Salinity Interdecadal Variability in the Western Equatorial Pacific and Its Effects During 1942-2018

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Abstract

Ocean reanalysis products are used to examine salinity variability and its relationships with temperature in the western equatorial Pacific during 1942-2018. An ensemble empirical mode decomposition (EEMD) method is adopted to separate salinity and temperature signals at different time scales; a focus is placed on interdecadal component in this study. Pronounced interdecadal variations in salinity are seen in the western equatorial Pacific, which exhibits persistent and transitional phases in association with temperature. A surface freshening is accompanied by a surface warming during the 1980s-1990s, but saltening and cooling in the 2000s, with interdecadal shifts occurring around the late 1970s, late 1990s, and in 2016-2018, respectively. Determined by anomaly signs of temperature and salinity, their combined effects can be density-compensated or density-uncompensated, acting to produce density variability that is suppressed or enhanced, respectively. The effects are phase- and region dependent. In the subsurface layers at 200m, where salinity and temperature anomalies are nearly of the same sign during interdecadal evolution, their effects are mostly density-compensated. The situation is more complicated in the surface layer. Variations in SSS and SST during the persistent phases tend to be of opposite sign with their density-uncompensated effects, acting to enhance density anomalies; but they can be of the same sign during the transitional periods, with density-compensated salinity effects. Examples are given for relationships among these fields which exhibit phase differences in anomaly transitions in the late 1990s in the western equatorial Pacific; salinity anomalies are seen to cause a delay in phase transition of density anomalies. Furthermore, their relative contributions to interdecadal variabilities of density and stratification are quantified. The consequences for salinity effects are also discussed with their feedbacks on local SST.

1. Introduction

The western equatorial Pacific is the climatically important region where pronounced climate signals emerge at various time scales. The warmest water pool is located in the western equatorial Pacific, where temperature exhibits variability at interannual and interdecadal scales associated with major climate modes in the region, including El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). Interannually, for example, the warm waters in the western Pacific in response to ENSO migrate eastward along the equator during El Nino but retreat westward during La Nina. Historically, temperature (thermal) fields have been extensively used to investigate ENSO-related interannual variations for theoretical analyses and numerical modeling.

Salinity is another important variable in the ocean, which can also be a good indicator for climate variability and predictability (Miller 1976; Lukas and Lindstrom 1991; Maes et al. 2006; Li et al. 2013; Qu et al. 2014; Hu and Sprintall, 2016; Guan et al. 2019; Du et al. 2019; Qi et al. 2019). For example, some notable salinity-related features emerge in the western equatorial Pacific, where fresh waters coexist with the warmest water pool. Climatologically, low salinity waters occupy in the far western equatorial Pacific, whereas in the central basin near the date line, saline waters are generated by less freshwater inputs into the ocean at the ocean-atmosphere interface, thus producing a strong salinity front between the western

and central equatorial Pacific. Variability of the low-salinity waters in the region is also closely related with the major climate modes (ENSO and PDO). For example, interannual freshening and saltening take place in the western-central equatorial Pacific in association with ENSO (Picaut et al. 1996; Delcroix and Picaut, 1998; Hasson et al. 2013; Gao et al. 2014). Surface-layer waters in the western tropical Pacific become fresher during El Nino events but saltier during La Nina events, respectively.

Temperature and salinity collectively determine ocean density, an important field to ocean pressure field and circulation. Depending on the relative contributions to density, salinity and temperature effects can give rise to different consequence for density anomalies. For example, when salinity anomalies are of the opposite sign with temperature, their combined net effects lead to enhanced density variability (i. e., density-uncompensated effect). In contrast, when temperature and salinity anomalies are of the same sign, their combined effects on density tend to be canceled out by each other (i. e., density-compensated), leading to density anomalies that are suppressed, with the amplitude of the resultant density variability being reduced. Furthermore, it is conceivable that the sign and amplitude of density variability can be even determined by salinity anomalies if its effects are greater than those of temperature.

As observed, pronounced salinity and temperature anomalies coexist in the tropical Pacific on different time scales, exhibiting their complicated interplays at different scales. On one hand, temperature and salinity anomalies are closely associated with the major climate modes in the region. So, temperature and salinity variabilities are seen to have a well-defined and coherent relationship. On the other hand, temperature and salinity are actually two different fields which are associated with different forcing, feedback effects, and the underlying processes and mechanisms. For example, interannual variabilities of these two fields have different characteristics and effects on density, which are strongly regionally dependent in the tropical Pacific. Associated with a direct forcing from freshwater flux, for instance, large interannual variability region of sea surface salinity (SSS) is located in the western equatorial Pacific. In contrast, large interannual variability of sea surface temperature (SST), directly affected by heat flux forcing, is located in the central and eastern equatorial basin. As a result, the way ocean density and pressure is affected by salinity and temperature is sensitively dependent on regions. In particular, because salinity variability in the western equatorial Pacific can have comparable amplitude to temperature, salinity can equally make contributions to density variability; but in the eastern equatorial Pacific, the effects of temperature largely dominate density variability. So, it is critically important to understand the characteristics of salinity variability, temperature-salinity (T-S) relationships and their combined net effects on density and resultant consequences.

Previously, temperature variability and its effects on density have been received extensive attention. Due to the difficulty in observations, salinity variability and its effects have been less investigated; its roles in the ocean circulation and climate variability have not been understood well. At present, systematic and comprehensive analyses for the salinity effects are still lacking in the tropical Pacific. As salinity observations and related reanalysis products become available, it is possible to examine salinity variability and its relationships with temperature and other related fields. On interannual time scales, for example, the extent to which salinity can play a role in determining density variability has been illustrated

(Vialard et al. 2002; Zhang and Busalacchi 2009; Singh et al. 2011; Zhang et al. 2012; Zheng and Zhang 2012; Vinogradova and Ponte 2013; Zhu et al. 2014; Tang and Simon 2017). On interdecadal scales, large salinity anomalies also coexist with temperature in the western equatorial Pacific, but salinity interdecadal variability and its relationship with temperature have not been clearly illustrated.

