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Barrier layer characteristics of the Indian Ocean sector of the Southern Ocean during austral summer and autumn

Pranab Deb, Mihir K. Dash, Prem Chand Pandey



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1 **Barrier layer characteristics of the Indian Ocean sector of the Southern Ocean during austral**

2 **summer and autumn**

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4 Pranab Deb^a, Mihir K. Dash^{b,*} and Prem Chand Pandey^b

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9 ^aSchool of Environmental Sciences, University of East Anglia, UK

10 ^bCentre for Oceans, Rivers, Atmosphere and Land Sciences, Indian Institute of Technology

11 Kharagpur, India

12

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16 * Corresponding author. Email address: mihir@coral.iitkgp.ernet.in

17

18 **Abstract**

19 Barrier layer in the Enderby Basin (EB) and the Australian Antarctic Basin (AAB) during late
20 summer (December & January) and early autumn (February & March) are studied using
21 temperature-salinity profiles collected between 1975 and 2012. A distinct difference in mixed
22 layer depth is observed over the eastern (i.e. the EB) compared to western (i.e. the AAB) side of
23 the Kerguelen Plateau (KP), with shallower mixed layer depths on the eastern side. Mixed layers
24 show an increase from less than 50m to ~150m from south to north in the EB. During autumn,
25 the wind strengthens and the upwelling over the eastern side of the KP (i.e. in the AAB)
26 weakens, resulting in deeper mixed layers (~80m – 100m) compared to summer. During
27 summer, deep barrier layer (BL) values (~50m or more) with porosity less than 0.3 was seen over
28 the Chun Spur region. The fresher melt water from the EB brought by the Fawn trough current
29 (FTC) across the KP may be responsible for the occurrence of BL over the region. During autumn,
30 BL is spread over a much larger area around the Chun Spur, which could be attributed to the
31 increase in the strength of FTC due to the intensification of wind over the region. A thorough
32 study of BL condition over this region is required to understand the processes behind the
33 discrepancies in sea ice conditions.

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36 Key Words: Barrier layer, Kerguelen Plateau, Enderby Basin, Australian Antarctic Basin

37 **1. Introduction**

38 The growth and decay of sea ice not only play an important role in governing the upper
39 ocean conditions over the marginal ice zone but affects the regional weather and global climate
40 through energy balance too (Ackley et al., 2015; Moore et al., 2002; Rind et al., 1995). A great
41 seasonal variability is present in Antarctic sea ice cover and a huge amount of fresh water is
42 released into the ocean during melting of sea ice. This fresh melt water affects the upper ocean
43 behavior in a regional as well as in basin scale (Shi and Lohmann; 2017). The density of polar
44 water is found to be influenced mainly by salinity because small changes are observed in
45 temperature (de Boyer Montégut et al., 2007). Influx of fresher melt water may result in shallow
46 density mixed layer and formation of barrier layer. The impacts of salinity on the stratification of
47 mixed layer in mid- and high latitudes have also been shown in studies by Reverdin et al., (1994)
48 and Reverdin et al., (1997). Usually, the depth of halocline and thermocline are not always the
49 same in the ocean. Instances where haloclines are shallower than the thermoclines (Lindstrom
50 et al., 1987) give rise to an intermediate layer, called the “barrier layer” (Godfrey and Lindstorm,
51 1989). The air-sea heat and momentum exchanges are amply modified by the presence of
52 barrier layer (Vialard and Delecluse, 1998). The barrier layer (BL) is an important parameter that
53 influences the sea surface by trapping heat within the shallow mixed layer, resulting in positive
54 SST anomalies (Vialard and Delecluse, 1998; Lewis et al., 1990). Furthermore, the modified heat
55 content in the mixed layer in polar region might has an impact on the sea ice formation and vice
56 versa. Thick BLs and strong vertical inversion have been detected over the Austral Ocean (south
57 of Polar Front). However, due to deeper mixed layers in polar and subpolar regions, especially
58 during winter, the climatic impacts of BL are questionable (Mignot et al., 2009). But, around the
59 Antarctic divergence and south of Polar Front, the mixed layers are comparatively shallower

60 during summer (Dong et al., 2008). So, the presence of BL could have a much profound effect on
61 the air-sea interaction during summer.

62 The Indian Ocean sector of the Southern Ocean is unique among all the three major
63 oceans, apparently not propagating the Antarctic circumpolar wave (Yuan and Martinson, 2000).
64 The Kerguelen Plateau (KP), extended almost meridionally, acts as a barrier to the Antarctic
65 Circumpolar Current (ACC) in this sector. The larger ACC transport is found to be deflected
66 towards north, with a secondary transport through the Antarctic zone between Kerguelen
67 Islands and Antarctica (Park et al. 1993). This gives rise to interesting regional circulation pattern
68 over the region. The Deep Western Boundary Current flowing towards northwest direction
69 along the eastern slope of the KP (Donohue et al., 1999; McCartney and Donohue, 2007) has
70 been found to carry deep water from the Antarctic coast or from Princess Elizabeth Trough to as
71 far north as 50.5°S (van Wijk et al., 2010). Van Wijk et al. (2010) found two distinct branches of
72 Polar front to the immediate west of KP. Their study also found that the southern branch of
73 Polar Front contributes to the Fawn Trough Current (FTC, identified by McCartney and Donohue,
74 2007). They also suggests that a possible southward shift of the southern branch of FTC to the
75 east of KP is responsible for the advection of warmer water from north. The estimated transport
76 over the eastern side of KP reflected a variability in the path and strength of both polar front
77 and deep western boundary current. So, it is likely that interaction between these regional
78 circulations and bathymetry of the region strongly influences the upper ocean behavior over the
79 region. The upper ocean is generally represented by the halocline and thermocline.

80 This study is to investigate the presence of BL over the Indian Ocean sector of the
81 Southern Ocean and the possible mechanisms of its formation in the context of regional

82 circulation. The study tries to create a robust picture of the mixed layer and barrier layer
83 distribution over the region. The study also calculates the ‘permeability’ or ‘porosity’ of the BLs
84 (Mignot et al., 2009) to indicate how effective the barrier layers are. A thorough study can give
85 us an insight into the impact of regional circulation on the upper ocean characteristics in this
86 region.

