Interannual sea surface salinity variations observed in the tropical North Pacific Ocean

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[1] Analysis of observational data sets reveals pronounced interannual variations of sea surface salinity (SSS) in the tropical North Pacific (7°N–15°N) during 2000–2012. SSS anomalies with maximum magnitudes >0.2 occur in the central Pacific and translate westward at a speed of 15–20 cm s⁻¹. The signals are weakened during their westward movement but reinforced in the Philippine Sea. Budget analysis for the mixed layer salinity suggests that in the central Pacific, El Niño–Southern Oscillation-related atmospheric freshwater forcing and ocean advection changes are both important in generating and maintaining these large SSS anomalies. In the advection term, the most contributing component is the meridional Ekman advection induced by trade winds. These SSS anomalies are subsequently carried westward by the North Equatorial Current, which is the primary cause of SSS variations in the Philippine Sea. Freshwater forcing is also at work in the Philippine Sea, but its role is generally secondary. Citation: Li, Y., F. Wang and W. Han (2013), Interannual sea surface salinity variations observed in the tropical North Pacific Ocean, Geophys. Res. Lett., 40, 2194–2199, doi:10.1002/grl.50429.

1. Introduction

[2] Recent observational and modeling studies have suggested the active role of ocean salinity in the tropical air-sea interactions [e.g., Vialard and Delecluse, 1998; Vialard et al., 2002; Maes et al., 2005]. However, quantifying sea surface salinity (SSS) variability used to be a challenging task due to the paucity of in situ observations. In the tropical Pacific Ocean, large seasonal SSS variations often occur in the intertropical convergence zone (ITCZ) and South Pacific convergence zone (SPCZ) regions and mainly controlled by rainfall changes [e.g., Delcroix and Henin, 1991; Delcroix et al., 1996; Hénin et al., 1998]. At interannual time scale, SSS variations are of larger amplitudes and more complicated patterns in response to El Niño–Southern Oscillation (ENSO)-related freshwater forcing and ocean current advection [Maes, 2000; Delcroix and McPhaden, 2002; Delcroix et al., 2011; Singh et al., 2011]. Modeling studies suggested that interannual variations of SSS and its associated barrier layer [Lukas and Lindstrom, 1991] are intrinsically connected with the dynamics of ENSO [e.g., Vialard and Delecluse, 1998; Maes et al., 2005; Yim et al., 2008] and playing a critical role in the evolution of specific events [e.g., Zheng et al., 2012; Zheng and Zhang, 2012].

[3] However, there is a difficulty in validating the modeled SSS variations because of the sparse spatiotemporal sampling of ship/mooring observations. The situation is now somewhat ameliorated by the rapid accumulation of high-quality Argo float profiles. Gridded data sets of Argo measurements combined with other data sources provide more robust spatiotemporal patterns of SSS variability. One of such data sets is the Grid Point Value of the Monthly Objective Analysis (MOAA-GPV) [Hosoda et al., 2008], which is a 1° × 1° gridded monthly product of temperature and salinity on standard pressure levels constructed with data records of Argo floats, buoy measurements, and casts of research cruises using the two-dimensional optimal interpolation method. Here we analyze the records between January 2003 and April 2012. Figure 1a shows the standard deviation (STD) of SSS (represented by 10 dbar salinity), which is low-passed with a 13 month running mean filter to underscore interannual signals. The strongest SSS variability appears in the far western equatorial Pacific, with STD > 0.2 (psu) and extending southeastward to the SPCZ, which has been investigated by previous studies [e.g., Delcroix and Henin, 1991; Delcroix et al., 2011; Singh et al., 2011]. Another relative maximum of variability occurs in the tropical North Pacific (TNP) between 7°N–15°N with STD > 0.15 near the dateline, and extends westward. In addition, variances with weaker strength can also be seen near the western boundary of the TNP (the Philippine Sea). Given the O(0.01) salinity measurement precision of Argo floats [e.g., Riser et al., 2008] and the < 0.03 interpolation error of SSS in MOAA-GVP [Hosoda et al., 2008], the observed SSS anomalies are rather significant. Because the TNP is an important region for tropical air-sea interactions, it is necessary for us to clarify the detailed spatiotemporal features and the controlling mechanism of these interannual SSS variations.

