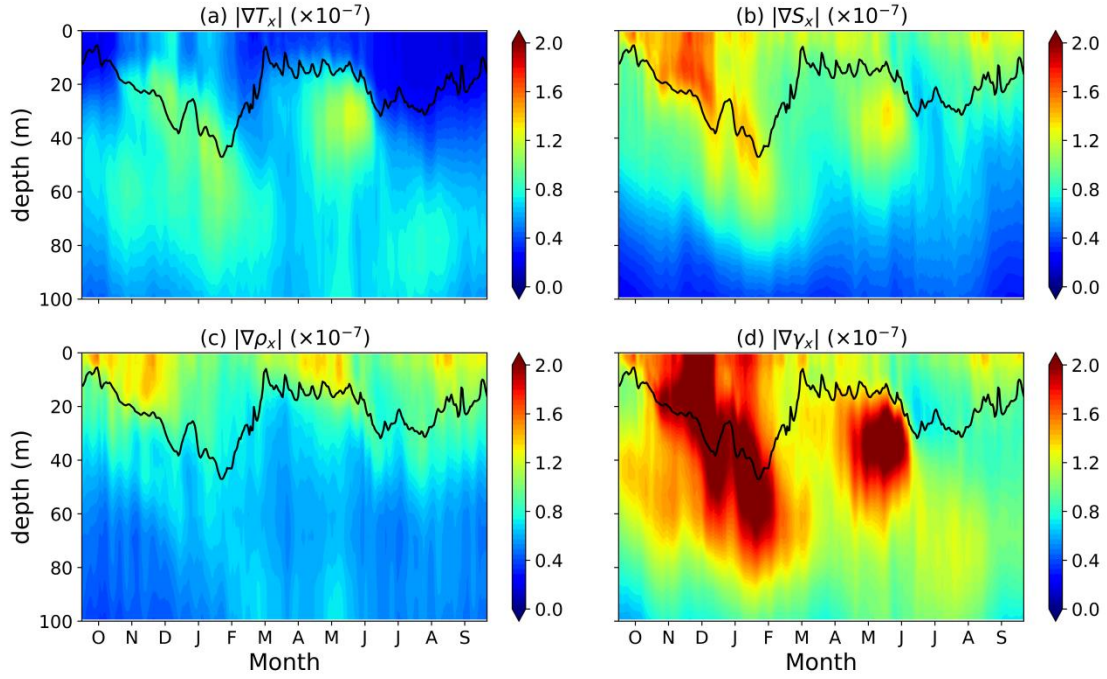
357

358 The gradients at subsurface are quite different from those at surface. Here the depth
 359 for subsurface is chosen as 50 m, i.e., the depth just below the mixed layer depth (Fig.

360 2). The values of $|\nabla T_x|$ in the subsurface are much larger than those at surface (Fig.
361 5d), while $|\nabla S_x|$ and $|\nabla \rho_x|$ are smaller than those at surface (Figs. 5e-5f). In particular,
362 $|\nabla \rho_x|$ in the subsurface is much smaller than $|\nabla S_x|$ and $|\nabla T_x|$, and large values
363 of $|\nabla \rho_x|$ are mostly confined to the coastal region. In other words, most of the $|\nabla T_x|$
364 and $|\nabla S_x|$ are opposed in the subsurface, producing small $|\nabla \rho_x|$. Compared to the
365 surface, the salinity-controlled features are much reduced in the subsurface (see also
366 Fig. S2b). Note that over the southeastern BoB region, subsurface gradients of
367 temperature and density are also remarkable. This region is featured with relative
368 shallow water depth, so the topography may be crucial in generating large gradients.
369 However, this is beyond the scope of the current study and will be addressed in future
370 research.

371

372 Obviously, large tracer gradients are not just confined to the surface layer. The depth-
373 time plots for laterally averaged $|\nabla T_x|$, $|\nabla S_x|$ and $|\nabla \gamma_x|$ over region R1 are shown in
374 Figure 6 in order to get a vertical view. Values of $|\nabla T_x|$ are relatively small in the
375 mixed layer and reach a maximum below the MLD (Fig. 6a), which may be related to
376 the intermittent tilting of the isotherms. In contrast, large $|\nabla S_x|$ are mostly confined to
377 the mixed layer and decrease with depth (Fig. 6b). The density gradients are mostly
378 smaller than the salinity gradients, indicating that the effects of temperature and
379 salinity on the density gradients are counteracted. On the contrary, the value of $|\nabla \gamma_x|$
380 is larger than all other tracer gradients, suggesting a large variation of thermohaline
381 properties along isopycnals. Clearly, $|\nabla \gamma_x|$ acts in the opposite direction to $|\nabla \rho_x|$,
382 and large magnitudes of $|\nabla \gamma_x|$ can be considered as a sign of temperature-salinity
383 compensation.



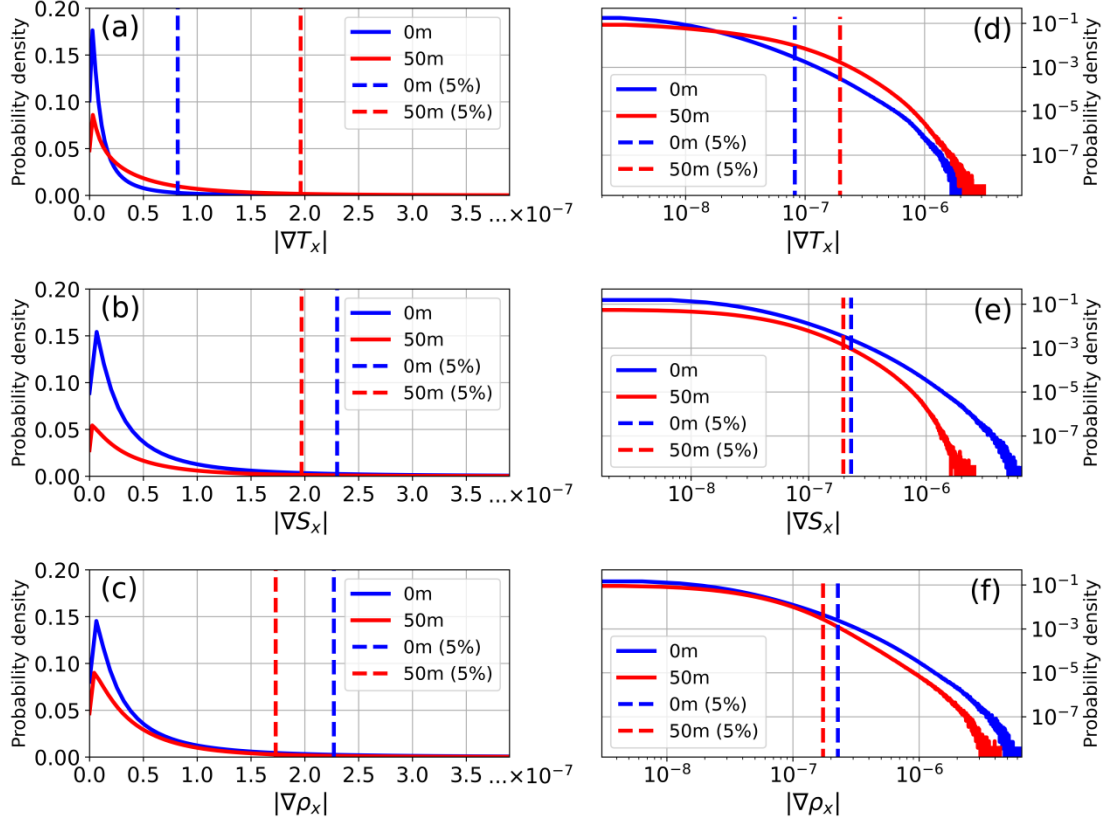
384

385 **Fig. 6.** Depth-time plot of lateral averaged (a) $|\nabla T_x|$, (b) $|\nabla S_x|$, (c) $|\nabla \rho_x|$ and (d) $|\nabla \gamma_x|$
 386 during October 2011 and September 2012 over region R1. The black lines in each
 387 panel show the mixed layer depth.

388

389 *(c) Selection of submesoscale fronts*

390 Since fronts are characterized by particularly large gradients, strong submesoscale
 391 frontal regions are defined here as locations with remarkable horizontal gradients. The
 392 probability density function (PDF) for $|\nabla T_x|$, $|\nabla S_x|$ and $|\nabla \rho_x|$ at surface and
 393 subsurface are shown in Figure 7 (solid lines). The dashed lines represent the largest 5%
 394 (8% or 10% doesn't make large differences, not shown) magnitude for each gradient,
 395 where the PDF slopes flatten (Barkan et al., 2017; Spiro Jaeger and Mahadevan, 2018;
 396 Lin et al., 2023). At the surface (blue lines in Fig. 7), the $|\nabla T_x|$ threshold is about
 397 three times smaller than those of $|\nabla S_x|$ and $|\nabla \rho_x|$, while at the subsurface (red lines
 398 in Fig. 7), the $|\nabla T_x|$ threshold is nearly identical to that of $|\nabla S_x|$ and larger than that
 399 of $|\nabla \rho_x|$. Meanwhile, the magnitudes of top 5% of surface $|\nabla S_x|$ and $|\nabla \rho_x|$ are larger
 400 than at subsurface, while the top 5% of $|\nabla T_x|$ at subsurface are larger than at surface
 401 (Figs. 7d~7f).



402

403 **Fig. 7.** Probability density function (PDF) for (a) $|\nabla T_x|$, (b) $|\nabla S_x|$ and (c) $|\nabla \rho_x|$ in the
 404 BoB, denoted by solid lines (blue for 0 m and red for 50 m). Dashed lines represent
 405 the top 5% magnitude of each gradient. (d-f) are the corresponding PDF in
 406 logarithmic scale.

407

408 5. Compensated and reinforced fronts in the nBoB

409 (a) *Quantify the role of compensation/reinforcement*

410 The density ratio (R_x) and Turner angle (Tu_x) are widely used to quantify the
 411 compensation/reinforcement effect (Ferrari and Rudnick, 2000). They are calculated
 412 by:

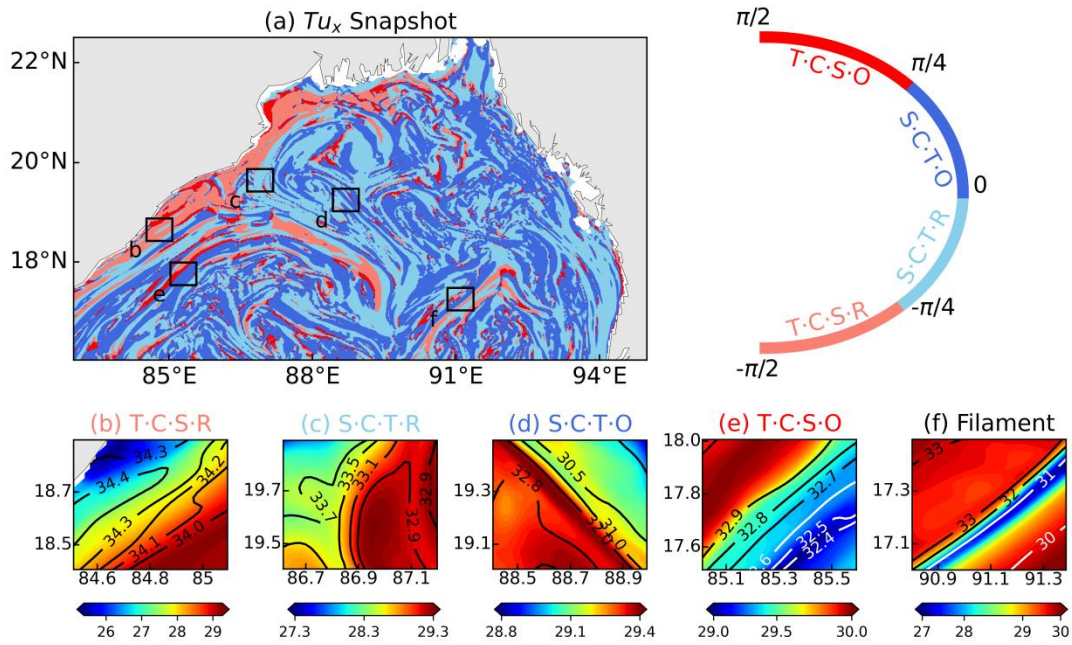
$$413 \quad R_x = -\nabla T_x / \nabla S_x \quad (4.1)$$

$$414 \quad Tu_x = \arctan R_x \quad (4.2)$$

415 where the negative sign means that the density decreases with temperature but
 416 increases with salinity. Since R_x can be very small (large) due to very small ∇T_x (∇S_x),
 417 it is more convenient to use Tu_x within a finite range ($-\pi/2 < Tu_x < \pi/2$), as was
 418 done by Spiro Jaeger and Mahadevan (2018) and Drushka et al. (2019).

419

420 A snapshot of Tu_x on April 29, 2012 in region R1 is shown in Fig. 8a. Positive and
 421 negative Tu_x appear alternately in the nBoB, indicating the role of compensation and
 422 reinforcement, respectively. Here, we classified the fronts into four types according to
 423 the value of Tu_x : Temperature Controlled Salinity Reinforcing (TCSR) with $-\pi/2 <$
 424 $Tu_x \leq -\pi/4$; Salinity Controlled Temperature Reinforcing (SCTR) with $-\pi/4 <$
 425 $Tu_x \leq 0$; Salinity Controlled Temperature Opposing (SCTO) with $0 < Tu_x \leq \pi/4$;
 426 Temperature Controlled Salinity Opposing (TCSO) with $\pi/4 < Tu_x < \pi/2$.



427
 428 **Fig. 8.** (a) Snapshot of normalized surface Tu_x on April 29, 2012 in region R1. (b-f)
 429 are the SST and SSS structure from the black boxes in (a): (b) TCSR front, (c) SCTR
 430 front, (d) SCTO front, (e) TCSO front and (f) cold filament. Note that the color
 431 shadings in (b-f) are for temperature ($^{\circ}\text{C}$) and the contours are for salinity (PSU).

432
 433 Several examples of each type of front in terms of horizontal temperature and salinity
 434 structure are shown in Figures 8b~8f from the Tu_x snapshot. The TCSR front is
 435 featured with warm/fresh water on the southeastern side and cold/salty water on the
 436 northwestern side (Fig. 8b). The SCTR front is featured with warm/fresh water on the
 437 eastern side and cold/salty water on the western side (Fig. 8c). The SCTO front is
 438 featured with warm/salty water on the southwestern side and cold/fresh water on the
 439 northeastern side (Fig. 8d). The TCSO front is featured with warm/salty water on the
 440 western side and cold/salty water on the eastern side (Fig. 8e). Figure 8f shows a

441 special cold filament structure (Gula et al., 2014), which is a combination of SCTO
442 and TCSR fronts. It is featured with cold water lying in the middle of warm water,
443 and salinity increasing northwestward.

