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Skewness of subsurface ocean temperature in the equatorial Pacific based on assimilated data*

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Abstract The skewness of subsurface temperature anomaly in the equatorial Pacific Ocean shows a significant asymmetry between the east and west. A positive temperature skewness appears in the equatorial eastern Pacific, while the temperature skewness in the western and central Pacific is primarily negative. There is also an asymmetry of the temperature skewness above and below the climatological mean thermocline in the central and western Pacific. A positive skewness appears below the thermocline, but the skewness is negative above the thermocline. The distinctive vertical asymmetry of the temperature skewness is argued to be attributed to the asymmetric temperature response to upward and downward thermocline displacement in the presence of the observed upper-ocean vertical thermal structure. Because of positive (negative) second derivative of temperature with respect to depth below (above) the thermocline, an upward and a downward shift of the thermocline with equal displacement would lead to a negative temperature skewness above the thermocline but a positive skewness below the thermocline. In the far eastern equatorial Pacific, the thermocline is close to the base of the mixed layer, the shape of the upper-ocean vertical temperature profile cannot be kept. Positive skewness appears in both below the thermocline and above the thermocline in the far eastern basin. Over the central and eastern Pacific, the anomalies of the subsurface waters tend to entrain into the surface mixed layer (by climatological mean upwelling) and then affect the SST. Hence, the positive (negative) subsurface skewness in the far eastern (central) Pacific may favor positive (negative) SST skewness, which is consistent with the observational fact that more La Niña (El Niño) occur in the central (eastern) Pacific. The present result implies a possible new paradigm for El Niño and La Niña amplitude asymmetry in the eastern Pacific.

Keyword: skewness; subsurface temperature; equatorial ocean

1 INTRODUCTION

The El Niño-Southern Oscillation (ENSO) is the dominant interannual variability in the Tropical Pacific. A considerable number of observational, theoretical and modeling studies have been conducted over the past decades to understand the structures and mechanisms of the ENSO cycle (Rasmusson et al., 1982; Cane et al., 1985; Philander, 1990; Zhang et al., 1993a). Several conceptual models have been proposed for the mechanism of ENSO oscillations, for example, the delayed oscillator (Battisti et al., 1989; Suarez et al., 1988), the self-excited oscillations in the nonlinear tropical air-sea coupled system (Zhang et al., 1993b), the recharge-discharge theory (Jin, 1997), the advective-reflective oscillator (Picaut et al., 1997), the western Pacific oscillator (Weisberg et al., 1997), and the stationary SST mode (Li, 1997).

However, there are still some key issues such as the ENSO amplitude asymmetry remaining unsolved. Observations show that the amplitude of sea surface temperature (SST) anomalies in the eastern equatorial Pacific during positive El Niño phases is significantly larger than that during negative La Niña phases (Burgers et al., 1999). This amplitude asymmetry might be caused by nonlinear ocean temperature advections (An et al., 2004; Su et al., 2009). One common index to quantify the asymmetry is the skewness. Skewness towards high values

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means that positive extremes are more probable than negative extremes. The ENSO amplitude asymmetry can be well represented by positive SST skewness in the eastern equatorial Pacific (Burgers et al., 1999; Fig.1a).