87

88 **2. Study area and data used**

89 The study is conducted with temperature-salinity profiles collected between 1975 and
90 2012. The profiles are taken from World Ocean Dataset (WOD) 2009 at the National
91 Oceanographic Data Center (NODC) (Boyer et al., 2009), the World Ocean Circulation
92 Experiment (WOCE) (WOCE Data Product Committee, 2002) and the Argo database (Coriolis
93 Global data Assembly Center, www.coriolis.eu.org). The profiles with spurious data are
94 removed. The temporal distribution of different profiles is shown in Fig. 1. The sparsity of in situ
95 data is evident before 1986; however, the number of observations increases gradually and with
96 the introduction of Argo floats, the number of in situ observations shows a steady rise after
97 2003 (Fig. 1). The profiles are then subjected to standard tests, e.g., spike test, gradient test and
98 density instability tests. These tests removed around 4% Conductivity-Temperature-Depth
99 profiles (CTD), 6.88% Profiling Floats profiles (PFL), 0.34% Autonomous Pinniped
100 Bathythermograph profiles (APB) and 2.27% Ocean Station Data profiles (OSD). At the end, 3948
101 profiles are taken for analysis.

102 The study area covers the Enderby Basin, the Australian Antarctic Basin, connected by
103 Fawn trough region present in the Indian Ocean sector of the Southern Ocean. Major current
104 and frontal systems and schematically presented in Fig. 2.

105

106 3. Profile characteristics

107 The profiles to the south of the Polar Front (PF) over the study region are associated with
108 the presence of Winter Water (WW) between 100m and 300m depth ranges (Fig. 3(a)). The WW
109 is the layer of cold winter temperature and is capped by warmer surface layer above it. Beneath
110 this layer of WW, the presence of Upper Circumpolar Deep Water (UCDW) is seen, which has a
111 temperature of around 2°C. The surface layer was found to be warmer than the UCDW layer.
112 Salinity is more or less uniform over the surface layer, but increases gradually with depth. This
113 temperature/salinity structure is a common occurrence to the south of PF (Fig. 3).

114 However, some of the profiles around the PF and to the north of it show the typical
115 stratification with decreasing temperature and increasing salinity with depth. Fig. 3(a) shows the
116 average temperature-salinity profile over the Enderby Basin (EB), while Fig. 3(b) shows the
117 average profile over the Australian-Antarctic Basin (AAB). Comparatively more saline surface
118 water (~34 psu) is observed over the AAB than the EB (~33.7 psu). The effect of saline and cold
119 WW is less prominent in the AAB profiles (Fig. 3(b)).

120

121 3.1 Calculation of mixed layer and barrier layer depths

122 Previous studies (Brainerd and Gregg, 1995; Thomson and Fine, 2003) have indicated that
 123 temperature mixed layer/isothermal layer depth (ILD) and density mixed layer depth (MLD)
 124 calculated from a difference criteria gives more realistic measures. We follow the difference
 125 criteria used by Dong et al. (2008) since it gives a stable measurement of mixed layers over the
 126 Southern Ocean. The temperature criteria is taken as $\Delta T=0.2^{\circ}\text{C}$; i.e. the ILD is defined as the
 127 depth at which the temperature falls below the surface temperature (T_s) by 0.2°C . The MLD is
 128 defined as the depth at which the density is increased by 0.03 kg m^{-3} (i.e. $\Delta\rho=0.03\text{ kg m}^{-3}$) from
 129 that of the surface value (ρ_s). Average temperature (T_s) /density (ρ_s) of top 10m layer is taken
 130 as reference. Using these criteria ILD, MLD and barrier layer thickness ($\text{BL} = \text{ILD} - \text{MLD}$) are
 131 calculated from the individual temperature and salinity profiles. These values from individual
 132 profiles are then used to generate the bi-monthly conditions of ILD, MLD and BL at $1^{\circ} \times 1^{\circ}$
 133 resolution over the study area for the austral summer (i.e. December-January months) and
 134 austral autumn (i.e. February-March months) periods. de Boyer Montégut et al. (2007)
 135 determined BL depth as the median of all available observations in each grid. However, Mignot
 136 et al. (2009) argued that BLs show intermittent nature in both space and time and the BL
 137 distribution within a grid cell is skewed towards high values rather than being Gaussian in
 138 nature. So taking median of all the observation (as in de Boyer Montégut et al., 2007)
 139 underestimates the BL thickness. In this study BL is estimated by taking the thickness median of
 140 the stations with effective BL values only, satisfying the following criteria (Mignot et al. 2009):

141 $\text{BL} > 5\text{m}$

142 $\text{BL} > 10\% (\text{ILD})$

143 To make the study more statistically robust, we calculated median at the grid points
144 having at least 5 stations.

145 The appearance and disappearance of BLs are associated with their own time and space
146 scale of formation. BL can effectively modify the air-sea interaction if it is sufficiently continuous
147 in space and time. To find the effective BL present over time, Mignot et al. (2009) introduced the
148 term 'barrier layer porosity' to specify the permeability of BLs. First the 'persistence' of BLs (R) is
149 calculated. It is defined as the ratio of the number of stations showing BL to the total number of
150 stations. Then barrier layer porosity is calculated as '1-R'. It gives an idea about how effective
151 the BL is. The MLD, ILD and BL climatologies for austral summer and austral autumn had
152 variabilities resulting from noisy nature of observations. So, we applied smoothing, similar to
153 that used by de Boyer Montégut et al. (2004). The regions with no data points were filled with
154 Laplace Interpolation, which is a specialized interpolation technique for restoring missing data
155 on a two or three dimensional grid. The technique does not change any known values. It is fast
156 and uses linear extrapolation. Averaged Ekman pumping and Ekman transport for summer
157 (December-January) and autumn (February-March) periods are calculated using QuikSCAT
158 monthly wind stress data (Pegion et al., 2000) over the study region.

159

160 **4. Results and discussions**

161 The Indian Ocean sector of the Southern Ocean is broadly divided into two regions (i)
162 Enderby Basin (EB) and (ii) Australian Antarctic Basin (AAB). Kerguelen Plateau (KP) separates
163 these two basins. Both the basins are different in their water mass characteristics and sea ice

164 extent/area. Generally sea ice edge is present more towards equator in the EB than that in the
 165 AAB.

166 The ILD for austral summer is shown in Fig. 4(a). The depth of ILD is more in the EB than
 167 that in the AAB covered within the study domain. Maximum ILD is found to be of the order of
 168 130m in the EB. Over the western part of the KP, the region south of 56°S is associated with ILD
 169 values less than 60m over the longitude range 50°E-70°E (Fig. 4(a)).

170 A distinct difference in ILD and MLD over the eastern and western part of the KP is
 171 observed. The average ILD value over the eastern part is found to be of the order of 70m (Fig.
 172 4(a)). The distribution of MLD over the study region is shown in figure 5(a). The MLD values
 173 follow similar distribution over the region as that of ILD, with deeper values to the north and
 174 shallower values to the south. Deeper ILD (~120m) and MLD values (>150m) are found on the
 175 western side of Heard Island in the KP (Fig. 4(a) & 5(a)). It may be the result of bathymetry
 176 driven downwelling. MLD values are found to be shallower (<50m) compared to ILD values over
 177 the Chun Spur region (to the east of Heard Island) and may be caused by the advection of melt
 178 water. ILD and MLD over the Weddell gyre region (20-40°E) show moderate values with values
 179 less than 70m to the south of 56°S and reaching up to 120m to the north of it.