444

445 *(b) Statistics of compensated/reinforced fronts*

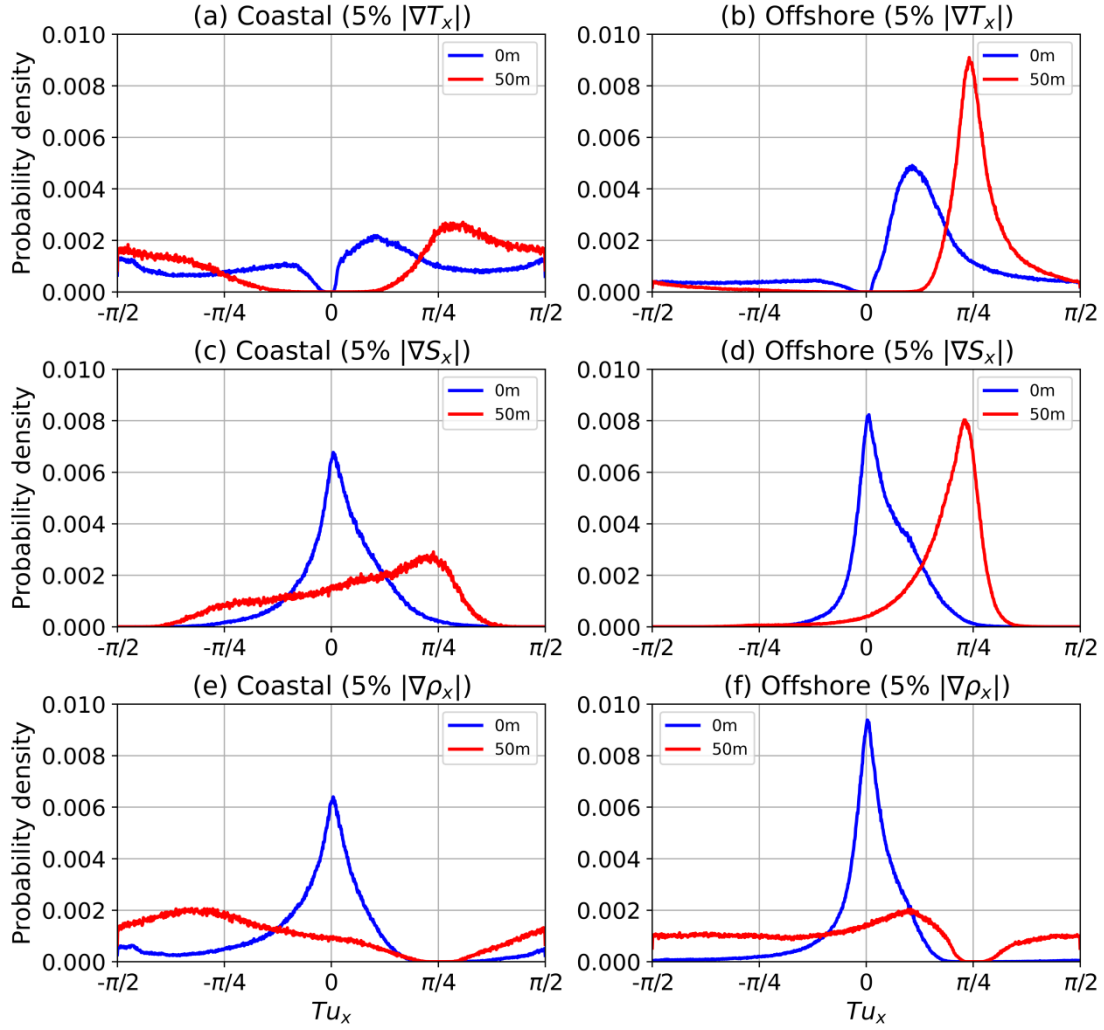
446 Since there is a large discrepancy in horizontal gradients between the coastal (< 200 m)
447 and offshore (> 200 m) regions, as well as between the surface and subsurface layers
448 (Fig. 5), the statistics of Tu_x are analyzed here using the conditional PDF method, and
449 the 5% thresholds are used here to separate the frontal regions (Fig. 9). Hereafter we
450 focus only on these frontal regions in region R1.

451

452 For regions with top 5% of $|\nabla T_x|$ (Figs. 9a and 9b), we can first expect that no Tu_x are
453 near zero because of the large value of $|\nabla T_x|$. At the surface (blue lines), there is a
454 peak of Tu_x located in $(0, \pi/4)$ for both coastal and offshore regions as SCTO fronts.
455 In other words, regions with top 5% magnitudes of $|\nabla T_x|$ are featured with even larger
456 $|\nabla S_x|$. Apart from the SCTO fronts, the probabilities of the remaining three types of
457 fronts at surface are almost identical. At subsurface (red lines), large $|\nabla T_x|$ are more
458 likely to be fully compensated by $|\nabla S_x|$ with a peak near $\pi/4$, especially far from the
459 coast.

460

461



462
 463 **Fig. 9.** Conditional PDF of Tu_x at (a) coastal regions with top 5% of $|\nabla T_x|$, (b)
 464 offshore regions with top 5% of $|\nabla T_x|$, (c) coastal regions with top 5% of $|\nabla S_x|$, (d)
 465 offshore regions with top 5% of $|\nabla S_x|$, (e) coastal regions with top 5% of $|\nabla \rho_x|$ and (f)
 466 offshore regions with top 5% of $|\nabla \rho_x|$. Blue lines for surface Tu_x and red lines for
 467 subsurface Tu_x .

468

469 The condition for top 5% of $|\nabla S_x|$ are quite different from that of $|\nabla T_x|$ in terms of the
 470 conditional PDF of Tu_x (Figs. 9c and 9d). No values of Tu_x are near $\pm\pi/2$ for
 471 large ∇S_x . Almost all the values of Tu_x are concentrated at $(-\pi/4, \pi/4)$, showing the
 472 predominance of salinity. The shape of the PDF at surface is characterized by a peak
 473 near 0, but there are still more positive (compensation) Tu_x than negative
 474 (reinforcement) ones. At subsurface, the peak of Tu_x is close to $\pi/4$, which is similar
 475 to the subsurface $|\nabla T_x|$, suggesting the tendency to be fully compensated.

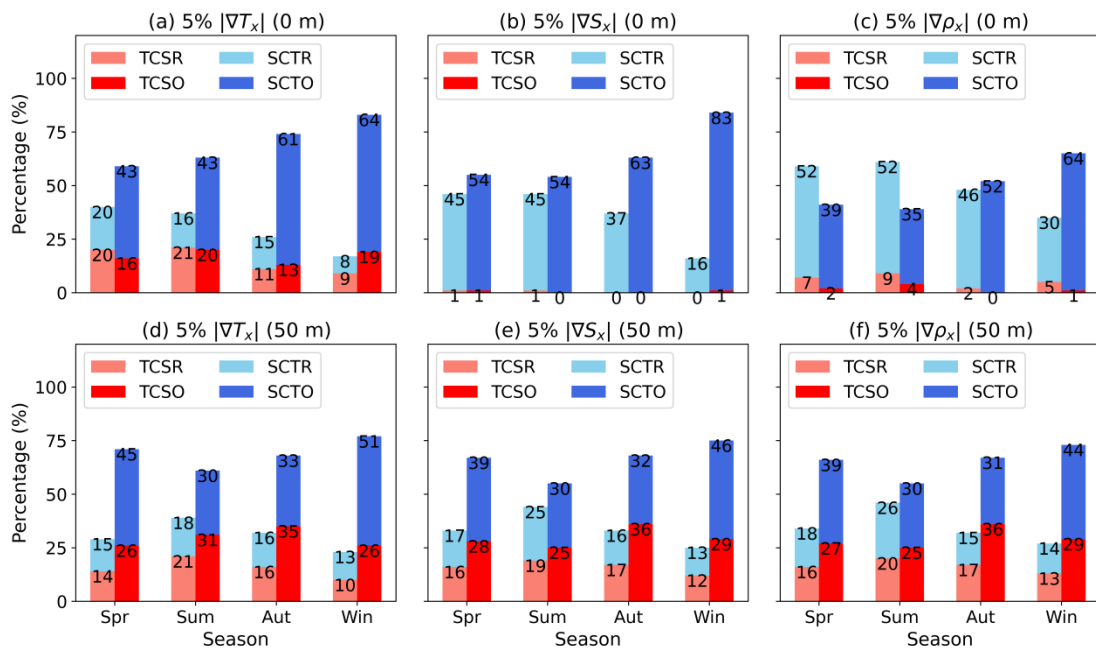
476

477 The shape of the Tu_x PDF for the top 5% of $|\nabla\rho_x|$ at surface is similar to that of
 478 $|\nabla S_x|$ (Figs. 9e and 9f). It is not possible for density fronts to be fully compensated, so
 479 no values of Tu_x are near $\pi/4$. At subsurface, there are more negative Tu_x
 480 (reinforcement effect) distributed over the coastal region, and this can help explain the
 481 large values of coastal $|\nabla\rho_x|$ in Figure 5f.

482

483 *(c) Seasonality of compensated fronts versus reinforced fronts*

484 According to the frontal classification method, we can further evaluate the seasonal
 485 variation of compensated fronts versus reinforced fronts over the study region. The
 486 ratios of compensation (dark colors) to reinforcement (light colors) effects for the top
 487 5% of $|\nabla T_x|$, $|\nabla S_x|$ and $|\nabla\rho_x|$ during different seasons are shown in Fig. 10. Overall,
 488 the seasonal variations are more pronounced at surface than at subsurface, considering
 489 that the surface layer is directly influenced by the seasonal atmospheric fluxes.
 490 Surface compensation is most likely to occur during winter, especially for $|\nabla T_x|$ and
 491 $|\nabla S_x|$ (more than 80%). The fresher side of a front is characterized by shallow MLD,
 492 so the temperature on this side will decrease more than on the saltier side when the
 493 ocean surface loses heat. As a result, there will be colder/fresher water on the one side
 494 and warmer/saltier water on the other side, and they will be compensated. This
 495 cooling-induced compensation has been revealed by Spiro Jaeger and Mahadevan
 496 (2018) and is further validated here.



497

498 **Fig. 10.** Seasonal ratio (%) of compensated (dark color bars) and reinforced fronts

499 (light Scolor bars) in region R1 for (a) surface top 5% of $|\nabla T_x|$, (b) surface top 5% of
500 $|\nabla_x|$, (c) surface top 5% of $|\nabla \rho_x|$. (d-f) are the same as (a-c) but for subsurface.

501

502 At the subsurface, the compensation ratio is also largest in winter, indicating the
503 penetration of cooling-induced compensation to the subsurface. However, the effects
504 of atmospheric flux are apparently reduced in terms of its weaker seasonal variation at
505 subsurface. Moreover, the dominance of compensation over reinforcement at
506 subsurface is present during all seasons. In spring, when the ocean is heated, the
507 surface fronts are less compensated, while the subsurface fronts are almost as
508 compensated as in winter. This enhanced subsurface compensation cannot be
509 explained by the cooling-induced effect. Other factors must be responsible for this
510 phenomenon. In the next subsection, we will briefly explain the subsurface spring
511 compensation.

512

513 *(d) Scale-dependent compensation*

514 The aforementioned compensation effect is actually composed of different spatial
515 scales of compensation. The submesoscale-selective compensation has been revealed
516 in the BoB (Spiro Jaeger and Mahadevan, 2018) and Taiwan Strait (Lin et al., 2023)
517 by using ship-based observations, respectively. Here, we attempt to validate whether
518 this submesoscale selective character is robust in the model data.

519

520 By choosing different horizontal sampling intervals from the model data, we can
521 calculate the tracer gradients at different scales, and compare the results with the
522 model scale of ~ 4 km (central difference, so 2 times of grid space). The time-depth
523 compensation ratio for ~ 4 km and ~ 100 km scales are shown in Figures 11a~11b.
524 Here the compensation ratio is defined as the ratio of the compensated grids over total
525 grids for each day at each depth. In general, the compensation effect is weaker at
526 larger scales. Strong compensation signals ($>70\%$) almost disappear at ~ 100 km at
527 subsurface, suggesting that the compensation effect at subsurface is submesoscale-
528 selective, as pointed out by Spiro Jaeger and Mahadevan (2018).

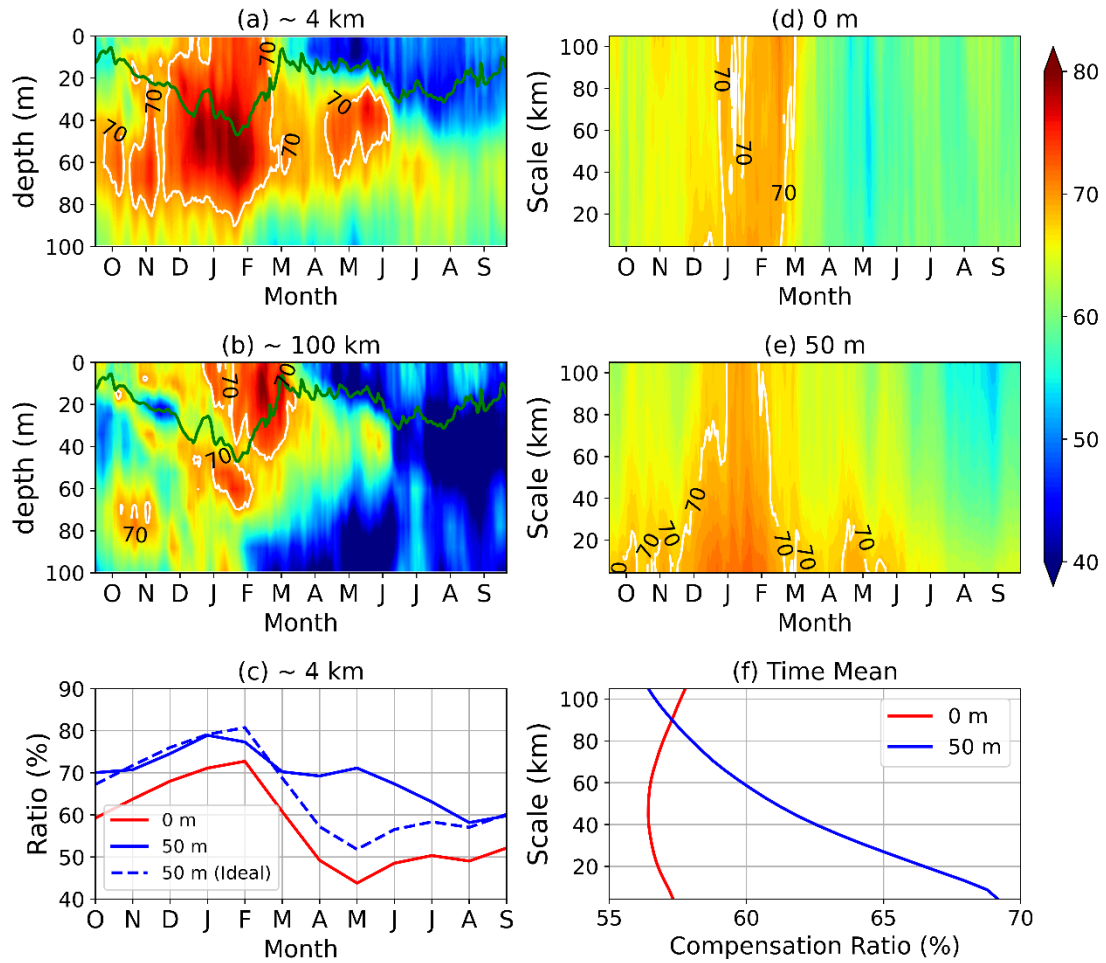
529

530 The compensation effects at surface and subsurface have some similarities. As the
531 surface layer is better mixed by atmospheric turbulence, the surface compensation

532 ratio is in general smaller than that of subsurface (Fig. 11c). The expected subsurface
533 compensation ratio (surface value adds 8%, blue dashed line in Fig. 11c) agrees well
534 with the real value (blue solid line in Fig. 11c), except during spring/early summer
535 which is featured with a rapid shallowing of mixed layer depth. While the surface
536 compensation during spring/early summer is much reduced by surface warming, large
537 value of subsurface compensation still holds because of the block effects of mixed
538 layer base.

539

540 A more accurate analysis between compensation ratio and sample interval is done,
541 and the compensation at subsurface is shown to be very sensitive to the spatial scale
542 all the time (Fig. 11e). During autumn and spring, for example, the grid scale (~4 km)
543 compensation is quite obvious at subsurface, but it gets weaker quickly toward scales
544 larger than 20~40 km. In comparison, at surface the phenomenon that compensation
545 rapidly diminishes toward larger scales only occurs during early winter (Fig. 11d),
546 which is the period of the observational data in Spiro Jaeger and Mahadevan (2018).
547 Large discrepancies of scale dependency of compensation are visible from the annual
548 mean compensation ratios at surface and subsurface (Fig. 11f). It is suggesting that a
549 more detailed observation with a longer time span is needed to verify the robustness
550 of submesoscale-selective compensation at surface.



551

552 **Fig. 11.** Time-depth plots of ratio (%) of compensation in region R1 for spatial scales
 553 of (a) ~4 km and (b) ~100 km. (c) Monthly mean and regional mean time series of
 554 compensation ratio at 0 m (red solid line), 50 m (blue solid line) and expected value at
 555 50 m (blue dashed line) for model grid scale. Compensation ratio as a function of
 556 scale and time at (d) 0 m depth and (e) 50 m depth. (f) Annual mean compensation
 557 ratio for different scales at 0 m (red line) and 50 m (blue line). Green lines in (a) and
 558 (b) show the mixed layer depth. White contours in (a), (b), (d) and (e) show the 70%
 559 compensation ratio.