2. Observed Interannual SSS Variability

[4] To confirm the robustness of the SSS variability pattern, we refer to another data set, the 1° × 1° monthly SSS product of Delcroix et al. [2011] for the tropical Pacific (hereafter TD211) based on measurements from voluntary observing ships, moorings, conductivity-temperature-depth (CTD) and Argo profilers. Because this product is updated to 2009, we estimate the mean and STD fields for the period of 2000–2009 (Figure 1b). Albeit with detailed discrepancies, the two products show similar patterns in both mean state and interannual variability, including the two aforementioned...
STD maxima in the central TNP and the Philippine Sea. Because surface freshwater flux, e.g., evaporation minus precipitation ($E-P$), is an important factor affecting SSS variations in the open ocean, we present $E-P$ fields from the objectively analyzed air-sea fluxes (OAFlux) evaporation [Yu, 2007] and the Tropical Rainfall Measuring Mission multisatellite precipitation [Kummerow et al., 1998] in Figure 1c. Note that $E-P$ field shows apparent differences from SSS in both mean state and variation. Mean $E-P$ exhibits a narrow minimum band ($< -0.5 \times 10^{-7} \text{ m s}^{-1}$) between $4^\circ \text{N} - 7^\circ \text{N}$, characterizing the ITCZ (Figure 1d), while the minimum band of SSS ($< 34.5$) locates generally north of these latitudes [Delcroix et al., 1996; Hénin et al., 1998]. This difference indicates the importance of ocean dynamics: fresh water formed within the ITCZ is carried northward by the Ekman flow (Figure 1e) associated with trade winds (Figure 1d). For interannual variability, the largest $E-P$ STD values are confined to the ITCZ and SPCZ. In the TNP where large SSS variations are observed, $E-P$ exhibits a relative maximum centered at $160^\circ \text{E}, 10^\circ \text{N}$. Its amplitude, however, is much weaker than that within the Philippine Sea, even though SSS STD is larger near the dateline. These results indicate that except freshwater flux, ocean dynamics is also important in modulating SSS variations in the TNP.

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Figure 2. Upper panels are time-longitude plots of (a) MOAA-GPV SSS, (b) mixed layer salinity, (c) \(E-P\) \((10^{-7} \text{ m s}^{-1})\), (d) CCMP \(\tau_c\) \((\text{N m}^{-2})\), and (e) Niño-3.4 index from the Climate Prediction Center of NOAA, which is defined as the sea surface temperature anomaly in the Niño-3.4 region \((170^\circ\text{W}−120^\circ\text{W}, 5^\circ\text{S}−5^\circ\text{N})\). Lower panels are time-longitude plots of (f) mixed layer salinity tendency \(S_t\), (g) SEF, (h) \(\text{ADV}\), (i) \(<U_g>S\), and (j) the advection with \(<U_g>S\) component extracted, \(\text{ADV}−(<U_g>S)S\). All the variables, except Niño-3.4 index, are shown as 13 month low-passed anomalies. Unit of the lower panels is \(10^8 \text{ s}^{-3}\).

[Ducet et al., 2000] suggests pronounced geostrophic current variability in this region, which may be important in modulating SSS variation through advection. Moreover, mixed layer depth (MLD) also shows large variations near the dateline (Figure 1f). Entrainment impact may be also not negligible. Here MLD is defined as the depth at which the potential density difference from 10-dbar value is equal to a threshold of \([\text{de Boyer Montégut et al., 2004}]\)

\[
\Delta \sigma = \sigma(T_{10}−0.2,S_{10},P_0)−\sigma(T_{10},S_{10},P_0),
\]

where \(T_{10}\) and \(S_{10}\) are temperature and salinity at 10 dbar, and \(P_0\) is sea surface pressure.

[7] A time-longitude plot of MOAA-GPV SSS averaged between \(7^\circ\text{N}−15^\circ\text{N}\) is shown in Figure 2a. Positive (negative) anomalies with magnitudes \(>0.2\) appear during 2008–2009 \((2003–2004)\) in the central Pacific. Weaker anomalies occur in 2005, 2006–2007, and 2011–2012. The patterns of SSS and mixed layer salinity \(S\) (Figure 2b) are strikingly alike, suggesting that \(S\) is a reliable proxy of SSS. These salinity anomalies persist for 2–3 years and exhibit westward translating behaviors. We roughly estimated the translating speed by dividing the total travel distance with translating time for each anomaly track. The results range from 15 to 20 \(\text{cm s}^{-1}\), which is quite close to the mean geostrophic velocity of the NEC near the sea surface. The salinity signals are reduced during the westward movements but reinforced in the Philippine Sea where salinity variations are influenced by both signal arrivals from the ocean interior and local anomaly generation. Salinity anomalies here can persist for only 1 year, showing higher frequencies compared with those in the central Pacific. It is noteworthy that the correlation between SSS and ENSO variations is quite evident. Positive (negative) SSS anomalies in the central Pacific are generated during La Niña (El Niño) episodes (Figure 2e). There are mainly two possible processes through which ENSO can dictate salinity variations in the TNP. Negative \(E-P\) anomalies and weakened trade winds
occur during warm conditions, while positive E-P anomalies and enhanced trade winds can be observed during cold conditions (Figures 2c and 2d). Variations of ocean current advection, especially meridional Ekman advection, induced by the zonal wind changes can be a very importance mechanism. Therefore, a quantitative analysis is demanded to clarify the relative importance of different processes.