180 During summer almost the whole study area shows negative wind stress curl (Fig. 6(a)
 181 for wind stress curl) signifying that upwelling persists over the region. It is supported by positive
 182 Ekman pumping (Fig. 7(a)).

183 Shallower thermocline present in the EB between 60-52°S latitude belt may be
 184 attributed to strong upwelling (Ekman pumping $>1.5 \times 10^{-7}$) (Fig. 7(a)) and is responsible for
 185 shallower MLD and ILD values (Fig. 4(a) & 5(a)). Deeper values of MLD are seen closer to the

186 northern boundary of the study area with some of the values exceeding 150m (Fig. 5(a)), which
187 may be attributed to the stronger wind (Fig. 6(a)) and downwelling observed over the region
188 (Fig. 7(a)). Thicker ILD and MLD are noticed on the western side of the KP than on the eastern
189 side (Fig. 4(a) and 5 (a)). This may be due to the complex interaction between the current and
190 topography of the region.

191 Before analyzing the barrier layer over a particular region, we first looked at the 'barrier layer
192 porosity' distribution over the study area (Fig. 8(a)). The BL porosity of 0.3 or less is found to be
193 spread over a $\sim 2^\circ \times 2^\circ$ region. Separate monthly studies are performed to understand the
194 situation during each month of the December and January. The BL porosity is found to be less
195 than 0.3 during both December and January months. During February, thick BL with porosity less
196 than 0.3 is observed over 75-80°E belt, to the south of 57°S (no observations present over Chun
197 Spur region during this month). During March, thick BLs with porosity less than 0.3 is observed
198 over the Chun Spur and over the 60-80°E longitude belt, south of 58°S. However, the
199 interpretation of BL porosity in determining its effect on air-sea interaction is important and it is
200 sensitive to both temporal and spatial resolution of the grid. The Chun Spur region shows a
201 porosity of 0.3 or less during both the bimonthly periods. Since a bimonthly data is presented, a
202 porosity of ~ 0.3 means that BL can appear more than 70% of the time i.e., more than three
203 fourth of the two month period.

204 Thus, the BL is spatially spread over a larger region and more than 70% of the profiles
205 over the region show deep BL. However, it cannot be specified whether BL is present
206 continuously over the entire two months period or over a comparatively smaller period (say, the
207 last 15 days of the bimonthly cluster). This is because the temperature salinity profiles are not

208 be available over the whole period. Hence, in this case, the porosity of 0.3 is present during both
 209 the months and spread over a larger ($\sim 2^\circ \times 2^\circ$) region over Chun Spur. So, this value of BL porosity
 210 (i.e., 0.3) is taken to be sufficient to affect the air-sea interaction over the region. The concept of
 211 BL porosity is inseparable from both time and space scales and a shorter temporal resolution
 212 would be helpful in understanding the BL persistence better. But unavailability of continuous
 213 data makes this impossible over the study area. The region surrounding Chun Spur shows thick
 214 BL values ($\sim 50\text{m}$ or more) (Fig. 9(a)) with porosity less than 0.3 (Fig. 8(a)) during summer. This
 215 indicates a strong and effective BL. The presence of strong Fawn Trough current (FTC) to the
 216 south of Heard Island across the KP, which brings fresher melt water from EB to the Chun Spur
 217 region (Rouquet et al., 2009), is responsible for the occurrence of BL over the region.

218 Additionally, wind-induced downwelling ($\sim -1 \times 10^{-6}$, Fig. 7(a)) is observed over the Chun
 219 Spur region, which is associated with deeper ILDs ($\sim 70\text{ m}$) compared to the neighbouring area
 220 (Fig. 4(a)). But fresher EB water carried by the FTC may play a role in the formation of BL. Apart
 221 from this, a small region between 30°E - 40°E , south of 57°S shows barrier layer with depth
 222 between 20m and 40m and porosity between 0.2 - 0.6 . The region is associated with a circular
 223 patch of comparatively weaker WS curl values ($\sim -1.5 \times 10^{-7}$, Fig. 6(a)) during summer, which may
 224 reduce the upwelling over this small region. The wind-driven northward advection of fresher
 225 melt water (Fig. 7(a)) creates a shallow density stratified layer, thus resulting in positive BL
 226 values there.

227

228 **4.1 Barrier layer characteristics during austral autumn**

229 Fig. 4(b) shows the ILD distribution during autumn. Deeper ILD values (120m-160m) are
 230 seen to the north of 57°S over the western side of the plateau. However, the eastern part of the
 231 study area shows ILD values between 80m and 100m. MLD distribution over the study region is
 232 shown in Fig. 5(b). Both ILD and MLD are found to be thicker during autumn than during
 233 summer. During autumn, the wind is intensified over the study region (Fig. 6(b)) compared to
 234 that during summer. This results in an increase in the wind-induced downwelling. Strong
 235 downwelling (of magnitude $>1.5 \times 10^{-7}$ m/s) can be seen between 50°S-53°S (Fig. 7(b)). The
 236 western escarpment of the Heard Island exhibits bathymetry-driven downwelling and hence
 237 comparatively deeper ILD/MLD values (Fig. 4(b) & 4(b)). Over the Weddell Gyre region, the ILD
 238 and MLD values are deeper (>70 m) to the north of 56°S while shallower (<50 m) to the south of
 239 it; this is associated with a shift in wind stress curl and Ekman pumping values across 56°S (with
 240 strong upwelling to the south of 56°S) over the region (Fig. 6(b)). Shallower MLDs (<30 m) appear
 241 over the Chun Spur region and the eastern side of the plateau over the southern belt (south of
 242 58°S) (Fig. 5(b)). The stratification caused by the advection of melt water might be responsible
 243 for the shallow MLDs.

