Upper Ocean Stratification in the Eastern Pacific during the SPURS-2 Field Campaign

Shota Katsura¹, Janet Sprintall², and F M Bingham³

¹Scripps Institution of Oceanography, University of California, San Diego ²University of California ³University of North Carolina Wilmington

November 24, 2022

Abstract

The region between a shallow mixed layer and a deep isothermal layer resulting from salinity stratification is called a barrier layer (BL). Since BLs hinder the surface heat and momentum exchange with the ocean subsurface, they play an important role in air-sea interaction. Synoptic features and formation of BLs and associated temperature inversions (TIs) in the Eastern Pacific Fresh Pool (EPFP) were investigated using shipboard observations. BLs and TIs were found in the high precipitation EPFP, a frontal transition zone (FTZ) and in the sea surface salinity (SSS) front during a 2016 boreal summer cruise. During a 2017 boreal autumn cruise, BLs and TIs were found from the southern part of the EPFP to the SSS front. The BLs in the SSS front and the FTZ were meridionally displaced from the precipitation maximum during both the 2016 and 2017 cruises. Freshening and cooling by tilting of both the isohalines and isotherms of the SSS front occurred via Ekman and geostrophic flow during both cruises, and also within the EPFP during 2016. The SSS front was a dominant contributor to the density gradient in the horizontal plane. A high dissolved oxygen content observed within BLs confirmed that the surface flow plays an important role in the BL and TI formation through the tilting process. Patchy distribution of freshening and cooling by tilting implies an intermittent BL and TI formation with short time scales.

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3 S. Katsura¹, J. Sprintall¹, and F. M. Bingham²

⁴ ¹ Scripps Institution of Oceanography, University of California, San Diego, La Jolla.

² Center for Marine Science, University of North Carolina Wilmington, Wilmington, North
 Carolina.

- 7
- 8 Corresponding author: Shota Katsura (<u>skatsura@ucsd.edu</u>)
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10 Key Points:

- In the eastern tropical Pacific, barrier layers were thickest in the salinity front and
 temperature inversions warmest in the fresh pool.
- Ekman and geostrophic flow form barrier layers and temperature inversions by tilting of
 salinity fronts on synoptic spatio-temporal scales.
- Tilting of salinity fronts occurs only intermittently resulting in a patchy distribution of
 barrier layer formation in the eastern Pacific.

17 Abstract

18 The region between a shallow mixed layer and a deep isothermal layer resulting from salinity

19 stratification is called a barrier layer (BL). Since BLs hinder the surface heat and momentum

20 exchange with the ocean subsurface, they play an important role in air-sea interaction. Synoptic

21 features and formation of BLs and associated temperature inversions (TIs) in the Eastern Pacific

22 Fresh Pool (EPFP) were investigated using shipboard observations. BLs and TIs were found in

the high precipitation EPFP, a frontal transition zone (FTZ) and in the sea surface salinity (SSS)
 front during a 2016 boreal summer cruise. During a 2017 boreal autumn cruise, BLs and TIs

were found from the southern part of the EPFP to the SSS front. The BLs in the SSS front and

the FTZ were meridionally displaced from the precipitation maximum during both the 2016 and

27 2017 cruises. Freshening and cooling by tilting of both the isohalines and isotherms of the SSS

front occurred via Ekman and geostrophic flow during both cruises, and also within the EPFP

during 2016. The SSS front was a dominant contributor to the density gradient in the horizontal

30 plane. A high dissolved oxygen content observed within BLs confirmed that the surface flow

31 plays an important role in the BL and TI formation through the tilting process. Patchy

32 distribution of freshening and cooling by tilting implies an intermittent BL and TI formation with

33 short time scales.

34 Plain Language Summary

35 In some regions of the ocean surface layer, the base of a density-defined mixed layer is shallower

than that of a temperature-defined isothermal layer due to a strong salinity stratification. The

37 region between the base of the mixed layer and the isothermal layer is called a barrier layer (BL).

The BL acts as a barrier to heat and momentum exchange between the surface and subsurface

39 ocean and may have an important role in air-sea interaction. When BLs contain temperature

40 inversions (TIs) of water warmer than the sea surface, they can work to increase sea surface

41 temperature being entrained into the overlying surface mixed layer and hence have a significant

42 impact. Based on shipboard observations, wind-driven Ekman flow and geostrophic flow caused

43 surface freshening and cooling that contributed to the formation of BLs and TIs in the Eastern

44 Pacific Fresh Pool. The role of the surface flows contributing to the BL and TI formation were

45 supported by the horizontal structure of the observed salinity, temperature and oxygen profiles.

46 However, the freshening and cooling of the BLs and TIs showed a patchy distribution suggesting

47 their formation occurs intermittently.

48 **1 Introduction**

Sea surface salinity (SSS) in the eastern tropical Pacific is minimum in the Eastern 49 Pacific Fresh Pool (EPFP) where the mean SSS is lower than 34.0 (Fig. 1). The EPFP has mean 50 SSS < 33.5 between 5° -15°N and east of 130°W resulting from precipitation associated with the 51 intra-American monsoon system (Amador et al., 2006) and westward transport of water vapor 52 across the Panama isthmus (Benway and Mix, 2004). The EPFP extends westward and forms a 53 54 zonal band of low SSS (< 34.0) along $\sim 10^{\circ}$ N likely related to high precipitation due to the Intertropical Convergence Zone (ITCZ) and/or westward advection by the North Equatorial 55 Current (NEC). The EPFP roughly aligns with the eastern Pacific warm pool adjacent to the 56 central American isthmus, where sea surface temperature (SST) is $> 28^{\circ}$ C (Fig.1). A seasonal 57 cycle in SSS is evident in the horizontal extent of the EPFP and is controlled by a combination of 58 freshwater flux, horizontal advection, and vertical mixing (Delcroix and Hénin, 1991; Fiedler 59

and Talley, 2006; Alory et al., 2012; Yu, 2014; Melnichenko et al., 2019). The western edge of

- 61 the EPFP also migrates interannually in association with precipitation anomalies related to the El
- Niño-Southern Oscillation (ENSO; Guimbard et al., 2017). The SSS front south of the EPFP
- 63 separates the fresher water induced by the ITCZ precipitation to the north from the saltier water
- to the south (Yu, 2014, 2015; Kao and Lagerloef, 2015). Seasonality in the meridional migration and intensity of the SSS front couples with the EPFP via the wind field and Ekman processes
- and intensity of the SSS front couples with the EPFP via the wind field and Ekman processes
 (Yu, 2015). Considering that salinity is an important indicator of the freshwater flux between the
- ocean and atmosphere (Schmitt, 2008; Lagerloef et al., 2010) and that heavy rainfall associated
- 68 with the ITCZ is a major source of freshwater input to the ocean (Waliser and Gautier, 1993; Yu
- et al., 2015), knowledge of the salinity structure and variability in the eastern tropical Pacific is
- important for a better understanding of the hydrological cycle. Indeed, a few recent studies have
- ⁷¹ linked SSS variability to terrestrial rainfall (e.g. L. Li et al., 2016a; 2016b; Rathore et al, 2020)
- although it remains unclear on the mechanisms that might result in such a statisticalcorrespondence.
 - 25°N 34 34.5 20°N 34 15°N 33.5 10°N 33 5°N 34 34.5 0° 35 5°S 150°W 140°W 130°W 120°W 110°W 100°W 90°W

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78 Throughout much of the world oceans, temperature controls mixed layer depth (MLD), although in some regions salinity stratification is important. When the density-stratified mixed 79 layer is shallower than the thermally-stratified isothermal layer, the salinity stratified region in 80 between is called a barrier layer (BL; Fig. 2). BLs can reduce the cooling effect of entrainment 81 because the entrained water has almost the same temperature as the overlying mixed layer (e.g., 82 Godfrey and Lindstrom, 1989; Vialard and Delecluse, 1998; Yan et al., 2017; Pujiana and 83 McPhaden, 2018). When a BL is associated with a vertical temperature inversion (TI; Fig. 2) 84 that contains warmer water than the surface mixed layer above, the entrainment effect can even 85 warm the mixed layer. BLs also trap momentum flux from the atmosphere to the ocean and can 86 result in accelerated flow within a shallower near-surface layer (Roemmich et al., 1994; Vialard 87 and Delecluse, 1998). For all these effects, the BL is an important factor in air-sea interaction 88 and offers a potential mechanism for linking the salinity stratification to the hydrological water 89 cycle (e.g., Drushka et al., 2014; Y. Li et al., 2017a; 2017b). 90

Figure 1. Distribution of mean sea surface salinity in 2016–2017 from SMAP. The rectangle
 indicates the region of the SPURS-2 field campaign (see Figure 3). Magenta lines indicate the
 mean surface temperature isotherms of 28°C in 2016–2017 from OISST.



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Figure 2. Vertical profiles of salinity (blue), temperature (red), and σ_{θ} (black) observed by an underway Conductivity-Temperature-Depth (uCTD) profiler at 9.771°N, 234.833°W on 26 Oct 2017. Horizontal dashed black and red lines indicate the MLD and ILD, respectively. In this case, the barrier layer (ILD - MLD) is 14 dbar thick.

