1 **Barrier Layers in a High-resolution Model in the Eastern Tropical Pacific**

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3 **F. M. Bingham[1], Z. Li[2], S. Katsura[3], J. Sprintall[3]**

4 [1]University of North Carolina Wilmington, Center for Marine Science, Wilmington, NC, USA.
5 [2]California Institute of Technology, Jet Propulsion Laboratory, Pasadena, CA, USA.

6 [3]Scripps Institution of Oceanography, University of California, San Diego

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8 Corresponding author: Frederick M. Bingham (binghamf@uncw.edu)

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10 **Key Points:**

11 • Salinity barrier layers (BLs) in the eastern tropical North Pacific are characterized using a
12 high-resolution numerical model

13 • BLs are associated with surface salinity fronts which tilt towards the fresh side at their
14 base

15 • Vertical circulation combined with surface divergence and convergence are proposed as
16 another formation mechanism for BLs in this region.
17

18   **Abstract**

19   This study examines salinity barrier layers (BLs) in the eastern tropical North Pacific (ETP) in
20   the region of the SPURS-2 (Salinity Processes in the Upper ocean Regional Studies – 2) field
21   campaign. We utilize a high-resolution numerical model to study BLs and their relationship to
22   frontal features and small-scale ocean variability, focusing on two specific events. One is
23   associated with a large outbreak of BL presence near 7°N along 125°W. The other is a relatively
24   isolated but persistent BL that forms near 13°N, again along 125°W. In both cases we find that
25   the BL is proximate to a salinity frontal feature in which isohalines tilt toward the fresh side of
26   the front at its base. The BLs studied are associated with divergent flow at the surface on the
27   fresh side of the front and convergent flow on the salty side. Tilting of the front is invoked to
28   explain this, with an additional mechanism involving a vertical circulation which causes the base
29   of the front to tilt preferentially.

30   **Plain Language Summary**

31   Salinity barrier layers (BLs) are common in the eastern tropical North Pacific (ETP) ocean. They
32   consist of a surface mixed layer that is homogeneous in temperature, but with a high salinity
33   layer at the base. They may play an important role in regulating the transfer of heat, momentum
34   and freshwater across the ocean surface and from there into the interior. This study examines
35   BLs in the ETP in the region of the SPURS-2 (Salinity Processes in the Upper ocean Regional
36   Studies – 2) field campaign using a high-resolution numerical simulation. SPURS-2 took place in
37   2016-2017 and was designed to study processes connecting salinity and rainfall in the ETP in the
38   vicinity of the intertropical convergence zone. Two specific examples of BLs are studied. In one,
39   there is a large outbreak of such layers throughout the ETP along a large-scale sea surface
40   salinity (SSS) front. In the other example, the BL was an isolated feature associated with another
41   sharp SSS front. So frontal features are an important part of the process of BL formation. In
42   addition, we find surface flow which converges towards the front on the salty side and diverges
43   away from it on the fresh side. BL formation at the front is a result of the front tilting away from
44   the vertical, and in the case of the fronts studied here, that tilting is concentrated at the front's
45   base. It is also likely associated with vertical circulation on either side of it.

46

47   **1 Introduction**

48   Barrier layers (BLs) are areas in the upper ocean where the surface mixed layer as
49   defined by temperature is greater than that as defined by density due to the presence of salty
50   water at the base of the mixed layer. They have been observed in the ocean since their discovery
51   about 30 years ago (Godfrey and Lindstrom, 1989; Lukas and Lindstrom, 1991). BLs have been
52   found in a diverse set of contexts (Sprintall and Tomczak, 1992; de Boyer Montegut et al., 2007),
53   most especially in the tropics and at high latitudes, and are an important part of upper ocean
54   dynamics in these areas (Roemmich et al., 1994; Vialard and Delecluse, 1998a). In the tropics in
55   particular, they are thought to modulate air-sea interaction by creating a layer of insulating
56   stratification, which can magnify the impact of heat and/or freshwater flux at the surface (Maes
57   et al., 2002; Maes et al., 2005). They also act to suppress entrainment cooling at the base of the
58   mixed layer, since water in the mixed layer is at the same temperature as water below it (Godfrey
59   and Lindstrom, 1989; Vialard and Delecluse, 1998b).

60   BLs have been extensively studied in the western Pacific, but not as much in the eastern
61   Pacific. Conditions are different in the eastern part of the basin where the forcing is more
62   seasonal. Katsura and Sprintall (2020; henceforth "KS20") have shown that BLs are ubiquitous
63   in the eastern tropical Pacific (ETP) under the intertropical convergence zone (ITCZ) (Qu et al.,
64   2014). Their presence is highly seasonal, with maximum likelihood and thickness in the summer
65   and fall (de Boyer Montegut et al., 2007). The KS20 study was a climatological seasonal one
66   based on sparse Argo data, so BLs were only discussed on a monthly time scale. KS20 attribute
67   the common presence of BLs in this region to convergent Ekman transport driven by wind stress
68   curl. The Ekman convergence creates mixed layer salinity fronts, which then tilt due to
69   instability and shear between the surface and the base of the mixed layer. This process of tilting
70   was first proposed by Cronin and McPhaden (2002; henceforth "CM02") as one potential
71   mechanism for BL formation. KS20's conclusion is congruent with Sato et al., (2004), Sato et al.
72   (2006), and Katsura et al. (2015), who all emphasized the role of sharp small-scale salinity fronts
73   and subduction of high salinity water in the tropical and subtropical ocean. However, the
74   conclusions of KS20 and those of Sato et al. (2006) are based on Argo data which are relatively
75   sparse in space and time. In particular, KS20 cannot co-locate the BLs relative to the concurrent
76   position of the North Equatorial Counter Current (NECC) or any property front associated with
77   the circulation system, nor do they shed any light on what specific dynamics may be occurring at
78   the front associated with BL formation. Indeed, it is difficult to obtain the direct measurements
79   of the 3-dimensional circulation and air-sea interaction that are needed to determine the
80   mechanisms responsible for BL formation using an *in situ* dataset.

81   Katsura et al. (2020) looked in more detail at BL and temperature inversion formation
82   using the higher resolution SPURS-2 (Salinity Processes in the Upper ocean Regional Studies –
83   2) in situ dataset. They reached a similar conclusion as KS20, that BLs form as a result of tilting
84   of mixed layer fronts. Additionally, they surmise that BLs form in a patchy and intermittent
85   manner on fast time scales and that surface geostrophic flow and Ekman flow play important
86   roles in causing the tilting of frontal isohalines - where BL formation occurs. However, Katsura
87   et al. (2020) is based on shipboard observations, so temporal changes in BLs cannot be described
88   even though synoptic BL features were observed.