244 BL is spread over a much larger area around Chun Spur during autumn, which could be the
 245 result of increase in the strength of FTC due to the intensification of wind over the region.
 246 Porosity values reach as low as 0.2 during this season and are spread over a larger area
 247 compared to summer period (Fig. 8(b)). The BL layer in this case is much more persistent.
 248 Another region south of 58°S and over the eastern part of the study area shows thicker BL
 249 values (16m-50m) (Fig. 9(b)) with porosity ranging from 0.2 to 0.6 (Fig. 8(b)). Also, the eastern
 250 side of southern KP is associated with a bathymetry-driven northward protrusion of sea ice
 251 cover, which is why fresher melt water reach a much northward extent along the eastern slope

252 of KP (figure not shown) and BL formation is seen there (Fig. 9(b)). Previous studies (Park et al.,
253 1993) have shown that sea ice over the eastern side of the plateau melts completely only at the
254 end of February, thus producing more melt water during February-March months. This late
255 melting on the eastern side may be the reason why no significant BL was observed during
256 December-January months. Apart from these two prominent regions, a region to the south of
257 57°S, 20°E-30°E (Weddell gyre region) exhibits BL with values ~50m and porosity 0.3-0.6 (Fig.
258 9(b) & 8(b)). The melt water carried by the eastern limb of the Weddell gyre might be
259 responsible for the observed BL. Another region of BL formation is to the south of Elan Bank
260 ~58°E-75°E, with BL values between 8m and 50m and porosity<0.2. The region shows a weaker
261 upwelling (~1-1.5x10⁻⁶ m/s, Fig. 7(b)) and deeper ILDs (70m – 110m) compared to neighbouring
262 areas (Fig. 4(b)). A strong wind-driven Ekman transport (Fig. 7(b)) causes northward advection of
263 melt water and results in shallower MLDs (<70m, Fig. 5(b)), which is responsible for the BL
264 formation over the region (Fig. 9(b)).

265 Above observations suggest that a persistent and thick BL appears consistently over the
266 Chun Spur region during both the seasons and is likely to have a strong influence on the air-sea
267 interaction over the region.

268 The major current system which flows across these two regions is the FTC. McCartney
269 and Donohue (2007) suggested that the surface expression of the Polar Front (SPF, defined by
270 Holliday and Read, 1998) to the west of FT results in a strong eastward flow through the trough.
271 This was later confirmed by van Wijk et al. 2010 (hereafter, vW10), suggested that cold and
272 fresh water from the south fill up the trough. Park et al. (2008) also suggested the FT as a
273 pathway for the advection of southern cold water towards northern plateau. The FTC turns

274 northward on the eastern end of the trough and then meanders to the east of the KP and moves
275 south-east in the AAB (Roquet et al. 2009). This is responsible for the southward advection of
276 warm sub-polar water in the AAB (vW10). A schematic diagram of the regional circulation over
277 the Chun Spur region (following vW10) is shown in Fig. 2. The broad circulation (Fig. 2) suggests
278 that, on exiting the FT, some streamlines move briefly to the northwest after passing Chun Spur
279 and then turns offshore while some streamlines directly go offshore near Chun Spur after exiting
280 the trough. Strong surface geostrophic flow indicates that cold and fresh surface water can
281 spread over a greater zonal extent. vW10 hypothesized that the Northern Polar front
282 (subsurface expression of the Polar Front) meets the SPF on the eastern side of the trough.

283 The confluence zone, however, shows wide variability in its location (Park et al. 2008, vW10),
284 indicating that the path and strength of SPF/FTC shows great variability as well. The transport
285 estimates over the eastern KP (Speer and Forbes, 1994; Donohue et al. 1999) also reflects this
286 variability.

287 The mean Ekman pumping and wind stress curl show that the Chun Spur is a
288 downwelling region (Fig. 6 and 7), and thus associated with thicker ILD (Fig. 4) compared to the
289 neighbouring areas over AAB. The presence of non-porous deep BLs (Fig. 9) in this region is
290 attributed to the FTC, which brings fresher water over the region creating strong density
291 stratified layers. During autumn, the region along the steep slopes of southern Heard Island also
292 shows the presence of BL with low porosity (Fig. 9(b)); this indicates the importance of
293 topography steered FTC in carrying fresher southern water up to the northern plateau in and
294 around the Chun Spur region. However, the strength and transport of FTC could be an important
295 variable.

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297 5. Summary

298 The ILDs, MLDs and BLs in the EB and the AAB during late summer and early autumn are
299 studied using temperature-salinity profiles collected between 1975 and 2012. A distinct
300 difference in mixed layer depth over the eastern (EB) and western (AAB) side of the KP is
301 observed, with shallower mixed layer depths on the eastern side. A strong upwelling over 60°S-
302 52°S latitude belt on the eastern side may be responsible for the shallower depth. Overall, the
303 region to the north of 56°S is seen to be associated with deeper mixed layers due to the
304 influence of the ACC and strong wind-induced downwelling. The region to the south shows
305 strong upwelling under the influence of Antarctic divergence and hence the region is associated
306 with shallower mixed layer. Over the EB, mixed layers show an increase from less than 50m to
307 ~150m from south to north. During autumn, the wind strengthens and the upwelling over the
308 eastern side of KP (i.e. in the AAB) weakens, resulting in deeper mixed layers (~80m – 100m)
309 compared to summer. On the western side of KP (i.e. in the EB), at southern latitudes (to the
310 south of 58°S) mixed layers are shallower than 50m, while to the north of it, wind-induced
311 mixing results in deeper layers with depth ranging from 100m to 160m. During summer, deep BL
312 values (~50m or more) with porosity less than 0.3 was seen over the Chun Spur region. The
313 fresher melt water from the EB brought by the FTC across the KP may be responsible for the
314 occurrence of BL over the region. During autumn, BL is spread over a much larger area around
315 the Chun Spur, with porosity values as low as 0.2, which could be the result of increase in the
316 strength of the FTC due to the intensification of wind over the region. A thorough observational
317 and modeling study of BL condition over the IOS will further enhance the understanding of the
318 processes behind the discrepancies in air-sea interaction and sea ice conditions over the region.