A seasonal climatological study of BLs and TIs based on Argo profiling float data by 96 Katsura and Sprintall (2020; henceforth KS2020) revealed that BLs are distributed along the SSS 97 front south of the EPFP with a seasonal peak in boreal summer and autumn. Bingham et al. 98 (2020) show an example of this from a high-resolution model. BLs in the SSS front tend to be 99 100 associated with TIs within the gap between the eastern and western warm pools (see Fig. 1) in boreal autumn. KS2020 further clarified that southward Ekman advection across the SSS front 101 driven by eastward wind works to both freshen and cool the surface layer and contributes to the 102 103 formation of BLs with TIs through the tilting of the SSS front in boreal summer and autumn. The SSS front is the dominant contributor to the horizontal density gradient and compensates the 104 horizontal temperature gradient, which make BL and TI formation possible through tilting 105 106 processes (Cronin and McPhaden, 2002). Precipitation was a secondary contributor to BL formation in autumn although it contributed to the broader distribution of BLs within the EPFP 107 in summer (KS2020). Considering the extremely shallow mixed layer in this eastern Pacific 108 region (Suga et al., 2004; Fiedler and Talley, 2006), BLs and associated TIs can have a 109 significant impact on SST and the heat budget of the overlying mixed layer and in the evolution 110 of ENSO (e.g., Maes et al., 2002; 2005). Nonetheless, the Argo data used in KS2020 permit 111 investigation of BLs and TIs only on monthly-time scales, even though both BLs and TIs may be 112 much shorter lived. In addition, BLs determined from individual profiles are known to exhibit 113 more uneven or "patchy" distribution compared to the fairly continuous distribution in spatial 114

extent and seasonality evident in monthly climatological studies such as KS2020 (Sato et al.,

116 2004; 2006; Mignot et al., 2009). Patchiness in BL presence or BL thickness in a region will

potentially degrade the impact of the role that BLs play in air-sea interaction. If the spatial gaps

- between BL presence are large or "porous" (Mignot et al., 2009) then the ability of BLs to
- reduce heat exchange will likely be much diminished, potentially permitting the maintenance of
- normal entrainment processes in the region.

The Salinity Processes in the Upper-ocean Regional Study 2 (SPURS-2) was a multiyear 121 field program to study the upper-ocean salinity structure and understand the physical processes 122 controlling the salinity balance in the precipitation-dominated eastern tropical Pacific (Lindstrom 123 et al., 2019). The focus area of SPURS-2 was around 10°N, 125°W in the western part of the 124 EPFP. Shipboard surveys on the R/V Roger Revelle were conducted in this area in 125 August-September 2016 and again in October-November 2017 (Fig. 1). During these two 126 cruises, concurrent observations of both the ocean and atmosphere were conducted at high spatial 127 resolution from various platforms (Bingham et al., 2019). The period of these two cruises 128

corresponds to the seasonal peak of BLs and TIs in boreal summer and autumn (KS2020), and
 indeed, BLs with TIs were detected during the SPURS-2 cruise (Sprintall, 2019).

131 The purpose of this study is to investigate the distribution and formation of the BLs and TIs during the SPURS-2 cruises. Here we take advantage of the high spatial resolution and 132 synoptic concurrent measurements collected during SPURS-2 to better understand the upper 133 ocean stratification on shorter space and time scales compared to the climatological study of 134 135 KS2020. The high horizontal along-track resolution from the meridional transects of hydrographic observations collected during the SPURS-2 cruises cannot be achieved by Argo 136 profiling floats, such as employed in the KS2020 study. In addition, repeat surveys along the 137 same meridional transect during both SPURS-2 cruises enables us to investigate more detailed 138 "synoptic" features of BLs and TIs, their patchiness in distribution, as well as determine their 139 relationship to the concurrent background hydrography and circulation. The data and methods 140 are described in Section 2. The distribution of BLs and TIs, their relationship to the background 141 hydrography and formation mechanisms are explored in Section 3. Finally, the synoptic features 142 and formation of BLs and TIs detected in the SPURS-2 cruises are summarized and discussed in 143 144 Section 4.

145 **2 Data and Methods**

In this study, we use vertical profiles of the upper ocean from an underway Conductivity-Temperature-Depth (uCTD) and a shipboard CTD-O₂ system collected during the two SPURS-2 cruises on the *R/V Roger Revelle* (Fig. 3). The first cruise in boreal summer from 21 August to 12 September 2016 collected 259 uCTD profiles and 50 CTD profiles. The second cruise in boreal autumn from 21 October to 11 November 2017 collected 493 uCTD profiles and 8 CTD

151 profiles.





Figure 3. Location of uCTD (black, orange, and red triangles), CTD (blue squares), and Argo profiles (green stars) during SPURS-2 (a) 2016 boreal summer cruise (21 August–12 September 2016) and (b) 2017 boreal autumn cruise (21 October–11 November 2017). Orange and red triangles indicate uCTD profiles along 125°W, which are slightly shifted zonally for visibility. Red triangles in (a) and (b) indicate uCTD profiles used for Figures 5 and 7, respectively.

Measurements of temperature and conductivity (and thus salinity) from 6-400 m were 158 obtained using the uCTD profiler. The observations were post-processed to remove salinity 159 160 spikes following Ullman and Hebert (2014) and then interpolated to a 1-dbar vertical resolution using an Akima spline (Akima, 1970). Potential temperature (θ) and density (σ_{θ}) were then 161 calculated. In each cruise, seven meridional transects of uCTD casts were conducted along 162 125°W at a ~0.1° latitude horizontal spacing (Fig. 3) which corresponds to ~30-minute or ~1-163 hour temporal intervals depending on the ship speed along-track. Additional uCTD casts were 164 located within the general SPURS-2 region (Fig. 3). 165

166 The temperature, salinity, pressure, and dissolved oxygen profiles from 0–1000 dbar 167 were obtained using the on-station shipboard CTD-O₂ system. The observations were vertically 168 averaged to a 2-dbar interval and θ and σ_{θ} were calculated for each profile. During the 2016 169 cruise, the 50 CTD profiles were collected in a grid-like pattern with a horizontal resolution of 170 0.5° latitude × 0.5° longitude (Fig. 3a). During the 2017 cruise, 8 CTD casts were conducted 171 along ~125°W (Fig. 3b).

Temperature and salinity profiles from Argo profiling floats were also available during each SPURS-2 cruise period (Fig. 3) and were obtained from the advanced automatic QC Argo data version 1.2. from the Japan Agency for Marine-Earth Science and Technology and were quality checked as outlined by Oka et al. (2007). The temperature and salinity profiles were 176 vertically interpolated to a 1-dbar interval using an Akima spline, and θ and σ_{θ} were 177 subsequently calculated.

Current velocity profiles were measured underway from the ship's hull via acoustic Doppler current profiler (ADCP) during the two SPURS-2 cruises. Specifically, here we use the shipboard data from an Ocean Surveyor narrowband 150 kHz system that measured currents from ~17 m to ~300 m depth at a vertical resolution of 8 m. The ADCP velocity data were quality controlled and processed using the University of Hawaii UHDAS software system, and vertically interpolated to a 1-dbar interval using an Akima spline.

Shipboard *in situ* air-sea flux state variables (e.g., SST, air temperature, wind etc.), and
rainfall (e.g. optical and manual rain gauges) measurements are also available during both
SPURS-2 cruises (Clayson et al., 2019). The 10-m values of wind speed and the bulk fluxes of
wind stress (corrected for ocean current using the near-surface ADCP velocity from the
uppermost bin) were computed using the COARE 3.5 algorithm (Fairall et al., 2003; Edson et al.,
2013).

SSS and SST were from the daily L3 8-day running mean 70-km version-4.0 product of
the National Aeronautics and Space Administration (NASA) Soil Moisture Active Passive
(SMAP; Meissner and Wentz, 2018) and from the Advanced Very High Resolution Radiometer
daily product of Optimum Interpolation Sea Surface Temperature (OISST; Reynolds et al.,
2007), respectively. The horizontal resolution of these gridded data is 0.25° latitude × 0.25°
longitude.

196Precipitation was from the NASA Integrated Multi-satellitE Retrievals for GPM197(IMERG) version 4.0, a merged satellite product available from 2014 every 30 min at 0.1° 198latitude $\times 0.1^{\circ}$ longitude horizontal resolution (Kummerow, 1998). IMERG is meant to provide199an improved rainfall product over the remotely sensed Tropical Rainfall Measuring Mission200(TRMM) that is based on a single sensor (Skofronick-Jackson et al., 2017).