560

561 6. Stratification induced by compensated fronts

562 (a) Statistical relation

563 As mentioned in Section 3, the barrier layer is thick in winter and thin in spring (Fig.
 564 2), together with the occurrence of subsurface temperature inversion in winter.
 565 Compensated fronts also prevail during winter, as seen in Section 5. Atmospheric
 566 cooling seems to play a dominant role, but oceanic processes are also significant. To

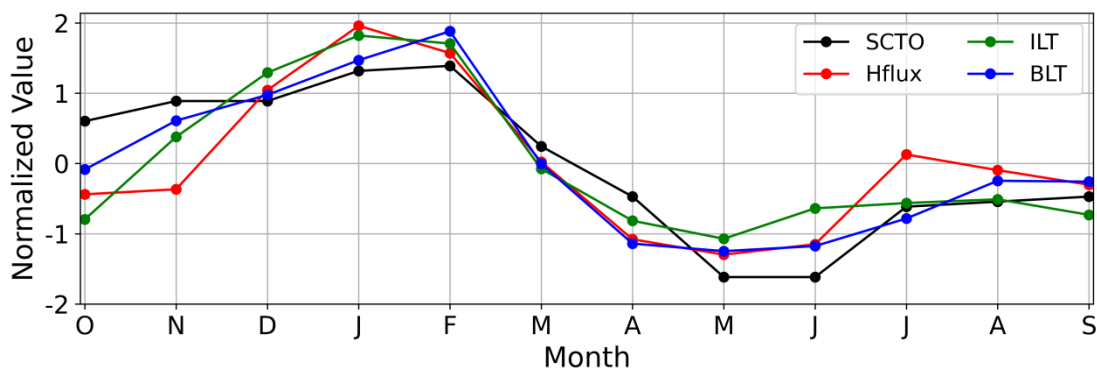
567 illustrate the statistical relationship between atmospheric forcing, oceanic fronts and
 568 vertical stratification, several variables are selected for comparison: a) ratio of
 569 compensation; 2) regional mean barrier layer thickness (BLT); 3) regional mean
 570 inversion layer thickness (ILT, defined as the layer where the vertical temperature
 571 gradient is negative); and 4) regional mean heat flux.

572

573 Here the surface, SCTO, density fronts are chosen as a representation of the
 574 compensation ratio for several seasons. First, SCTO fronts are much more popular
 575 over the nBoB region than TCSO fronts. Second, the density fronts are more
 576 appropriate than salinity/temperature fronts, as density is directly related to the
 577 pressure gradients and thus ocean movement. Last but not least, surface fronts are
 578 characterized by more obvious seasonal variations than subsurface fronts.

579

580 The mutual correlation between all variables is quite good, with all peaks in winter
 581 and troughs in late spring/summer (Fig. 12). The ocean loses heat during winter and
 582 gains heat during late spring and summer. Under the condition of horizontal salinity
 583 gradients, compensated fronts are most prominent in winter due to the cooling-
 584 induced compensation effect. Meanwhile, the cooling effect forms a deeper
 585 thermocline than the halocline and creates a thick barrier layer. The barrier layer can
 586 limit the winter cooling to the shallow surface layer, and warm water can be trapped
 587 in the subsurface layer, creating a temperature inversion.



588

589 **Fig. 12.** Time series of ratio of SCTO (black), regional average heat flux (red), ILT
 590 (green) and BLT (blue) over region R1. All values are normalized by their mean
 591 values and standard deviations.

592

593 Numerical studies have shown that temperature inversions can also form when the

594 compensated fronts collapse (Spiro Jaeger and Mahadevan, 2018; Pham and Sarkar et
595 al., 2019; Ramachandran and Tandon, 2020). Thus, in addition to the atmospheric
596 cooling effect, oceanic frontal dynamics may also be responsible for the vertical
597 stratification in frontal regions. Considering that there are four types of fronts (TCSR,
598 SCTR, SCTO and TCSO), the resulting stratification may be quite different for
599 different fronts. To illustrate the specific frontal processes for different fronts,
600 idealized frontal experiments are conducted in the next section.

601

602 *(b) Idealized numerical model*

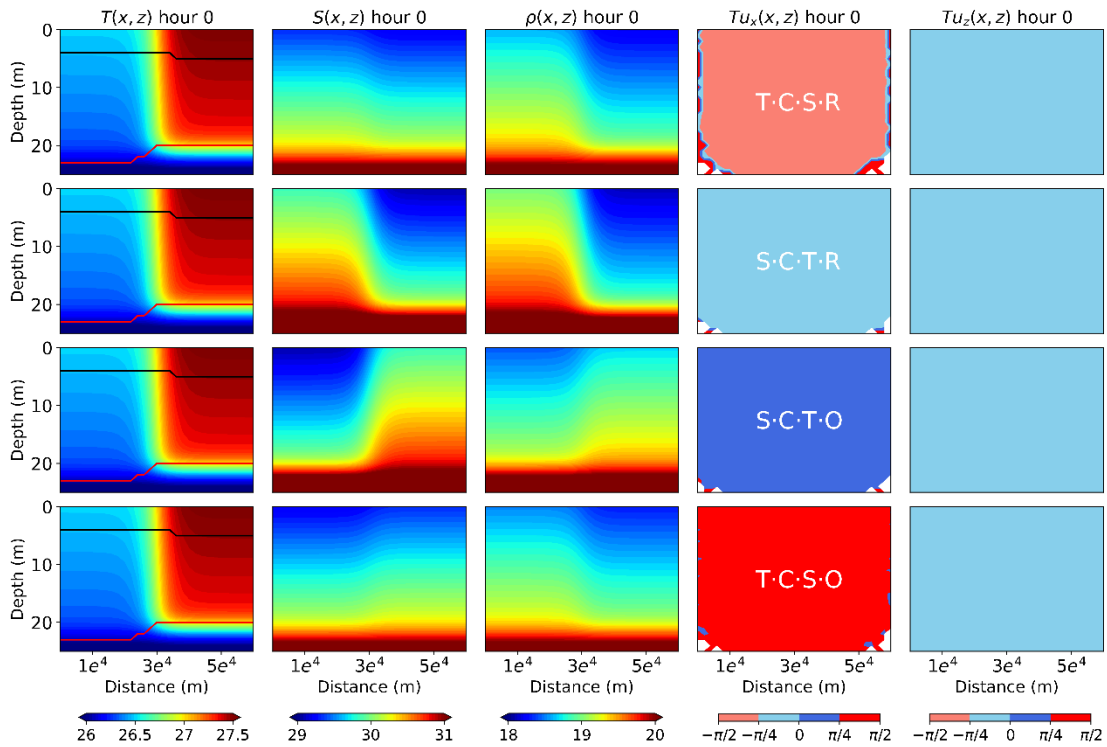
603 In this subsection, four sets of frontal experiments with different types of fronts using
604 CROCO are conducted, and the model setups are described in Section 2. The models
605 are run for 2.5 days, and the initial state and final states are selected for comparison.

606

607 Regardless of the frontal type, the isopycnals are tilted (third column in Fig. 13), so
608 the fronts will slump due to the gravitational effect. The frontal types are indicated by
609 the initial values of Tu_x (fourth column in Fig. 13). The values of the Turner angle in
610 the vertical direction (Tu_z) are also shown (last column in Fig. 13). Tu_z is calculated
611 by:

$$612 \quad Tu_z = \arctan(-\nabla T_z / \nabla S_z) \quad (6.1)$$

613 It represents the effects of vertical compensation/reinforcement. In the initial state, the
614 warm/fresh water is in the surface and the cold/salty water is in the subsurface, so Tu_z
615 is negative everywhere (reinforcement).



616

617 **Fig. 13.** The cross front temperature (first column), salinity (second column), density
 618 (third column), Tu_x (fourth column) and Tu_z (last column) for TCSR front (first row),
 619 SCTR front (second row), SCTO front (third row), and TCSO front (last row) of the
 620 initial state. Black lines represent the MLD and red lines represent the ILD. The layer
 621 in between is the barrier layer.

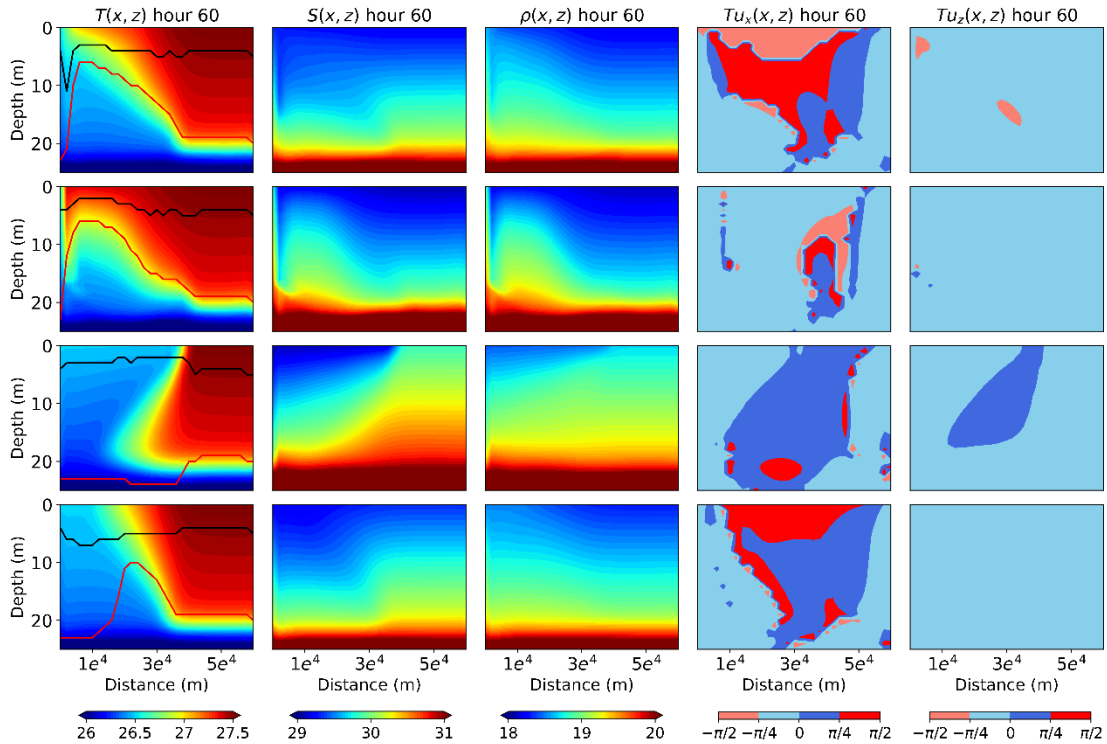
622

623 The final state after 2.5 days of running is shown in Figure 14. As the lighter waters
 624 are located on the right side of the TCSR, SCTR and TCSO fronts (third column in
 625 Fig. 13), they all tend to slump to the left, and the warm water tends to rise above the
 626 cold water (first column in Fig. 14). No temperature inversion is formed and the
 627 barrier layer is reduced more or less by the slump of the isotherms. The values of Tu_z
 628 remain negative for these three fronts (last column in Fig. 14).

629

630 The evolution of the SCTO front is quite different from other fronts (third row in Fig.
 631 14). In this case, the lighter waters are on the left side of the front. When the front
 632 slumps, the fresh waters tend to be above the salty waters, but the warm waters tend to
 633 be below the cold waters due to the tilt of the isotherms. Also, the ILD remains deep,
 634 so the barrier layer remains thick. The values of Tu_z become positive around the
 635 temperature inversion region, indicating the vertical compensation effect. These

636 results may help to further explain why SCTO fronts and temperature inversion layers
 637 / barrier layer are collocated.



638
 639 **Fig. 14.** The same as Fig. 13, but after 2.5 days of model running.

640

641 7. Discussion and conclusions

642 In this study, we used high-resolution model output (LLC4320) to investigate the
 643 characteristics of compensated/reinforced submesoscale fronts in the northern BoB.
 644 The model is shown to describe the main temperature and salinity features in the
 645 study region realistically. Large surface horizontal temperature, salinity and density
 646 gradients occur over the northern bay, with salinity/density gradients nearly 3 times
 647 larger than temperature gradients. At subsurface, temperature gradients are apparently
 648 increased compared to that at surface, while density gradients are much reduced due
 649 to the increasing counteracting effect between temperature and salinity.

650

651 Probability density functions of gradients tend to flatten at magnitudes of the largest 5%
 652 of each gradient, and regions where gradients larger than these thresholds are
 653 considered as submesoscale frontal regions. The roles of compensation and
 654 reinforcement across fronts are quantified using the Turner angle. Based on the value
 655 of the Turner angle, submesoscale fronts are classified into 4 types: SCTO (salinity-

656 controlled fronts compensated by temperature), SCTR (salinity-controlled fronts
657 reinforced by temperature), TCSO (temperature-controlled fronts compensated by
658 salinity), and TCSR (temperature-controlled fronts reinforced by salinity).

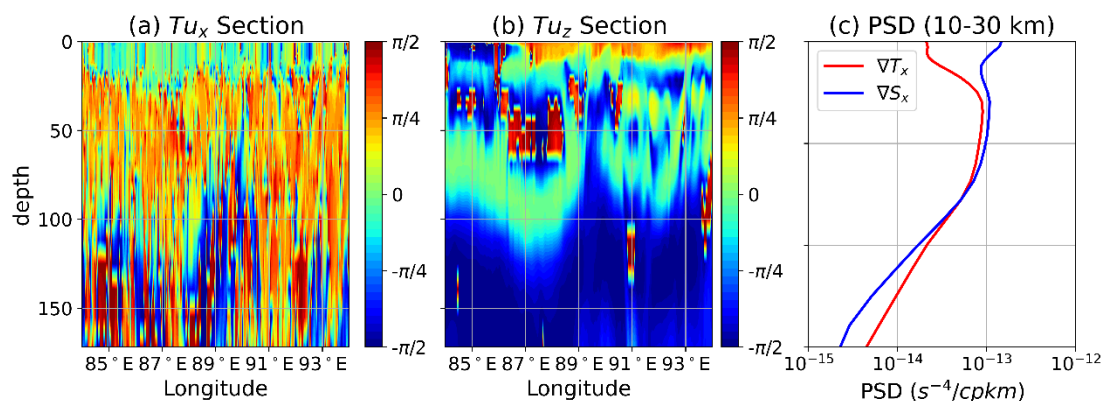
659

660 The statistics of different types of fronts are analyzed. Surface fronts are mostly
661 controlled by salinity and partly compensated by temperature, while subsurface fronts
662 are controlled by both temperature and salinity and tend to be fully compensated.
663 Seasonal variations for surface fronts are more pronounced than for subsurface fronts,
664 with SCTO fronts being most pronounced in winter, due to the combined effects of
665 the existence of strong salinity fronts and heat losses of the ocean. The subsurface
666 layer has more compensation than the surface layer, and the submesoscale-selective
667 compensation is proved by choosing different horizontal sampling intervals. The
668 SCTO fronts are suggested to be closely related to the vertical barrier layer and
669 temperature inversion, and this is further confirmed by idealized models. The
670 intermittent appearance of the temperature inversion layer and the barrier layer in the
671 BoB region may be related to the formation and dissolution of compensated
672 submesoscale fronts.

673

674 The subsurface compensation is shown to be an inherent feature in the ocean. When
675 the idealized fronts (Section 6) slumps, a lot of compensation signals occur at
676 subsurface (5-15 m in this case) for different types of fronts. Zonal sections of Tu_x
677 and Tu_z from LLC4320 for a typical spring day are shown in Figure 15. Positive Tu_x
678 are mostly confined at subsurface (compensation), while negative Tu_z are dominated
679 except at surface layer in order to stay vertical stable. At subsurface, Tu_z is combined
680 with positive values (compensation) and small negative values (weak reinforcement).
681 Under a small disturbance, the vertical weak reinforcement is easy to change its sign
682 to compensation, and the vertical compensation can easily convert to horizontal
683 compensation when the isopycnals tilt. At surface, although large vertical
684 compensation exists, the surface wind stirs and homogenizes this layer, so
685 compensation is less prevailing. This subsurface layer is the so called pycnocline by
686 Spiro Jaeger et al. (2020), which is featured with most remarkable spice variation, and
687 can be proved from the submesoscale (10-30 km) power spectrum density (PSD) for
688 ∇T_x and ∇S_x (Fig. 15c). This can help to explain why subsurface compensation is

689 much more pronounced and more submesoscale-selective than surface.



690

691 **Fig. 15.** Zonal section of (a) Tu_x and (b) Tu_z from LLC4320 for a typical spring day.

692 (c) Annual mean and regional averaged power spectrum density (PSD) of ∇T_x and ∇S_x
693 at submesoscale range (10-30 km) in logarithmic scale.

694

695 A front is either compensated or reinforced. Compensated fronts are characterized
696 with a density gradient at least smaller than either temperature gradient or salinity
697 gradient, while reinforced fronts are featured with larger density gradient than both
698 temperature and salinity gradient. Compensated fronts with smaller density gradients
699 are thus not favorable for frontal instability and associated energy transfer and
700 transformation compared to reinforced fronts. In an ideal ocean without any forcing,
701 temperature and salinity always tend to be fully compensated in order to get a
702 completely stable state. But in the real ocean, this is never the truth thanks to the
703 omnipresent disturbance.