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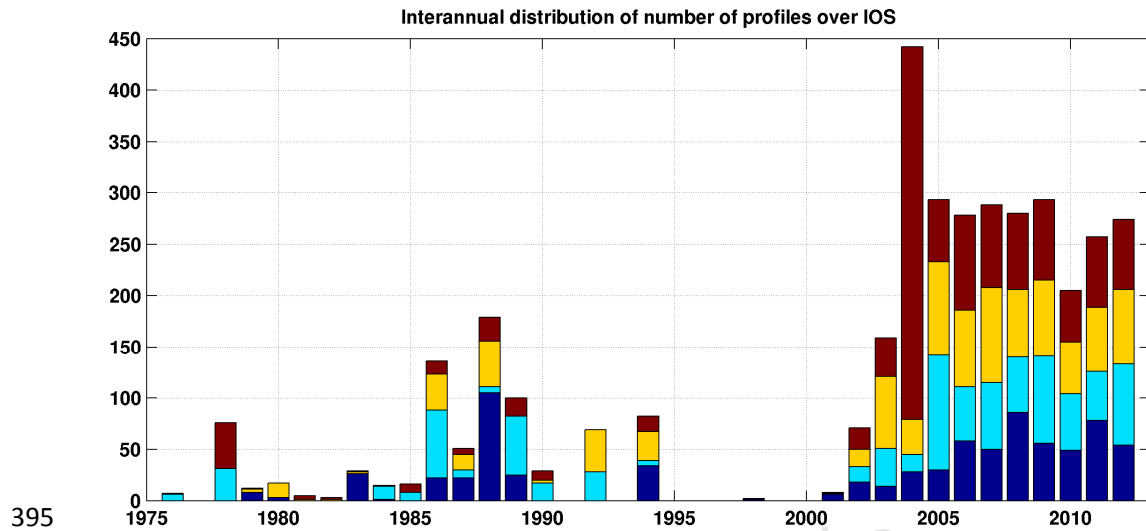
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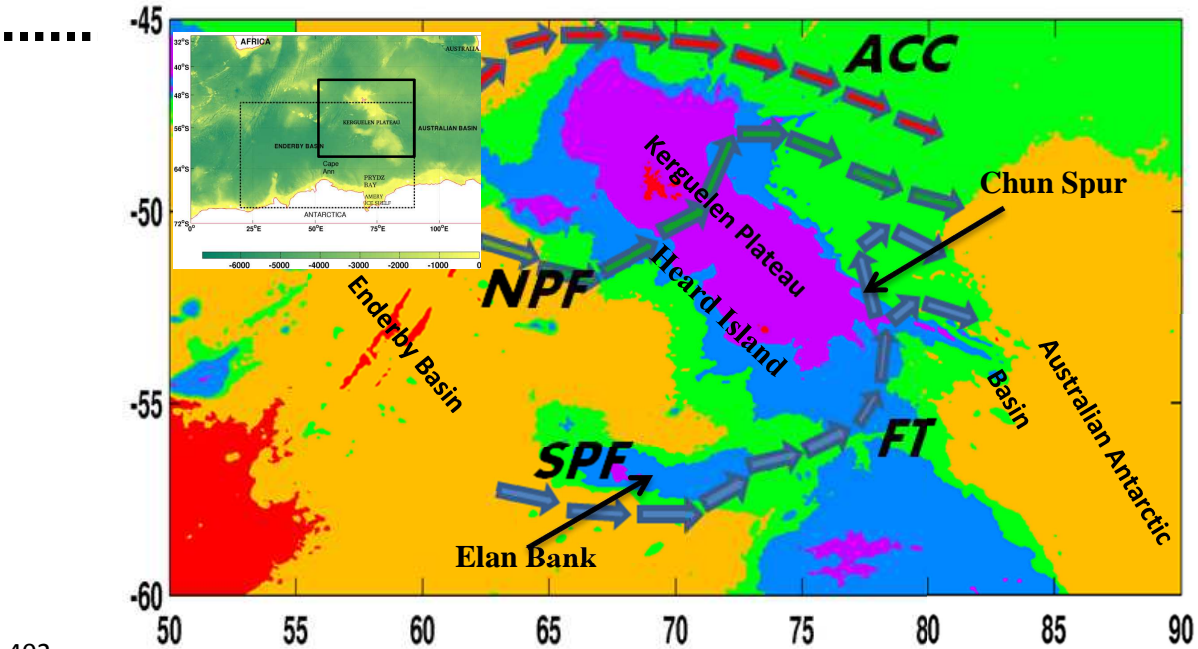
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395
 396 **Fig. 1.** Inter-annual variation of profile numbers with monthly distribution; blue part of the bar
 397 shows number of profiles in December, sky-blue part shows the same in January, yellow part
 398 shows the number of profiles in February while the red part represents the number of profiles in
 399 March for that particular year.

400

401



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403 **Fig. 2.** The inner figure shows the study area is shown with a thick solid rectangular box.

404 The colour bar represents the bathymetry of the region. The dashed box shows the Indian

405 Ocean sector of the Southern Ocean Parkinson and Cavalieri (2012). The outer figure

406 shows the schematic diagram of the circulation over the Fawn trough (FT) region

407 (following van Wijk et al., 2010); red arrows show the Antarctic Circumpolar Current

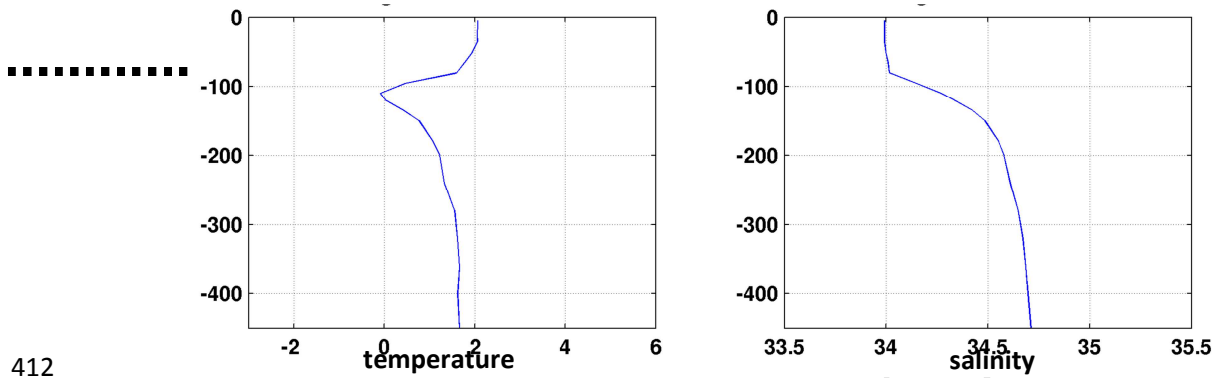
408 (ACC), green arrows show the Northern Polar Front (NPF) and blue arrows show the

409 Southern polar Front (SPF).

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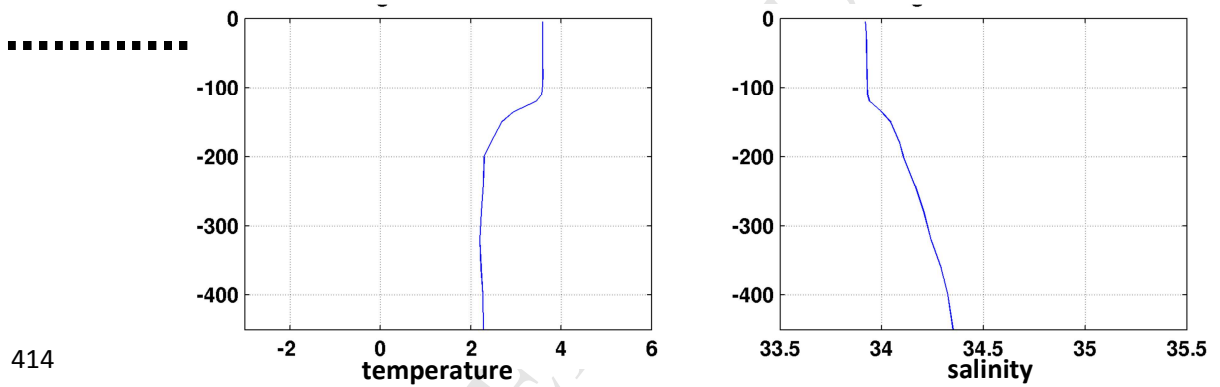
(a)