3. Budget Analysis

[8] We then perform a budget analysis using conservation equation of the mixed layer salinity [Qu et al., 2011],

\[ S_t = SEF + ADV + SUB + R, \]

where \( S_t = \partial S / \partial t \) is the tendency of mixed layer salinity \( S \), \( SEF \) denotes surface external forcing from atmosphere which is expressed as

\[ SEF = S(E - P)/h. \]

[9] Here \( h \) denotes MLD. \( ADV \) in equation (2) represents advection term \( ADV = -(US_x + VS_y) \). Here monthly \( U \) and \( V \) fields are estimated from OSCAR product. \( SUB \) in (2) denotes the subsurface impact including entrainment and vertical pumping,

\[ SUB = - \frac{\partial h}{\partial t} \frac{\Delta S}{h} - w_E \frac{\partial S}{\partial z}, \]

where entrainment term is multiplied with a heaviside function \( h \), which equals zero for a shoaling mixed layer (\( \partial h / \partial t < 0 \)) and equals 1 for a deepening mixed layer (\( \partial h / \partial t > 0 \)), \( \Delta S \) is the salinity difference between the mixed layer and immediately below, and \( w_E \) is the Ekman pumping velocity calculated as \( w_E = \text{curl}(\vec{f}) \sigma_0 \) by Cross-Calibrated Multi-Platform (CCMP) wind stress \( \vec{f} \) is the Coriolis parameter, and \( \sigma_0 = 1021 \text{ kg m}^{-3} \) is the reference density. The residual \( R \) includes lateral and vertical mixing processes and estimation errors in the other three terms on the right-hand side of equation (2).

[10] Time-longitude plots of \( S_t, SEF, \) and \( ADV \) are shown in Figures 2f–2h. Both \( SEF \) and \( ADV \) are of large interannual amplitude, but the westward translating features in \( S_t \) are seen only in \( ADV \). Hence, the westward movements of SSS anomalies are mainly through ocean current advection. We then average all the terms in equation (2) in three longitude ranges \( 180^\circ \text{W} - 160^\circ \text{W}, 160^\circ \text{E} - 180^\circ \), and \( 130^\circ \text{E} - 150^\circ \text{E} \) within the TNP latitude band \( 7^\circ \text{N} - 15^\circ \text{N} \) and plot the low-passed anomalies in Figure 3 to show interannual variations. Two boxes are defined for the central TNP. In the \( 180^\circ \text{W} - 160^\circ \text{W} \) box, the most significant contribution is made by \( ADV \) (Figure 3a), which shows large in-phase variations and a linear correlation of \( r = 0.73 \) (> 95% confidence level) with \( S_t \). Although \( SEF \) also has large interannual variations, its correlation with \( S_t \) is very weak \( (r = 0.06) \) in this region. Because of the importance of \( ADV \), we further decompose it into zonal and meridional components, \( -US_x \) and \( -VS_y \). The results show that neither of the two terms is negligible, but \(-VS_y\) is of larger amplitude and better correlated with the total \( ADV \) \( (r = 0.74) \). We further estimate the advection by the mean zonal geostrophic flow of the NEC, \(-U_g\), which is calculated using AVISO SSH data, and meridional Ekman advection \(-V_E S_y\) with Ekman velocity \( V_E \) being calculated by \( V_E = -\vec{v}/\sigma_0 h \) using CCMP wind stress data. These two processes can explain most of the \(-US_x \) and \(-VS_y \) variations, with correlations reaching 0.88 and 0.89, respectively. Therefore, between \( 180^\circ - 160^\circ \text{W} \), meridional Ekman advection is the controlling process of the interannual SSS variability.