In this study, salinity variability and its effects on density in the western equatorial Pacific are analyzed using historical ocean reanalysis data. As seen, salinity variability exhibits multiple scale signals in the tropical Pacific. To separate various components at different time scales, the ensemble empirical mode decomposition (EEMD) method is first used to extract different frequency components (Wu and Huang 20007). Then, signals with specific frequency bands can be reconstructed. In this study, a focus is placed on salinity interdecadal variability and its relationships with temperature and other derived fields in the western equatorial Pacific. As the amplitude of T and S variabilities is comparable to each other in the region, salinity is expected to have important effects on density anomalies. Relative contributions of temperature and salinity anomalies to anomalies of density and other related fields in the upper ocean are quantified to demonstrate the role played by salinity in producing density variability and vertical stratification (as represented by Brunt-Vasaila frequency, N^2).

The paper is organized as follows. Section 2 describes the methodology and dataset used in this study. Section 3 provides a brief description of the EEMD method that is used to extract signals at different time scales. Section 4 analyzes the effects on density, followed by relative contribution analyses in Sect. 5. Section 6 gives the conclusion and discussion.

2. Reanalysis Data Used

Ocean reanalysis products are used to illustrate salinity variability and its relationships with temperature in the tropical Pacific. Ocean salinity and temperature fields are available from the ensembles (EN)_4.2.1.q ocean data product (1901-present) provided by the Met Office Hadley Center (Good et al., 2013), which cover the global ocean with horizontal resolution of $1^\circ \times 1^\circ$ and vertical depths from 5m to 5000m.

Furthermore, some additional oceanic fields are diagnosed using the three-dimensional salinity and temperature fields, including potential density (hereafter it is simply referred as density), N^2 , and the mixed layer depth (MLD). A standard routine in Gill (1982) is taken to calculate density (i.e., relative to the sea surface) and N^2 . The MLD is calculated using a threshold method with a fixed density criterion (e.g., Monterey and Levitus, 1997; Maes, 2000), in which the depth of ML is defined as the depth where the ocean density increases to 0.125 kg m^{-3} relative to that at the ocean surface.

The long-term climatological fields for temperature and salinity (denoted as T_{clim} and S_{clim}) are calculated during the periods 1942–2018. Then, their corresponding total interannual anomalies (denoted as T' and S') are obtained relative to the long-term climatological fields, with which the total fields can be written as $T = T_{\text{clim}} + T'$; $S = S_{\text{clim}} + S'$. Figure 1 shows the horizontal distribution of the standard deviation

(STD) for total interannual SSS anomalies in the tropical Pacific. As shown before, climatologically, low SSS regions are seen in the western equatorial Pacific, with a strong salinity front near the date line; so low-salinity waters coexist with warm waters in the far western equatorial Pacific; interannual salinity variability is closely associated with ENSO cycles, characterized by zonal displacement of the fresh pool along the equator in the western tropical Pacific. Low-salinity fronts migrate eastward during El Nino but retreat westward during La Nina. So, large SSS variability center is located in the western equatorial Pacific, largely reflecting the zonal displacement of the salinity front. This is contrasted to temperature variability whose large anomaly region is located in the eastern equatorial Pacific (the corresponding figures are not given here).

The original time series of the total interannual anomalies for salinity, temperature and density in the region A (the western equatorial Pacific) are shown in Fig. 2 during periods 1942–2018. Multiple-scale signals coexist, which reflect the major climate modes in the region, including ENSO and PDO. A well-defined relationship can be seen among anomalies of temperature, salinity and density. For example, in the surface layer (Fig. 2a), SST and SSS anomalies are largely of the opposite sign, and their effects on sea surface density (SSD) tend to be uncompensated for by each other. The amplitude of SSS and SST variabilities is comparable in the region, and so salinity can play an important role in density variability. In subsurface layers, say at the depth of 200 m (Fig. 2b), temperature and salinity anomalies are nearly of the same sign, their effects are density-compensated. Indeed, variations in density follow closely with those of temperature, indicating that temperature anomalies are a dominant contributor to density variability.

3. Signal Separations By Using The Eemd Method

Multiple-scale signals coexist in the equatorial Pacific as clearly represented by ENSO and PDO phenomena. It is desirable to separate these components at different time scales. Here, such a separation is realized by using the ensemble empirical mode decomposition (EEMD) method (Wu and Huang, 2007). For example, the total interannual anomalies (S') are decomposed into a set of intrinsic mode functions (IMFs) and a long-term trend, respectively.

More specifically, the total salinity interannual anomaly field (S') can be separated into interannual, decadal, interdecadal, and trend components as follows

$$S' = S_{\text{interan}} + S_{\text{deca}} + S_{\text{interde}} + S_{\text{trend}} ,$$

in which S_{interan} , S_{deca} , S_{interde} and S_{trend} stand for interannual, decadal, interdecadal and trend components, respectively. Figure 3 illustrates examples for such a separation of the total SSS interannual variability into these temporal components. It is evident that signals are clearly separable for different time scales. For example, interannual component is associated with ENSO as represented by the IMF 5; the IMF 6 to IMF8 exhibit signals in the decadal and interdecadal bands. In addition, a salinity trend is

clearly evident, with a saltening/freshening trend in the 1990s and 2000s, respectively. The significance of these IMFs is tested and indicates that these extracted signals are all significant.

A similar analysis is performed for temperature fields (Fig. 4), That is, the total temperature interannual anomaly field (T') is separated into interannual, decadal, interdecadal, and trend components, respectively; well-defined variability signals and spatial patterns are seen. For example, interannual component is associated with ENSO as represented by the IMF 5. Also, a warming trend is identified. Inspections of these EEMD-based salinity and temperature analyses indicate their well-defined anomaly patterns, with coherent and consistent relationships at different time scales.

Based on these signal separations, we can reconstruct a field of interest at specific frequency bands for salinity and temperature anomaly fields. For example, we can obtain three-dimensional anomaly fields and their evolutions for interdecadal component as follows. First, a decomposition of total salinity interannual anomalies at each spatial grid point is performed into various temporal components: interannual, decadal and interdecadal bands, respectively. Then, salinity variability signal for a specific time scale can be identified from these IMFs for different temporal bands. Because the IMF7 is representing interdecadal time scale (about 20 years), in his study, we select this component for representing interdecadal variability and performing corresponding reconstruction and analyses; examples for the spatial structure and evolution of the reconstructed interdecadal variability from the IMF7 are shown in Figs. 5–9. As part of climate variations, well-defined T-S anomaly relationships and their space-time evolutions are seen. In terms of their reconstructed interdecadal anomaly fields, then, the total T-S fields can be obtained by adding them onto corresponding climatological fields as $S = S_{\text{clim}} + S_{\text{interde}}$; $T = T_{\text{clim}} + T_{\text{interde}}$. In this paper, the analyses will be focused on S_{interde} and T_{interde} fields and their relative effects on density and other related fields.

