Salinity fronts in the tropical Pacific Ocean

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Abstract This study delineates the salinity fronts (SF) across the tropical Pacific, and describes their variability and regional dynamical significance using Aquarius satellite observations. From the monthly maps of the SF, we find that the SF in the tropical Pacific are (1) usually observed around the boundaries of the fresh pool under the intertropical convergence zone (ITCZ), (2) stronger in boreal autumn than in other seasons, and (3) usually stronger in the eastern Pacific than in the western Pacific. The relationship between the SF and the precipitation and the surface velocity are also discussed. We further present detailed analysis of the SF in three key tropical Pacific regions. Extending zonally around the ITCZ, where the temperature is nearly homogeneous, we find the strong SF of 1.2 psu from 7° to 11° N to be the main contributor of the horizontal density difference of 0.8 kg/m³. In the eastern Pacific, we observe a southward extension of the SF in the boreal spring that could be driven by both precipitation and horizontal advection. In the western Pacific, the importance of these newly resolved SF associated with the western Pacific warm/fresh pool and El Niño southern oscillations are also discussed in the context of prior literature. The main conclusions of this study are that (a) Aquarius satellite salinity measurements reveal the heretofore unknown proliferation, structure, and variability of surface salinity fronts, and that (b) the fine-scale structures of the SF in the tropical Pacific yield important new information on the regional air-sea interaction and the upper ocean dynamics.

1. Introduction

In the tropical Pacific, the west to east zone of low sea surface salinity (SSS) features the western Pacific fresh pool (WPFP), intertropical convergence zone (ITCZ), and the eastern Pacific fresh pool (EPFP) responding to the high precipitation (Figure 1). The mixed layer salinity also shows the strongest interannual variations in these regions associated with the El Niño Southern Oscillation (ENSO) events [Hasson et al., 2013]. The importance of salinity in the tropical Pacific has been discussed in Delcroix and Hénin [1991]. For example, the SSS is a good indicator of the freshwater flux (evaporation minus precipitation) [Donguy and Hénin, 1976; Lagerloef et al., 2010]. In addition, the SSS variations are so large in the equatorial Pacific that it may dominate the mixed layer depth (MLD) and lead to the circumstance favorable for the formation of barrier layer (BL) [Lukas and Lindstrom, 1991]. This condition can be seen especially at the regions with large horizontal salinity gradients (i.e., the salinity fronts; SF), which are observed at the edge of strong atmospheric convection, such as the eastern edge of western Pacific warm pool (WPWP) [Picaut et al., 2001; Maes et al., 2006] or the western edge of EPFP [Alory et al., 2012].

SF are most well-studied over the WPFP and the location of SF are found highly related to the ENSO activities (blue box in Figure 1). It has been shown that the zonal migration of the SF (i.e., 34.6 psu isohaline) coincides with the eastern edge of WPWP (i.e., 28°C isotherm) at the equator associated with the variations of zonal currents [Picaut et al., 1996, 2001; Maes, et al., 2006]. Two major equatorial currents in the Pacific are the eastward north equatorial counter current (NECC) and the westward south equatorial current (SEC). The saltier SEC and the fresher NECC converge at the western equatorial Pacific and contribute to the formation of the SF. The currents are so strong here that the zonal advection dominates the zonal migrations of the SF rather than the precipitation [Delcroix and Picaut, 1998]. The role of the precipitation in the driving the SF is to enhance the strength of the SF by freshening the western side of the fronts.

As for the central Pacific area (red box in Figure 1), the SSS minima occur in September–October [Delcroix and Hénin, 1991] when ITCZ is most active roughly from May through October [Wang and Magnusdottir, 2006]. The SF under the ITCZ is not as well studied as the SF in the eastern and the western Pacific. However, the NECC is aligned with the ITCZ in the northern hemisphere around 8°–10° N. The alignment with ITCZ and the hemispheric asymmetry of the countercurrents is induced by the wind curl associated with...
The lowest SSS in the tropical Pacific occurs in the eastern tropical Pacific. The eastern Pacific fresh pool of low SSS (<33 psu; magenta contour in Figure 1) is located at 80°–90°W and 2°–7°N, between the warm pool (centered at 15°N) and the equatorial cold tongue [Alory et al., 2012]. At the equator, the cold and salty water is brought up by the upwelling, and strong meridional sea surface temperature (SST) and SSS gradients are found and contribute to the tropical instability waves (TIW) in this particular area [Lee et al., 2012].