704

705 There are still some limitations of the model data. For example, the temporal
706 frequency and the way to include river run-off in the model may impact the
707 submesoscale fronts, especially the coastal regions close to the river mouth. The
708 model is using climatological river discharge and converting it to freshwater flux, and
709 the season variation of river discharge is not included. As a result, the model
710 overestimates freshwater in spring and underestimates freshwater in autumn.
711 Additionally, converting river freshwater into surface flux may omit the river
712 diffusion processes, which could generate some small scale processes. The
713 submesoscale salinity fronts captured by the model may be underestimated. A real
714 river forcing with relative high frequency is needed to better understand the

715 submesoscale frontal dynamics around the river mouth.

716

717

718

719

720 *Acknowledgments*

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722 (42276014, 42276189, 41876002), Science and Technology Planning Project of
723 Guangdong Province, China (Grant No. 2022B1212050003), and supported by High
724 Performance Computing Platform, Hohai University.

725

726 **Open Research**

727 *Data Availability Statement*

728 The authors declare that the data supporting the findings of this study are available
729 within the article and the multisource data used in this study can all be found online.
730 The LLC4320 model output used for analysis can be directly accessed from the
731 ECCO Data Portal via https://data.nas.nasa.gov/ecco/eccodata/llc_4320/ (Menemenlis
732 et al., 2008). The WOA18 climatological temperature and salinity data used for model
733 validation are available at <https://www.ncei.noaa.gov/products/world-ocean-atlas>
734 (Locarnini et al., 2018; Zweng et al., 2018). Sea surface salinity data from SMOS L4
735 used for model validation are available at [https://data.catds.fr/cecos-](https://data.catds.fr/cecos-locean/Ocean_products/SSS_SMOS-SMAP_OI_L4/)
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741 model outputs for different types of fronts are available at
742 <https://doi.org/10.5281/zenodo.13235434>. Figures were made with Matplotlib version
743 3.9.0 at <https://doi.org/10.5281/zenodo.11201097> and available under the Matplotlib
744 license at <https://matplotlib.org/> (Hunter, 2007).

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Figure 01.

Model SST

GHRSSST SST

Model SSS

SMOS SSS

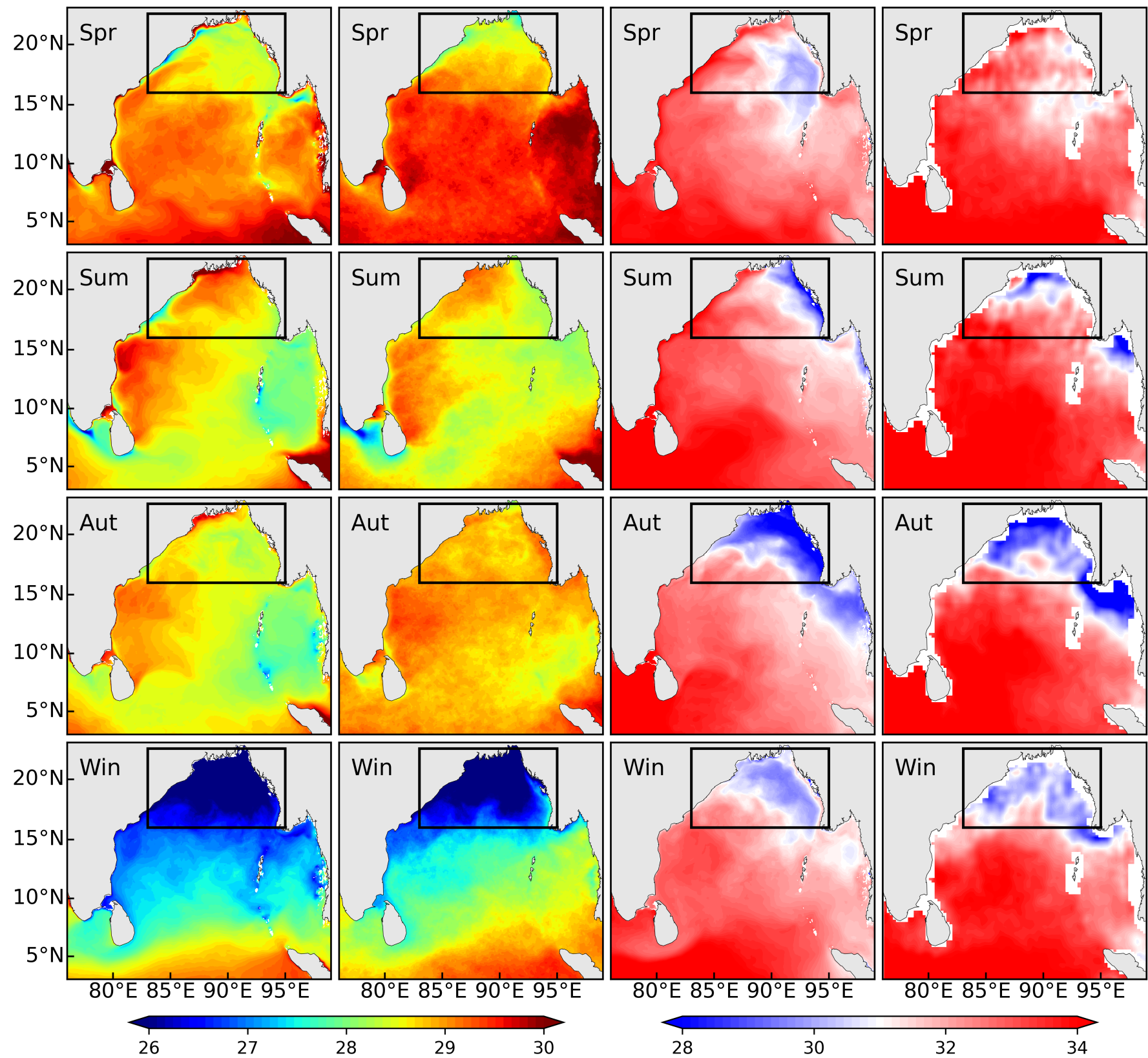
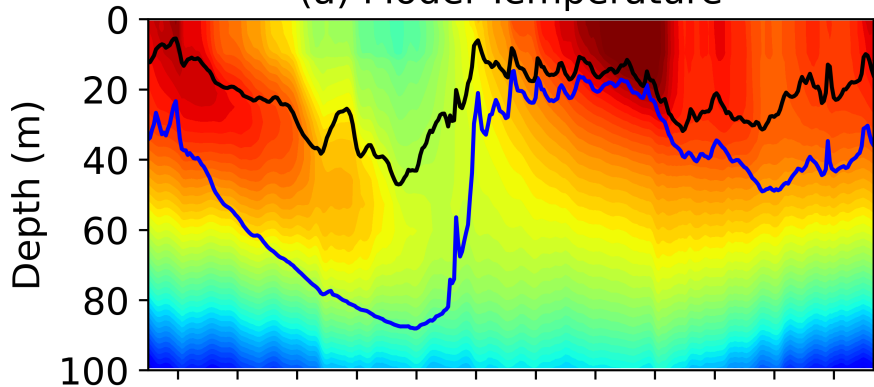
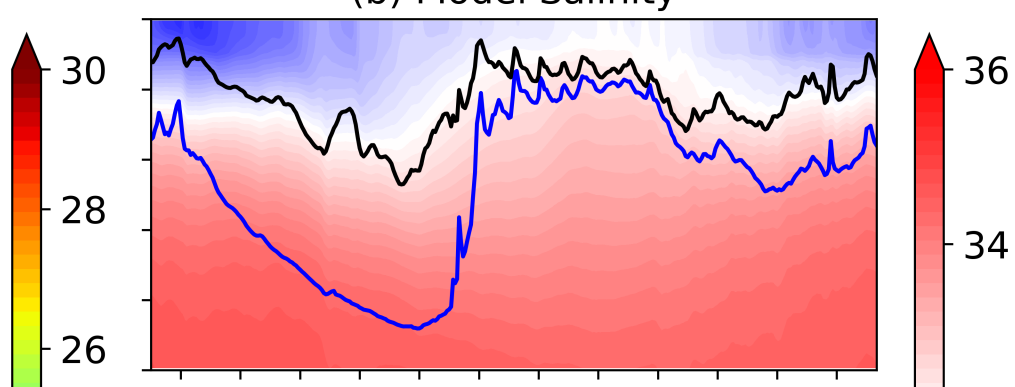


Figure 02.

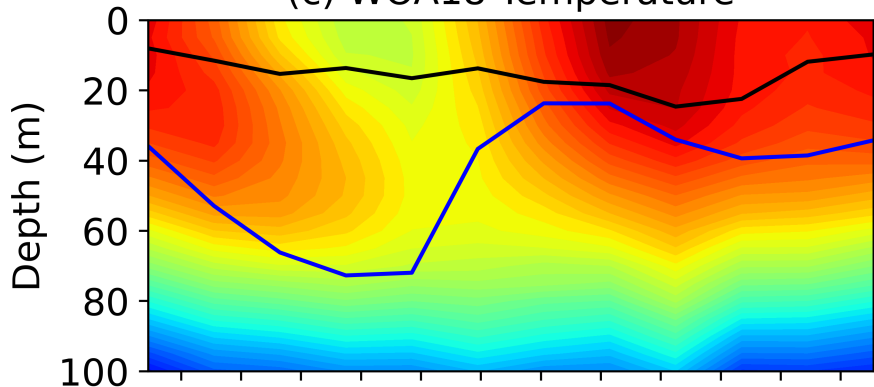
(a) Model Temperature



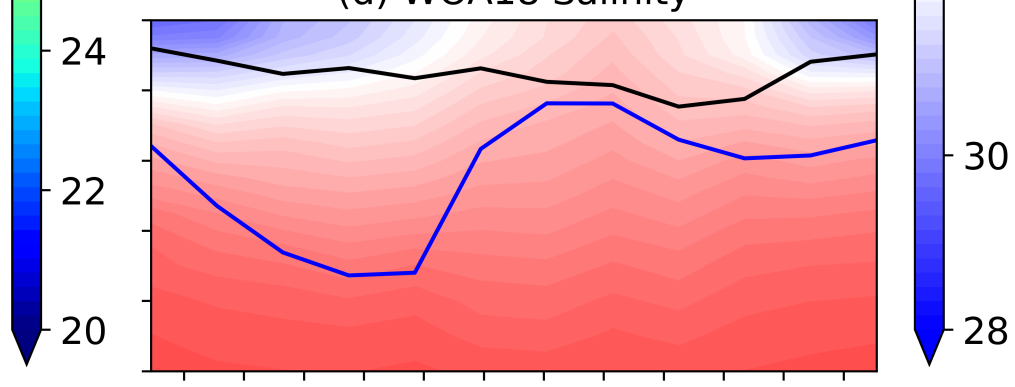
(b) Model Salinity



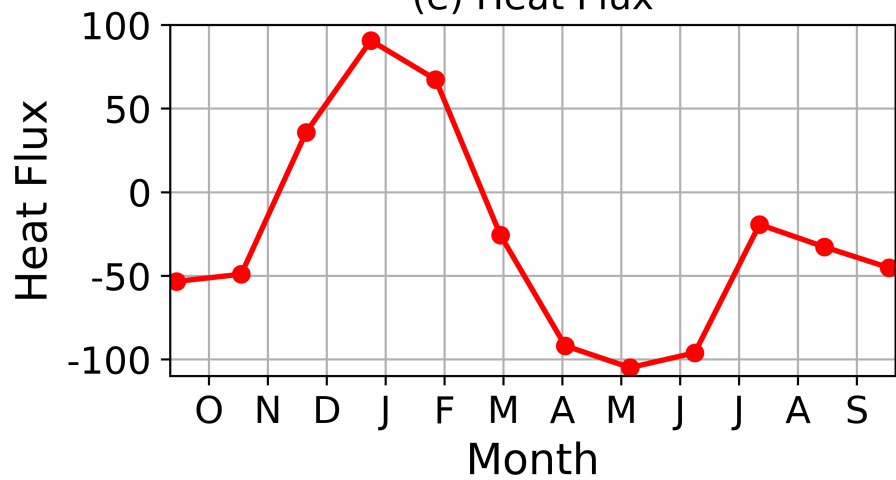
(c) WOA18 Temperature



(d) WOA18 Salinity



(e) Heat Flux



(f) Freshwater Flux

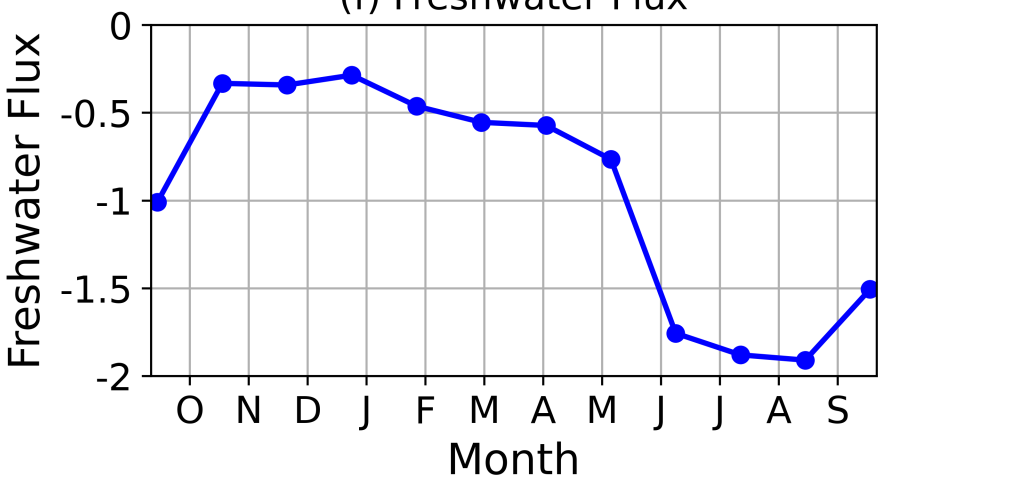


Figure 03.