89   The ETP is the location of the seasonal extension of the ETP fresh pool (Alory et al.,
90   2012; Melnichenko et al., 2019), a low surface salinity feature which extends westward from the
91   coast of Central America. It reaches its maximum extent in the October/November period,
92   reaching out to ~160°W, as defined by the 34 isohaline, with minimum extent in
93   January/February at ~125°W. Its meridional extent, again defined by the 34 isohaline, is about
94   10° in the mean between about 5 and 15°N (Guimbard et al., 2017; Fiedler and Talley, 2006). At
95   the southern edge of this fresh pool extension is a surface front separating the relatively fresh
96   eastern Pacific water from higher salinity surface water found at the equator. This front forms in
97   January near ~3°N, migrates to the north over the course of the year, and dissipates in the months
98   of January-February after reaching a maximum latitude of about 12°N (Yu, 2015). In the
99   October-November period it is generally found around 6-7°N, which is one location where the
100   present study will focus. The ETP is unique due to the intense currents, strong fronts, dominance
101   of Ekman transport, and shallow mixed layers that are present. These all likely point to the
102   CM02 tilting mechanism as the most important one for BL formation. BLs in the ETP are
103   generally thinner than in the western Pacific (Fiedler and Talley, 2006). The ETP is also a site of
104   intense rainfall (Schanze et al., 2010). However, according to KS20, rainfall and BLs do not

105 generally coincide, meaning that rainfall may not be an important mechanism contributing to the
106 formation. Thus, we would like to look at the tilting mechanism in the ETP in more detail.

107   Using a numerical model, we can focus in on the mechanisms responsible for BL
108 formation, and examine how or whether the BL formation is related to 3-dimensional frontal
109 structures and their temporal evolution. As stated by Tanguy et al. (2010), a complete
110 understanding of BL formation requires information "on the 3-dimensional structure of the upper
111 ocean, T, S, velocity, vertical shear, local surface forcing and turbulent mixing". BL formation in
112 numerical models has been studied by Veneziani et al. (2014) in the South Atlantic, using the
113 same model formulation we use here, though configured specifically for that different region.
114 They emphasized the importance of advection, and, importantly, of the influence from
115 submesoscale processes at 1-9 km spatial scales and their impact on vertical transport of heat and
116 salt. The ETP was the location, in 2016-2017, of the SPURS-2 field campaign (Lindstrom et al.
117 (2019) and references therein), carried out to study the impact of rainfall on the upper ocean
118 salinity field, and the creation of the Pacific basin-wide low sea surface salinity (SSS) feature
119 (e.g. Schanze et al., 2010). Associated with the field campaign, there was an effort to simulate
120 the dynamics in a regional ocean model based on the Regional Ocean Modeling System (ROMS;
121 Li et al., 2019, henceforth "Li19"; Shchepetkin and McWilliams 2011).

122   In this paper, we study BL formation in a couple of individual events within the high-
123 resolution ROMS daily output. The ROMS output displays BLs in the ETP, which can be related
124 to surface circulation, surface convergence, salinity, winds and freshwater forcing from the
125 atmosphere. ROMS allows us to examine the processes involved in BL formation at a scale and
126 level of detail that is not possible with in situ data. Also, while BLs have been frequently studied
127 in the western Pacific, less is known about their characteristics and formation mechanisms in the
128 ETP where forcing is much more seasonal as it is aligned with the seasonal march of the ITCZ.
129 The choice of events to study was somewhat arbitrary. We wanted to look at one instance that
130 could be directly compared to data collected during the SPURS-2 field campaign and another
131 event that was relatively isolated and long-lived. These events are not necessarily typical.
132 However, by studying a couple of individual instances, we may be able to infer more broadly
133 about how BLs relate to the dynamics of the ETP fresh pool and its seasonal extension across the
134 Pacific.

135

2 Data and Methods

2.1 ROMS Simulation

138   The ROMS simulation (Li, 2020) uses data assimilation to constrain the large-scale and
139 large mesoscale circulations as a method for more realistically reproducing BL formation. The
140 model is nested in three levels, 9 km, 3 km and 1 km (see Figure 2 in Li19). We use the 3 km,
141 middle level, with daily average output. In the vertical, the model has 52 levels. To effectively
142 resolve dynamical processes associated with BL formation 22 of those are within the top 100 m,
143 with the topmost level at 1 m. Model output was interpolated onto a set of standard levels to do
144 the calculations discussed and displayed in this paper (Figure 1b). The model covers the time
145 period 1 February 2017 – 31 January 2018, whereas the SPURS-2 field campaign went from late
146 August 2016 to early November 2017. Thus, the model and field campaign overlap for about 9
147 months of 2017 (Figure 1).

148   The atmospheric forcing for ROMS is derived from the 18 km resolution NCEP GFS
149   (National Centers for Environmental Prediction Global Forecast System) operational
150   atmospheric model output. A bulk flux formula (Fairall et al., 2003) is used to calculate the
151   forcing. The inputs include 3-hourly atmospheric fields of 10-m wind speed and direction, net
152   shortwave radiation, downward longwave radiation, 2 m air temperature, 2 m relative humidity,
153   and precipitation. Rainfall in this region tends to come in very heavy and patchy downpours
154   whose sizes are on the order of a few km (Rutledge et al., 2019; Thompson et al., 2019). The 18
155   km resolution of the model forcing does not allow one to distinguish these individual rain events
156   and thus changes to SSS associated with convective rainfall are not represented in the ROMS
157   simulation.

158   The model assimilates a number of datasets. One of these is the monthly-average data
159   from version 4 of the Met Office Hadley Centre ''EN'' series (Good et al., 2013). This monthly
160   dataset constrains three-dimensional T/S fields on spatial scales larger than 400 km and thus is
161   used to reduce model bias. Another assimilated dataset is the gridded AVISO (Archiving,
162   Validation and Interpretation of Satellite Oceanographic data) sea surface height product. This
163   product has a grid of 0.25°, but the effective resolution is about 300 km (Pujol et al., 2016).
164   Satellite SST measurements from the Advanced Microwave Scanning Radiometer-2 (AMSR-2),
165   a passive microwave radiometer flying on NASA's Aqua satellite, are also assimilated. The
166   AMSR-2 SST has a resolution of 0.25°. Using the multi-scale scheme as described in Li et al
167   (2015, 2019), the data assimilation is configured to primarily constrain eddies and circulation
168   with spatial scales larger than 300 km. There are no SPURS-2 in situ observations assimilated in
169   this 3 km model domain.

170   Real-time forecasts of the modeling system during the SPURS-2 field campaign have
171   been encouraging. As presented in Li19, a range of evaluations showed the modeling system
172   predicted the time evolution of the mesoscale circulation compared to measurements of SSH,
173   SST and surface currents. For example, the 2-day SSH forecast had a spatial correlation larger
174   than 0.9 and a root-mean-square error (RMSE) of less than 4 cm against the AVISO gridded data
175   product on a daily basis, and the model SST forecast had a RMSE of 0.6°C against observations
176   from as many as 130 drifters. The vertical T/S profiles are comparable to the observed. As such,
177   we are convinced that the BLs that the model produces essentially represent the same dynamical
178   processes that are responsible for the generation of the observed BLs.

179   From the model output, we computed such quantities as divergence and vorticity.
180   Isothermal layer depth (ILD) and mixed-layer depth (MLD) were determined using the method
181   of deBoyer Montegut et al. (2007). In that paper, the ILD (their "D_{T-02}") is defined as the depth
182   where potential temperature is greater than that at a reference depth by 0.2°C. The MLD (their
183   "D_σ") is the depth where "the potential density … has increased from that at the reference depth
184   by a threshold … equivalent to the density difference for the same temperature change at
185   constant salinity". They use a reference depth of 10 m, but here we use 0 m. BL thickness (BLT)
186   is the difference between ILD and MLD when that difference is greater than zero.