SSS in the EPFP (green box in Figure 1) has been described along a few tracks from Voluntary Observing Ships (VOS) [Alory et al., 2012]. Along the ship tracks, SF has been found at the outer edge of the fresh pool.

Taking the advantage of high-resolution SSS observed from Aquarius, we aim to reveal the detailed structures and the variations of SSS and SF. An interesting feature of double ITCZ found in the eastern Pacific will be discussed later in this paper.

This paper delineates the SF across the tropical Pacific, and describes their variability and regional dynamical significance. Section 2 describes the data used for the analysis. Section 3 presents overview of the SF in the tropical Pacific. Sections 4–6 examine the regional analysis of SF focusing at the ITCZ, western edge of EPFP, and the eastern edge of WPFP, respectively. Our conclusions and their implications are summarized in section 7.

2. Data

Both in situ Argo floats [Roemmich et al., 2009] and Aquarius satellite [Lagerloef et al., 2008] observations of SSS are used in this analysis. Aquarius satellite provides SSS data with an average spatial resolution of about 130 km [Lagerloef et al., 2008]. The 1° × 1° monthly salinity maps are generated at Earth and Space Research from Aquarius V2.5.1 (an interim test processing leading to the release of V3.0). Local polynomial fitting with 150 km radius is applied [Lilly and Lagerloef, 2008] and the intrabeam differences within the three beams of Aquarius are reduced by averaging the long-wave along track variations. Aquarius has been collected data since September 2011, so in this paper we use the time period from September 2011 to August 2013 to show 2 years of SSS data. For gridded in situ data analyses, we use the Asia-Pacific Data Research Center (APDRC) of the International Pacific Research Center (IPRC) 1° × 1° Argo maps of SSS, SST, barrier layer thickness (BLT), and MLD generated with ~500 km smoothing scale. For SST, we also use Optimum Interpolation (OI) SST V2 [Reynolds et al., 2007], which is obtained using both in situ and satellite SST. Here, we use the weekly data with 1° × 1° spatial resolution for generating the maps. The scope of this paper is to describe the major structures of these fronts, so 1° data averaged for each month data are used for maps. The monthly 1/3° × 1/3° SSS and SST are only used in the T–S diagram (Figure 7) to show the regional variations. For surface currents, we use the data from OSCAR (Ocean Surface Current Analyses–Real time; Dohan and Maximenko [2010]). OSCAR calculates the ocean surface velocity averaged in the upper 30 m from satellite fields, including near surface winds and sea surface height (SSH). The data are available from October 1992 until present. Monthly 1° × 1° data are used here and can be downloaded from the
NASA PO.DACC (http://podaac.jpl.nasa.gov/). For precipitation, we use daily high-resolution precipitation of $1/4^\circ \times 1/4^\circ$ from CMORPH (CPC MORPHing technique) [Joyce et al., 2004].

3. Overview

3.1. Salinity Front from Aquarius and Argo

SSS maps in October 2012, one of the months with the most evident SF, are shown in Figure 2 to demonstrate the gain in SSS spatial resolution from gridded Aquarius satellite data relative to the smoothed gridded Argo data. A band of low SSS under the Pacific ITCZ and two major fresh pools on both sides of the tropical Pacific are observed in both maps (Figures 2a and 2b). In contrast to the very smooth Argo salinity map, $1/4^\circ \times 1/4^\circ$ SSS map from Aquarius satellite shows more detailed structures. Figure 2c shows the value of Aquarius SSS minus Argo SSS. The negative value along the ITCZ is partly due to the stratification of salinity. Aquarius observes the skin salinity and is systematically fresher than Argo data (which is sampled around 5 m depth). The positive values in Figure 2c indicate the mislocation of the boundary of the freshwater in the Argo data.