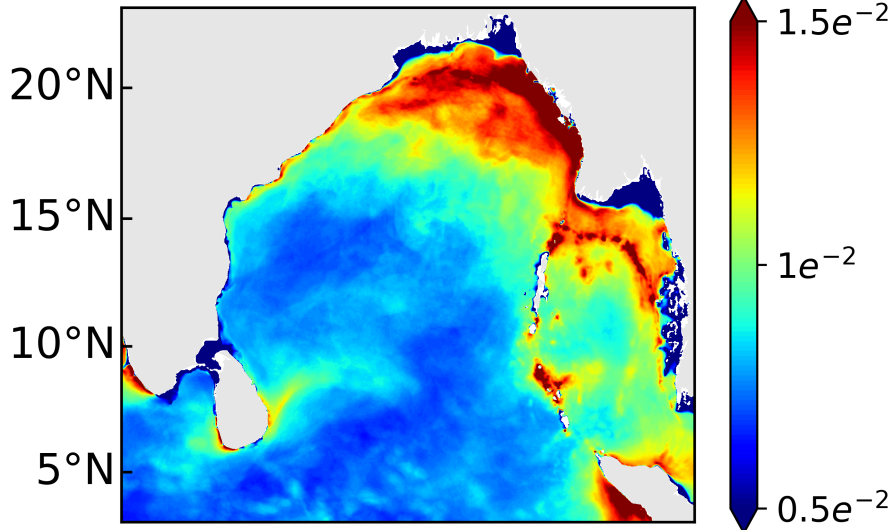
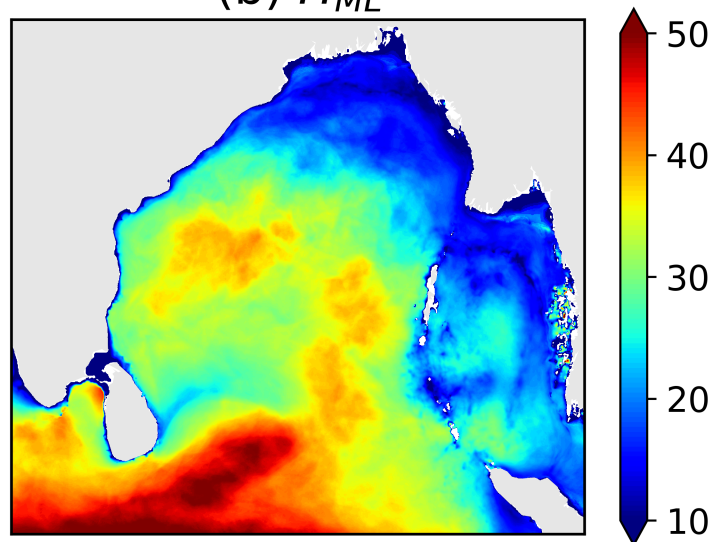
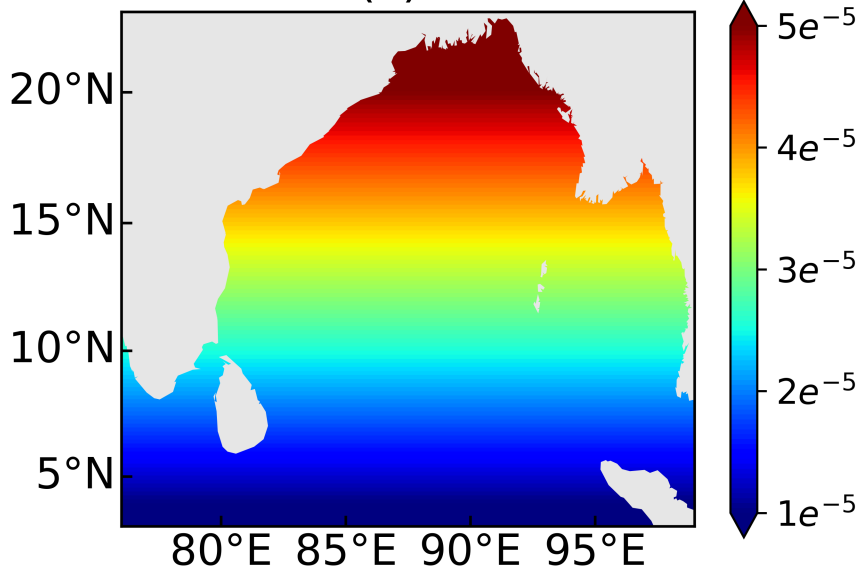
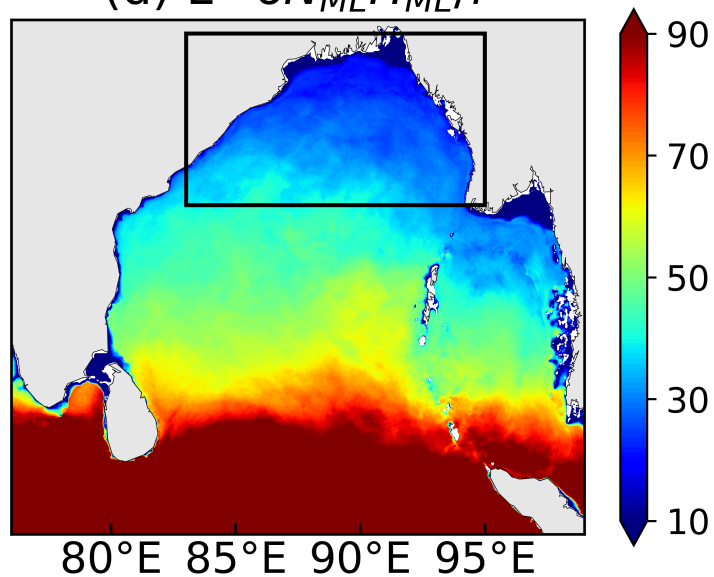
(a) N_{ML} (b) H_{ML} (c) f (d) $L=6N_{ML}H_{ML}/f$ 

Figure 04.

(a) MODIS

(b) LLC4320

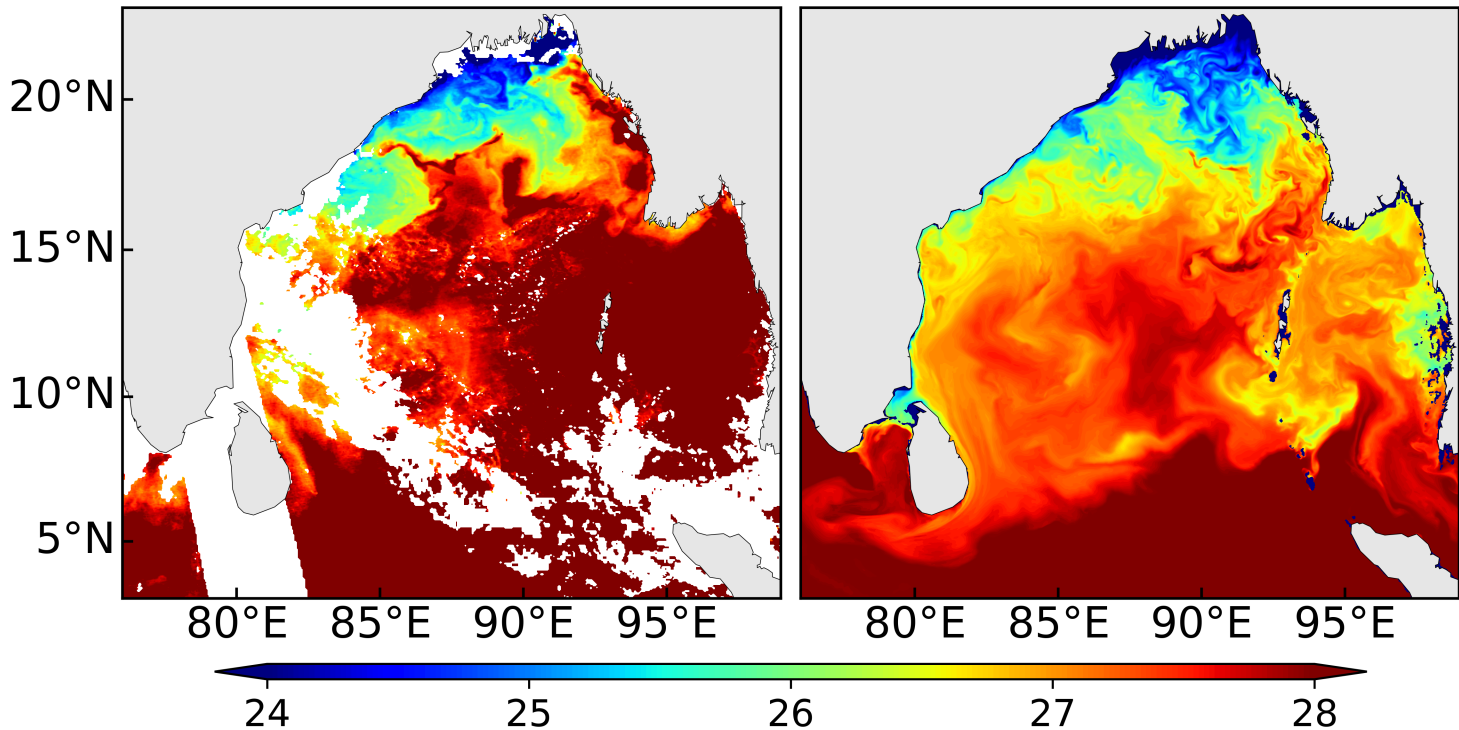
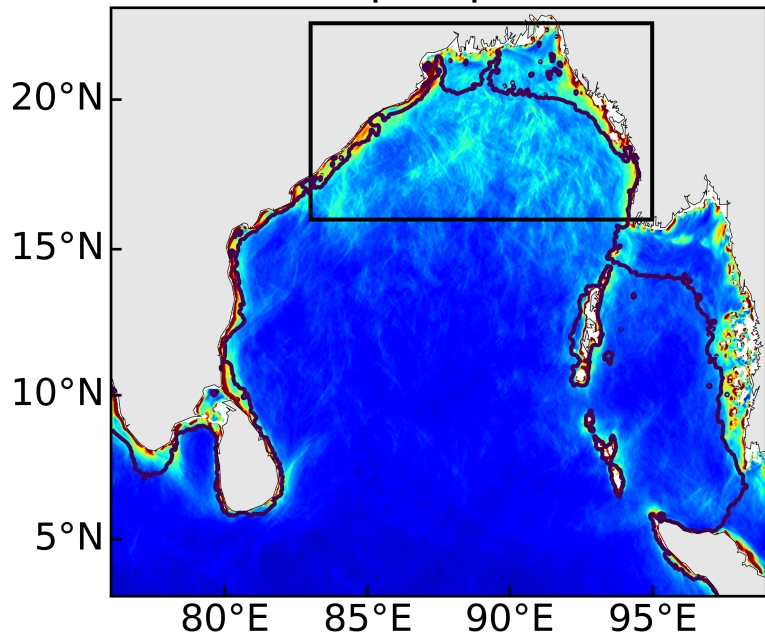
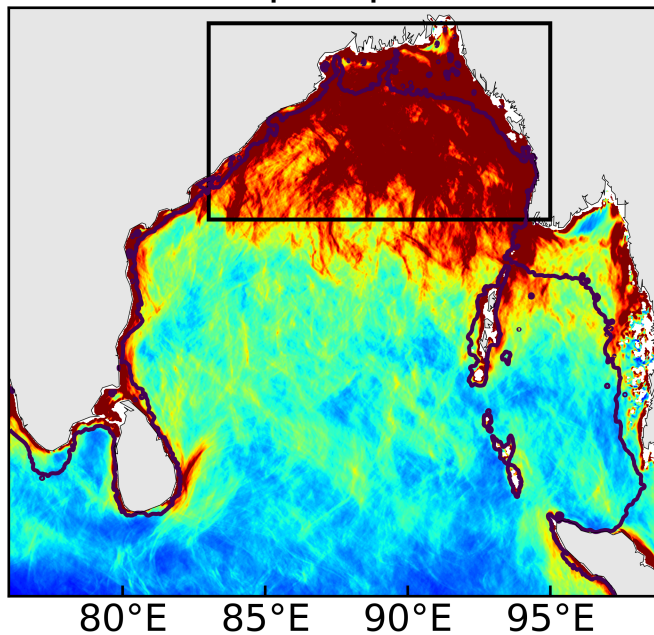


Figure 05.

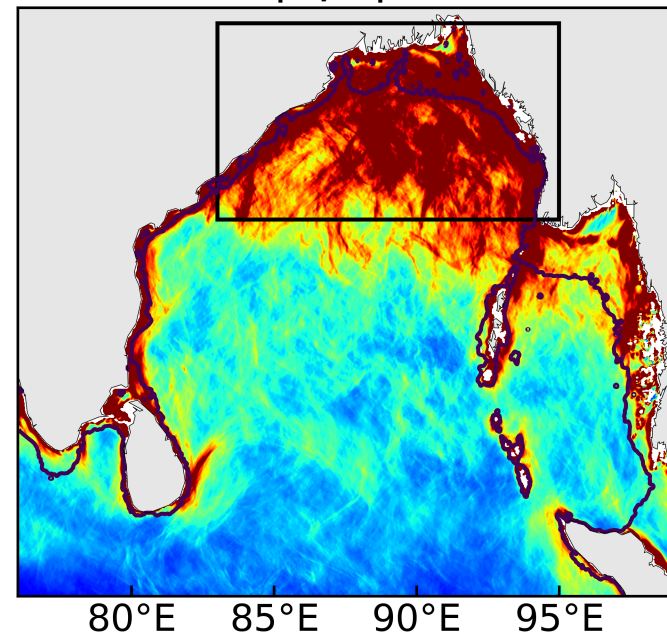
(a) 0m $|\nabla T_x|$ ($\times 10^{-7}$)



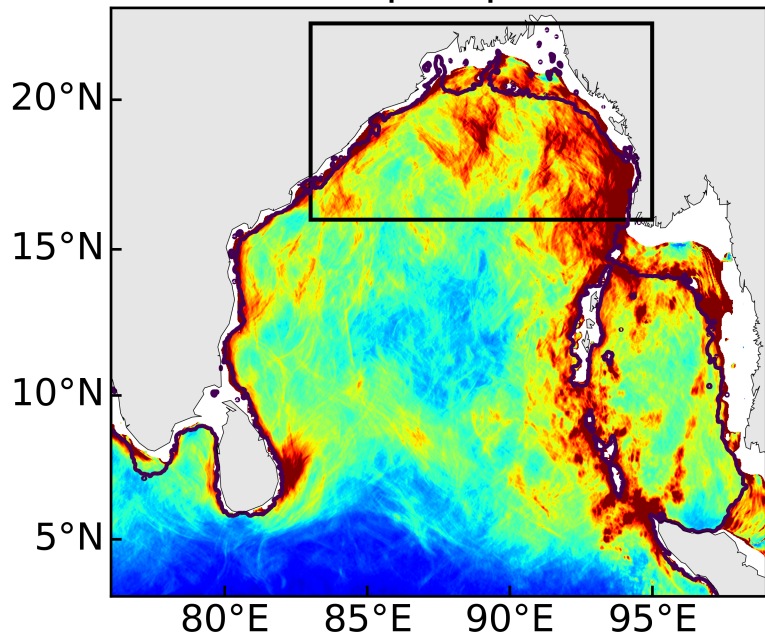
(b) 0m $|\nabla S_x|$ ($\times 10^{-7}$)



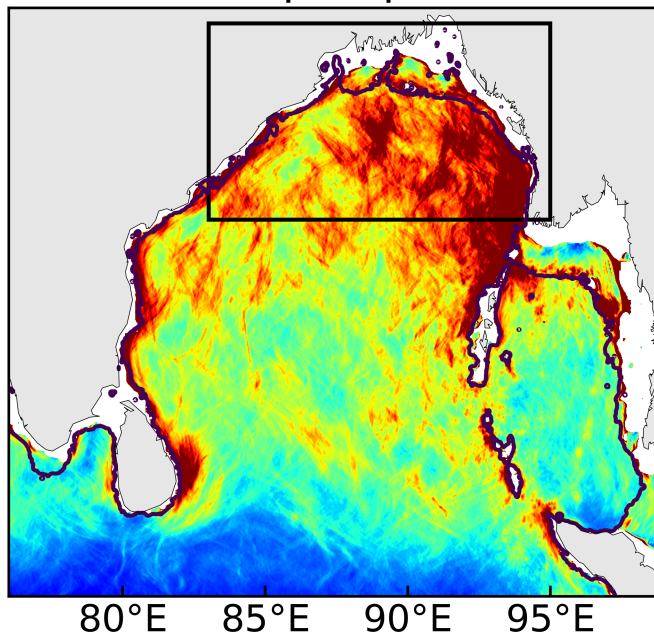
(c) 0m $|\nabla \rho_x|$ ($\times 10^{-7}$)



(d) 50m $|\nabla T_x|$ ($\times 10^{-7}$)



(e) 50m $|\nabla S_x|$ ($\times 10^{-7}$)



(f) 50m $|\nabla \rho_x|$ ($\times 10^{-7}$)

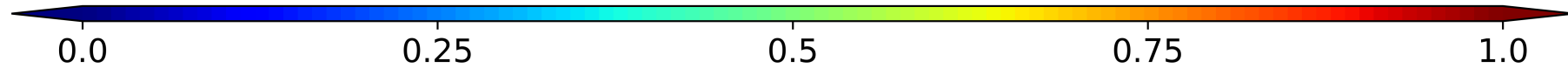
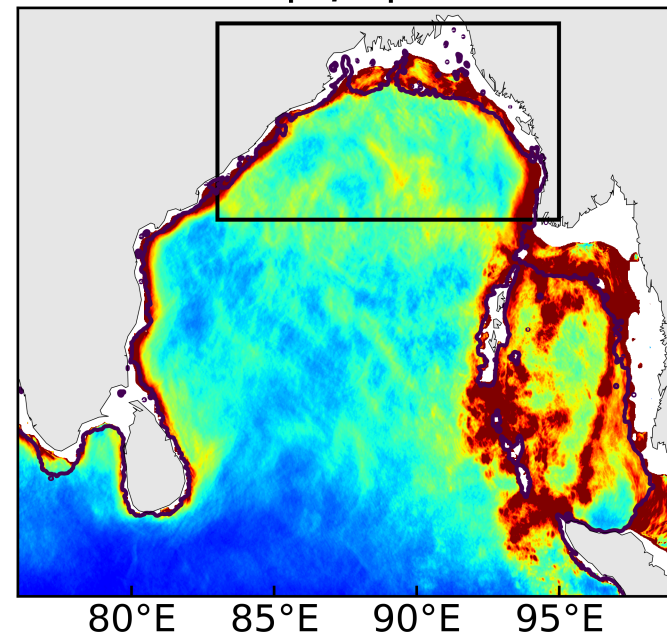


Figure 06.