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(a)   (b)
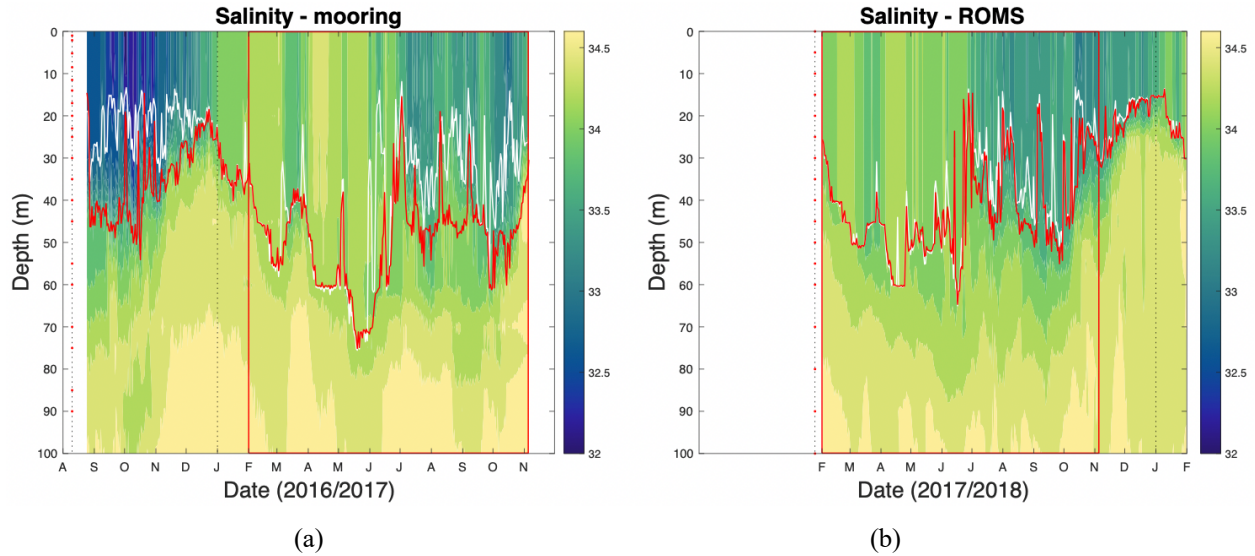
189 Figure 1. Time series of salinity vs. depth observed at (a) the SPURS-2 central mooring
190 (10°N,125°W) (Farrar, 2020) and from (b) the corresponding grid cell in the ROMS simulation.
191 ILD is in white and MLD in red. The difference between them is the BLT. Color scales are at
192 right for each panel. Also note these two panels do not cover the same periods. Mooring salinity
193 covers the period August 2016 – November 2017, whereas the ROMS salinity is computed over
194 February 2017 – January 2018. A red box in each panel outlines the overlapping time period,
195 February-November 2017. At the left of each panel are vertically-arranged red dots showing the
196 locations of the mooring instruments above 100 m in panel (a) and the ROMS interpolated
197 vertical levels above 100 m in panel (b).

198   2.2 In situ data

199   Brief use is made in this paper of data (Farrar, 2020) from the SPURS-2 central mooring
200 (Figure 1a). See Farrar and Pluedemann (2019) for a description of the methods associated with
201 this dataset.

202   Brief use is also made below of underway CTD (uCTD) data from SPURS-2 (Sprintall,
203 2019a,b). These data have vertical resolution of about 6 m. For the section we display below, the
204 horizontal resolution is about 0.1° along-track (Katsura et al., 2020).

205 **3 Results**

206   In the supporting information we include an animation of BLT within the model during
207 the SPURS-2 period along with SSS (Animation S1). Thick BLs are often generated within
208 eddies (e.g. 8-Feb – 20-Feb-2017 at 12.5°N,124°W) or across strong fronts (e.g. 12-May – 22-
209 May-2017 at 13°N,125°W). These BLs can persist for days or weeks, or appear and disappear in
210 a day or two (e.g. 31-July – 1-August-2017). They can be isolated in time and space, or be
211 ubiquitous throughout a large part of the domain shown (e.g. 29 June 2017). BLs appear in the
212 model output, but they are not generally as thick or persistent as those in the *in situ* data. This is
213 evident through a comparison (Figure 1) between model output and observed T/S data from the
214 SPURS-2 central mooring. Note the ubiquitous presence of 20-30 m thick BLs in late summer
215 and fall in the mooring data which are either absent or more sporadic in the ROMS simulation.

216   3.1 October Event

217   Thick BLs are present intermittently along an SSS front south of 10°N that persists for
218   much of October and November (Animation S1). Figure 2 shows this for a three-day period near
219   the end of October. A strong relationship is seen between SSS fronts and BLs. Thick BLs are
220   often present on the fresh side of a front. Examples are seen at 7.5°N,128°W, or 7°N,123°W on
221   all three days. Some of these features are persistent over the three-day period (e.g.
222   7.5°N,128°W). Others evolve rapidly, either dissipating (e.g. 8.5°N,127°W), or suddenly
223   appearing (e.g. 6.5°N,125°W). It's this last feature that we will now study in detail as it
224   develops.

225   Figure 2. Contours: SSS with color scale at left. Shading: BLT in meters with color scale at right.
226   a) 25-October. b) 26-October. c) 27-October.

227   On 27-October-2017 there is a very thick BL around 6-7°N from 126°W to 120°W
228   (Figure 2c). It does not seem to be connected to BLs seen further west in the prior days, as the
229   current speeds are not fast enough for advection to work. Much of the model domain south of
230   8°N on 27-October shows BLs that are >25 m thick. These thick BLs are associated with a

231 complex SSS front that snakes through the region from (6°N,120°W) to (7°N,129°W)
232 (Animation S1, Figure 2c) on this day. On 27-October the BL is centered at about 6.75°N, but is
233 relatively thick from 6°N to 7.5°N along 125°W (Figure 3 right panel). What is clear from the
234 SSS is the low salinity water spreading to the south during the prior two days. The SSS front
235 relaxes and becomes more diffuse at 125°W as seen in the contrast between 26 and 27 October
236 as seen in Figures 2 and 3 and Animation S1. Water in the vicinity of the thick BL is much
237 fresher on 27-October than the two previous days (Figure 3a, b) when no or minimal BLs
238 existed.

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242 Figure 3. SSS from the ROMS domain on (left panel) 25, (center panel) 26 and (right panel) 27
243 October 2017. Color scale is at the top. Red line is along 125°W. The thick green line represents
244 the BLT at 125°W at a given latitude, where zero BLT is the red line and 25 m BLT is indicated
245 by the scale bar at 10.5°N in the left panel.