4. The Effects On Density

The T-S relationships and their effects on density are examined in this section, with a focus on interdecadal signal extracted by the EEMD method (S_{interde} and T_{interde}); their space-time evolution and salinity effects on density are illustrated in combination with temperature. The reconstructed interdecadal anomaly fields along the equator are shown in Fig. 5 for the surface layer; examples for their spatial patterns are shown in Figs. 6–7, representing different phases during interdecadal evolution. Also, the vertical structures of temperature and salinity interdecadal anomalies are illustrated in Figs. 8–9 for the western equatorial Pacific.

A pronounced signal of temperature and salinity interdecadal variabilities is clearly seen in the upper ocean. Correspondingly, the interdecadal evolution undergoes persistent and transitional phases (Fig. 5). During the analysis period from 1942 to 2018, for example, warm and fresh surface conditions persist from the late 1970s to late 1990s (the left panels), and cold and salty surface conditions during the 2000s (the right panels), respectively. Correspondingly, two interdecadal phase transitions are clearly evident. One interdecadal transition takes place around the late 1970s from cold and salty condition to

warm and fresh condition, and the other in the late 1990s from warm and fresh condition to cold and salty condition, respectively. More recently, another transition is likely to take place during 2016–2018.

Vertically, a coherent pattern can be seen in the upper ocean during the interdecadal evolution. Temperature anomalies are seen to have out-of-phase relationships in the surface layer and subsurface layers, with the largest anomalies occurring in the subsurface layers around at 200 m (Fig. 8a). In contrast, salinity anomalies indicate a uniform sign in the upper 300 m, with the largest anomalies occurring in the surface layer (Fig. 8a). Correspondingly, salinity and temperature anomalies tend to have phase differences in the vertical during their interdecadal evolutions, being mostly out-of-phase in the surface layer but nearly in-phase in the subsurface layers (Figs. 8a-b). Case analyses for the space-time evolution characteristics and salinity effects are detailed below.

4.1 The persistent phases

The vertical structures of salinity and temperature interdecadal anomalies averaged in the western equatorial Pacific are shown in Figs. 8–9. During the interdecadal evolution, temperature and salinity fields exhibit clear differences in their anomaly signs in the vertical direction between the surface layer and subsurface layers: temperature anomalies exhibit out-of-phase signs in the surface layer and in the subsurface layers (Fig. 8a and Fig. 9), whereas salinity anomalies have the nearly in-phase sign transitions in the upper ocean (Fig. 8b). The corresponding combined effects of temperature and salinity anomalies on density exhibit clear differences in the upper ocean (Fig. 8c and Fig. 9).

(1) In the surface layer

Figure 6 shows the reconstructed SSS and SST interdecadal anomaly fields in the tropical Pacific for the interdecadal persistent phases, as represented during the 1970s-1990s for warm and fresh conditions, and during the 2000s for cold and salty conditions, respectively. Spatially, large SSS anomalies are located in the western Pacific, which mainly reflects the zonal migration of the fresh pool along the equator. A pronounced covarying pattern in salinity and temperature anomalies is seen in the western equatorial Pacific. In the surface layer, SSS and SST anomalies tend to be of the opposite sign during the persistent phases, with their effects being density-uncompensated. For example, positive SST anomalies are accompanied with negative SSS anomalies during the 1980s-1990s (the left panels in Fig. 6); these individual anomalies both contribute to negative density anomalies. So, their combined effects lead to the negative density anomalies that become more negative as compared with those induced by temperature or salinity alone. During cold and salty phase in the 2000s (the right panels in Fig. 6), an opposite situation takes place in the western equatorial Pacific. Cold SST anomalies produce positive density anomalies; the effects of negative salinity anomalies make the temperature-produced positive density anomalies more positive. So, the amplitude of density variability is increased due to the uncompensated salinity effects.

Because the amplitude of salinity anomalies in the surface layer is comparable to that of temperature anomalies, salinity is expected to make an important contribution to density variability. As shown in

Fig. 9a, SSD interdecadal anomalies are seen to follow closely with SSS during the persistent phases. So, SSS anomalies can have important effects on density. The relative contributions of individual salinity and temperature anomalies to density and other related fields will be quantified in Sect. 5.

(2) In the subsurface layers

In the western equatorial Pacific, large temperature anomalies are seen in the subsurface layers, whereas large salinity anomalies are located in the surface layer. In addition, salinity interdecadal anomalies tend to have the same sign with those of temperature in the subsurface layers during interdecadal evolution (Figs. 8–9); so, salinity anomalies present a compensated effect on density, relative to temperature. During the 1980s-1990s, for example, negative temperature anomalies in the subsurface layers are accompanied with negative salinity anomalies: the former produces positive density anomalies but the latter gives rise to negative density anomalies, respectively. Their combined effects lead to the positive density anomalies that become reduced (compensated) as compared with those induced by temperature alone. Nevertheless, interdecadal variability of salinity is weak relative to that of temperature in the subsurface layer; so its effect on density is weak. Thus, density interdecadal anomalies are dominantly determined by temperature. During the 2000s, the relationships among these anomalies and salinity effects are in an opposite sense (Figs. 8–9). Because the effects of temperature are greater than those of salinity, the sign of density anomalies follows closely with that of temperature.

(3) Differentiated salinity effects on vertical stratification in the upper ocean

During the interdecadal persistent phases, salinity and temperature anomalies tend to be largely of the opposite sign in the surface layer (Fi. 9a), but nearly of the same sign in the subsurface layers (Fi. 9b). Correspondingly, salinity has density-uncompensated effect in the surface layer, giving rise to enhanced density anomalies. In contrast, salinity has density-compensated effect in the interior subsurface layers, producing density anomalies that are reduced. As such, salinity anomalies act to have asymmetric effects on density in the surface layer and subsurface layer.