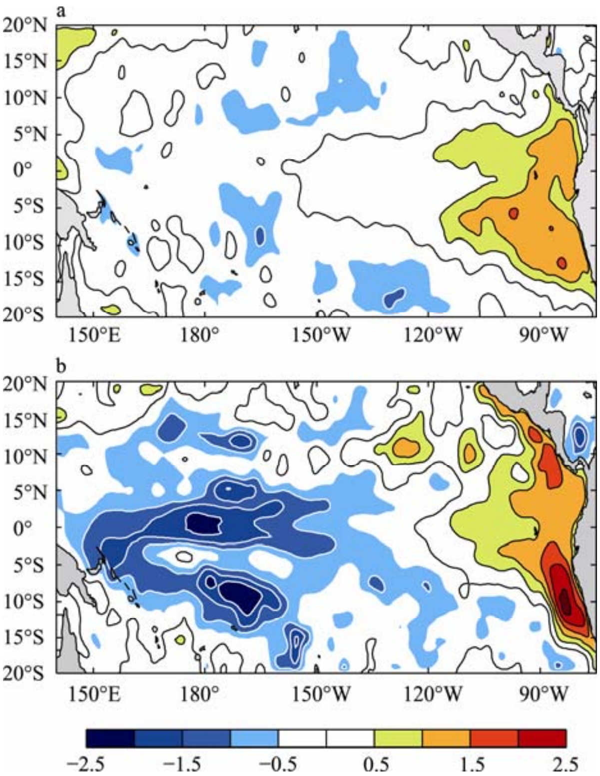

Fig.1 Skewness of (a) annual mean SST and (b) annual mean subsurface (76–120 m) temperature

Contour intervals are 0.5. The shadings with black (white) contour lines indicate positive (negative) values.

Associated with the ENSO cycle, the temperature variability not only appears in the SST, but also shows significant anomalies in the subsurface temperature fields. Signals of anomalous subsurface temperature were observed to form in the western Pacific and propagate eastward mainly along the main thermocline during ENSO cycle (McPhaden, 1999; McPhaden et al., 1999; Li et al., 1999; Chao et al., 2003). The ocean temperature variability related to thermocline change has attracted much attention, for example, on timescales of seasons (Sun et al., 2004), years (Lin et al., 2004), and decades (Gu et al., 2004). The subsurface salinity also shows apparent interannual variation during ENSO cycle (Li et al., 2006).

The surface temperature asymmetry between El Niño and La Niña motivates us to address the following questions: Is there an analogous asymmetry in the subsurface temperature? If so, what is the mechanism for such an asymmetry? What is the relationship between the asymmetry of the surface and subsurface temperatures? This paper intends to address these questions using observational and assimilated data.

2 DATA AND METHODS

The Simple Ocean Data Assimilation (SODA) version 1.4.2 product of Carton et al. (2000) for 1958–2000 is used as a major dataset for the ocean diagnosis. The horizontal resolution of the SODA data is 0.5°×0.5°. There are 40 levels in the vertical, with a variable grid of about 10 m in the upper 100 m. The SODA data have been previously used for studying the Pacific and Indian Ocean dynamics (An et al., 2004; Hong et al., 2008; Su et al., 2009). Observed temperature data are from the Tropical Atmosphere and Ocean (TAO, McPhaden et al., 1998) array.

The skewness is a measure of the asymmetry of a probability distribution function, and a value of 0 represents a normal distribution (White, 1980). The skewness is defined as: skewness=$m_3/(m_2)^{3/2}$, where m_k is the kth moment, $m_k = \sum_{i=1}^{N} \frac{(x_i - \bar{X})^k}{N}$ and x_i is the ith observation (annual mean field), $\bar{X}$ the long-term climatological mean, and N the number of observations. Another index to describe the asymmetry is kurtosis: kurtosis= $m_4/(m_2)^2$, The kurtosis for a standard normal distribution is three. For this reason, the following definition of kurtosis: kurtosis= $m_4/(m_2)^2$-3 is used in this study. This definition is used so that the standard normal distribution has a kurtosis of zero. In addition, with the second definition a positive kurtosis indicates a "peaked" distribution and a negative kurtosis indicates a "flat" distribution. The statistical significance of the skewness may be estimated when the number of independent samples is known (White, 1980). Because the time series of temperature anomalies might not be statistically independent, we use a range-estimate instead, following Hong et al. (2008). It is estimated that for the given data length, a confidence level of 95% corresponds to the amplitude of the skewness exceeding ±0.67.

3 SPATIAL PATTERN OF THE SUBSURFACE TEMPERATURE SKEWNESS

The skewness of the surface sea temperature anomalies over the tropical Pacific derived form the SODA data shows an east-west asymmetry (Fig.1a).