246   The ocean current vectors (Figure 4) on 27-October show water flowing eastward
247 throughout the entire domain. The thick BL of 27-Oct is associated with the sharply decreased
248 SSS brought about by advection and the southward motion of a SSS front. A convergent feature
249 is evident in the northern part of the region of thick BLs around 7°N (Figure 4 right panel). Just
250 to the south of this convergent feature is an area of divergence near the center of the area of thick
251 BL. This same convergent feature has migrated over the previous two days when it is also
252 associated with thick BLs, although not as thick as on 27 October (e.g. 7.2°N on 26 October). So
253 thick BL formation in this instance appears to be associated with surface convergence and
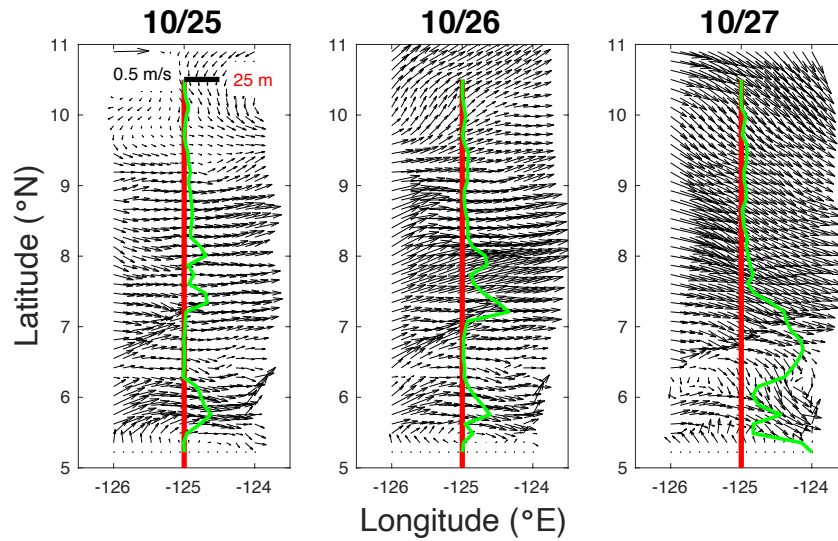254 divergence.

255

Figure 4. As in Figure 3, but for current velocity vectors. A scale arrow is at the top left in the left panel.
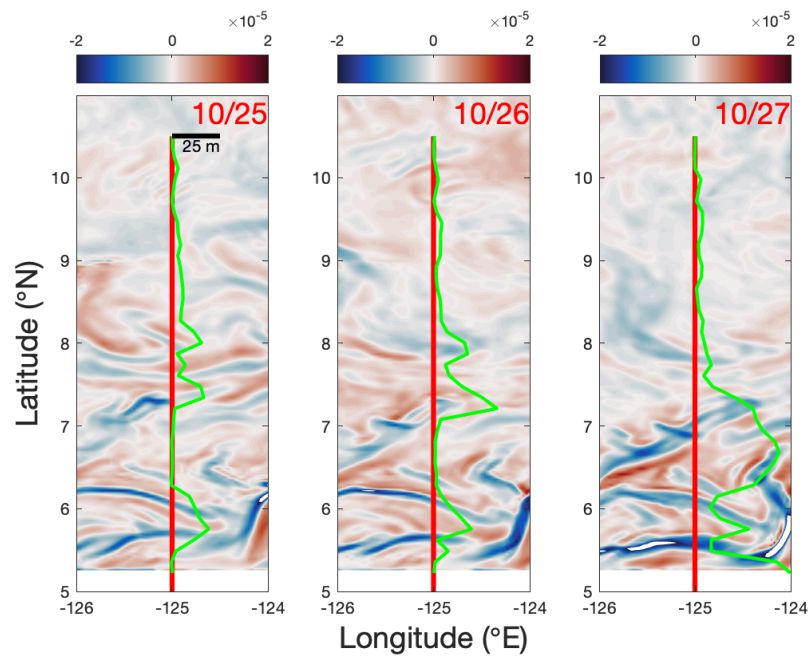
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259

260   Figure 5. As in Figure 3, but for horizontal divergence. Color scale is at the top of each panel in
261   units of s^{-1}.

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263   The thick BLs on all three days are associated with areas of intense surface divergence
264   and convergence culminating on 27 October (Figure 5 right panel). The thickest BLs are
265   associated with surface divergence on the fresh side of the front and there is some indication that
266   surface convergence is associated with reduced BLT (e.g., 5.5°N and 6°N on 27 October). There
267   are also places where thick BLs are associated with alternating surface convergence and
268   divergence, for example around 6°N on 25 October and 7.25°N on 26 October. It should be
269   noted here that we have examined other variables such as SST and vorticity over large scales.
270   Divergence seems to have the most consistent relationship with BLs such as is seen in Figure 5.

271   The precipitation forcing the model is very small on 27 October and far removed from
272   where the thick BLs are formed (Figure 6, right panel). An area of heavy precipitation is located
273   at (7.75°N,125.5°W) on 26 October which may have had an influence on the thick BLs at 6.75°N
274   the following day, though this is not obvious from the SSS shown in Figure 3. Note that this map
275   of precipitation is very smooth compared to the ones of Thompson et al. (2019) and Rutledge et
276   al. (2019) from the same region and time period, and has larger scales of variability.
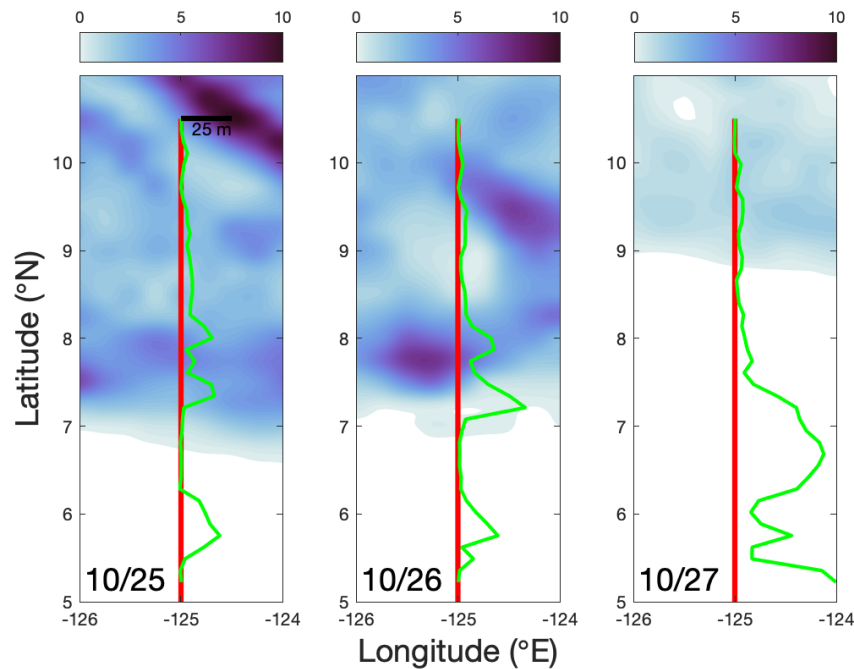
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278

279   Figure 6. As in Figure 3, but for daily average precipitation rate. Color scale is at the top for each
280   panel in units of mm hr^{-1}.