Such a differentiated salinity effect on density produces large density gradient in the vertical direction, and so the vertical stratifications should be strongly affected (see Sect. 5 for more details), which can further modulate vertical mixing and SST. For example, during warm and fresh interdecadal persistent periods in the 1980s-1990s (Figs. 5a-b and Fig. 8), warm SST anomalies and negative SSS anomalies have uncompensated effects on density, in which the latter makes the negative density anomalies more negative in the surface layer. But in the subsurface layers (Fig. 8), the negative temperature anomalies, accompanied with negative salinity anomalies, have compensated effects, with the latter making the positive density anomalies less positive. So, salinity effects give rise to an increased density contrast in the upper ocean and thus produces more stable vertical stratification, which acts to suppress the vertical mixing, helping sustain the warm SST anomalies. This indicates a positive feedback onto SST. During cold and salty interdecadal persistent phases in the 2000s, the relationships among these anomaly fields and salinity effects are in an opposite sense, in which positive salinity anomalies in the upper ocean cause more positive density anomalies in the surface layer, but less negative density anomalies in the

subsurface layers. So, the salinity effects cause weaker gradient of density in the upper ocean and less stable stratification, helping sustain the cold SST anomalies. Thus, salinity-induced effects act to serve as a positive feedback onto local SST during interdecadal persistent phases.

4.2 The transitional periods

The interdecadal persistent conditions are seen to transit into its opposite condition in relatively short periods (Fig. 9). Examples for horizontal distributions of the reconstructed interdecadal anomalies of SSS, SST and SSD are shown in Fig. 7 for transitional periods as represented in years 1998 and 2017, respectively. The corresponding vertical structures are demonstrated in Figs. 8–9. During the transitional periods, temperature and salinity anomalies exhibit clear differences in their sign changes in the vertical direction between the surface layer and subsurface layers: temperature anomalies undergo out-of-phase transitions in the surface layer and in the subsurface layers (Fig. 8a), whereas salinity anomalies have the nearly in-phase sign changes in the upper ocean (Fig. 8b). Vertically, as represented in 1998 and 2017, temperature and salinity anomalies exhibit clear differences in their sign transitions in the surface layer, but largely in-phase sign transitions in the subsurface layer. In this subsection, such situations are further analyzed in more detail, with case analyses being highlighted for the interdecadal transitions occurring in the late 1990s and early 2000s.

(1) The surface layer

Although surface temperature and salinity anomalies in the western equatorial Pacific are largely of the opposite sign during the persistent phases (Fig. 9), they can be of the same sign during the transitional periods. One striking case can be noted from these anomaly relationships during transitional periods in 1995–2002 (Fig. 9), when SSS anomalies exhibit the same sign with SST anomalies. In such a case, salinity can also have compensated effects on density. As the amplitude of salinity variability in the surface layer can be comparable to that of temperature, salinity can play an important role in determining density anomalies during the transitional periods.

More detailed evolutions can be analyzed as follows. During the interdecadal persistent phases in the 1980s-1990s, warm SST anomalies and negative SSS anomalies are seen in the western equatorial Pacific; their effects are density-uncompensated, leading to enhanced density anomalies. Then, a phase transition occurs in the late 1990s through early 2000s (Fig. 9a): SST is seen to first take a transition in 1995 and becomes cold anomaly (contributing to a positive density anomaly); at this time, SSS anomalies remain negative until 2002 (contributing to negative density anomaly). A striking feature here is that temperature and salinity anomalies are of the same signs during 1995–2002, with their effects being thus density-compensated. Note that the corresponding density anomalies remain to be negative until around 1999 and then become positive. Thus, the sign of density anomalies during 1995–1999 does not follow with change in temperature, but with salinity. Clearly, the phase transition of the negative density anomaly is delayed by the effect of the negative salinity anomalies. This means that the contribution of negative salinity anomalies to density anomalies is even greater than that of the positive

temperature anomalies during 1995–1998, with the sign of density anomalies being determined dominantly by salinity anomalies.

Another case can be also seen for the salinity effects on sign transitions of density anomalies during 2014–2018, when positive SST anomalies are accompanied with positive SSS anomalies. Because these anomalies are of the same sign, their effects are density-compensated. The fact that the corresponding density anomalies remain positive until 2018 indicates that the positive SSS anomalies play a dominant role in determining the sign of positive density anomalies. Detailed inspections further indicate that there is a delay in phase transition of the positive density anomaly in 2018 due to the positive salinity anomaly effect; without the salinity effect, otherwise, density would transit into negative anomalies earlier in 2014 as SST transits into positive anomalies. This means that the effect of positive salinity anomalies on density is even greater than that of positive temperature anomalies so that the sign of density anomalies is determined dominantly by salinity contribution.

(2) The subsurface layers

Clear transitions are seen in the subsurface layers during interdecadal transitional periods (Fig. 9b); salinity and temperature anomalies are nearly of the same sign, with little phase differences in their sign changes. So, salinity is seen to have a compensated effect on density relative to temperature. Because the amplitude of salinity variability is smaller compared with that of temperature, salinity-induced compensated effects are weak. Density anomalies are dominantly determined by temperature. Indeed, the sign of density anomaly follows closely with that of temperature during interdecadal transitional periods. In addition, it is evident that phase transitions in the subsurface layers (Fig. 9b) are delayed relative to those in the surface layer (Fig. 9a).

(3) The compensated salinity effects and negative feedback on SST

During the transitional periods as represented in 1998 and 2017 (Fig. 7 and Figs. 9–10), the sign transitions for anomalies of SST, SSS and SSD exhibit clear differences in the western equatorial Pacific. In this subsection, more details are examined to demonstrate the changes in the T-S relationships, salinity effects on density and feedbacks onto SST during transitional phases.

Accompanied with interdecadal evolution of temperature and salinity anomalies, salinity effects indicate an obvious transition from being density-uncompensated during persistent phases to being density-compensated during transitional periods, respectively. During the persistent phases in the 1980s-1990s, for example, warm SST anomalies and negative SSS anomalies both contribute to negative density anomalies (i. e., uncompensated effect on SSD). So, salinity effects make the negative density anomalies in the surface layer more negative (being lighter), causing more stable stratification and weak vertical mixing in the upper ocean during persistent period, which helps sustain warm SST anomalies. This correspondingly indicates a positive feedback onto SST during the persistent phases.