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(b)



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Fig. 3. Typical temperature (left) and salinity (right) profile over (a) the Enderby

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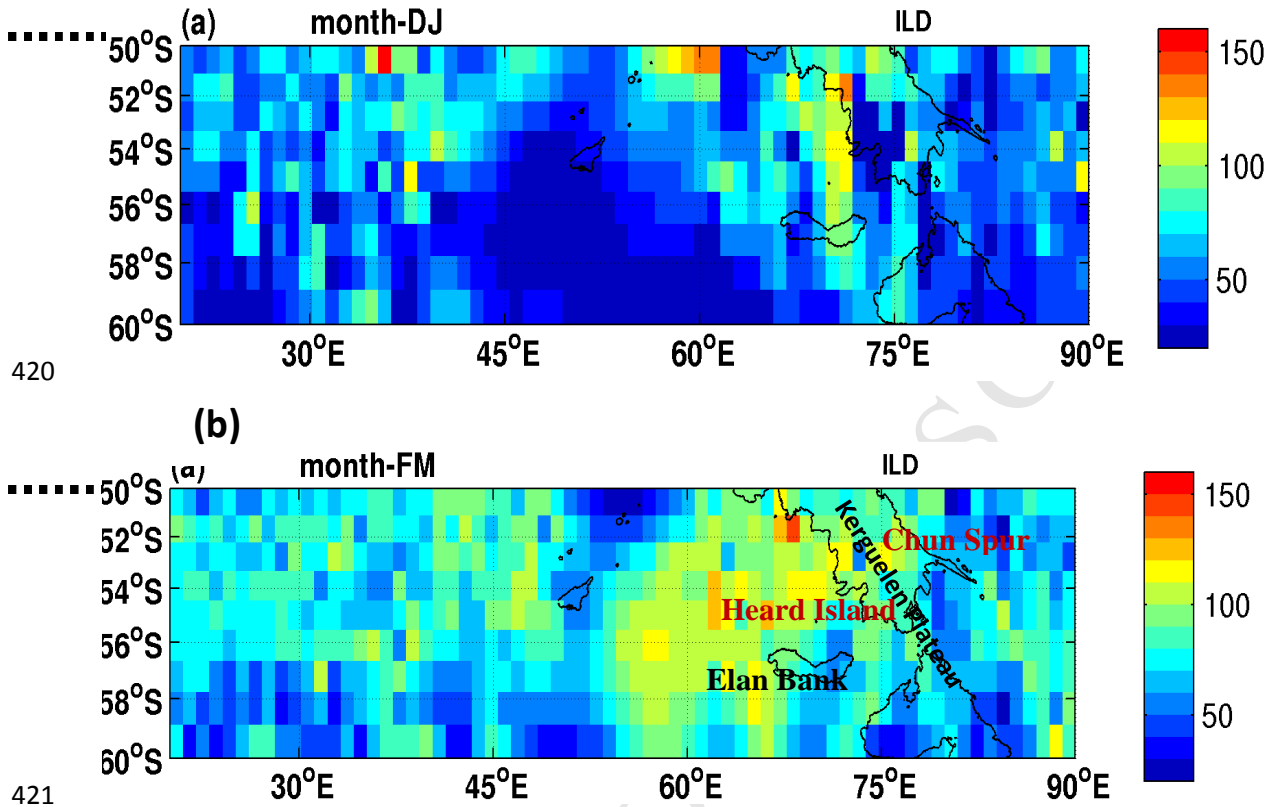
Basin and (b) over the Australian-Antarctic Basin for regions to the south of Polar

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front. Upper (lower) panel represent the EB (AAB).

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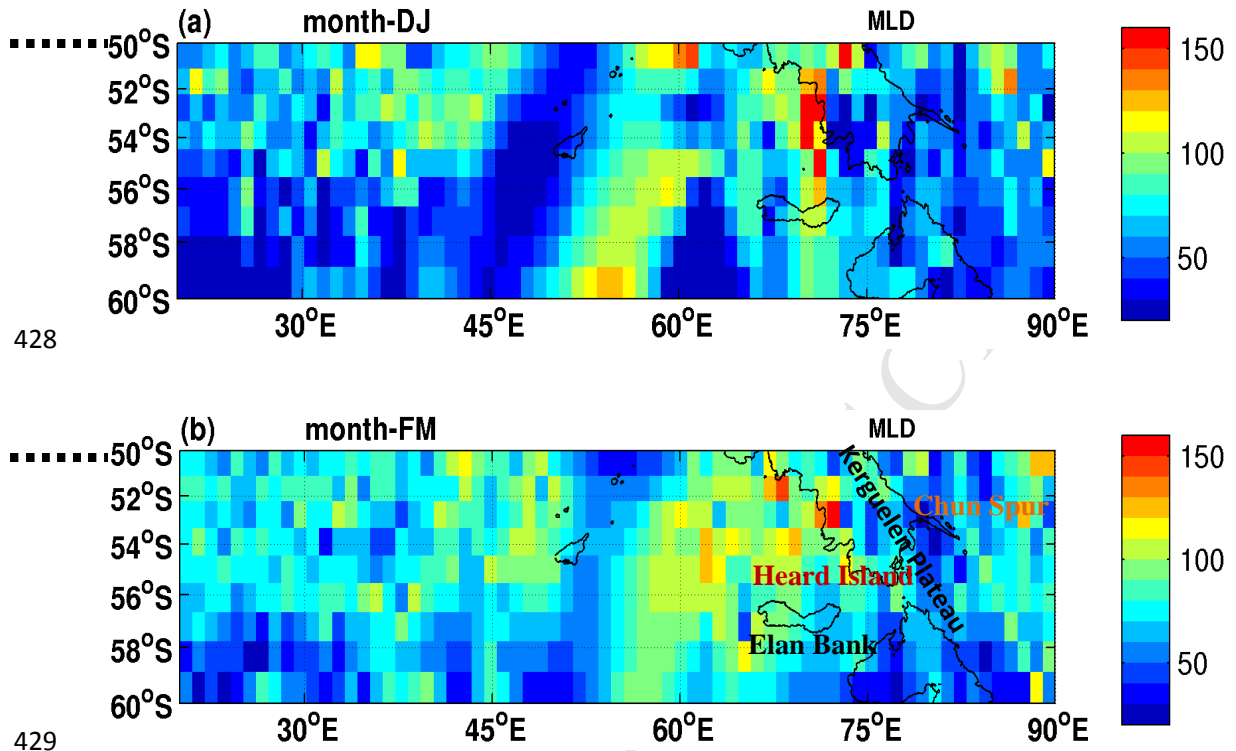
423 **Fig. 4.** Horizontal distribution of average isothermal layer depth (ILD, in m) calculated

424 from in-situ observations between 1975 and 2012 for (a) summer (December-January)

425 and (b) autumn (February-March) seasons over the study area.