Based on these SSS maps, we then calculate the strength of horizontal salinity gradient combining both in the zonal and meridional directions (equation (1)) to find the SF in the tropical Pacific (Figures 2d and 2e).

$$\nabla S = \sqrt{\nabla S_x^2 + \nabla S_y^2}$$

Aquarius data clearly resolve considerably more detail and extreme SSS frontal structures than is resolved in the spatially smoothed Argo map interpolated from sparse observations. The horizontal salinity gradient can be as large as $4 \times 10^{-3}$ psu/km from Aquarius satellite observations (Figure 2e). The black contours in Figures 2a, 2b, 2d, and 2e indicate the 34.6 psu isohaline, which clearly aligns with the prominent zonal SSS frontal structures along the ITCZ, particularly its southern boundary, and aligns with the SF at the EPFP (Figure 2e). The same isohaline is used as an indicator of the SF at the eastern edge of WPWP [Maes et al., 2006]. Another feature revealed by Aquarius is the split SF in the eastern Pacific. In Argo map (Figure 2d), there is one wide front extending from the coast of South America covering from $0^\circ$ to $10^\circ$ N. In contrast, more detailed structures of the EPFP are delineated in the Aquarius map (Figure 2b). In Figure 2e, two fine SF are shown with one close to the equator and the other to the north ($\sim 10^\circ$ N) associated with the northern and southern boundaries of EPFP. The difference between the Figures 2d and 2e is shown in Figure 2f. The SF that are captured by the Aquarius but not Argo are extraordinarily consistent with the 100 mm/month precipitation isoline, suggesting that the SSS from Aquarius reveals more detailed
signatures for the surface ocean response to freshwater fluxes. Figure 2 demonstrates that the Aquarius satellite is providing new salinity information to better understand the upper ocean dynamics in the tropical Pacific region.

3.2. Seasonal Cycles of Salinity Fronts and Associated Precipitation and Currents

The seasonal cycle of SSS in the tropical Pacific has been described in general by Bingham et al. [2010] and Lagerloef et al. [2010]. Here we further show 4 months of the maps to demonstrate the seasonal cycle of the SF. Four notable features of the SF can be seen in Figure 3 (left): (1) The SF under the ITCZ is most extensive and intensive fall (October). (2) SF usually appears in the southern boundaries of the fresh pool under the ITCZ. (3) SF in the South Pacific convergence zone (SPCZ) are generally much weaker than at the ITCZ [Gouriou and Delcroix, 2002].

Precipitation and horizontal currents are two major components that can influence the formation and strength of the SF. The strong precipitation can cause the regional freshening and strengthen the salinity gradient at the boundaries of the fresh pools. In Figure 3 (left), strong SF are observed near the boundaries of the fresh pool under the ITCZ in October when the rainfall is the strongest as shown in Figure 3 (middle). The black contours in Figure 3 (middle) show the 3 mm/day isolines of the precipitation to represent the boundary of the ITCZ. However, the SF in the central to western Pacific is much weaker in April when the zonal rain band also happens along the whole Pacific basin. The result indicates that in addition to rainfall, there are other mechanisms that control the strength of the SF. On the other hand, we notice that the current systems look different in these seasons (Figure 3, right). The black contours in Figure 3 (right) show the 0 m/s isolines for the zonal currents. In October, the strong NECC occurring under the ITCZ also aligns with locations of the SF. In contrast, the NECC fades in April, when the SF are weak. The dynamic connection between the SF and the NECC is still unknown. One of the possible explanations is that the strong meridional salinity gradient dominates meridional density gradient, which tends to enhance the zonal currents.