Isothermal layer depth (ILD) was defined as the depth at which θ decreases by 0.2°C 201 from 10-dbar depth (de Boyer Montégut et al., 2007). MLD was defined as the depth at which σ_{θ} 202 increases from 10-dbar depth by the equivalent value to a temperature decrease of 0.2°C at 10-203 dbar salinity (Sprintall and Tomczak, 1992). Barrier layer thickness (BLT) was defined as the 204 difference between the ILD and MLD when that difference is greater than zero. The amplitude 205 of the temperature inversion associated with any BL ($\Delta \theta$) was defined as the difference between 206 the temperature at the vertical temperature maximum within the BL minus the temperature at the 207 MLD (KS2020). Following previous studies, we only considered BLs with BLT > 10 dbar and 208 TIs with $\Delta\theta > 0.1$ °C (e.g., Sato et al., 2004; 2006; KS2020). This does not mean BLs with 0 < 209 BLT < 10 dbar are not important because in some regions even thin BLs have been shown to 210 211 interfere with the cooling effect of entrainment and modify the heat budget of overlying mixed layer (Drushka et al., 2014). Rather, in our study we are more interested in understanding the 212 conditions that might lead to BL and TI formation, as well as being mindful about the vertical 213 resolution of the data in determining BLT. For the 2016 and 2017 cruises, 36.0% and 26.2% of 214 all profiles were found to have non-zero BLT < 10 dbar, respectively. 215

For each of the uCTD transects along 125°W during the two SPURS-2 cruises, we defined three regions: the SSS front, the frontal transition zone (FTZ), and the EPFP. Mean SSS in the EPFP was 32.95 during the 2016 summer cruise compared to 33.41 during the 2017 autumn cruise reflecting the seasonality of the region, so SSS was not necessarily a good criterion to define the EPFP during both cruises. Alternatively, we found that $\partial SSS/\partial y$ clearly

separated the EPFP from the SSS frontal region. The boundary between the SSS front and the

FTZ was best defined as the location where $\partial SSS/\partial y < -10 \times 10^{-6} \text{ m}^{-1}$. The SSS front was then

defined as the region to the south of that boundary. The FTZ was defined as the region between this boundary and a change of 0.5° in latitude to the north. The EPFP was then defined as the

region north of the northern edge of the FTZ. When an SSS front was not detected in a transect

based on this criterion, all of the profiles in the transect were assumed to be within the EPFP.

227 The boundary was detected in 3 transects in each cruise, and the mean latitude during the 2016

and 2017 cruises was $7.18^\circ N \pm 0.03^\circ$ and $7.06^\circ N \pm 0.57^\circ,$ respectively.

3 **Results**

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3.1 Hydrography and Distribution of BLs and TIs during SPURS-2 Field Campaign

The mean distribution of SSS during the 2016 boreal summer cruise showed a zonal band 231 of low SSS (< 33.0) at 8°-11°N (Fig. 4a) with SSS increasing to the south. North of 11°N, SSS 232 233 lower than 33.0 was found west of 126°W, and SSS higher than 33.0 extended northeastward from 11°N, 126°W. The distribution of mean SST in the 2016 summer cruise mirrored the mean 234 SSS distribution (Fig. 4b); high SST corresponding with low SSS. A zonal band of high SST > 235 28.5°C was found at 8°-11°N, corresponding to the zonal band of low SSS, and SST decreased 236 to the south. SST lower than 28.5°C extended eastward from 11°N, 126.5°W, with SST higher 237 than 28.5°C found to the north. During the 2016 summer cruise, northeastward winds prevailed 238 north of 8.5°N and near calm winds south of 8.5°N (Fig. 4c), corresponding to the expected 239 seasonality of the regional wind field in the eastern Pacific (Guimbard et al., 2017; KS2020). 240 The eastward flowing North Equatorial Countercurrent (NECC) was evident near 7°N in the 241 near-surface with speeds $< 0.5 \text{ m s}^{-1}$ during the 2016 summer cruise (Fig. 4d). Occasional weak 242 westward currents and small-scale perturbations were detected along the 125°W section. 243



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Figure 4. Distribution of (a) BLT (dbar) and (b) $\Delta\theta$ (°C) from uCTD casts (triangles), CTD casts 245 (squares), and Argo profiling floats (stars) during SPURS-2 2016 cruise. Triangles along 125°W 246 are slightly shifted zonally to improve visibility. Contours indicate (a) the mean SSS from 247 SMAP and (b) the mean SST from OISST (°C) from 21 August to 12 September 2016. Gray 248 shading indicates (a) SSS lower than 33.0 and (b) SST higher than 28.5°C. Distribution of (c) 249 wind stress (N m⁻²) and (d) near-surface current (m s⁻¹) during the SPURS-2 2016 cruise, 250 averaged 1-hour prior and posterior to the time of uCTD and CTD profiles. Red and blue arrows 251 in (c) and (d) indicate eastward and westward direction, respectively. 252

During the 2016 boreal summer cruise, BLs with TIs were detected in all three regimes, albeit with different characteristics: BLs within the SSS front were thicker than in the EPFP and FTZ, while BLs within the EPFP showed a more coherent distribution. TIs were less frequent in the SSS front compared to the FTZ and the EPFP. The BL presence north of 8.5° N in the EPFP corresponded to where the mean SSS was < 33.0 (Fig. 4a). These BLs tended to be associated with the TIs in the zonal band where the mean SST > 28.5°C (Fig. 4b).

The temperature and salinity profiles captured during the longest transect along $125^{\circ}W$ (Fig. 5) are largely representative of the profiles from the other six transects during the 2016 cruise. The ILD was around 55 dbar while MLD ranged from 15-50 dbar in the EPFP and FTZ, resulting in BLs with 10–40 dbar thickness. In the SSS frontal region, thick BLs > 35 dbar were associated with the southern edge of an isolated warm, fresh region at around 6°N but otherwise were practically non-existent. TIs were observed in the EPFP where the temperature within isothermal layers was warmer than 28.5°C (Fig. 5b) and were warmest just north of the FTZ.

For all meridional transects along 125°W during the 2016 cruise, the mean BLT in the SSS frontal regime was 29.22 dbar and 28.71 dbar in the FTZ, thicker than in the EPFP at 20.29 dbar, although there was little statistical difference between the mean BLT across all regimes

268 dbar, although there was little statistical difference between the mean BLT across all regimes 269 (Table 1). The mean $\Delta\theta$ in the SSS front was nearly half the amplitude of the $\Delta\theta$ in the EPFP

and FTZ. The frequency of BLs and TIs in the FTZ was 100% and 85.7%, respectively,

compared to only 64.9% (43.9%) of profiles with BLs and 37.3% (2.4%) of profiles with TIs in

the EPFP (SSS front).





Figure 5. Meridional transects of (a) salinity and (b) θ (°C), and (c) distribution of BLT (dbar; line) and $\Delta\theta$ (°C; dots) along 125°W from uCTD profiles observed during 8–10 September 2016 (red triangles in Figure 2a). Inverted triangles at the top of each panel indicate the locations of uCTD profiles in the EPFP (blue), the FTZ (green), and the SSS front (red). Gray shading in (a) and (b) indicates salinity lower than 33.5 and θ higher than 28°C, respectively, and blue and red curves indicate the MLD and ILD, respectively. Dashed contours in (b) denote $\theta = 28.2^{\circ}$ C.

Black dots in (b) denote the depth of the vertical temperature maximum where $\Delta \theta > 0.1$ °C.

		MLD (dbar)	ILD (dbar)	BLT (dbar)	Δθ (°C)	Number of Profile	Number of Profile with BL and Frequency	Number of Profile with TI and Frequency
	EPFP	29.50 (1.72)	44.21 (2.23)	20.29 (2.02)	0.233 (0.026)	134	87 (64.9%)	50 (37.3%)
2016	FTZ	24.71 (3.97)	53.43 (2.78)	28.71 (6.17)	0.224 (0.046)	14	14 (100.0%)	12 (85.7%)
	SSS front	26.02 (5.10)	41.27 (5.77)	29.22 (5.16)	0.122 (-)	41	18 (43.9%)	1 (2.4%)
	EPFP	25.35 (1.03)	44.46 (2.15)	30.22 (2.61)	0.188 (0.017)	226	130 (57.5%)	63 (27.9%)
2017	FTZ	18.78 (2.58)	58.17 (3.23)	39.39 (3.31)	0.149 (0.015)	18	18 (100.0%)	11 (61.1%)
	SSS front	37.55 (4.89)	64.08 (5.37)	32.14 (5.79)	0.147 (0.020)	53	42 (79.2%)	12 (22.6%)

Table 1. Mean values of MLD (dbar), ILD (dbar), BLT (dbar) and magnitude of $\Delta\theta$ (°C) and the 282

- number of profiles in the EPFP, the FTZ, and the SSS front along the 125°W transects during the 283
- 2016 and 2017 cruises. Values in the parentheses indicates the 95% confidence interval. 284
- Calculation of mean BLT and mean $\Delta\theta$ was performed for all uCTD profiles with BLT > 10 dbar 285
- and $\Delta \theta > 0.1$ °C, respectively. Frequency of profiles with BLs and TIs were relative to the total 286 number of profiles in each regime. 287
- Mean SSS during the 2017 boreal autumn cruise was saltier compared to the 2016 boreal 288
- summer cruise. The EPFP region, where SSS < 33.5, was restricted to $7.5^{\circ}-12.5^{\circ}N$, with 289
- minimum SSS < 33.0 found between 8.5°-10.5°N east of 125.5°W (Fig. 6a). The SSS front 290
- south of the low SSS between 6.5°-8.5°N was sharper than in the 2016 boreal summer cruise 291
- (Figs. 4a and 6a). The mean SST during the 2017 cruise had a meridional maximum (SST >292 28.2°C) in the northern part of the SPURS-2 region between 11°-14.5°N (Fig. 6b) that did not 293
- coincide with the location of the SSS minimum (Fig. 6a). Southwestward winds prevailed north 294
- of 9.5°N with northwestward trades to the south, meridionally converging from 8°-11°N (Fig. 295
- 6c). The eastward NECC was dominant south of 11.5°N during the 2017 cruise and much 296
- stronger and more well defined compared to the 2016 cruise (Fig. 6d). The near-surface 297
- westward flowing NEC was restricted to north of 12°N. 298



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Figure 6. Distribution of (a) BLT (dbar) and (b) $\Delta\theta$ (°C) from uCTD casts (triangles), CTD casts (squares), and Argo profiling floats (stars) during SPURS-2 2017 cruise. Triangles along 125°W are slightly shifted zonally to improve visibility. Contours indicate (a) the mean SSS from SMAP and (b) the mean SST from OISST (°C) from 21 October to 11 November 2017. Gray shading indicates (a) SSS lower than 33.5 and (b) SST higher than 28.2°C. Distribution of (c) wind stress (N m⁻²) and (d) near-surface current (m s⁻¹) during the SPURS-2 2017 cruise, averaged 1-hour prior and posterior to the time of uCTD and CTD profiles. Red and blue arrows

in (c) and (d) indicate eastward and westward direction, respectively.