This is contrasted to the situation during the transitional period, when the SST anomalies and SSS anomalies can be of the same sign (as analyzed above), acting to have a SSD-compensated effect on density. In particular, the sign of density anomalies can be determined by salinity anomalies, with density anomalies following with salinity, rather than temperature. Specifically, during the transitional period as represented in 1998 (Fig. 7), cold SST anomalies are accompanied by negative SSS anomalies (Fig. 9a); the former causes an increase in density, but the latter gives rise to a decrease in density (thus being compensated effects in the surface layer). The fact that density anomalies in the surface layer remain to be negative until 1999 indicates that the negative SSS anomalies play a dominant role in keeping negative density anomalies. Thus, the density-compensated salinity effects maintain negative density anomalies in the surface layer during this period (being lighter), causing more stable stratification in the upper ocean. The more stable stratification leads to a decrease in vertical mixing, acting to have a weakening effect on the cold SST anomalies. So, SSS-induced effect in the surface layer can have a negative feedback onto SST during the transitional periods, a very different situation during the persistent phases, in which SSS-induced effects have a negative feedback onto SST.

5. The Relative Contributions Of Salinity And Temperature Anomalies

As demonstrated above, various signals of temperature and salinity variabilities can be extracted by the EEMD method for different time scales, including interannual, decadal, interdecadal and trend components. Large salinity interdecadal variability in the western equatorial Pacific is seen to play an important role in contributing to density anomalies. The relative contributions of temperature and salinity anomalies to density can be further quantified by separating their individual effects. In this section, we present some related analyses, with a focus on interdecadal component.

The reconstructed interdecadal components of temperature and salinity anomalies can be added onto their climatological parts to form total fields: $S = S_{\text{clim}} + S_{\text{interde}}$, $T = T_{\text{clim}} + T_{\text{interde}}$. A diagnostic analysis is then performed to quantify the individual contributions of salinity and temperature anomalies to a field of interest (F); its interdecadal anomalies can be calculated from contributions of temperature and salinity anomalies by considering temperature and salinity to be interdecadally varying (T_{interde} and S_{interde}) or climatological (T_{clim} and S_{clim}), respectively. $F(T_{\text{interde}}, S_{\text{interde}})$ denotes a reference analysis in which both temperature and salinity fields are taken to be interdecadally varying in calculating F ; $F(T_{\text{interde}}, S_{\text{clim}})$ is for a thermosteric analysis in which temperature field is taken as interdecadally varying but salinity field is taken as climatological; $F(T_{\text{clim}}, S_{\text{interde}})$ is for a halosteric analysis in which salinity is taken as interdecadally varying but temperature field is taken to be climatological; $F(T_{\text{clim}}, S_{\text{clim}})$ is a climatological field in which both temperature and salinity climatological fields are taken in calculating F , serving as a climatology from which interdecadal anomalies are calculated. As demonstrated above, density anomalies in the western region can be equally importantly contributed from salinity anomalies, whereas they are dominantly determined by temperature in the central and eastern equatorial Pacific. So, a focused analysis is placed on the western equatorial Pacific in the region A (2.5°S – 2.5°N , 160°E – 180°). Detailed attribution analyses are given below for relative contributions of temperature and salinity

anomalies to interdecadal anomalies of density and N^2 , respectively. Table 1 quantifies the relative effects of $T_{interde}$ and $S_{interde}$ anomalies on density and N^2 in the western equatorial Pacific during interdecadal evolution as represented by some representative periods.

Table 1. Interdecadal anomalies of temperature, salinity and some derived fields in the western equatorial Pacific, including sea surface density (SSD), the mixed layer (ML) depth (MLD), oceanic density at the base of ML (DENS_MLD), N^2 near the sea surface at 5m ($N^2_{5\text{ m}}$) and at the base of ML (N^2_{MLD}), respectively. Three calculations are performed to quantify their individual contributions to a field of interest, in which temperature and salinity fields can be taken as interdecadally varying or climatological. Results are shown for the western equatorial Pacific (the region A) during the different periods of the interdecadal evolution, which correspond to the persistent phases in 1979-1996 and 1999-2016, and to transitional periods as represented in 1998 and 2017, respectively.

Time Fields		Interdecadal anomalies calculated in the region A (6°S-4°N, 150°E-180°)			
		1979-1996	1998	1999-2016	2017
SSTA (°C)		0.042	-0.041	-0.047	0.064
SSSA (g/kg)		-0.065	-0.058	0.048	0.080
SSD (kg/m ³)	(T _{interde} , S _{interde})	-0.058	-0.003	0.067	0.010
	(T _{interde} , S _{clim})	-0.012	0.041	0.031	-0.054
	(T _{clim} , S _{interde})	-0.051	-0.044	0.036	0.064
N ² _{5m} (10 ⁻⁵ s ⁻²)	(T _{interde} , S _{interde})	-0.092	1.078	-0.74	-0.712
	(T _{interde} , S _{clim})	-0.065	0.392	-0.08	-0.072
	(T _{clim} , S _{interde})	-0.025	0.685	-0.67	-0.641
DENS_MLD (kg/m ³)	(T _{interde} , S _{interde})	-0.032	0.013	0.021	-0.025
	(T _{interde} , S _{clim})	-0.008	0.025	-0.010	-0.012
	(T _{clim} , S _{interde})	-0.025	-0.013	0.031	0.042
N ² _{MLD} (10 ⁻⁵ s ⁻²)	(T _{interde} , S _{interde})	0.574	-0.053	-1.002	0.623
	(T _{interde} , S _{clim})	0.425	0.198	-0.848	0.753
	(T _{clim} , S _{interde})	0.150	-0.250	-0.154	-0.130

(1). Density (ρ)

Figure 10 displays the results from diagnostic calculations performed to quantify the relative contributions of interdecadal components of $T_{interde}$ and $S_{interde}$ to density anomalies in the upper ocean of the western equatorial Pacific (the region A); the corresponding time series are shown in Fig. 11 for the sea surface and at subsurface depth of 200 m, respectively. As evident, $\rho(T_{interde}, S_{interde})$ is nearly the sum of $\rho(T_{interde}, S_{clim})$ and $\rho(T_{clim}, S_{interde})$. Inspection of these anomaly fields indicates that the way

density is affected in the upper ocean is varying during interdecadal evolutions. In the subsurface layers, the situation is quite simple (Fig. 11b), in which salinity and temperature anomalies are largely of the same sign, with density anomalies being dominantly attributed from temperature anomalies. Indeed, $\rho(T_{\text{interde}}, S_{\text{interde}})$ follows closely with $\rho(T_{\text{interde}}, S_{\text{clim}})$ in the subsurface layer (Fig. 11b).