To further quantify the intensity of the SF in different seasons, we then show in Figure 4 the variations of SSS, SF, precipitation, and zonal currents from the equator to 15°N averaged between 120°W and 150°W. We notice that the SSS from equator to 5°N does not show much seasonal variations. The freshening around 10°N is cause of the SF. In October (blue-green line in Figure 4), the strong SF around 8°N
(Figure 4b) is observed as a result of the freshening at 10°N (Figure 4a). The strong SF accompanies with the intense precipitation (Figure 4c) and the strong NECC (Figure 4d).

The intense precipitation can enhance the SF by freshening. The role of the zonal currents, especially NECC, is not so clear. Although the locations of the strong NECC are found to be coincide with the SF in July (red) and October (blue-green). More analysis is needed to better understand the connection between the NECC and the SF. We also notice that the intensity of the precipitation is comparable in April and in July (green and red lines in Figure 4c), but the SF formed in July but not in April. The differences indicate that other than the precipitation, there may be other dynamics involved. For example, Yu [2014; this special issue] argues that the SF in the central Pacific is a manifestation of the Ekman convergence. Further investigation of salinity front formation mechanisms will be included in future studies and is beyond the scope of this paper.

We calculated the sea surface density (SSD) to study in more detail the effects of the SF on the upper ocean dynamics. The equation of state was used to combine the high-resolution of SSS data from Aquarius and the SST data from NOAA OISST. We located the density fronts in the tropical Pacific from calculating the horizontal density gradients substituting density for salinity in equation (1) and show the results in in Figure 5 (right). Comparing with the SF and the SST fronts, we then evaluate which part of the density fronts are contributed by the SSS or by the SST. As discussed, the SF are most evident at the boundaries of ITCZ and the edges of the fresh pools. The SST fronts (Figure 5, middle) are most evident in the equatorial central to eastern Pacific and the north boundaries of the eastern Pacific warm pool. The SST over the WPWP is so homogeneous that SST fronts are weak in the western Pacific. Density fronts reflect the locations of both the SF and the SST fronts. The locations of SST and SSS fronts have already been shown to influence the TIW.
dynamics [Lee et al., 2012]. These results are described in the context of the regional SF discussions in the following sections.

4. Salinity Fronts at the Intertropical Convergence Zone

As seen in Figures 2 and 3, the SF are well defined at the boundaries of the ITCZ rain band with the strongest gradients occurring September–October–November. In this season, there is also thick BL observed over the whole Pacific ITCZ (Figure 6c), especially where the SF is the strongest (Figure 6b). The results show that the SF can be an indicator of the existence of BL not only in the western Pacific [Maes et al., 2005] but also under the ITCZ. The thick green line ($7^\circ$–$11^\circ$N, $120^\circ$W) in Figure 6b indicates a transect crossing through a strong SF. Along this line, the SST is nearly homogeneous (black line in Figure 6a) and the BLT is around

Figure 5. Maps of the SSS fronts (left), SST fronts (middle) and the density fronts (right) in January, April, July, and October. The units are in psu/km, °C/km, and kg/m$^3$/km, respectively.

Figure 6. Maps of (a) SST, (b) salinity front and (c) barrier layer thickness (BLT) in October 2012. The green/black lines in Figures 6b/6a and 6c show the cross section of the strong SF used in Figure 7.
The relationships between SST, SSS, SSD, and BLT across this SF are displayed in a modified T-S diagram (Figure 7). The BLT (color) is plotted at every grid point with 1/3° resolution along the transect. SST is quite constant at around 27.8°C to 28.1°C, whereas, the SSS varies from 33.1 to 34.3 psu, indicating the existence strong SF with strength of 1.2 psu from 7°N to 11°N (~444.78 km), and the salinity-based density variations as much as 0.8 kg/m³ along this cross line. These results show an example of strong SF detected with Aquarius in the area where the SST has little variations and a sharp density front can be formed majorly contributed by the SSS. The results also show that strong density variance (density fronts) can be calculated combining the Aquarius SSS and SST from satellite observations. The in situ data alone are too sparse to resolve the SF.