During the 2017 cruise, BLs showed a more coherent distribution from the southern part of the EPFP to the SSS frontal region with BLT maximum occurring in the southern part of the EPFP (~8°N) (Fig. 6a). The distribution of TIs was found in two separate regions within the middle of the EPFP ($8.5^{\circ}-10^{\circ}N$) and in the FTZ (7°-7.5°N) (Fig. 6b). BLs within the EPFP were detected only south of 11°N (Fig. 6a). BLs were thicker than those found during the 2016 cruise with BLT > 50 dbar found in the SSS frontal region. TIs were found mostly concentrated in the EPFP around ~9.5°N and in the FTZ around 7°N (Fig. 6b).

A representative meridional transect along 125°W, which is the longest of the seven 315 transects that sampled across all three regimes during the 2017 cruise, shows ILD increased 316 southward from 30 dbar at 12.5°N in the EPFP to 80 dbar at 6.5°N in the SSS front while MLD 317 was mostly shallower than 50 dbar, resulting in BLs occurring only south of 10°N (Fig. 7a). 318 BLTs exceeded 30 dbar in the FTZ at ~8°N due to a surface puddle of fresher water that resulted 319 in very shallow mixed layers (Figs. 7a and c). TIs were also confined to occur mostly south of 320 10°N and were associated with a subsurface layer where $\theta > 28.2$ °C (Fig. 7b). The strongest TI 321 amplitudes with $\Delta \theta > 0.2^{\circ}$ C were mostly observed in the southern part of the EPFP between 322 8°-10°N (Fig. 7c). 323

324 For all the meridional transects along 125°W during the 2017 cruise, the mean ILD increases southward from 44.46 dbar in the EPFP to 64.08 dbar in the SSS frontal region (Table 325 1). The mean MLD was shallowest (18.78 dbar) in the FTZ, resulting in the thickest BLs of 39.4 326 dbar occurring in the FTZ (Table 1). As during the 2016 summer cruise, the frequency of 327 328 occurrence of BLs was 100% in the FTZ and only 57.5% occurrence in the EPFP (about the same as in 2016) and 79.2% in the SSS front (nearly double as many as found in 2016). Similar 329 330 to the patterns observed during the 2016 cruise, the mean $\Delta\theta$ in the EPFP (0.19°C) was highest among the three regimes, while TIs were most frequently observed in the FTZ. 331





Figure 7. Meridional transects of (a) salinity and (b) θ (°C), and (c) distribution of BLT (dbar; line) and $\Delta\theta$ (°C; dots) along 125°W from uCTD profiles observed during 3–5 November 2017 (red triangles in Figure 2b). Inverted triangles at the top of each panel indicate the locations of uCTD profiles in the EPFP (blue), the FTZ (green), and the SSS front (red). Gray shading in (a) and (b) indicates salinity lower than 33.5 and θ higher than 28°C, respectively, and blue and red curves indicate the MLD and ILD, respectively. Dashed contours in (b) denote $\theta = 28.2$ °C. Black dots in (b) denote the depth of the vertical temperature maximum where $\Delta\theta > 0.1$ °C.

340

3.2 Contribution of precipitation and Ekman advection to BL and TI formation

Formation of BLs can be attributed to freshening near the sea surface and/or salinification in the subsurface resulting from different processes (Cronin and McPhaden 2002; Katsura et al. 2015). In the EPFP, on seasonal time scales, Ekman advection works to both freshen and cool the mixed layer in boreal autumn and contributes to BL and TI formation through the tilting of the SSS front (KS2020). Precipitation also contributes to BL formation in the EPFP region in boreal summer. In this subsection, we assess the formation of BL and TI formation through

precipitation and Ekman advection on more synoptic spatio-temporal scales using measurements 347 from the SPURS-2 cruises. 348

Here, we estimate the contribution of Ekman advection and precipitation to BL formation 349 through surface freshening within the SPURS-2 region, based on uCTD and CTD profiles (Fig. 350 3). We use the mixed layer salinity budget equation (Ren and Riser, 2009; Katsura et al., 2013) 351 to better understand what processes might result in the BL and TI formation observed during the

352

SPURS-2 cruises. The precipitation term was calculated as 353

$$S_{prec} = -\frac{PS_m}{h_m},\tag{1}$$

where P is precipitation, S_m is mixed layer salinity, h_m is MLD. P was obtained from the nearest 355 IMERG grid point to each uCTD and CTD profile and averaged over 24-hours prior to the time 356 of each uCTD and CTD cast. Meridional Ekman salinity and temperature advection terms were 357 calculated as 358

$$S_{Ek} = -v_{Ek} \frac{\partial S_m}{\partial y} \tag{2}$$

360 and

359

361

$$T_{Ek} = -\nu_{Ek} \frac{\partial T_m}{\partial \nu},\tag{3}$$

respectively, where T_m is mixed layer temperature and v_{Ek} is the meridional Ekman velocity. The 362

363 meridional differentiation was determined from the uCTD profiles along the 125°W transects

during each cruise, as well as the shorter sections along 124°W and 125.5°W in 2017 (Fig. 3). 364

Meridional Ekman velocity v_{Ek} was calculated as 365

366

$$v_{Ek} = -\frac{\tau^x}{\rho_0 f h_m} \tag{4}$$

where τ^x is zonal wind stress (positive eastward), ρ_0 is the reference density of seawater, taken to 367 be 1025 kg m³, and f is the Coriolis parameter. Zonal wind stress τ^x measured during the cruise 368 was averaged over 1-hour prior and posterior to the time of each uCTD and CTD cast (Figs. 4c 369 and 6c). Here, we only focus on freshening and cooling (i.e., negative values of precipitation 370 and Ekman advection terms), which respectively contribute to BL and TI formation. 371

During the SPURS-2 2016 summer cruise, precipitation and associated surface 372 freshening were largest in the EPFP under the ITCZ but mainly occurred north of the thickest 373 374 BLs in the SSS front and the FTZ (Figs. 4a, 8a and Table 2).

For all the meridional transects along 125° W, the highest mean values of P (0.240 mm hr⁻ 375 ¹) and S_{prec} (-0.084 × 10⁻⁶ s⁻¹) occurred in the EPFP, compared to the FTZ (0.052 mm hr⁻¹ and -376 0.023×10^{-6} s⁻¹, respectively) and the SSS frontal region (0.057 mm hr⁻¹ and -0.030×10^{-6} s⁻¹, 377 respectively) (Table 2). This is in contrast to where the thickest BLs were found in the FTZ and 378 379 the SSS front (Table 1). In the EPFP and the FTZ, 46.3% and 50.0% of the uCTD profiles were associated with both the presence of a BL and precipitation freshening, respectively. Whereas in 380 the SSS front only 29.3% of casts showed the co-occurrence of both BL and precipitation. The 381 382 discrepancy between the location of the precipitation maximum and the location of the BLT maximum in boreal summer is consistent with the seasonal climatology of KS2020. 383

During the SPURS-2 2017 cruise, similar to that found in the 2016 summer cruise, the 384 surface freshening due to precipitation was larger in the EPFP than in both the SSS front and the 385 FTZ (Fig. 8b and Table 2) where the thick BLs were found (Table 1). The precipitation 386 maximum was located between 7.5°-12°N and mean precipitation was larger during this 2017 387 cruise than during the 2016 boreal summer cruise (Fig. 8b). Freshening due to precipitation 388 associated with the precipitation maximum which exceeded 0.4 mm hr⁻¹, corresponded to where 389 the BLs were thickest in the southern part of the EPFP (Fig. 6a). In contrast, thick BLs in the 390 SSS front and in the FTZ between 6°-7.5°N were located south of the ITCZ and were not 391 associated with freshening due to precipitation. 392

For all the meridional transects along 125°W during the 2017 cruise, the mean values of $P (0.288 \text{ mm hr}^{-1})$ and $S_{prec} (-0.108 \times 10^{-6} \text{ s}^{-1})$ in the EPFP were largest of the three regimes compared to the FTZ (0.186 mm hr⁻¹ and $-0.090 \times 10^{-6} \text{ s}^{-1})$ and the SSS frontal region (0.139 mm hr⁻¹ and $-0.034 \times 10^{-6} \text{ s}^{-1}$) (Table 2). In the EPFP and the FTZ, nearly half of all the uCTD profiles (51.8% and 50.0%, respectively) were associated with both BL and precipitation freshening, while only 18.9% of profiles showed concurrent BL presence and precipitation in the SSS front.