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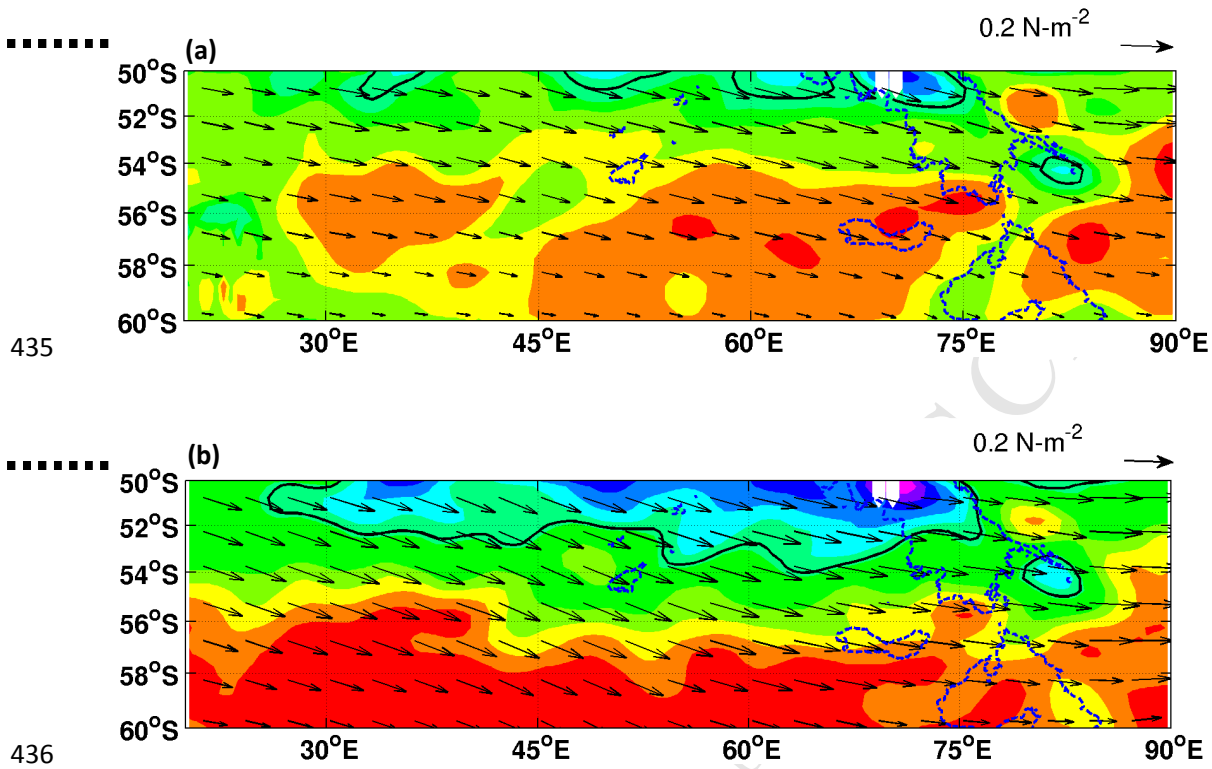
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430 **Fig. 5.** Horizontal distribution of average density mixed layer depth (MLD, in m)
 431 calculated from in-situ observations between 1975 and 2012 for (a) summer (December-
 432 January) and (b) autumn (February-March) over the study area.

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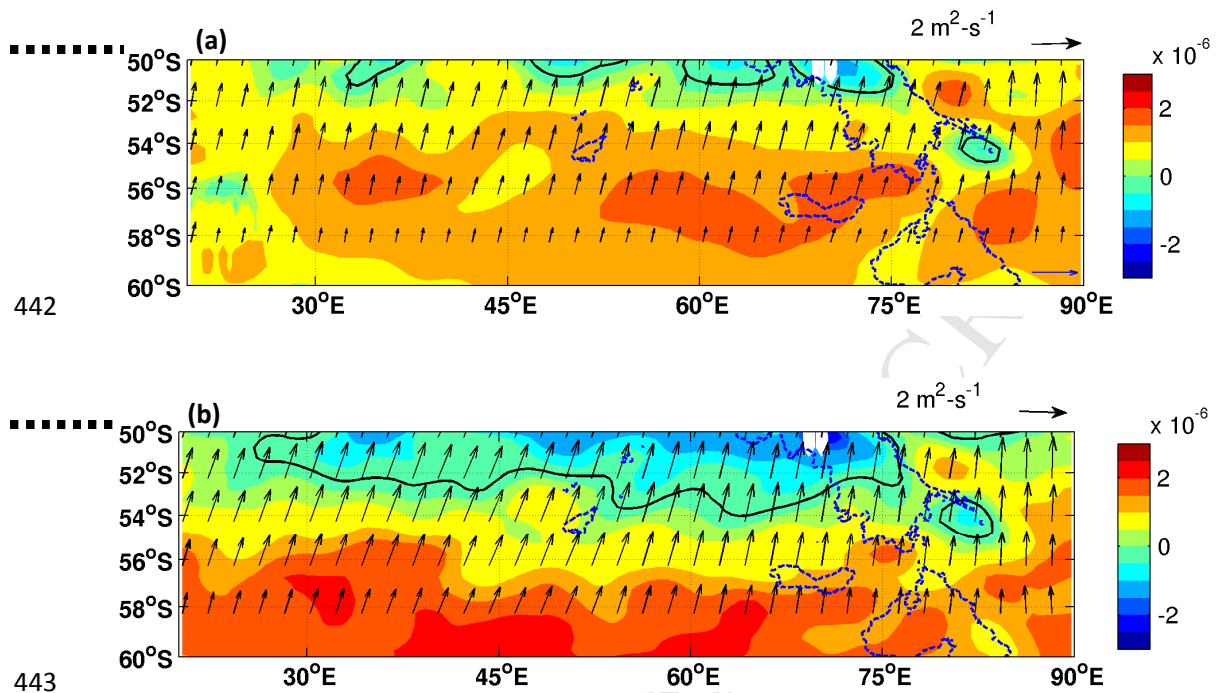
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437 **Fig. 6.** Horizontal distribution of average wind stress curl (shaded, in Nm^{-3}) with wind
 438 stress vectors (vectors, in Nm^{-2}) overlaid on it, for (a) summer (December-January) and
 439 (b) autumn (February-March) over the study area.