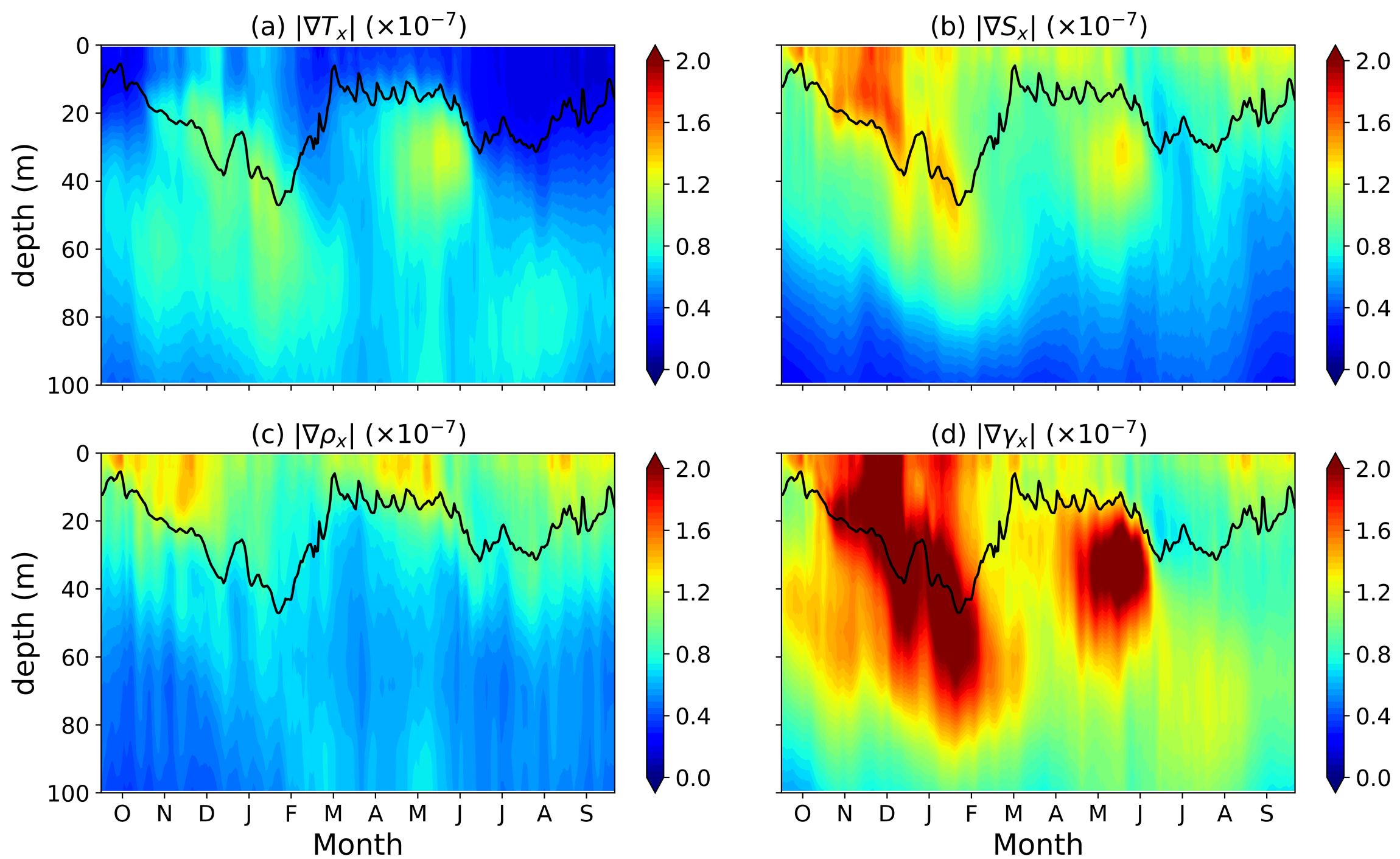


Figure 07.

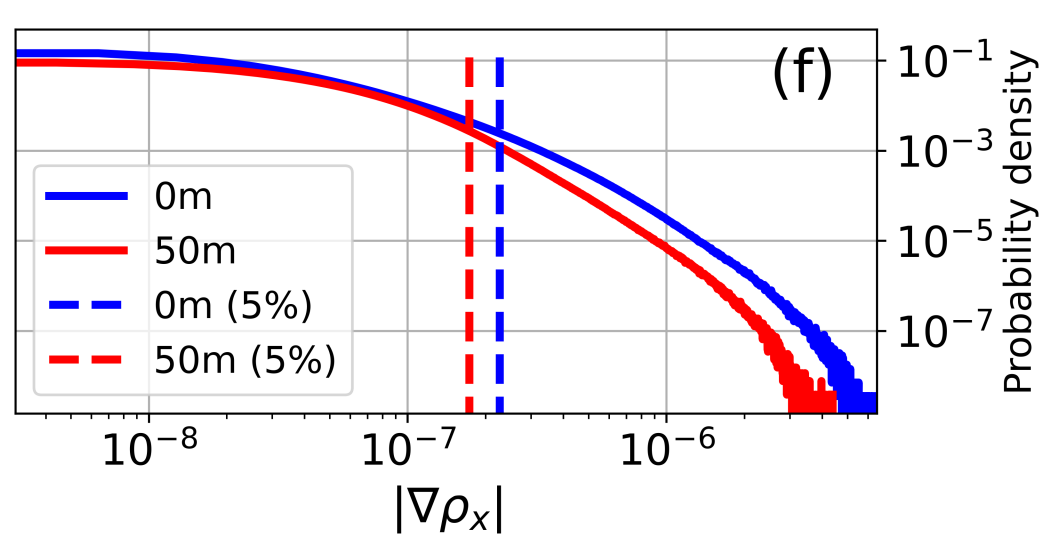
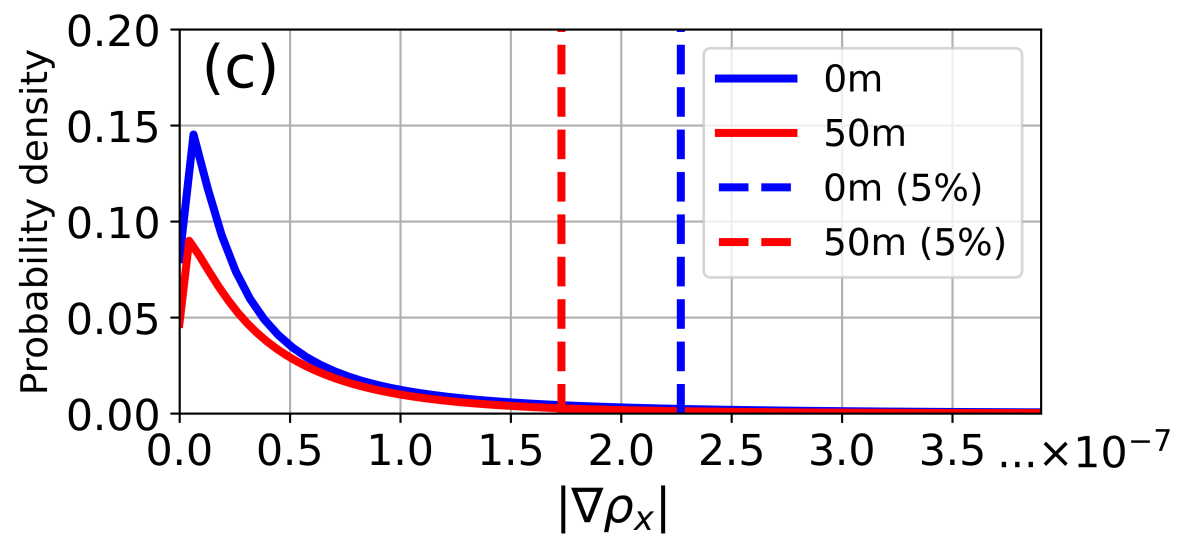
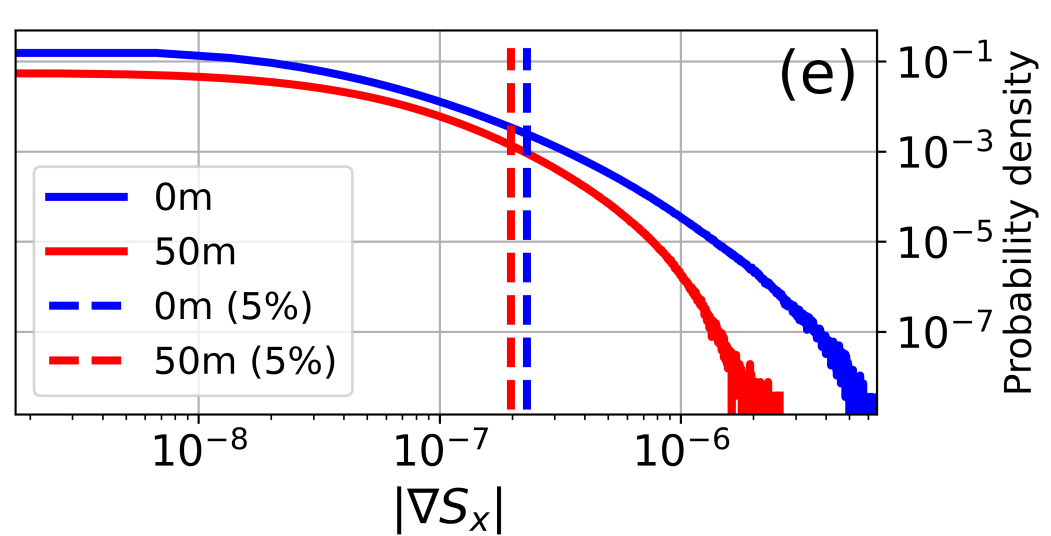
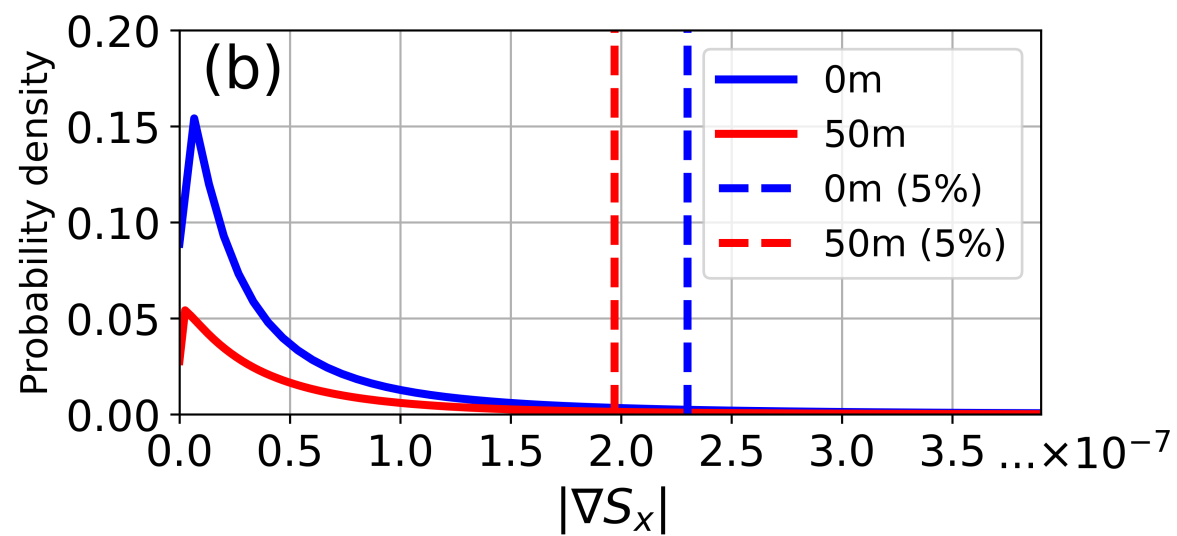
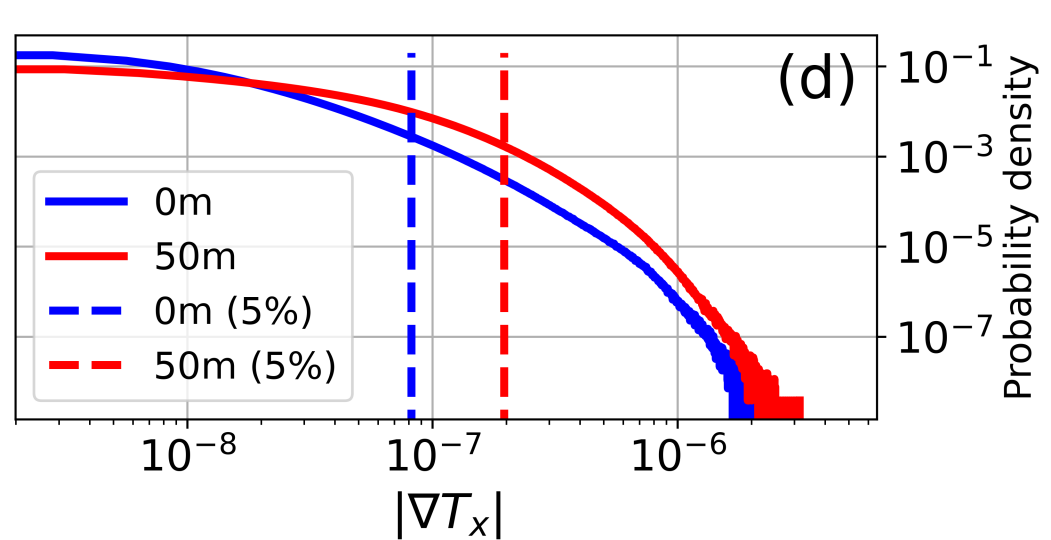
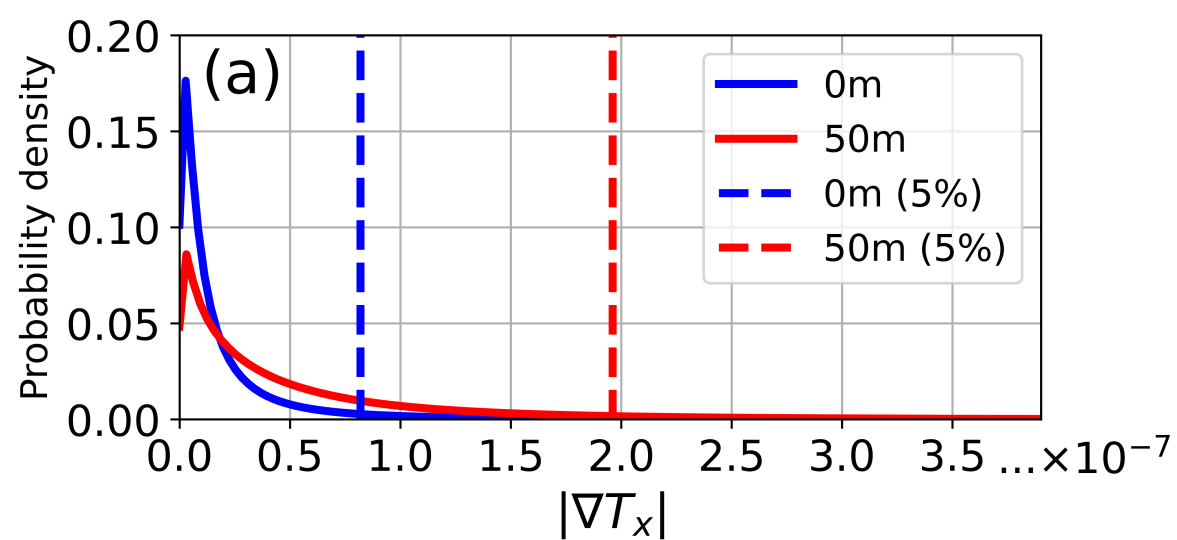
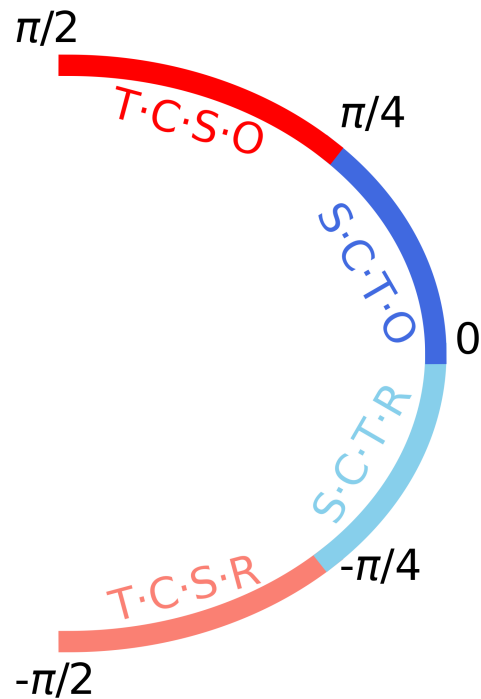
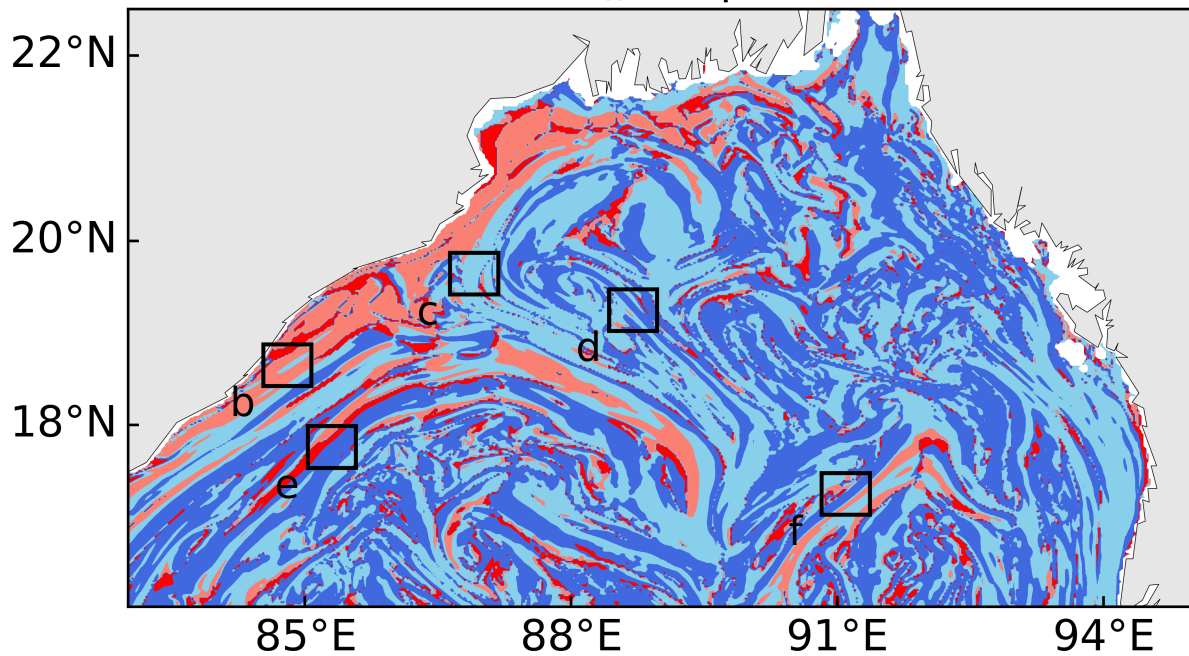
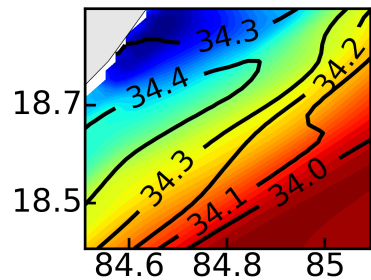