Figure 8. Distribution of S_{prec} from uCTD (colored triangles and circles) and CTD (colored squares) profiles during the SPURS-2 (a) 2016 cruise and (b) 2017 cruise. Triangles along 125°W are slightly shifted zonally to improve visibility. Note only freshening ($S_{prec} < 0$) is shown by the negative color bar. White symbols indicate the value of zero. Contours indicate

400

the mean precipitation from IMERG (mm hour⁻¹) (a) from 21 August to 12 September 2016 and

406 (b) from 21 October to 11 November 2017. Gray shading indicates precipitation higher than 0.2407 mm hour⁻¹.

		P (mm hour ⁻¹)	S_{prec} (10 ⁻⁶ s ⁻¹)	Number of Profile with BL and $S_{prec} < 0$ and Frequency
	EPFP	0.240 (0.041)	-0.084 (0.016)	62 (46.3%)
2016	FTZ	0.052 (0.013)	-0.023 (0.012)	7 (50.0%)
	SSS front	0.057 (0.033)	-0.030 (0.018)	12 (29.3%)
2017	EPFP	0.288 (0.091)	-0.108 (0.039)	117 (51.8%)
	FTZ	0.186 (0.140)	-0.090 (0.080)	9 (50.0%)
	SSS front	0.139 (0.113)	-0.034 (0.029)	10 (18.9%)

408

Table 2. Mean values of *P* and S_{prec} and the number of profiles with both $S_{prec} < 0$ and a BL in

the EPFP, the FTZ, and the SSS front along the 125°W transects during the 2016 and 2017

411 cruises. Values in parentheses indicate the 95% confidence interval. Calculation of mean *P* and

412 mean S_{prec} was performed only for uCTD profiles with $S_{prec} < 0$. Frequency of profiles with both

BLT > 10 dbar and $S_{prec} < 0$ were relative to the total number of profiles in each regime.

During the 2016 boreal summer cruise, Ekman advection of fresher and cooler water contributed to BL and TI formation in both the EPFP and in the SSS front (Fig. 9, Table 3).

416 Freshening due to Ekman advection occurred north of 9°N in the EPFP (Fig. 9a). Ekman

advection also worked to cool the mixed layer north of 9°N in the high SST region (Fig. 9b).

The southward Ekman advection in the EPFP resulted from the northeastward wind, while the

419 northward Ekman flow in the SSS front resulted from northwestward wind (Table 2, Fig. 4c).

The mean Ekman advection from all the 2016 125°W transects shows that freshening in 420 the EPFP ($-0.202 \times 10^{-6} \text{ s}^{-1}$) was larger than in the SSS front ($-0.130 \times 10^{-6} \text{ s}^{-1}$), while mean 421 Ekman cooling in the SSS front (-0.358 \times 10⁻⁶ °C s⁻¹) was double that in the EPFP (-0.166 \times 10⁻ 422 ⁶ °C s⁻¹) (Table 2). In the FTZ, the weak meridional Ekman velocity beneath the ITCZ led to the 423 weakest Ekman freshening $(-0.064 \times 10^{-6} \text{ s}^{-1})$ and cooling $(-0.039 \times 10^{-6} \text{ °C s}^{-1})$ among the three 424 regimes. However, the frequency of coincidence of both BL and Ekman freshening (TI and 425 426 Ekman cooling) was 31.3% (20.6%) in the EPFP and only 20.5% (2.6%) in the SSS frontal region, much less than the 61.5% (30.8%) occurrence in the FTZ (Table 3). Overall, for the 427 three regimes, the freshening and cooling by Ekman advection showed a patchy and/or porous 428 distribution (Fig. 9), with 31.1% (17.5%) of all profiles associated with both BL and Ekman 429

430 freshening (TI and Ekman cooling).



431

Figure 9. Distribution of (a) S_{Ek} and (b) T_{Ek} from uCTD profiles along 125°W during the SPURS-2 2016 cruise (colored triangles). Triangles along 125°W are slightly shifted zonally to improve visibility. Note only freshening ($S_{Ek} < 0$) and cooling ($T_{Ek} < 0$) are shown, as indicated by the

negative color bars. White triangles indicate positive values (salinification and warming).

Contours indicate (a) the mean SSS from SMAP and (b) the mean SST from OISST (°C) from 21
August to 12 September 2016. Gray shading indicates (a) SSS lower than 33.0 and (b) SST

438 higher than 28.5°C.

		$v_{Ek} (\mathrm{m \ s}^{-1})$	$S_{Ek} (10^{-6} \text{ s}^{-1})$	$T_{Ek} \ (10^{-6} \ ^{\circ}\mathrm{C \ s^{-1}})$	Number of Profiles with BL and $S_{Ek} < 0$ and Frequency	Number of Profiles with TI and $T_{Ek} < 0$ and Frequency
2016	EPFP	-0.024 (0.007)	-0.202 (0.061)	-0.166 (0.066)	41 (31.3%)	27 (20.6%)
	FTZ	0.003 (0.010)	-0.064 (0.049)	-0.039 (0.022)	8 (61.5%)	4 (30.8%)
	SSS front	0.037 (0.011)	-0.130 (0.113)	-0.358 (0.248)	8 (20.5%)	1 (2.6%)
2017	EPFP	0.013 (0.006)	-0.141 (0.039)	-0.090 (0.023)	67 (29.9%)	36 (16.1%)
	FTZ	0.006 (0.031)	-0.169 (0.167)	-0.220 (0.096)	8 (44.4%)	8 (44.4%)
	SSS front	0.010 (0.026)	-0.314 (0.172)	-0.236 (0.102)	17 (32.7%)	6 (11.5%)

439

Table 3. Mean values of v_{Ek} , S_{Ek} and T_{Ek} and the number of profiles with both a BL and $S_{Ek} < 0$

and a TI and $T_{Ek} < 0$ in the EPFP, the FTZ, and the SSS front along the 125°W transects during the 2016 and 2017 cruises. Values in the parentheses indicates the 95% confidence interval. 443 Calculation of mean S_{Ek} and mean T_{Ek} was performed only for uCTD profiles with $S_{Ek} < 0$ and 444 $T_{Ek} < 0$, respectively. Frequency of profiles was relative to the total number of profiles in each 445 regime.

During the 2017 boreal autumn cruise, both freshening and cooling by Ekman advection were found in the three regimes, but were maximum in the SSS front (Fig. 10 and Table 3), coinciding with where thick BLs with TIs were found (Figs. 6a and b). North of about 8.5°N in the EPFP, the magnitude of both Ekman freshening and cooling was much smaller. In general, both Ekman freshening and cooling showed a patchy and porous distribution (Fig. 10).

For all the meridional transects along 125°W during the boreal autumn, the mean 451 amplitude of Ekman freshening and cooling was weakest in the EPFP ($-0.141 \times 10^{-6} \text{ s}^{-1}$ and -452 0.090×10^{-6} °C s⁻¹, respectively), increasing southward to the SSS frontal region (-0.314 × 10⁻⁶ s⁻¹) 453 ¹ and -0.236×10^{-6} °C s⁻¹, respectively) (Table 3). The coincidence of both Ekman freshening 454 and BL presence in the FTZ was 44.4%, but only 29.9% in the EPFP and 32.7% in the SSS front. 455 The coincidence of both Ekman cooling and TIs occurred mostly in the FTZ (44.4%), compared 456 to the EPFP (16.1%) and the SSS frontal region (11.5%). As in the 2016 summer cruise, the 457 coincidence of Ekman advection with BLs and TIs was found in less than half of all profiles 458 where BLs and TI occurred (Table 2), again suggesting a patchy distribution of Ekman 459 freshening and cooling. Overall, for the three regimes, the coincidence of both BLs and Ekman 460 freshening (TIs and Ekman cooling) was found in 34.6% (14.7%) of all profiles. 461



Figure 10. Distribution of (a) S_{Ek} and (b) T_{Ek} from uCTD profiles during the SPURS-2 2017 cruise (triangles). Triangles along 125°W are slightly shifted zonally to improve visibility. Note only freshening ($S_{Ek} < 0$) and cooling ($T_{Ek} < 0$) are shown, as indicated by the negative color bars. White triangles indicate positive values (salinification and warming). Contours indicate (a) the mean SSS from SMAP and (b) the mean SST from OISST (°C) from 21 October to 11 November 2017. Gray shading indicates (a) SSS lower than 33.5 and (b) SST higher than 28.2°C.