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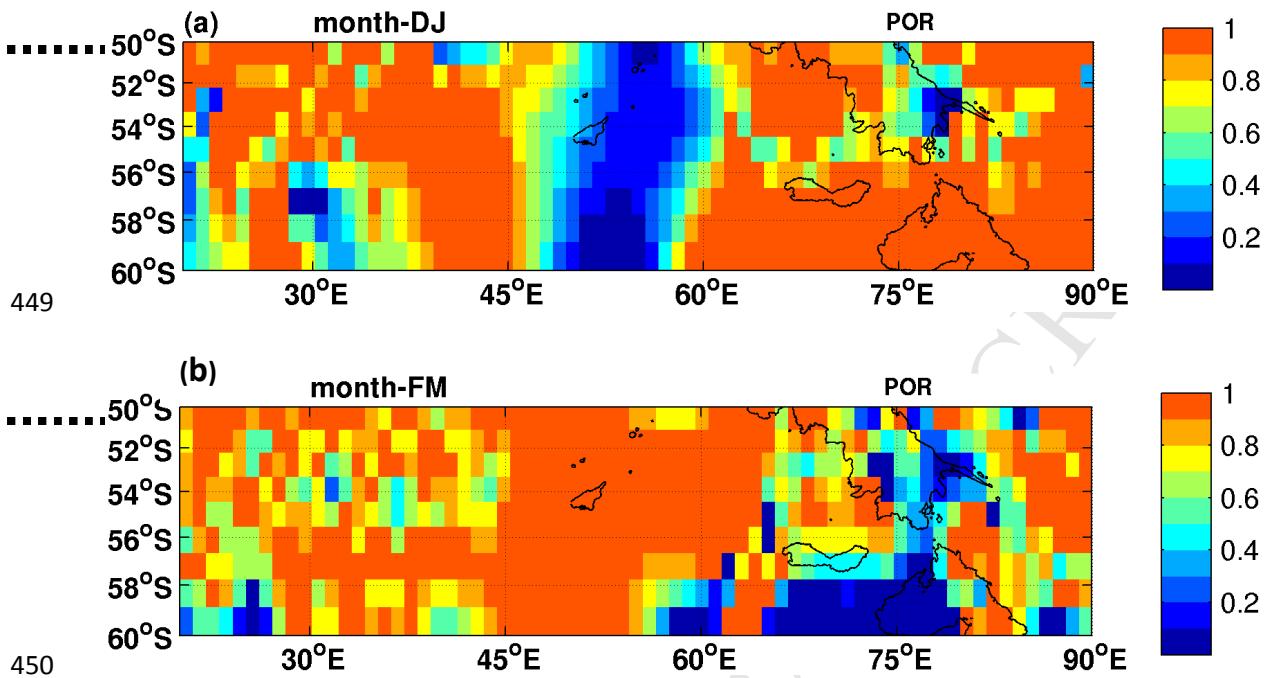
441



444 **Fig. 7.** Horizontal distribution of average Ekman pumping (shaded, in $\text{m}^2\cdot\text{s}^{-1}$) with Ekman
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 446 autumn (February-March) over the study area.

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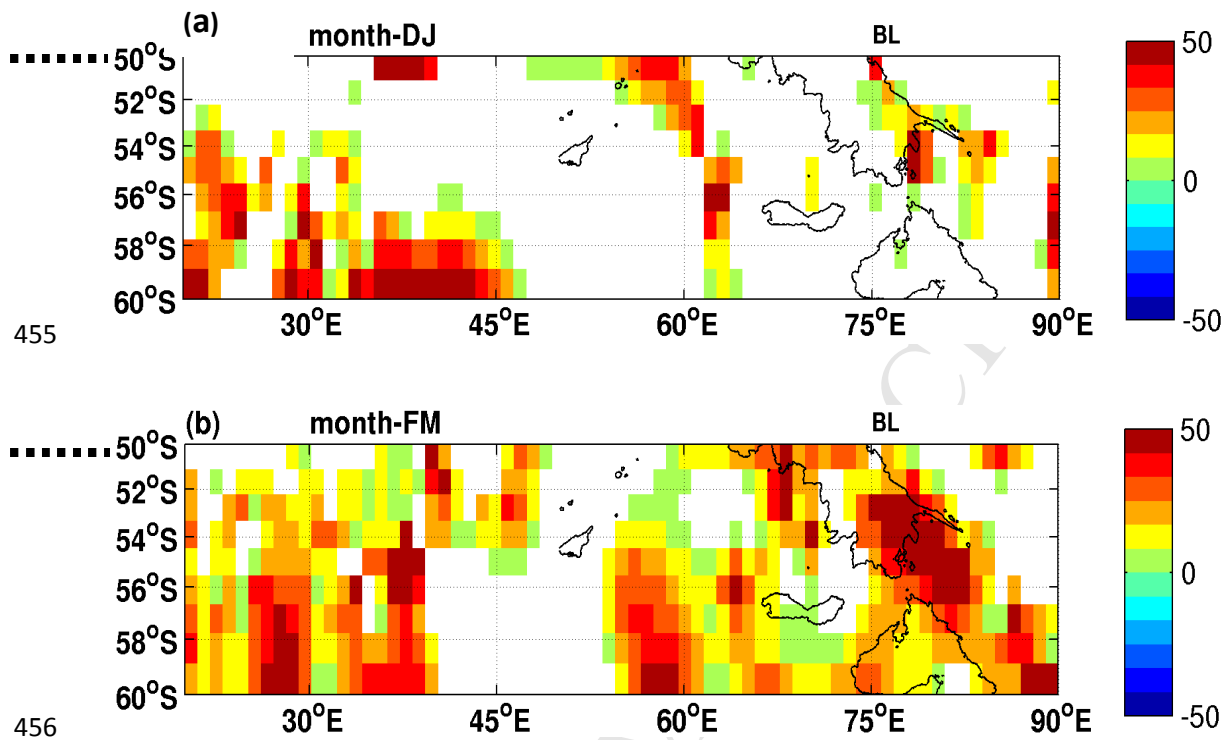
448



451 **Fig. 8.** Horizontal distribution of average barrier layer porosity (dimensionless) for (a)
452 December-January months and (b) February-March months over the study area.

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454



457 **Fig. 9.** Horizontal distribution of average barrier layer depth (in m) for (a) December-
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459

460 Figure Captions:

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