281   Wind speed undergoes a rapid change from 25-26 October to 27 October (Figure 7). On
282   27 October, the winds were nearly calm, whereas in the region of thick BL the winds were up to

283   8 m s⁻¹ on the previous two days. The winds on 25-26 October were mainly out of the south (not
284   shown). Perhaps the sudden change in the winds allowed low SSS water at the surface to drift
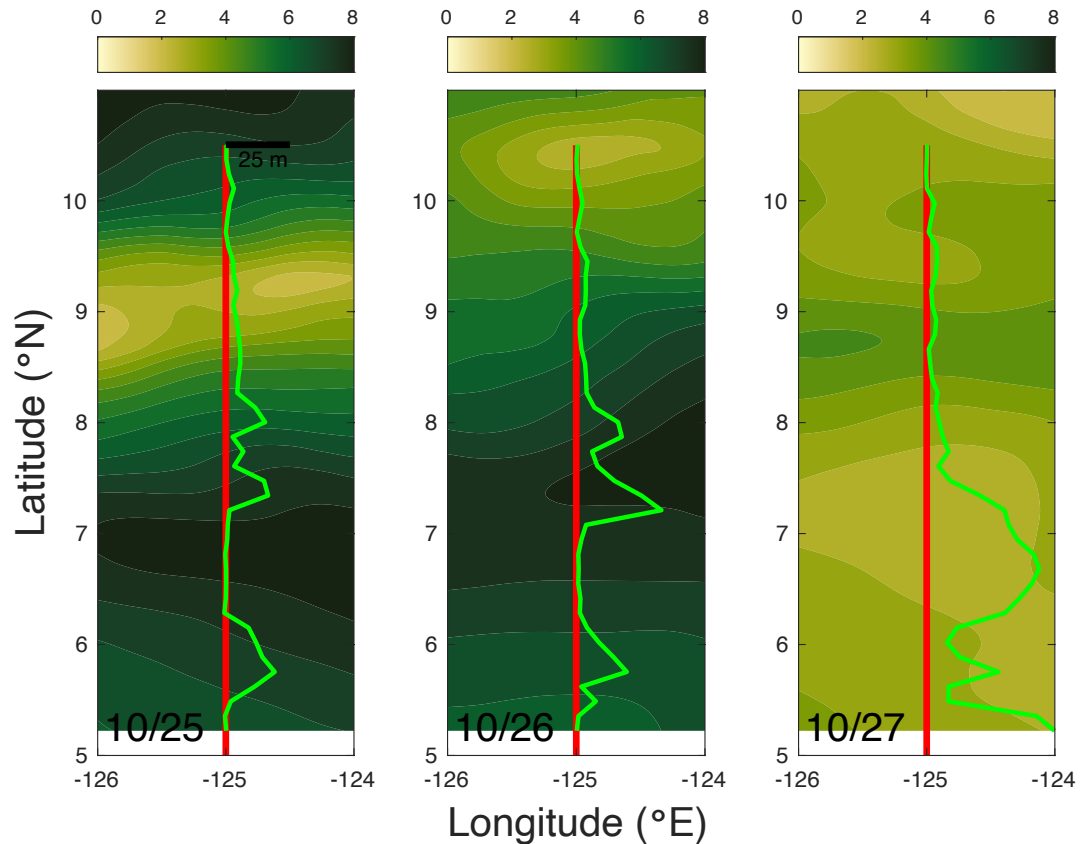285   southward after the change.

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288

289   Figure 7. As in Figure 3, but for surface wind speed. Color scale is at the top for each panel in
290   units of m s⁻¹.

291

292   A meridional section along 125°W (Figure 8) shows fresh surface water spreading across
293   the area between 6 and 7°N and the generation of a thick BL. On 25 and 26 October, there is a
294   thin BL between 7 and 8 °N (Figure 8a and b). By 27-October, relatively fresh surface water had
295   spread southward to around 6°N (Figure 8c). This spreading occurred in the upper 20 m as
296   evident in the large salinity difference shown in Figure 8d. The spreading left a thick BL
297   between 6.25 and 7.5°N. South of there, between 26 and 27 October, the ILD shoaled from 60 to
298   30 m. What we see here is somewhat like the tilting of isohalines posited by CM02, but it is not
299   exactly the same. In the main, the isohalines tilt during the days shown, but the tilting goes on
300   mostly below 20 m depth. That is, the base of the isohalines tilts, but the upper part remains
301   vertical. The salinity front at 7.5°N relaxes and spreads southward. CM02 implied that BLs are

302 generated by current shear which causes the tilting (see their Figure 1). A complicating fact is
303 that the zonal flow is much stronger than meridional. Perhaps in this case the tilting is not caused
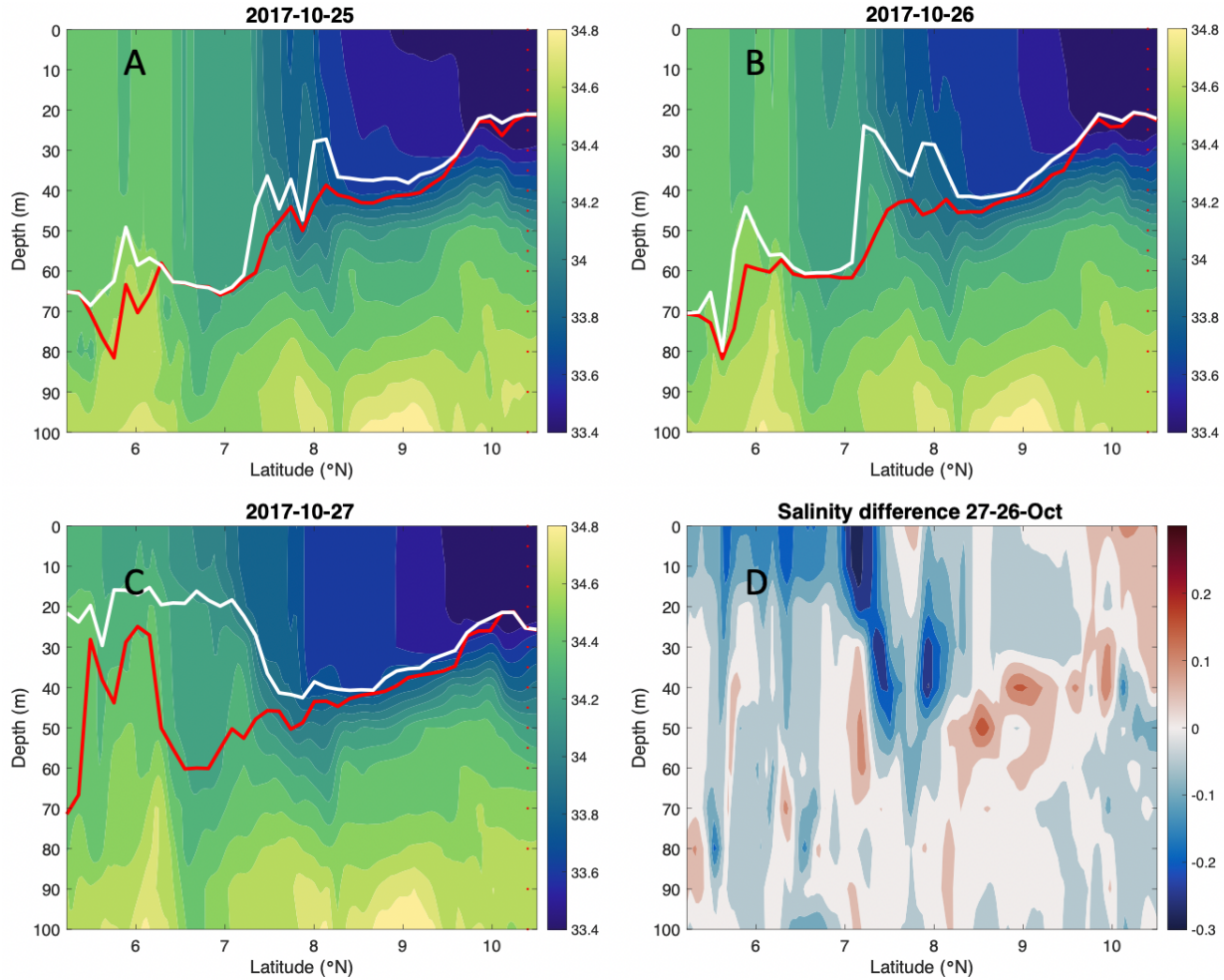304 by cross-front vertical shear, but by some other mechanism.