Figure 08.

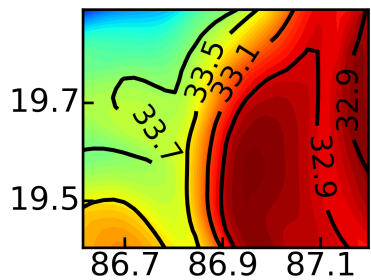
(a) Tu_x Snapshot



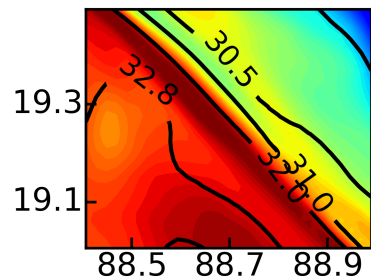
(b) T·C·S·R



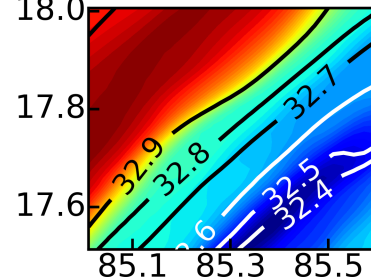
(c) S·C·T·R



(d) S·C·T·O



(e) T·C·S·O



(f) Filament

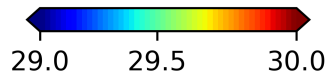
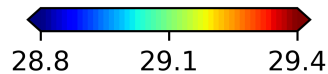
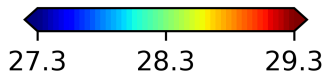
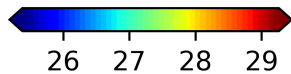
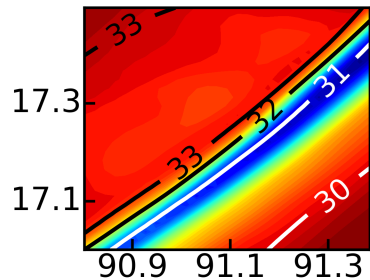


Figure 09.

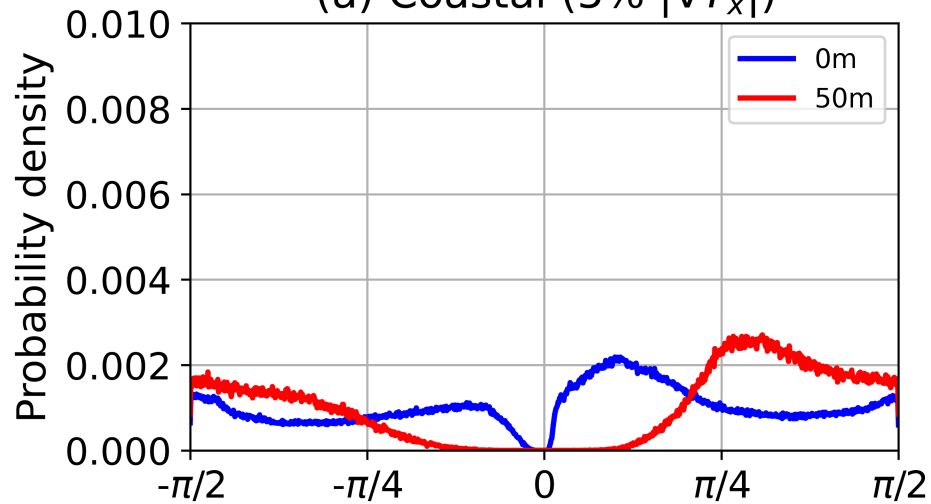
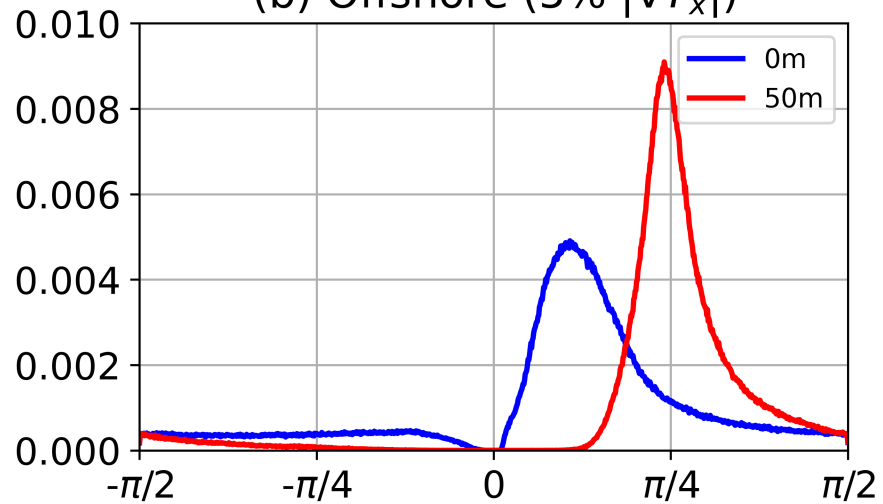
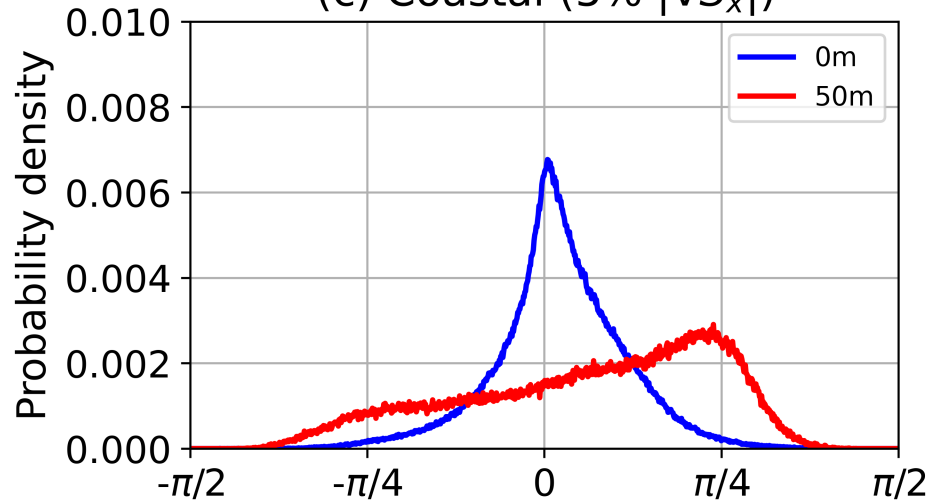
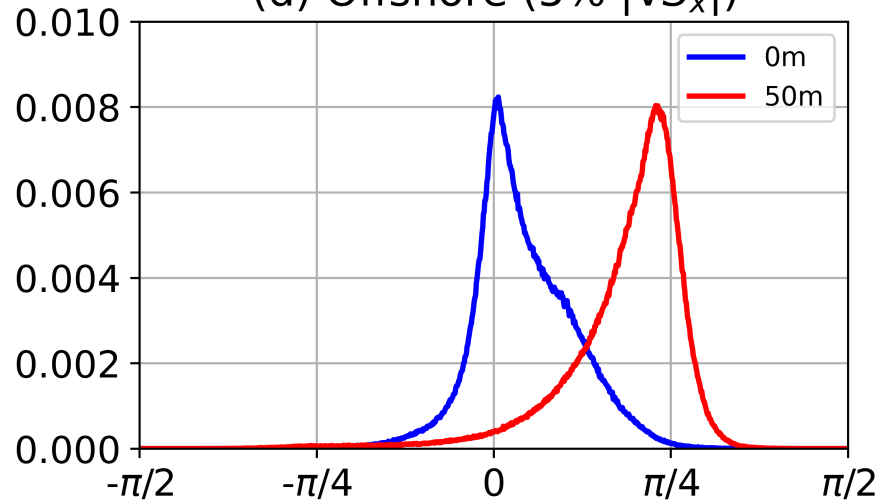
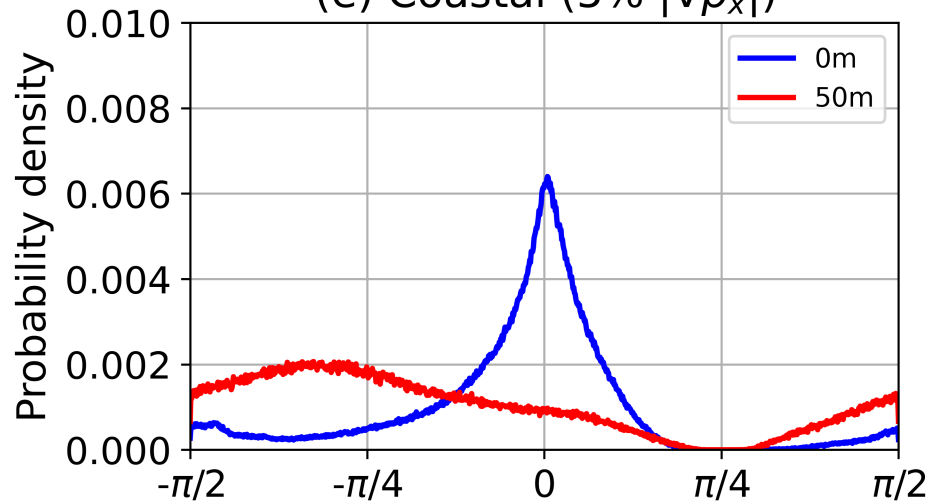
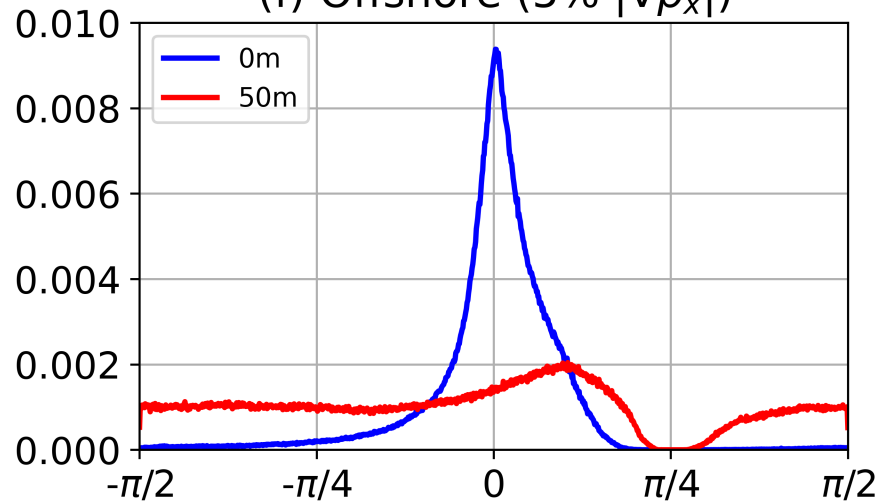
(a) Coastal (5% $|\nabla T_x|$)(b) Offshore (5% $|\nabla T_x|$)(c) Coastal (5% $|\nabla S_x|$)(d) Offshore (5% $|\nabla S_x|$)(e) Coastal (5% $|\nabla \rho_x|$)(f) Offshore (5% $|\nabla \rho_x|$) Tu_x Tu_x

Figure 10.