470 3.3 BL and TI Formation through the Tilting Process

471 Ekman advection worked to freshen and cool the mixed layer both in the EPFP and in the 472 SSS front during the 2016 cruise and in the SSS frontal region during the 2017 cruise. To test 473 whether this Ekman advection resulted in formation of BLs with TIs through the tilting of the 474 SSS front, the rate of net change of salinity ($S_{tilting}$; s⁻¹) and temperature ($T_{tilting}$; °C s⁻¹) in the 475 surface layer caused by the vertically sheared meridional velocity to the vertical salinity and 476 temperature gradient within the isothermal layer was calculated as

477
$$S_{tilting} = -(v_{surface} - v_{ILD})\frac{\partial S_m}{\partial y}$$
(5)

478 and

479

$$T_{tilting} = -(v_{surface} - v_{ILD})\frac{\partial T_m}{\partial y},\tag{6}$$

480 where $v_{surface}$ and v_{ILD} are meridional velocity at the sea surface and at the ILD, respectively

481 (Cronin and McPhaden 2002). Negative $S_{tilting}$ ($T_{tilting}$) indicates a net freshening (cooling) at the 482 sea surface caused by the tilting process. Surface meridional velocity $v_{surface}$ was derived from

the shallowest bin of the ADCP velocity (typically ~17 dbar) while v_{ILD} was velocity at the depth of the ILD. When the ILD was shallower than the shallowest bin of the ADCP velocity, the calculation of $S_{tilting}$ and $T_{tilting}$ was not defined. Among the uCTD profiles used for the calculation of the advection term, only 15 (8.2%) and 1 (0.2%) uCTD profiles had ILD < 17 dbar for the 2016 and 2017 cruises, respectively, and so were omitted from the calculation. Finally, both $v_{surface}$ and v_{ILD} were averaged over 1-hour prior and posterior to the time of each uCTD cast (Figs. 4d and 6d).

During the 2016 cruise, the tilting process was found to contribute to BL and TI formation both in the EPFP and in the SSS frontal region, with the largest contribution in the FTZ (Fig. 11 and Table 4). In the EPFP, freshening and cooling by the tilting process was found between $9.5^{\circ}-11^{\circ}N$ and also at ~7°N (Figs. 11a and b). These regions correspond to the distribution of thick BLs with TIs (Figs. 4a and b), consistent with BL and TI formation through the tilting process in KS2020.



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Figure 11. Distribution of (a) $S_{tilting}$, (b) $T_{tilting}$, and (c) $\beta S_{tilting}$ - $\alpha T_{tilting}$ from uCTD profiles along 497 125°W during the SPURS-2 2016 cruise (colored triangles). Triangles along 125°W are slightly 498 shifted zonally to improve visibility. Note only freshening ($S_{tilting} < 0$) and cooling ($T_{tilting} < 0$) 499 are shown in (a) and (b), respectively, as indicated by the negative color bars. White triangles 500 indicate positive values (salinification and warming) or undefined values. Contours indicate (a 501 and c) the mean SSS from SMAP and (b) the mean SST from OISST (°C) from 21 August to 12 502 September 2016. Grav shading indicates (a and c) SSS lower than 33.0 and (b) SST higher than 503 28.5°C. 504

For all the meridional transects along 125°W during 2016, mean freshening (-0.644×10^{-1}) 505 ⁶ °C s⁻¹) and cooling (-0.762 × 10⁻⁶ °C s⁻¹) caused by tilting were largest in the FTZ among the 506 three regimes (Table 4). However, the Ekman contribution to freshening and cooling was found 507 to be very weak in the FTZ (Table 3), implying that geostrophic advection mainly contributes to 508 the tilting process in the FTZ. The frequency of BL occurrence associated with tilting and 509 freshening was 61.5% in the FTZ but only 31.2% in the EPFP and 26.7% in the SSS front. The 510 frequency of TI occurrence associated with tilting and cooling was also higher in the FTZ 511 512 (30.8%) compared to the EPFP (16.0%) and the SSS front (3.3%). These results indicate that the FTZ is a critical region for BL and TI formation through tilting due to geostrophic advection. 513 Overall, for the three regimes, the freshening and cooling showed a patchy and porous 514 515 distribution in the SPURS-2 region (Figs. 11a and b) with only 30.1% (13.7%) of all profiles associated with concurrence of both BL (TI) and freshening (cooling) due to the tilting process. 516

		$S_{tilting} (10^{-6} \text{ s}^{-1})$	$T_{tilting} (10^{-6} \text{ °C s}^{-1})$	Number of Profile with BL and S _{tilling} < 0 and Frequency	Number of Profile with TI and $T_{tilting} < 0$ and Frequency	Number of Profile with BL and $-1 < R_y < 1$ and Frequency	Number of Profile with TI and $0 < R_y < 1$ and Frequency
	EPFP	-0.472 (0.146)	-0.245 (0.079)	39 (31.2%)	20 (16.0%)	66 (50.8%)	14 (10.8%)
2016	FTZ	-0.644 (0.677)	-0.762 (1.196)	8 (61.5%)	4 (30.8%)	9 (69.2%)	5 (38.5%)
	SSS front	-0.526 (0.320)	-0.555 (0.500)	8 (26.7%)	1 (3.3%)	14 (35.9%)	0 (0%)
2017	EPFP	-0.441 (0.102)	-0.285 (0.066)	66 (29.6%)	38 (17.0%)	102 (45.7%)	35 (15.7%)
	FTZ	-0.394 (0.425)	-0.992 (0.527)	8 (44.4%)	7 (38.9%)	11 (61.1%)	6 (33.3%)
	SSS front	-0.161 (0.148)	-0.338 (0.150)	11 (21.2%)	8 (15.4%)	32 (61.5%)	4 (7.7%)

517

Table 4. Mean values of $S_{tilting}$ and $T_{tilting}$ and the number of profiles with both BL and where $S_{tilting} < 0$ and $-1 < R_y < 1$; and the number of profiles with both TI and where $T_{tilting} < 0$ and $0 < R_y < 1$ in the EPFP, the FTZ, and the SSS front along the 125°W transects during the 2016 and 2017 cruises. Values in the parentheses indicates the 95% confidence interval. Calculation of mean $S_{tilting}$ and mean $T_{tilting}$ was performed only for uCTD profiles with $S_{tilting} < 0$ and $T_{tilting} < 0$, respectively. Frequency of profiles was relative to the total number of profiles in each regime.

During the 2017 cruise, the contribution of tilting to BL and TI formation was found 524 broadly spread over in the SPURS-2 region, indicating patchiness and porosity (Fig. 12). 525 Freshening and cooling by tilting were strongest in the EPFP and the FTZ, respectively (Table 526 4). Freshening due to tilting was broadly spread occurring mainly from the FTZ at ~7°N to the 527 middle of the EPFP at ~10.5°N (Fig. 12a) where thick BLs were also found (Fig. 6a). The tilting 528 also resulted in cooling between 6.5°-8°N in the SSS front and the FTZ and between 8.5°-10°N 529 530 in the EPFP (Fig. 12b). These latitudes corresponded to the location of the warmest TIs (Fig. 6b). 531

532 For all 125°W meridional transects during 2017, freshening by tilting in the EPFP (-0.441 $\times 10^{-6}$ s⁻¹) and the FTZ (-0.394 $\times 10^{-6}$ s⁻¹) were more than twice as strong as found in the SSS 533 front (-0.161 \times 10⁻⁶ s⁻¹; Table 4). Cooling by tilting was strongest in the FTZ with a mean value 534 of -0.992×10^{-6} °C s⁻¹. The meridional difference in the tilting process between the three 535 regimes is opposite to that found for Ekman advection, which is highest within the SSS front 536 (Table 3). The frequency of BL occurrence associated with both tilting and freshening was 537 538 highest in the FTZ (44.4%) compared to the EPFP (29.6%) and the SSS front (21.2%). The frequency of TI occurrence in profiles associated with tilting and cooling was also highest in the 539 FTZ (38.9%) compared to the EPFP (17.0%) and the SSS front (15.4%). As in the 2016 cruise, 540 these results confirm that the FTZ is a critical region for BL and TI formation through the tilting 541 process and that the geostrophic component is dominant. Overall, for the three regimes, the 542 coincidence of tilting and freshening with BL presence was found in 34.6% of all profiles, and 543 the coincidence of tilting and cooling with TI presence was found in 16.5% of all profiles. 544

545



Figure 12. Distribution of (a) $S_{tilting}$, (b) $T_{tilting}$, and (c) $\beta S_{tilting}$ - $\alpha T_{tilting}$ from uCTD profiles during the SPURS-2 2017 cruise (triangles). Triangles along 125°W are slightly shifted zonally for

improved visibility. White triangles indicate undefined values. Note only freshening ($S_{tilting} < 0$)

and cooling ($T_{tilting} < 0$) are shown in (a) and (b), respectively, as indicated by the negative color

551 bars. White triangles indicate positive values (salinification and warming) or undefined values.

552 Contours indicate (a and c) the mean SSS from SMAP and (b) the mean SST from OISST (°C)

from 21 October to 11 November 2017. Gray shading indicates (a and c) SSS lower than 33.5

and (b) SST higher than 28.2°C.