5. Salinity Fronts at Eastern Pacific Fresh Pool

At the eastern tropical Pacific, in addition to the fresh pool under the major ITCZ at around 5°N, another branch of fresh water (“second ITCZ” hereafter) is observed near the coast of South America during the boreal spring, as the results of a second rain band at around 5°S. The two regional freshenings off the equator are the results of the double ITCZ, which are first observed from the atmospheric convection and precipitation [Waliser and Gautier, 1993; Zhang, 2001]. The double ITCZ is generated during the boreal spring when the warm water (>27.5°C) in the eastern Pacific warm pool is separated by the upwelling at the equator. Identifying the double ITCZ is useful for examining simulations of general circulation models (GCMs) [Mechoso et al., 1995; Lin, 2007] and better understanding the upper ocean dynamics at the eastern Pacific.

Figure 8 shows the detailed maps of the double ITCZ in precipitation and SSS from January to May. During this time period, a branch of enhanced precipitation forms and grows around 5°S (left panels of Figure 8). In the SSS maps (Figure 8, middle), a fresh pool (<32 psu; black solid contours show the 32 psu isohaline) is present around 80°W to 90°W and 2°–7°N. In addition, there is a separation of fresh water around 33.5 psu extending southward around 5°S from January to April and then soon dissipates in May. The SF calculated from these SSS maps are strong at the boundaries of the fresh pool and the south boundary of the second ITCZ (right panels of Figure 8). The SF at the boundaries of the fresh pool aligns with the 32.5 psu (black solid contours) and the SF at the south boundary of the second ITCZ well align with the 34.3 psu (black-dashed contours).

To demonstrate the meridional variations of the SSS in the eastern Pacific on a seasonal cycle, Figure 9 shows the Hovmöller diagrams averaged from 90° to 110°W. The lowest SSS (<33 psu) is observed under the ITCZ in the northern hemisphere, especially around October (Figure 9a). A branch of less fresh water extends from the equator to around 5°S from February to May. The warm water split by the cool upwelling at the equator forms the essential SST pattern that contributes to the double ITCZ (Figure 9b) [Zhang, 2001]. The black contours in Figure 9b represent the 27.5°C isotherm being separating at the equator. The strong precipitation corresponds to the warm pool variations, with the strongest intensity over the ITCZ in the northern hemisphere and a weaker regional precipitation pattern seen ~5°S during the boreal spring. The regional freshening forms sharp SF (Figure 9d) at the south boundary of the southern ITCZ. The SF in the eastern Pacific visibly shows a southward extension from 5°S in February to 10°S in May, which is not seen in the precipitation data (Figure 9c). The results imply that the southward extension of the SF may be associated with the meridional currents (Figure 9e) carrying the freshwater southward. The results imply that the salinity pattern in the EPFP may be influenced by both the precipitation and the meridional advections.
In Figure 9, we also observe a strong SF in the eastern Pacific right on the equator throughout the whole year. The existence of this SF is the reason why the TIW signature is most evident in SSS \(-0^\circ\) compared to SST and SSH or to the SSS at 4\(^\circ\)N [Lee et al., 2012]. In the eastern tropical Pacific, the MLD and the isothermal layer depth is generally shallow due to the strong upwelling. Therefore, even though the strong SF and shear currents are observed in these areas, the BL is much thinner than that in the western Pacific (Figure 9f). The results suggest that although the SF may be an indicator of the location of the BL in the central to western Pacific, the SF at the surface does not guarantee the existence of BL if the MLD is shallow as in the eastern Pacific.

6. Salinity Fronts at Western Pacific Fresh Pool

Figure 2 shows that Argo provides vague contours for the SF in the tropical Pacific, but Aquarius provides more detailed and better-identified SF, which can be approximately presented by the 34.6 PSU isohaline. Figures 10a and 10b zoom into the western equatorial Pacific and in more details, we see that the SF aligns in northeast-southwest direction only at the equator around 5\(^\circ\)S–5\(^\circ\)N (Figure 10b). Then the SF extend to the east as they spread poleward in both hemispheres. At the equator (Figure 10c), the zonal migrations of the eastern edge of WPWP and the eastern edge of WPFP are dominated by the equatorial currents (SEC and NECC) through the
horizontal advection [Bosc et al., 2009]. However, the domain of the warm pool and the fresh pool, representing by 28°C and 34.6 psu, respectively, are distinct away from the equator, indicating that the mechanism that controls variations of the WPWP and that of the WPFP are not exactly the same (Figures 10a and 10e).