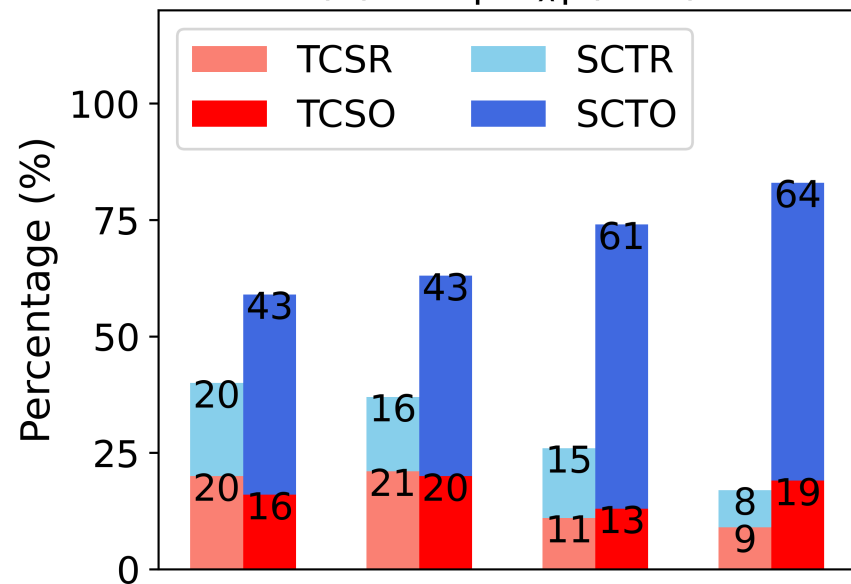
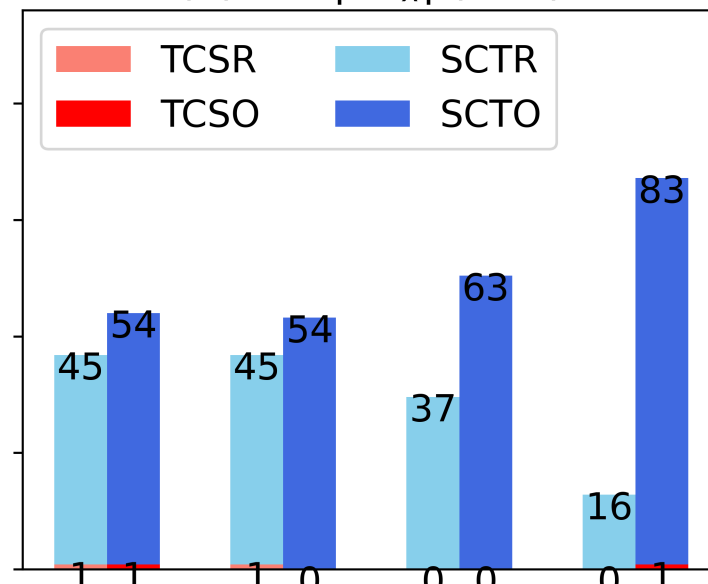
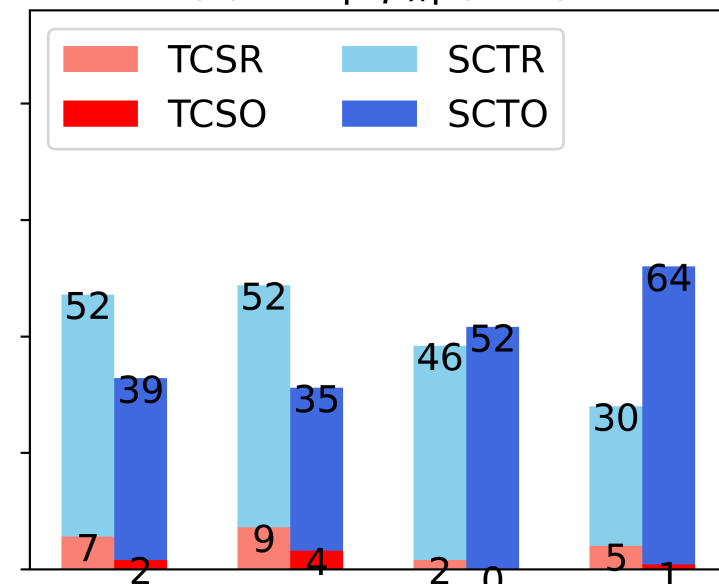
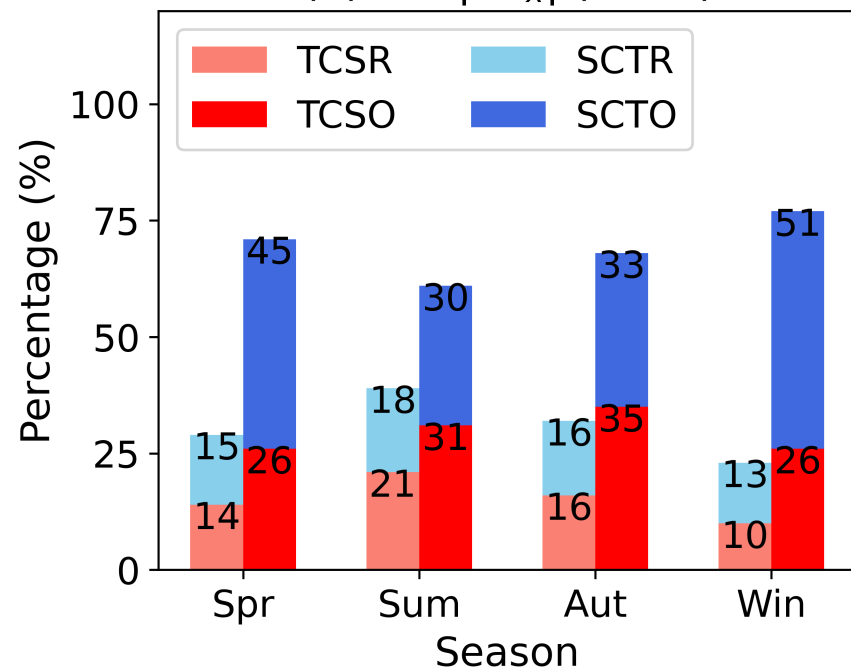
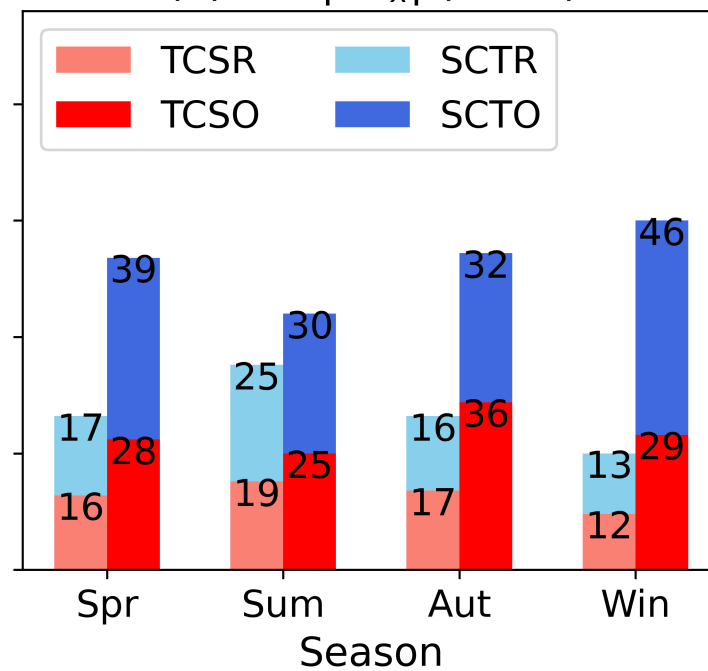
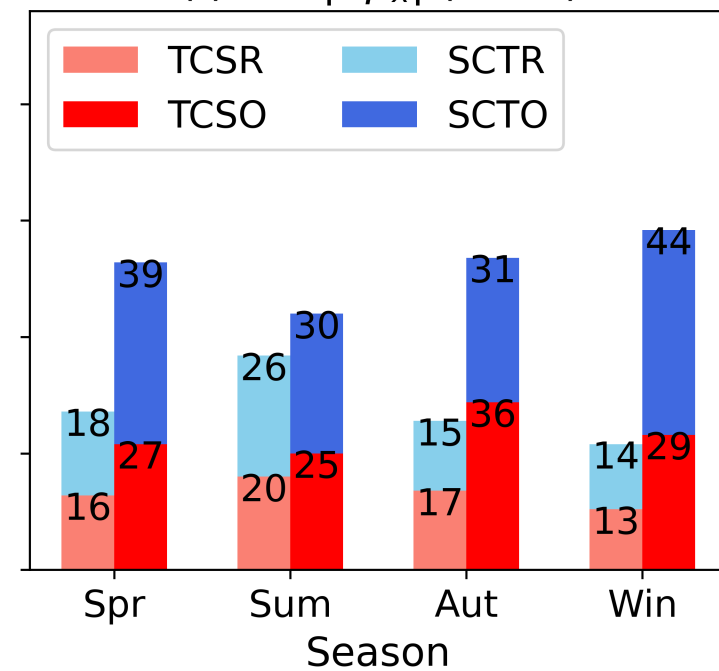
(a) 5% $|\nabla T_x|$ (0 m)(b) 5% $|\nabla S_x|$ (0 m)(c) 5% $|\nabla \rho_x|$ (0 m)(d) 5% $|\nabla T_x|$ (50 m)(e) 5% $|\nabla S_x|$ (50 m)(f) 5% $|\nabla \rho_x|$ (50 m)

Figure 11.

Figure 12.

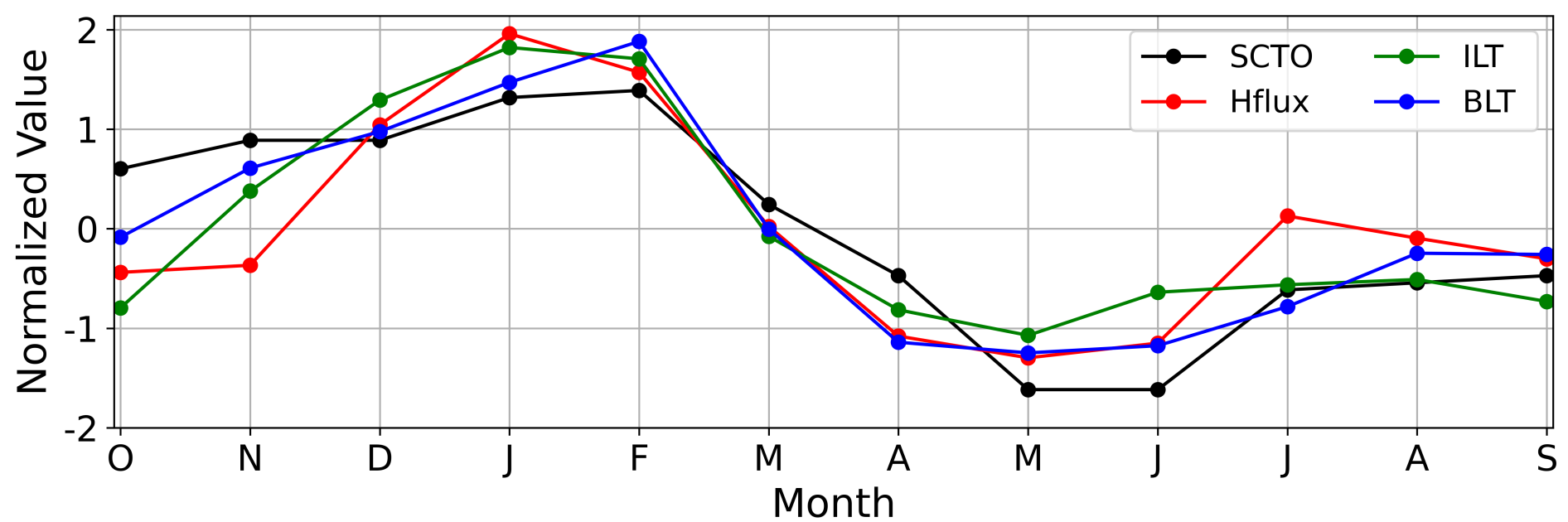


Figure 13.

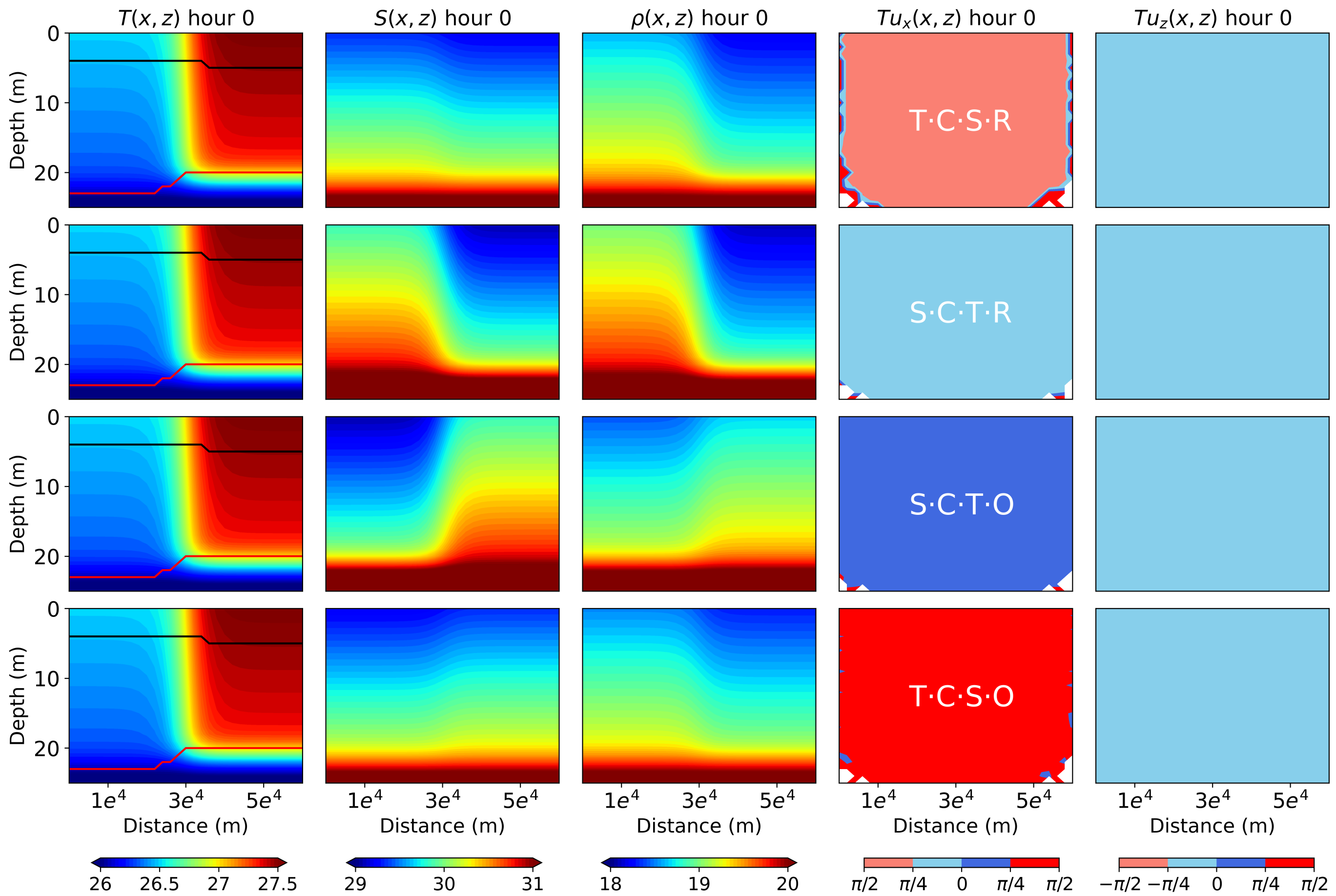


Figure 14.

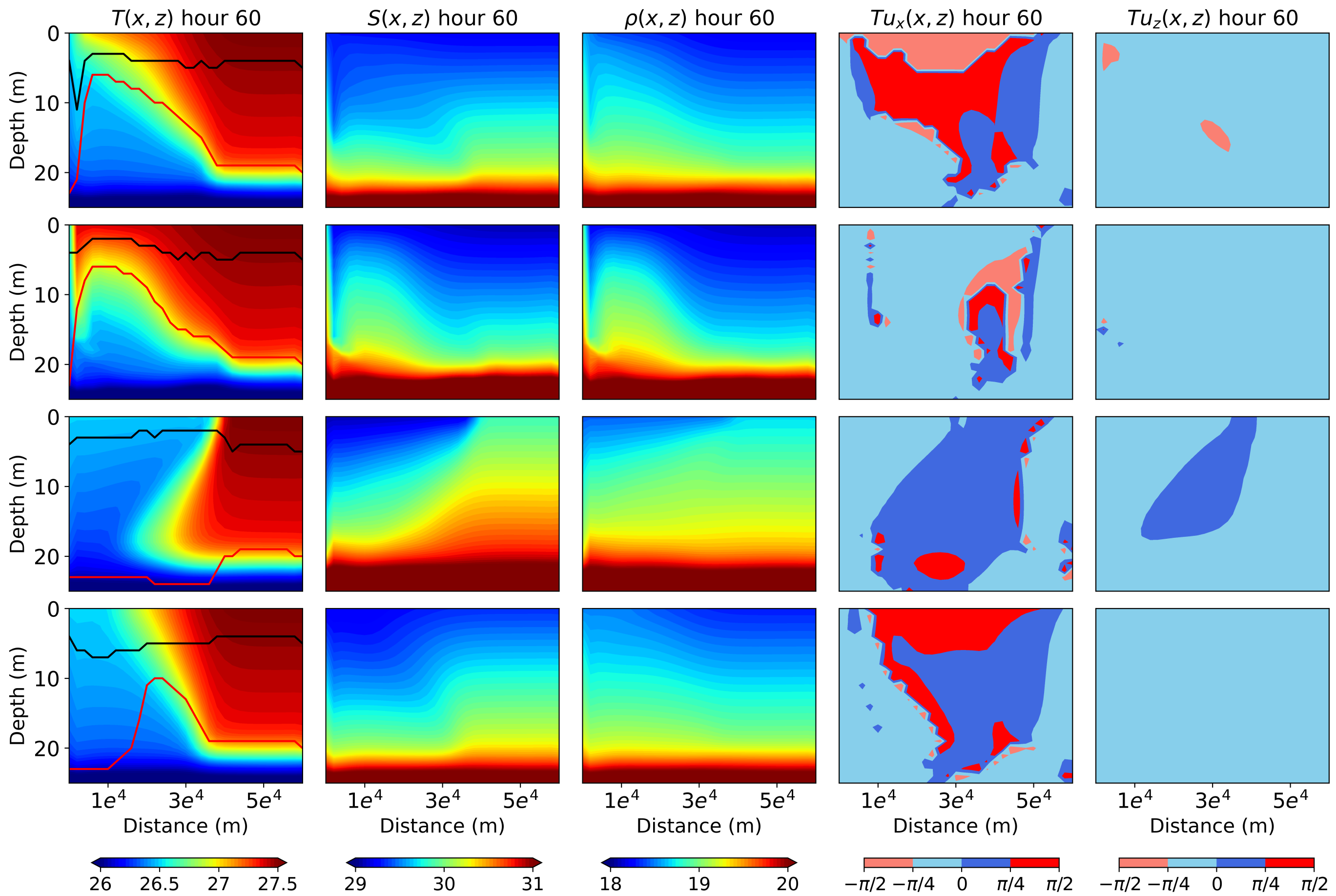


Figure 15.