The situation is more complicated in the surface layer (Fig. 11a), which will be our focus in the following analyses. As demonstrated above, salinity in the surface layer can have both uncompensated and compensated effects on density. During the persistent phases, SSS and SST anomalies are largely of the opposite sign, and their contributions to density anomalies are in the same direction, acting to increase density anomalies. The relative effects of T_{interde} and S_{interde} on density are well reflected in these three calculations for density anomalies (Fig. 10 and Fig. 11a). During persistent phases, for example, SSS and SST anomalies are of the opposite sign and the corresponding $\rho(T_{\text{interde}}, S_{\text{clim}})$ and $\rho(T_{\text{clim}}, S_{\text{interde}})$ fields are not compensated, making the amplitude of $\rho(T_{\text{interde}}, S_{\text{interde}})$ larger. During transitional periods, on the other hand, SSS and SST anomalies can be of the same sign and their effects are density-compensated. So, the $\rho(T_{\text{interde}}, S_{\text{clim}})$ and $\rho(T_{\text{clim}}, S_{\text{interde}})$ fields make the amplitude of $\rho(T_{\text{interde}}, S_{\text{interde}})$ smaller, consistent with the analyses in the Sect. 4. One striking feature is that the sign and amplitude of $\rho(T_{\text{interde}}, S_{\text{interde}})$ is determined by $\rho(T_{\text{clim}}, S_{\text{interde}})$ due to the dominant effect of salinity anomalies.

One interesting case can be illustrated in more details during the transitional periods as indicated during 1995–2003, when anomalies of SST, SSS and SSD indicate the differences in their sign transitions (Fig. 9). As analyzed above, for example, negative SST anomalies are accompanied with negative SSS anomalies, acting to produce negative density anomalies (Fig. 9a), which are dominantly contributed from the negative density anomalies during 1995–1999. The delayed effects on sign transitions of density anomalies are well reflected in these three density calculations (Fig. 11a). For example, $\rho(T_{\text{interde}}, S_{\text{clim}})$ takes a lead in transition into positive anomaly in 1995; $\rho(T_{\text{clim}}, S_{\text{interde}})$ takes a late transition into positive anomaly in 2002 (a lag); $\rho(T_{\text{clim}}, S_{\text{interde}})$ remains to be negative anomaly until 1999 and then transits into positive anomaly, a lag caused by salinity effects relative to $\rho(T_{\text{interde}}, S_{\text{clim}})$. The comparison among these three density calculations indicates that negative salinity anomaly is making a dominant contribution to the negative SSD anomaly (Fig. 11a).

Quantitatively, Table 1 lists the relative contributions of salinity and temperature anomalies to density and the other related fields during different phases of the interdecadal evolution. These calculations indicate that salinity can play a dominant role in producing density anomalies during interdecadal transitional periods. For example, the negative SSD anomaly in 1998 (-0.003 kg m^{-3}) is attributed to the combined effects of a negative SSS anomaly (-0.058) and a negative temperature anomaly (-0.041), respectively. Also for the transitional period in 2017, the positive SSD anomaly in 2017 ($+0.01 \text{ kg m}^{-3}$) is attributed to the combined effects of a positive SSS anomaly ($+0.080$) and a positive temperature anomaly ($+0.064$), respectively. Clearly, salinity anomalies play an important role in determining not only the amplitude but also the sign of density anomalies during the interdecadal evolution.

(2). The Brunt–Väisälä frequency squared (N^2)

Density interdecadal anomalies are used to calculate its vertical gradient and the corresponding Brunt–Väisälä frequency squared (N^2), a parameter representing the stratification stability. The vertical structure of interdecadal variability for N^2 in the upper ocean of the western equatorial Pacific is shown in Fig. 12, which corresponds well to that for density (Fig. 8c). On interdecadal time scales, N^2 anomalies exhibit well-defined see-saw patterns vertically with large anomalies centered at depths of 100m and 200m, respectively. During the interdecadal evolution, transitions take place between stable and unstable stratification conditions in the upper ocean. For example, during warm and fresh phases in the 1980s–1990s, the stratification is stable in the upper 150m, but unstable below it. A transition takes place during transitional period in the late 1970s and the late 1990s, respectively. During the cold and salty phases in the 2000s, the stratification becomes unstable in the upper layer of 150m but stable below it. Such changes can be explained by changes in density, which are attributed to temperature and salinity effects. In the subsurface layers, as demonstrated above, salinity and temperature anomalies are of the same sign and their effects are density-compensated during interdecadal evolution; so, N^2 anomalies are dominantly determined by changes in the vertical structure of temperature.

The situation is quite complicated in the surface layer, where salinity can have both uncompensated and compensated effects on density during interdecadal evolution. As seen above, salinity anomalies exhibit the differences in its effects on density in the upper ocean: uncompensated effect in the surface layer acting to increase density anomalies, but compensated effect in the subsurface layers acting to reduce density anomalies, respectively. These salinity effects on density are well reflected in its vertical gradient (N^2). For example, during warm and fresh persistent phases, negative salinity anomalies make the temperature-induced negative density anomalies more negative in the surface layer, thus making more stable stratification in the upper layer of 150m. Similarly, during cold and salty persistent phases, positive salinity anomalies make the temperature-induced positive density anomalies more positive, thus making less stable stratification. During transitional periods, the sign and amplitude of SSD anomalies can be dominantly determined by salinity anomalies, and so of N^2 anomalies.