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308   Figure 8. ROMS Salinity sections along 125°W for (a) 25 October, (b) 26 October and (c) 27
309 October. Each panel represents a daily average centered at 1500 Z each day. Color scales are at
310 right. Small red dots near the right side of panels a-c are the locations of the model levels used in
311 this paper. Thick red line is the ILD, while thick white line is the MLD. (d) Difference between
312 panels (c) and (b).

313

314   October 2017 coincided with one of the two main SPURS-2 cruises. A uCTD section to
315 ~250 m was obtained along 125°W from 10.5 to 5°N on 26-28 October (Figure 9). This uCTD
316 section also showed that a thick BL existed, but it was much thicker (~50 m) and more extensive
317 (from 9° to 6°N) than that produced in the ROMS output (Figure 8). There is as salinity front at
318 the surface near 6.5°N. We also see the same configuration of the front, vertical isohalines at the
319 surface and tilted ones below it as was observed for the model. The difference here is the that BL

320   is much thicker in the uCTD data and the part of the water column with vertical isohalines much
321   thinner. Katsura et al. (2020) show a similar section from a few days later, 3-5 November.
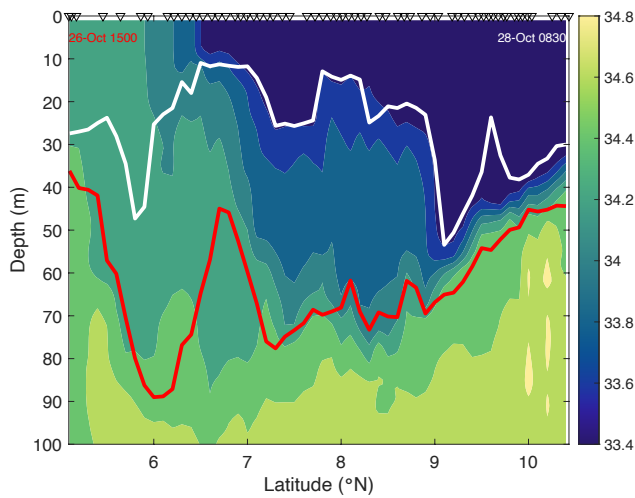

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323   Figure 9. Salinity section from uCTD data (Sprintall, 2019a,b) along 125°W collected on the
324   R/V Roger Revelle, 26-28 October 2017. Color scale is shown at right. Thick red line is the ILD,
325   while thick white line is the MLD. Vertical resolution of uCTD data is ~6 m. Dates and times
326   shown at the top left and right are for the first and last casts. Thus, the section data were
327   collected as the ship moved from south to north and took about 1.7 days to complete. Inverted
328   triangles at the top are the locations of the casts – there were 62 of them.

329   It is clear from Figures 4 and 5 that the presence of BLs is strongly related to surface
330   horizontal divergence/convergence. Thus, because divergence and convergence are usually
331   accompanied by vertical motion, it is likely related to vertical processes such as vertical flows,
332   mixing and entrainment. The vertical velocity along 125°W (Figure 10) shows alternating bands
333   of strong upward and downward flow in the mixed layer south of 7.5°N on 27 October. As
334   expected, these bands are directly related to the maps of surface divergence (Figure 4), upward
335   flow occurs where there is surface divergence and downward flow where there is convergence.
336   The strong flow ceases at the base of the mixed layer, except for one band of downward flow at
337   5.6°N. For the most part, where the BL is thickest, the flow is upward. Where vertical velocity is
338   minimal, north of 8°N, BLs are thin to non-existent. This pattern is repeated at 5.5-6°N and 7.5-
339   8°N on the previous day (Figure 10a).

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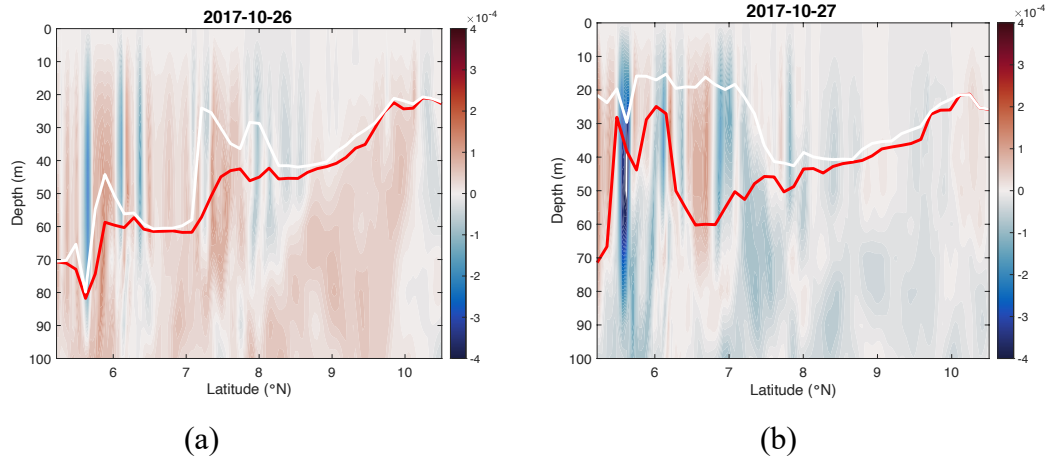342   (a)   (b)

343   Figure 10. Vertical velocity sections along 125°W for (a) 26 and (b) 27 October. Color scales (in
344   m/s) are at right. Red colors are upward and blue downward. Thick red line is the ILD, while
345   thick white line is the MLD.