The importance of the SF in the equatorial western Pacific is that the SF is known to migrate simultaneously with the eastern edge of warm pool and show strong interannual variations related ENSO activities [Picaut et al., 1996, 2001; Delcroix and Picaut, 1998; Bosc et al., 2009]. In addition, studies have shown that SF at the western equatorial Pacific form where the westward salty SEC converges with the eastward fresh NECC. The
Salinity stratification is enhanced when the salty water from the east subducting under the fresh water from the west. The shear currents and the contrasting mixed-layer salinity form a condition that is favorable for the formation of the BL through the horizontal advection mechanism [Cronin and McPhaden, 2002]. In fact, high correlation between the SF and the BLT in the western Pacific are observed, and the existence of thick BL has been considered important during the onset of ENSO events [Maes et al., 2005]. It is noticed that the thickest BL is usually found at the west of the SF (Figures 10a and 10f). This is the result of the westward salty SEC subducting under the eastward fresh NECC when they converge in the western equatorial Pacific and enhance the vertical salinity stratification to the west of the SF (see Figure 2 in Bosc et al. [2009]).

Overall, the better depictions of the horizontal structures and strength of SF by Aquarius satellite could help us better understand the relationship between the SF and BL in the western Pacific more than just on the equator. The structure of the BLT (Figure 10f) is more similar to the SST (Figure 10e) than to the SSS (Figure 10a). The results indicate that SF can be an indicator of where the BL is formed, but the warm water column is what determines the thickness of the BL. In other words, the SF are favorable for the shallow mixed layer, but the deep isothermal layer is essential for the thick BL formation.

7. Summary and Discussion

The main purpose of this paper is to reveal that for the first time the fine-scale structures of the SF captured by the Aquarius satellite with a focus in the tropical Pacific. The importance of the SF includes finding the density front caused by the SF (Figures 5 and 7), possible indicator of thick BL (Figures 6, 7, and 10), improving the regional surface salt advection calculation, enhancing the TIW SSS signals at $0^\circ$ in the eastern Pacific [Lee et al., 2012], tracking the southward extension of the freshwater related to the second ITCZ in the eastern Pacific during the spring time (Figures 8 and 9), and strong interannual variations correlated with the ENSO activities [Picaut et al., 1996; Delcroix and Picaut, 1998; Maes et al., 2006].

Our study shows that both high rainfall rates and surface current convergence are essential ingredients for the formation and strengthening of SF. It will be our next step to further investigate how the freshwater flux and horizontal advection contribute to the variations of SF. At the same time, the SST is nearly homogeneous in the central to western Pacific. As seen in in Figure 5 (middle), the strong SST fronts are

Figure 10. The maps of (a) SSS, (b) SSS fronts, (c) zonal currents, (d) precipitation, (e) SST, and (f) BLT over the western Pacific fresh/warm pool in October 2012. The values of the isolines are labeled in the titles.
concentrated mainly in the eastern Pacific. As a result, surface density variations observed over most of the tropical Pacific are primarily contributed by SSS. The detailed surface density information calculated from SST and Aquarius SSS measurements is useful for understanding the upper ocean dynamics.

The principal advantage of Aquarius satellite salinity measurements is the finer spatial resolutions that reveal the SF structure obscured by the sparse sampling and smoothing scales of the in situ measurement array. Although the SF in the western Pacific has been greatly studied because of the high correlations with ENSO activities, the SF in the eastern Pacific are even stronger from Aquarius observations. The detailed structures and the variations of the SF in the tropical Pacific yield important new information on the regional air-sea interaction and the upper ocean dynamics. While the precise dynamics of SF in the tropical Pacific remains obscure, this paper has clarified the observed aspects of SF and will serve as an observation target for future dynamical studies.

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