[11] In the box west of the dateline \( (160^\circ \text{E} - 180^\circ) \) where SSS anomaly maxima occur, salinity variance is greatly elevated (Figure 3c). Both \( SEF \) and \( ADV \) terms show large interannual fluctuations and significant correlations with \( S_t \) \( (r = 0.31 \) for \( SEF, r = 0.75 \) for \( ADV) \). Hence atmospheric freshwater flux and ocean advection are both important in producing and maintaining these large SSS anomalies. For the advection term, neither of \(-US_x \) and \(-VS_y \) is negligible (Figure 3d). They are both well correlated with the total \( ADV \) \( (r = 0.62 \) for \(-US_x, r = 0.73 \) for \(-VS_y), and can again be mostly explained by \(-U_g \)

\( S_t \) \( (r = 0.93) \) and \( -V_E S_y \) \( (r = 0.95) \), respectively. In fact, \(-U_g \)

\( S_t \) stands for the anomalies advected from east of the dateline, which are in turn controlled by \(-V_E S_y\). (recall Figures 3a and 3b). We can hence conclude that in the advection term, the most contributing component is the meridional Ekman advection \(-V_E S_y\). We should also note that in both \( 160^\circ \text{E} - 180^\circ \) and \( 180^\circ - 160^\circ \text{W} \) boxes, \( S_t, SEF, ADV, \) and \(-V_E S_y\) are all well correlated with Niño-3.4 index with \( r \) ranging between 0.40–0.54. Hence, \( E-P \) forcing and anomalous Ekman advection induced by trade wind changes are the primarily mechanisms transferring ENSO signals to the TNP SSS variability.

[12] In the western Pacific box \( (130^\circ \text{E} - 150^\circ \text{E}) \), the dominance of horizontal advection is very evident \( (r = 0.84 \) between \( S_t \) and \( ADV \)) (Figure 3e). \( SEF \) also plays some role in SSS variations \( (r = 0.13) \). Compared with the situation in the central Pacific, \( S_t \) in the western Pacific exhibits larger higher-frequency power \( (e.g., 2-4 \text{ year period}) \) and reduced correlation with Niño-3.4 index \( (r = 0.15) \). The 2–4 year variances seem primarily from \( SEF \), which shows low simultaneous correlation with Niño-3.4 index \( (r = 0.06) \). Throughout the three boxes, \( SUB \) is generally negligible in amplitude and not well correlated with \( S_t \) \( (below 0.2) \). Interestingly, the residual \( R \) is also of large interannual amplitude, but its contribution to \( S_t \) is negative \((r = -0.08, -0.46, \) and \(-0.35 \) respectively in the three boxes). This may arise from our overestimation of the terms on the right-hand side of equation (2), especially \( ADV \), and also from enhanced mixing processes in the western Pacific which acts to dump produced signals [Li et al., 2012]. Among the components of \( ADV \), \(-U_g \) is the most important process (Figure 3f). It is highly correlated with the total \( ADV \) \( (r = 0.71) \), suggesting that interannual SSS variations of in the Philippine Sea is mainly dominated by anomalies advected from the central TNP by the NEC. Inspired by this result, we plotted a time-longitude map of \(-U_g \) (Figure 2i), in which westward signal propagation is clearly discernable. On the other hand, the remnant of \( ADV \), i.e., \( ADV - (-U_g) \), is of little translating tendency (Figure 2j). This comparison leads us to the conclusion that it is the advection of the NEC that is responsible for the westward translating feature of the observed SSS anomalies.

4. Summary

[13] Based on two gridded data sets (MOAA-GPV and TD11) of in situ observations during the past decade, pronounced interannual SSS variability with STD > 0.15 are detected in the TNP region \( (7^\circ \text{N} - 15^\circ \text{N}) \). Observed SSS
fluctuations are first produced near the dateline with peak magnitudes \( > 0.2 \). These anomalies can persist for 2–3 years and translate westward at a speed of 15–20 cm s\(^{-1}\). They diffuse quickly during their westward movement but get reinforced in the Philippine Sea. Checking E-P, wind stress, surface current, SSH, and MLD fields suggests that various processes are possibly at work in forming the observed spatial-temporal features of SSS variability in the TNP.

Combined with satellite observations, we quantified the interannual variations of the terms in the conservation equation of the mixed layer salinity. Comparing seasonal SSS variability which is primarily dominated by E-P forcing according to previous studies [e.g., Delcroix and Henin, 1991; Delcroix et al., 1996; Hénin et al., 1998], our analysis demonstrate that ocean dynamics is of higher-level of importance at interannual time scale. In the central Pacific, meridional Ekman advection \(-V_E S_y\) and E-P forcing are both important in producing and maintaining the low-frequency, large-magnitude SSS anomalies, and the two effects are also both closely associated with ENSO events. After generation, these SSS anomalies are carried westward to the Philippine Sea by the zonal flow of the NEC and thus exhibit westward translating features. In the Philippine Sea, salinity variations are of higher frequency and mainly dominated by arrivals of SSS anomalies from the interior ocean, i.e., \(-<U_g>S_x\) impact. E-P forcing also contributes to SSS variations in the Philippine Sea, but its role is generally secondary comparing with ocean current advection.

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