346

347   3.2 May Event

348   Between 7 and 26 May 2017, especially starting around 9 May, a BL developed across a
349   north-south oriented front between 12 and 13°N near 125°W (Animation S1). This BL reached a
350   maximum BLT of more that 25 m and persisted for more than two weeks within the front,
351   eventually migrating northward to turn to an east-west orientation further north before
352   dissipating by 30-May. The BL is clearly evident in the horizontal plan view (Figure 11a,
353   Animation S2). Similar to the October event, there is tilting of isohalines (Figure 11b). The BL is
354   situated on the low salinity side of the front at 125°W, with fresher water to the east. The front is
355   tilted in the vertical, but not uniformly. All of the tilting occurs at the base of the front between
356   30 and 60 m depth, similar to that found in the October event (Figure 8c). The horizontal
357   velocity field shows a tilting convergent strip that is close to the front near the surface, but tilts
358   through the front to the fresh side with depth (Figure 12a), with the strongest convergence being
359   at the front base at a depth of 60-70 m. The vertical velocity (Figure 11c) has upwelling (red
360   color) just below the surface decreasing to zero at the surface on the fresh side of the front
361   indicating surface divergence. On the opposite side of the front there is downwelling below the
362   surface (blue color) decreasing to zero at the surface indicating surface convergence (Figure 13).
363   At the base of the ML, the sense of change of vertical motion changes, implying convergence at
364   the base of the ML on the fresh side of the front and divergence on the salty side. It should also
365   be noted that no rainfall fell anywhere near the location of this front in this time period, and that
366   examination of the distribution indicated no strong front in temperature as there is in salinity.
367   The temperature difference between the salty and fresh side of the front is at most ~0.1-0.2°C,
368   with the salty side being colder.
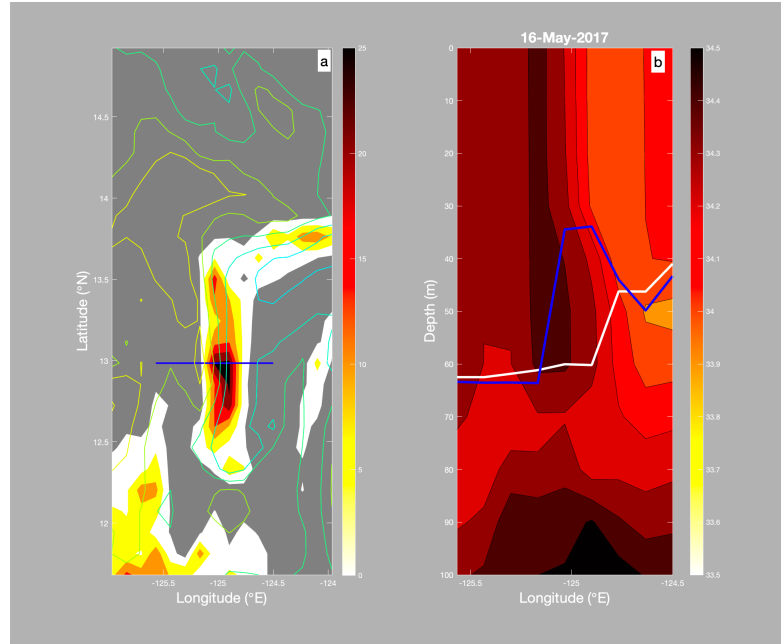
369

370

Figure 11. BLT and salinity on 16 May 2017 extracted from Animation S2. a) Plan view.
Colored contours: SSS with contour interval 0.1. High SSS in yellow and low SSS in blue.
Colors: BLT with color scale at right. Grey color indicates zero BLT. Blue line is the location of
the vertical section displayed in the right panel. b) Vertical salinity section across the front in the
left panel. Blue line is the ILD. White line is the MLD. The difference between them is the BLT.

376

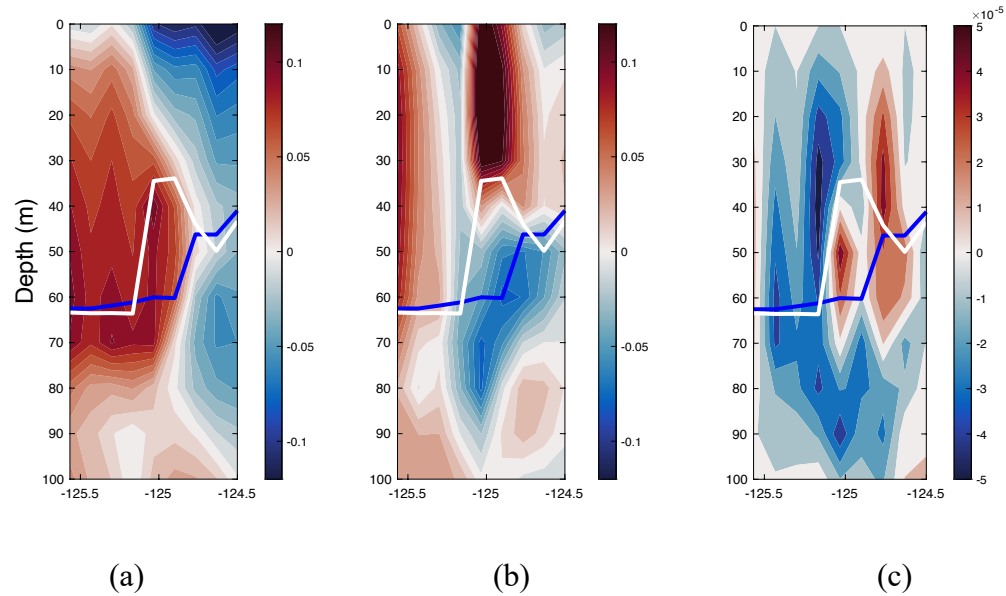377   (a)   (b)   (c)

Figure 12. a) Zonal velocity (m/s) along the same section as in Figure 11 right panel for 16 May
2017. White line is the MLD and blue line is the ILD. Red (blue) colors indicate positive
(negative) velocity, or to the left (right) in the section. b) Same as panel a), but for meridional

381   velocity. Red (blue) colors indicate flow northward or into the page (southward or out of the
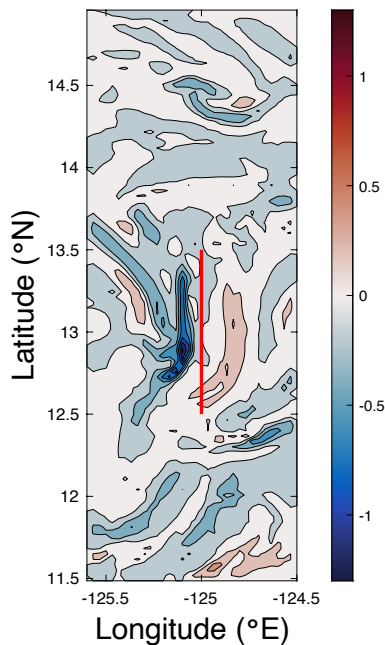382   page) c) Same as panel a) but for vertical velocity. Upward flow in red colors, downward in blue.

383

384   Figure 13. Surface divergence on 16 May 2017. Units are 10^{-5} s^{-1} with color scale at right. A
385   vertical red line indicates the approximate position of the sharpest part of the SSS front in Figure
386   11.

387

4 Summary and Discussion

389   Using a version of ROMS set up for the SPURS-2 region in the eastern tropical Pacific
390   Ocean, we have studied two events when BLs appeared in the model. Both events were
391   associated with sharp mixed layer salinity fronts. The first occurred at 6-7°N in October 2017,
392   and was part of a complex of BLs formed along a large-scale front. The other occurred at 12-
393   13°N in May 2017, at the leading edge of the extension of the EPFP. In each case, a thick BL
394   was created when the bottom part of a salinity front tilted towards the fresh side of the front. In
395   the October event, the formation of the BL was associated with spreading of fresh over salty
396   water and motion of the salinity front. In the May event, the front remained relatively stationary,
397   and persisted for more than two weeks.