Net strong freshening and cooling at the sea surface was caused by tilting of isohalines and isotherms in the SPURS-2 region, particularly in the FTZ, which are favorable to the formation of BLs with TIs. To further explore the possibility of BL and TI formation through tilting, the meridional density ratio R_y (Tippins and Tomczak 2003; Katsura et al. 2015) was calculated as

560
$$R_{y} = \frac{\alpha \, \partial T / \partial y}{\beta \, \partial S / \partial y} \tag{7}$$

where α is the thermal expansion coefficient and β is the saline contraction coefficient. Here we 561 562 use SST from OISST and SSS from SMAP as well as near-surface temperature and salinity values from uCTD profiles during the cruise periods. For BL formation through the tilting 563 process, the contribution of the salinity gradient to the density gradient must be larger than that 564 565 of the temperature gradient in the horizontal direction in order to maintain vertical stability after BL formation, and so $-1 < R_y < 1$ must be satisfied (Katsura et al., 2015). For TI formation, the 566 horizontal salinity and temperature gradient must have a compensating contribution to the 567 horizontal density gradient, meaning that $0 < R_v < 1$ must be satisfied (KS2020). These R_v 568 conditions for BL (-1 < R_v < 1) and TI (0 < R_v < 1) formation are due to the need for stability in 569 the MLDs associated with BLs and TIs (Mignot et al., 2012). 570

During the 2016 cruise, the condition for BL formation was satisfied over the most of the 571 SPURS-2 region, and the condition for TI formation was satisfied in the southern part of the 572 EPFP and the FTZ (Fig. 13). In general, R_v in the EPFP was mostly positive in the southern part 573 of the EPFP (Fig. 13a), as well as in the mixed layer along 125°W (Fig. 13b), corresponding to 574 where BLs with TIs occurred (Figs. 4a and b). Although R_y was mostly negative south of 8°N in 575 the mean state during the 2016 cruise (Fig. 13a), positive R_y was found in the uCTD profiles at ~ 576 7°N in the FTZ. This distribution of R_y corresponded to the region with thick BLs and TIs (Figs, 577 4b and 13b), confirming their formation through the tilting process. Indeed, the distribution of 578 579 $\beta S_{tilting}$ - $\alpha T_{tilting}$, which is the net density change due to tilting, was significantly correlated (R =0.94) with S_{tilting} (Figs. 11a and c) during the 2016 summer cruise, indicating that it is the 580 freshening due to tilting that leads to a net decrease of surface density and hence BL formation. 581 In contrast, the net density change from temperature had a -0.53 correlation. This negative 582 correlation indicates that the net decrease of surface density caused by the tilting due to 583 freshening (i.e. where $\beta S_{tilting} - \alpha T_{tilting} < 0$) tends to be associated with where the conditions are 584 unfavorable to TI formation through cooling (i.e., where $R_v < 0$). Similar to the tilting 585 components (Fig. 11), R_v also showed a patchy distribution (Fig. 13b) and the coincidence of BL 586 (TI) with where $-1 < R_y < 1$ (0 < $R_y < 1$) occurred in 48.9% (10.4%) of all uCTD profiles during 587 the cruise. 588

For all the meridional transects along 125°W during summer 2016, the frequency of BL occurrence with $-1 < R_y < 1$ was highest in the FTZ (69.2%), compared to the EPFP (50.8%) and

the SSS front (35.9%) (Table 4). This is consistent with the highest frequency of BL occurring where there is freshening due to tilting in the FTZ (Table 4). The frequency of TI occurring with where $0 < R_y < 1$ was also highest in the FTZ (38.5%) compared to the EPFP (10.8%) and the SSS front (0%). This agrees with the finding that most TIs occur where there is cooling due to the tilting process in the FTZ. This is also consistent with BL and TI formation occurring through the tilting process, especially in the FTZ.

During the 2017 cruise, the $-1 < R_v < 1$ required for BL formation was broadly satisfied in 597 the SPURS-2 region (Fig. 14a). Positive R_{y} was generally found in the EPFP between 598 8.5°-13°N in both the mean SSS and SST (Fig. 14a) and the uCTD profiles along 125°W (Fig. 599 14b). Although R_{y} derived from mean SSS and SST was negative in the SSS front (Fig. 14a), 600 positive R_v was detected in the uCTD profiles in the FTZ at ~7°N where TIs occurred (Figs. 6b 601 and 14b). This correspondence of R_{y} to the presence of BLs and TIs further confirms the 602 603 formation of BLs and TIs through the tilting process. As in the 2016 cruise, the distribution of $\beta S_{tilting}$ - $\alpha T_{tilting}$ was highly correlated (R = 0.96) with $S_{tilting}$ (Figs. 12a and c), indicating that 604 freshening through tilting works to decrease the surface density and leads to BL formation. The 605 net density change due to the temperature term was again weak, although during the 2017 fall 606 cruise, unlike the 2016 cruise it was positively correlated (R = 0.27). This weakly positive 607 correlation indicates that the net decrease of surface density from tilting due to freshening (i.e. 608 where $\beta S_{tilting}$ - $\alpha T_{tilting} < 0$) tends to be associated with where there is cooling, which is favorable 609 to TI formation (i.e., $0 < R_v < 1$). As during the 2016 cruise, R_v also showed a patchy distribution 610 (Fig. 14), with 49.5% (15.4%) of all profiles associated with the presence of a BL (TI) where -1 611 $< R_{v} < 1 \ (0 < R_{v} < 1).$ 612

For all the meridional transects along 125° W during the 2017 autumn cruise, the frequency of occurrence of BL with where $-1 < R_y < 1$ was higher in both the FTZ (61.1%) and the SSS frontal region (61.5%) than in the EPFP (45.7%) (Table 4). This result is consistent with BL formation through the tilting of isohalines in the FTZ. The frequency of TI occurring with where $0 < R_y < 1$ in the FTZ (33.3%) was higher than in the EPFP (15.7%) and the SSS front (7.7%). Similar to the 2016 cruise, these results show a high occurrence of TI and cooling, and BL and freshening, due to tilting processes in the FTZ (Table 4).



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Figure 13. Distribution of R_y at the sea surface (a) based on the mean SSS from SMAP and SST from OISST from 21 August to 12 September 2016 (color) and (b) near-surface temperature and salinity from uCTD measurement along 125°W during the SPURS-2 2016 cruise (triangles). Only values that satisfy the criteria for BL formation ($-1 < R_y < 1$) are shown, as indicated by the color bar. Black triangles are values that are outside the criteria range. Triangles along 125°W in are slightly shifted zonally to improve visibility. Contours indicate the mean SSS from SMAP from 21 August to 12 September 2016. Gray shading in (b) indicates SSS lower than 33.0.



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Figure 14. Distribution of R_y at the sea surface (a) based on the mean SSS from SMAP and SST from OISST from 21 October to 11 November 2017 (color) and (b) near-surface temperature and salinity from uCTD measurement during the SPURS-2 2017 cruise (triangles). Only values that satisfy the criteria for BL formation (-1 < R_y < 1) are shown, as indicated by the color bar. Black triangles are values that are outside the criteria range. Triangles along 125°W are slightly shifted zonally to improve visibility. Contours indicate the mean SSS from SMAP from 21 October to 11 November 2017. Gray shading in (b) indicates SSS lower than 33.5.

Oxygen profiles from the CTD- O_2 casts enable a unique opportunity to further 636 corroborate whether the cooling and freshening through the tilting process was caused by surface 637 or subsurface flow. If BLs are formed by subsurface processes such as subduction or advection 638 of the higher salinity water within the BL, then dissolved oxygen (DO) should be lower within 639 the BL than within the overlying surface mixed layer due to the oxygen consumption by 640 biological activity. Conversely, if BLs are formed through surface processes such as 641 precipitation and surface advection of fresher water that produce caps of low salinity water in the 642 near-surface, the DO within the BL should be the same or higher than found within the surface 643 mixed layer. Indeed, the DO concentration within BLs in the CTD-O₂ profiles showed almost 644 the same or higher levels compared to levels within the overlying mixed layers (Fig. 15). Here, 645 we defined the MLD₀₂ as the depth at which DO saturation decreases by 1% from the value at 646 10-dbar, which can be interpreted as a measure of the extent of vertical mixing. Almost all 647 CTD- O_2 profiles during the SPURS-2 cruises showed MLD₀₂ to be deeper than or similar to the 648

ILD (Figs. 15 and 16). This implies that BLs were formed by surface capping of fresher water 649 induced through surface processes. Indeed, some BLs with TIs contained higher DO water than 650 the overlying mixed layer (Fig. 15). The depth of the vertical oxygen maximum detected in 20 651 CTD-O₂ profiles during the two SPURS-2 cruises corresponded to the depth of the temperature 652 maximum associated with TIs, with a significant positive correlation (R = 0.87). The subsurface 653 oxygen maximum is known to be prominent during the late summer (Reid, 1962; Jenkins and 654 Goldman, 1985; Hayward, 1994; Sukigara et al., 2011). The subsurface oxygen maximum 655 results from the seasonal pycnocline which prevents photosynthetically-produced oxygen from 656 escaping to the atmosphere (Najjar and Keeling, 1997). Thus, the correspondence of the 657 subsurface temperature and oxygen maxima implies that BLs and TIs were formed through 658 surface processes and confirms that the surface flow plays an important role in the tilting 659

660 process.