Similar attribution analyses are performed for the effects of T_{interde} and S_{interde} on N^2 interdecadal anomalies. The extent to which N^2 is affected by salinity is shown in Fig. 12 for three diagnostic calculations to quantify the relative contributions of T_{interde} and S_{interde} in the western equatorial Pacific; the corresponding time series are shown in Fig. 13 for the sea surface and at subsurface depth of 200 m, respectively. As evident, the sum of $N^2(T_{\text{interde}}, S_{\text{clim}})$ and $N^2(T_{\text{clim}}, S_{\text{interde}})$ almost recovers the signal of $N^2(T_{\text{interde}}, S_{\text{interde}})$. In the subsurface layers (Fig. 13b), $N^2(T_{\text{interde}}, S_{\text{interde}})$ is dominantly determined by temperature in the western equatorial Pacific so $N^2(T_{\text{interde}}, S_{\text{interde}})$ follows closely with $N^2(T_{\text{interde}}, S_{\text{clim}})$. As shown in Fig. 13a, the salinity effects on N^2 are mainly in the surface layer, where salinity plays a dominant role in producing N^2 anomalies, with $N^2(T_{\text{interde}}, S_{\text{interde}})$ following $N^2(T_{\text{clim}}, S_{\text{interde}})$. Indeed, the delayed effects on sign transitions of density are also reflected in its effects on N^2 (Figs. 12–13). These

analyses indicate that salinity effect in the surface layer makes dominant contribution to the stratification, including the amplitude and sign of N^2 variability.

Quantitatively, Table 1 lists the relative contributions of salinity and temperature anomalies to N^2 in the western equatorial Pacific during different periods. These calculations indicate that salinity can play a dominant role in producing N^2 anomalies during interdecadal evolution. For example, the positive N^2 anomaly ($+1.078 \times 10^{-5} \text{ s}^{-2}$) for the transitional period in 1998 is attributed to the combined effects of a negative SSS anomaly (-0.058) and a negative temperature anomaly (-0.041), respectively. Also for the transitional period in 2017, the negative SSD anomaly in 2017 ($-0.712 \times 10^{-5} \text{ s}^{-2}$) is attributed to the combined effects of a positive SSS anomaly (+0.080) and a positive temperature anomaly (+0.064), respectively. Clearly, salinity anomalies play an important role in determining not only the amplitude but also the sign of N^2 anomalies during the transitional phase.

7. Conclusion And Discussion

Ocean salinity and temperature anomalies exhibit multiple-scale variability signals in the tropical Pacific. Their reanalysis data are used to derive interannual anomalies relative to seasonally varying climatology, which are then subject to the EEMD into separable signals for interannual, decadal, interdecadal bands, and trend component, respectively. Large salinity interdecadal variability is seen in the upper ocean over the western equatorial Pacific. Because the amplitude of salinity interdecadal variability is comparable to that of temperature in the region, salinity can play an important role in contributing to density anomalies. A focus of this study is on salinity interdecadal variability and its effect on density and stratification in the western equatorial Pacific. A diagnostic calculation is performed to quantify the relative contributions of temperature and salinity anomalies to variabilities of density and the related stratification in the region.

Salinity interdecadal variability indicates a uniform anomaly pattern with the same sign in the upper ocean of 200 m, whereas temperature variability exhibits out-of-phase anomaly patterns in the surface layer and subsurface layers, respectively. During interdecadal evolution, temperature and salinity anomalies undergo opposite sign changes in the surface layer (e. g., from positive SST anomalies and negative SSS anomalies to negative SST anomalies and positive SSS anomalies, respectively), but are nearly of same signs in the subsurface layers (e. g., from both positive SST and SSS anomalies to both negative SST and SSS anomalies). Interdecadal evolution of temperature and salinity anomalies can be characterized by persistent and transitional phases in the upper ocean. During the 1970s-1990s, surface warm and fresh surface conditions persist in the western equatorial Pacific, which quickly transits into cold and salty conditions in the late 1990s. Then, surface cold and salty conditions persist in the 2000s and take another transition around in 2016-18, respectively.

Salinity exerts strong effects on density in different ways respectively during persistent and transitional phases, depending on the T-S relationships and their relative contributions. Obvious changes in salinity effects exist in the surface layer and subsurface layers. During interdecadal evolution, temperature anomalies are of the opposite sign in the surface and subsurface layers, which experiences a transition

coherently in the upper ocean. In contrast, salinity anomalies are of the same sign in the upper ocean, which undergoes a sign transition uniformly. So, the salinity effects on density indicate obvious differences in the upper ocean. In the subsurface layers, salinity and temperature anomalies are nearly of the same sign and their effects are density-compensated, in which density anomalies are dominantly contributed from temperature, with weak salinity effects. The situation is more complicated in the surface layer, where the salinity effects play an important contribution to density anomalies because temperature and salinity anomalies tend to have comparable amplitude. During persistent phases, temperature and salinity anomalies are largely of the opposite sign, salinity effects are density-uncompensated, leading to enhanced density variability in the surface layer. During transitional periods, anomalies of SST, SSS and SSD are not in-phase, but have obvious differences in their sign transitions. One striking feature is that during transitional periods, SSS and SST anomalies can be of the same sign, with which salinity effect plays a dominant role in determining the sign of density anomalies. The delayed effect of salinity anomalies on the sign transitions of density anomalies is such an interesting example.

The uncompensated and compensated salinity effects cause different consequences for changes in density and stratification during the persistent and transitional phases, respectively. Horizontally, for instance, the enhanced density anomalies due to uncompensated effects correspondingly produce large horizontal gradients of density and pressure. In contrast, compensated salinity effects contribute to suppressed density anomalies, which produce weak horizontal gradient of density and pressure. Vertically, asymmetric effects on density induced by salinity anomalies in the surface layer and subsurface layers lead to large density contrast in the upper ocean, leading to changes in vertical stratification, which affects vertical mixing and SST. So salinity effect can induce a feedback onto local SST in the western equatorial Pacific. However, the ways density is affected differently by salinity anomalies leads to different consequences for SST modulations. As demonstrated in this study, there are obvious differences in the salinity-induced feedback onto local SST. In the case with uncompensated salinity effects, salinity anomalies induce a positive feedback onto local SST during persistent periods. In the case with compensated salinity effects, salinity anomalies can have a negative feedback onto SST during transitional periods. So, salinity can be dominant attributors to changes in density and stratification in the western equatorial Pacific. The diagnostic analyses clearly illustrate the relative contributions of temperature and salinity interdecadal anomalies to density and N^2 . In particular, the signs of density and N^2 anomalies can be determined by salinity anomalies during transitional periods.