398   The hypothesis of KS20 and CM02 is that BLs can be formed by tilting of vertically-
399   oriented isohalines by shear flow at a mixed layer salinity front. The analysis of the May and
400   October events suggests a modified version of this mechanism (Figure 14) that the full
401   concurrent property and velocity fields from the model simulation enable us to better resolve
402   compared to *in situ* observations. This starts with a vertical front of salinity in the mixed layer.
403   On the fresh side of the front the flow is horizontally divergent at the surface, and pulls water up
404   from the mixed-layer base. On the salty side of the front, the flow is convergent at the surface,
405   and pushes water down into the mixed layer. The opposite is the case at the base of the mixed

406   layer, with divergence on the salty side and convergence on the fresh side. Thus, a small vertical
407   circulation cell is set up with water flowing across the front at the mixed layer base from the
408   salty to the fresh side. At the base of the mixed layer, the isohalines then tilt generating the BL
409   that is observed. The mixed layer front is accompanied by a strong vertical shear through the
410   thermal wind relation. This vertical shear may play a role in generating and maintaining the
411   horizontal convergences and divergences that drive the vertical circulation (KS20). In particular,
412   the surface divergence on the fresh side of the front may be due to acceleration of the flow by
413   concentration of the front's isohalines at the location of the BL (Figure 12b).

414   CM02 postulated that a strong salinity gradient can generate a shear flow across the front
415   and tilt the isohalines in the absence of other processes that might balance the pressure gradient.
416   Perhaps there are other processes occurring at the surface (e.g. turbulent mixing or wind stress)
417   that can balance the pressure gradient keeping the front vertical there, but not at the base of the
418   ML. Maybe the front itself generates along-front vertical shear (Figure 12b) as it forms through
419   the thermal wind relation which is able to balance the across-front pressure gradient near the
420   surface but not as much at the ML base. The front shown in Figure 11 is there for a long enough
421   time to become geostrophically balanced, and so the thermal wind relation holds there, and the
422   across-front shear is much stronger near the surface than at the ML base (Figure 12a).
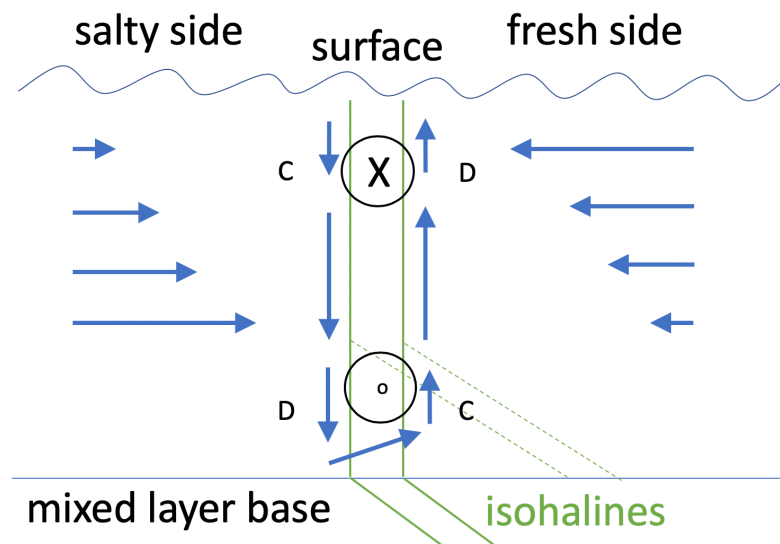

423

424   Figure 14. Schematic view of proposed BL formation mechanism in the ETP showing a section
425   across a zonal salinity front in the mixed layer as in Figure 11b. The zonal velocity, the arrows at
426   the left and right, indicate a tilting shear flow. On the salty side of the front there is horizontally
427   convergent flow at the surface and divergent flow at the base of the mixed layer. By contrast, on
428   the fresh side there is divergent flow at the surface and convergent flow at the base of the mixed
429   layer. This sets up a vertical circulation that acts to tilt isohalines mainly at the front's base
430   (dashed lines) and generate a thick BL. Included is a strong vertical shear parallel to the front
431   (into/out of the page) which helps to maintain the vertical orientation of the front at the surface
432   and contribute to the convergent and divergent parts of the flow.

433   The proposed mechanism shown in Figure 14 is two-dimensional. However, it greatly
434   simplifies the mesoscale surface circulation that in reality generates and moves the front and
435   associated convergence/divergence, and it ignores mixing and entrainment of salt through the

436   base of the mixed layer. The schematic does however, place emphasis on vertical processes in
437   the vicinity of a front, which seems appropriate given the apparent association between BL
438   formation, horizontal divergence and the presence of fronts (KS20). Indeed, Vialard and
439   Delecluse (1998b) suggest a similar mechanism, including downwelling near the front, but
440   emphasize the role of precipitation to a greater degree. That study was conducted in the western
441   tropical Pacific where precipitation may be more important in the BL formation process.

442   KS20 emphasize the importance of Ekman transport in the formation of BLs, especially
443   in summer and fall in the eastern tropical North Pacific. We note that formation of thick BLs in
444   the October event is associated with a sudden relaxation of the winds between 26 and 27-October
445   (Figure 7b, c). There is no indication that the currents slowed or stopped as a result of this
446   (Figure 4). However, the disturbance in the wind forcing may have been enough to produce
447   submesoscale eddies (Thomas et al., 2008) and a growing set of convergences and divergences at
448   the surface (Figure 5) that were able to generate fronts and BLs during October 2017 (see also
449   Animation S1, 18-31-October-2017).

450   Tanguy et al. (2007) discuss the diversity of situations and causes responsible for the BLs
451   observed in the tropical Atlantic. Some instances of BLs arise in similar ways to those depicted
452   here in the ETP, on the fresh side of a mixed layer salinity front and at the front's base (see their
453   Figures 11c, e and f). As noted above, it has been hypothesized that BLs act to insulate the full
454   mixed layer from surface buoyancy flux and entrainment cooling from below (Godfrey and
455   Lindstrom, 1989; Vialard and Delecluse, 1998a) and concentrate heating into the upper part of
456   the mixed layer. If this is the case, then it follows that in the tropics, as these BLs are formed,
457   heating preferentially occurs on the fresh sides of submesoscale fronts. As the mixed layer is
458   heated in that region, the density contrast across the front is enhanced, along with the lifetime of
459   the front. This may be why these fronts can last for long periods of time, such as the one in the
460   Animation S2 which lasts more than two weeks, despite the fact that they are unstable. A
461   counterpoint to this is the fact that strong gradients in SST never develop in the two instances
462   where SSS fronts are studied, which we would have expected in the event of differential heating.

463   In this work, we have analyzed two very limited appearances of BLs, and attributed
464   certain characteristics to them. This is not to say that all, or even most, BLs in the ETP
465   necessarily follow this script. However, given the ubiquity of these features as seen in Animation
466   S1 and documented by KS20, there is no doubt the BLs introduce variance into the processes of
467   entrainment at the base of the mixed layer and the flux of heat and fresh water across the surface.
468   This variance itself may help to generate the submesoscale flows that create fronts (Thomas et al,
469   2008) and in turn work to increase variance in salinity, a positive feedback loop. This positive
470   feedback, acting on the large scale salinity field can perhaps lead to or accelerate the extension of
471   the surface salinity minimum that stretches across the tropical Pacific during the summer and fall
472   (Melnichenko et al., 2019).

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