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Figure 15. Vertical CTD profile of (a) θ (red curve), salinity (blue curve), (b) σ_{θ} (black curve), and dissolved oxygen saturation (green curve) at 8.5°N, 124.5°W observed on 4 September 2016. Horizontal red, blue, and green dashed lines indicate the MLD, ILD, and MLD₀₂, respectively. Red and green dots indicate the vertical temperature and oxygen maximum, respectively.



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Figure 16. Scatter diagram of the ILD and the MLD₀₂ from CTD-O₂ profiles in the SPURS-2 2016 (circles) and 2017 cruises (stars). Black symbols are for BLT < 10 dbar. Blue symbols are for BLT > 10dbar and $\Delta\theta$ < 0.1°C. Red symbols are for BLT > 10dbar and $\Delta\theta$ > 0.1°C.

671 4 Discussion and Summary

672 BLs and associated TIs were investigated, and their formation mechanisms explored using shipboard observations with high spatial resolution during the SPURS-2 cruises. During 673 the 2016 summer cruise, BLs and TIs occurred within the low SSS and high SST region, that 674 corresponded to the EPFP. Thick BLs and warm TIs were also found in the FTZ and the SSS 675 front to the south of the EPFP. During the 2017 autumn cruise, BLs were found in the southern 676 part of the EPFP. BLs in 2017 were thicker than those in 2016, and the thickest BLs were found 677 in the FTZ. In 2017, TIs were also found in the southern part of the SSS front and concentrated 678 in the middle of the EPFP and in the FTZ. During both the 2016 and 2017 cruise, the occurrence 679 of BLs and TIs was most frequent in the FTZ, indicating that the FTZ is the critical region of BL 680 681 and TI formation.

To investigate the formation mechanisms of BLs and TIs during the SPURS-2 cruises, the contribution of precipitation and meridional Ekman advection to surface freshening were

evaluated. During both cruises, BLs within the EPFP were distributed in the fresher region 684 associated with precipitation under the ITCZ while thick BLs in the SSS front and in the FTZ 685 occurred south of the precipitation maximum. Ekman advection worked to freshen and cool the 686 surface layer in the EPFP and the SSS front, which is favorable to BL and TI formation through 687 the tilting process. During the 2016 cruise, freshening and cooling by Ekman advection were 688 strongest in the EPFP and the SSS front and weak in the FTZ. During the 2017 cruise, 689 freshening and cooling caused by Ekman advection occurred mostly in the SSS front compared 690 to the EPFP and the FTZ. 691

To further assess the formation of BLs and TIs through tilting, the net surface freshening 692 and cooling due to the vertically sheared velocity within the isothermal layer was examined. 693 During the 2016 and 2017 cruises, tilting processes contributed to both freshening and cooling 694 from the SSS front to the EPFP and corresponded to the prevalence of BLs and TIs. Both 695 freshening and cooling due to tilting was strongest in the FTZ, indicating that it is a critical zone 696 for BL and TI formation through the tilting process. In addition, the salinity gradient was the 697 dominant contributor to the horizontal density gradient during both cruises, which corroborates 698 the formation of BLs and TIs via the tilting mechanism. DO within BLs showed almost the same 699 or higher values compared to that found within the overlying mixed layer, further confirming 700 that BLs and TIs are formed through surface processes and hence that the tilting of the SSS front 701 702 is largely in response to the surface flow.

The distribution of BLs and TIs during the two SPURS-2 cruises was mostly consistent 703 704 with the seasonal climatology of KS2020. The results largely support KS2020's idea that BLs and TIs are formed by tilting of the SSS front in boreal summer and autumn and that 705 precipitation is also important for the BL formation in boreal summer. On the other hand, some 706 new insights into BL and TI formation are obtained from the results of this study. During both 707 the 2016 and 2017 cruises, surface freshening and cooling by tilting showed a very patchy and/or 708 porous distribution (Figs. 11 and 12) compared to the distribution of BLs and TIs (Figs. 4 and 6). 709 710 This is in contrast to the continuous distribution of Ekman freshening along the SSS front found in the climatological study by KS2020. This implies that the BL and TI formation through the 711 tilting mechanism occurs only intermittently and on much faster time scales than resolved by 712 KS2020. At the same time, the patchiness and porosity in the distribution of BLs and TIs 713 714 implies that their destruction can also occur as a result of destabilization by wind mixing and/or evaporation. This patchiness and porosity in the distribution of BLs and TIs can dampen the 715 overall effect of BL and TI presence in reducing heat exchange through entrainment or through 716 air-sea interaction. To better assess the impact of BLs and TIs on the entrainment process and 717 air-sea interaction, time-series observations such as from moorings, will be important in future 718 719 studies.

During the 2016 summer cruise, although freshening and cooling by tilting was strong in 720 the FTZ, the freshening and cooling by Ekman advection was weak. Similarly, during the 2017 721 autumn cruise, freshening attributed to tilting was strong in the EPFP and the FTZ, while the 722 freshening by Ekman advection was weak. Cooling by tilting in the FTZ was also distinct from 723 the weak cooling by Ekman advection. These results imply that the surface geostrophic flow has 724 an important role in the tilting of the SSS front and hence in the formation of BLs and TIs on 725 synoptic scales, especially in the FTZ. This is in contrast to KS2020, who found that on seasonal 726 time scales, Ekman advection acted alone to freshen and cool the surface layer, contributing to 727 the formation of BLs with TIs through the tilting of the SSS front in boreal summer and autumn. 728

The eastward NECC is the prevailing current in the EPFP, but meridional perturbations in 729 the NECC flow such as from small meanders, mesoscale eddies and/or tropical instability waves 730 and filaments, may cross and tilt the SSS front contributing to BL and TI formation, such as 731 732 shown in the modelling study by Bingham et al. (2020). Unfortunately, our SPURS-2 observations were mainly oriented north-south and so we are unable to estimate the vertical shear 733 of the meridional geostrophic flow without transect observations in the zonal direction. Thus, we 734 cannot fully understand how the geostrophic flow in the meridionally-meandering NECC might 735 contribute to the vertical sheared velocity in the meridional direction. Similarly, we can only 736 estimate the meridional component of Ekman advection and its contribution to the tilting process 737 as the SPURS-2 observations lack sufficient resolution in the zonal direction (see Figure 3). 738 Although the zonal gradient of SSS and SST is much smaller than the meridional gradient (e.g., 739 Figs. 4 and 6), the strong eastward NECC can also potentially contribute to BL and TI formation 740 through the tilting process and so compensate for the small zonal gradient of SSS and SST to 741 potentially result in surface freshening and cooling. Studies using high-resolution ocean models 742 will be important to further pursue the small spatio-temporal scale formation of BLs and TIs in 743

the eastern Pacific as well as any contribution to their formation by the NECC.

745 Acknowledgments

SK is supported by JSPS Overseas Research Fellowships. JS and SK are supported by
NASA Grant Number 80NSSC18K1500. FB's work on SPURS-2 was supported by NASA
grant NNX15AF72G, and by the Jet Propulsion Laboratory through the Salinity Continuity
Processing activity. The authors are thankful to an anonymous reviewer for their valuable and
constructive comments. The SPURS-2 uCTD and CTD data collected and reported on in this
manuscript were supported through NNX15AF67G to JS. The Argo float data used in this study
were collected and made freely available by the International Argo Project and the national
programs that contribute to it (http://www.argo.ucsd.edu; http://www.jcommops.org/argo). Argo

programs that contribute to it (http://www.argo.ucsd.edu; http://www.jcommops.org/argo). Argo
 is a pilot program of the Global Ocean Observing System. The Argo profiles were from the

Argo Global Data Assembly Center (ftp://usgodae.org/pub/outgoing/argo;

756 ftp://ftp.ifremer.fr/ifremer/argo) and Advanced automatic QC Argo data version 1.2. by the

757 Japan Agency for Marine-Earth Science and Technology (see

- http://www.jamstec.go.jp/ARGO/argo_web/argo/?page_id=100&lang=en). The L3 70-km
- version-4.0 product of the NASA Soil Moisture Active Passive was provided by NASA's
- 760 Physical Oceanography Distributed Active Archive Center (PO.DAAC;
- 761 <u>https://podaac.jpl.nasa.gov/dataset/SMAP_RSS_L3_SSS_SMI_MONTHLY_V4</u>). The
- Advanced Very High Resolution Radiometer product OISST was provided by the National
- 763 Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental
- Information (<u>https://www.ncdc.noaa.gov/oisst</u>). The uCTD, CTD, and ADCP profiles from the
- 765 SPURS-2 cruises are available from the PO.DACC SPURS-2 webpage (<u>https://podaac-</u>
- tools.jpl.nasa.gov/drive/files/allData/insitu/L2/spurs2/). The authors are thankful to Drs. Carol
- Anne Clayson and James Edson for shipboard wind and precipitation data from the SPURS-2
- cruises, which are also available at the PO.DAAC SPURS-2 webpage. Information on the
- shipboard ADCP data acquisition, processing, and distribution is found at the UHDAS site
- (http://currents.soest.hawaii.edu/docs/ adcp_doc/index.html). IMERG data were obtained from
- the NASA Goddard Earth Sciences Data and Information Services Center
- $(https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGDF_06/summary?keywords=\%22IMERG\%2$
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