This paper presents preliminary results for salinity interdecadal variability and its effects in the western equatorial Pacific. Many related issues exist that remain to be addressed in the future. For example, the causes of salinity interdecadal variability in the western equatorial Pacific have not been presented in this paper. Indeed, many processes coexist in the region that can be responsible for it, including wind forcing, freshwater flux forcing and extratropical ocean influences. For instance, large changes in precipitation are observed over the western tropical Pacific (Yu and Weller 2007), which is closely related with the SPCZ (Kessler 2002). Also, salinity advections from the extratropical oceans are evident in the South Pacific (Luo et al. 2002; Luo et al. 2004; Zhang and Wang 2014). The roles of off-equatorial salinity anomalies

and the SPCZ-induced direct freshwater flux forcing in salinity variability over the western equatorial Pacific are interesting topics that need to be addressed in the future.

The focus of this paper is on salinity variability and its effects on interdecadal time scale; many other time-scale signals coexist in the region (Fig. 3), including interannual variability associated with ENSO. Previously, salinity interannual variability in the tropical Pacific and its effects have been examined extensively (Zhang et al. 2012; Zhi et al. 2017). One important related issue here is the obvious interplays between interannual and interdecadal variabilities. As demonstrated in this study, salinity effects cause more stable stratification in the upper ocean of the western equatorial Pacific in the 1980s-1990s (correspondingly a warm and fresh interdecadal phase). This indicates a positive feedback onto SST, which is favorable for sustaining warm SST anomalies in the western-central equatorial Pacific. Note that this interdecadal warm and fresh period coincides with the frequent occurrence of more and stronger El Nino events (Zhang et al. 1998). So, salinity interdecadal variability may have influences on interannual variability in the tropical Pacific. The relationships between interannual and interdecadal variabilities in the region and possible modulating effects of salinity interdecadal variability on ENSO in the region should be addressed in more detail.

Declarations

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Figures

SSSA std

Figure 1

Horizontal distribution of the standard deviation (STD) for SSS interannual fields in the tropical Pacific, which is calculated from the reanalysis data during the periods 1942-2018. The green line denotes the focused analysis region (A) in this study: the western equatorial Pacific region (2 °S-2 °N, 150 °E-170 °W), where a spatially averaged value for a field of interest is obtained accordingly. The unit is g kg⁻¹.

(a) Surface in region A

(b) Subsurface in region A

Figure 2

Original time series of total interannual anomalies averaged in the western equatorial Pacific (the region A as indicated in Fig. 1) during the periods 1942-2018: (a) SST, SSS and sea surface density (SSD); (b) temperature, salinity and density at the subsurface depth of 200 m. The salinity and density anomaly values in (b) are artificially multiplied respectively by 4 and 10 in the plotting for visual clarity. The units are g kg⁻¹ for SSS, °C for SST, and kg m⁻³ for density.

Figure 3

Examples for the mode separations of total SSS interannual variability into temporal components at different time scales by adopting the ensemble empirical mode decomposition (EEMD) method. Shown in (a) are for the original time series, and respectively for a set of intrinsic mode functions (IMFs) and a long-term trend, in which the IMF 7 represents interdecadal signal, a focus in the present study. Shown in (b) are the tests for the significance of the IMFs.

Figure 4

The same as in Fig. 3 but for the mode separations of total SST interannual variability.

Figure 5

Examples for the reconstructed interdecadal components for anomalies of (a) SST, (b) SSS and (c) SSD along the equator. The results are obtained using the EEMD-extracted component with signals retained to have periods around 20 years. The units are $^{\circ}\text{C}$ for SST, g kg^{-1} for SSS and kg m^{-3} for SSD.

Figure 6

Examples for horizontal distributions of the reconstructed interdecadal components for anomalies of (a, d) SST, (b, e) SSS and (c, f) SSD in the tropical Pacific during 1979-1996 (the left panels) and during 1999-2016 (the right panels), respectively; these periods represent persistent interdecadal phases. The units are $^{\circ}\text{C}$ for SST, g kg^{-1} for SSS and kg m^{-3} for SSD.

Figure 7

Examples for horizontal distributions of the reconstructed interdecadal components for anomalies of (a, d) SST, (b, e) SSS and (c, f) SSD in the tropical Pacific during the transitional period as represented in 1998 (the left panels) and in 2017 (the right panels). The units are $^{\circ}\text{C}$ for SST, g kg^{-1} for SSS and kg m^{-3} for SSD.

Figure 8

The depth-time sections of the reconstructed interdecadal anomalies for salinity (a), temperature (b) and density (c) in the upper ocean in the region A, which is obtained using the EEMD-extracted component with signals retained to have periods around 20 years. The units are g kg⁻¹ for salinity, °C for temperature, and kg m⁻³ for density.

(a) Surface in region A

(b) Subsurface in region A

Figure 9

The time series of the reconstructed interdecadal anomalies for salinity, temperature and density at the sea surface (a) and at subsurface depth of 200 m (b) in the region; the results are obtained using the EEMD-extracted component with signals retained to have periods around 20 years. The salinity and density anomaly values in (b) are artificially multiplied respectively by 4 and 10 in the plotting for visual clarity. The units are g kg^{-1} for salinity, $^{\circ}\text{C}$ for temperature, and kg m^{-3} for density.

Figure 10

Results from diagnostic calculations performed to quantify the relative contributions of interdecadal components (T_{interde} and S_{interde}) to density anomalies in the region A. Shown are the depth-time sections of density anomaly fields for (a) $\rho(T_{\text{interde}}, S_{\text{interde}})$, (b) $\rho(T_{\text{clim}}, S_{\text{interde}})$, and (c) $\rho(T_{\text{interde}}, S_{\text{clim}})$. These density anomalies are calculated relative to its climatological density field (i.e., $\rho(T_{\text{clim}}, S_{\text{clim}})$). The unit is kg m⁻³ for density.

Figure 11

The same as in Fig. 10 but for the corresponding time series of the three calculated density anomaly fields at the sea surface (a) and at subsurface depth of 200 m (b). The unit is kg m^{-3} for density.

Figure 12

The same as in Fig. 10 but for (a) $N^2(T_{interde}, S_{interde})$, (b) $N^2(T_{interde}, S_{clim})$, and (c) $N^2(T_{clim}, S_{interde})$, respectively. The unit is $10^{-5} s^{-2}$ for N^2 .

Figure 13

The same as in Fig. 12 but for the corresponding time series of the three calculated N^2 fields at the sea surface (a) and at subsurface depth of 200 m (b). The unit is 10^{-5} s^{-2} for N^2 .