A strong positive skewness appears over the tropical eastern Pacific, indicating that the amplitude of warm surface temperature anomalies there tends to be stronger than that of cold temperature anomalies. A negative skewness appears in the tropical western central Pacific, and extends into the subtropical regions.

The east-west contrast of the temperature skewness is more pronounced in the ocean subsurface levels (at 76–120 m corresponding to the model 8–10 levels, Fig.1b). In the eastern Pacific a positive skewness appears in the subsurface temperature anomaly field, with a pattern and values similar to those of the surface temperature. However, the negative skewness to the west is much stronger in the subsurface than in the surface. Different from the surface level, the subsurface negative skewness in the western-central equatorial Pacific is greater than that of the subsurface positive skewness in the eastern equatorial Pacific.

The temperature extreme can also be informed by the kurtosis (Fig.2). Higher values of kurtosis mean that more extremes departures from the mean. The kurtosis of SST shows positive values in the equatorial eastern Pacific, primarily east of 120°W. This positive kurtosis is consistent with positive skewness there. In the subsurface, the values of the positive kurtosis in the equatorial eastern Pacific are larger than those of the surface. In the western Pacific, there are also positive values of kurtosis. Note that, the kurtosis only gives the information of absolute values of extreme events. Whether the positive kurtosis is caused by positive extreme or by negative extreme can not be determined by the values of kurtosis itself. In fact, the positive kurtosis in the western Pacific is attributed to the strong negative extremes there.

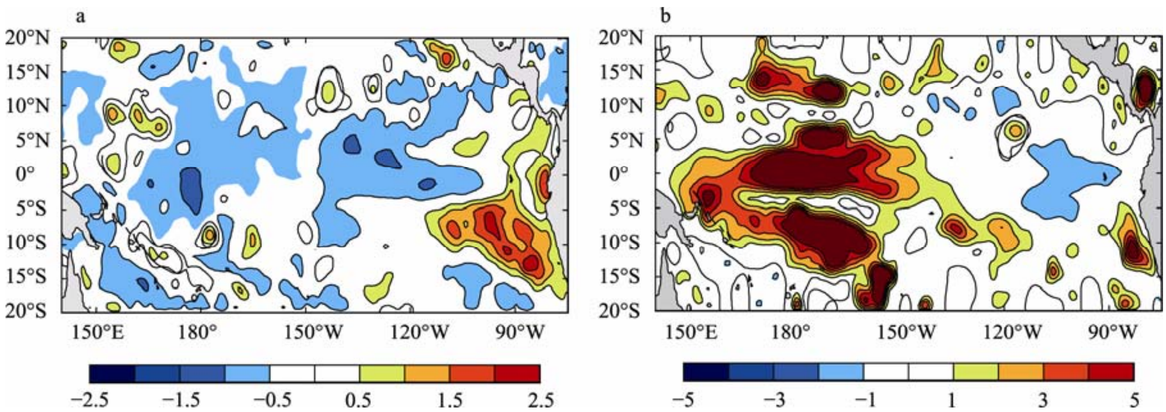

Fig.2 Kurtosis of (a) annual mean SST and (b) annual mean subsurface (76–120 m) temperature

Contour intervals are 0.5 for (a) and 1.0 for (b); the shadings with black (white) contour lines indicate positive (negative) values

The east-west contrast of the subsurface temperature skewness derived from the SODA data may be confirmed by the TAO observations (Fig.3). In the eastern equatorial Pacific at (0°, 110°W), the subsurface (100 m) temperature anomalies exhibit a positive skewness — the amplitude of positive temperature anomalies observed during 1982–1983, 1991–1992 and 1997–1998 El Niño events is much greater than that of the negative temperature anomaly in 1998. In the central equatorial Pacific at (0°, 180°W), it is opposite. The amplitude of the negative temperature anomaly there in 1998 is much greater than that of positive temperature anomalies at depth of 100 m.

Fig.3 also demonstrates that the interannual subsurface temperature variability in the SODA data well match the observed TAO data. For example, the negative subsurface temperature anomaly at (0°,

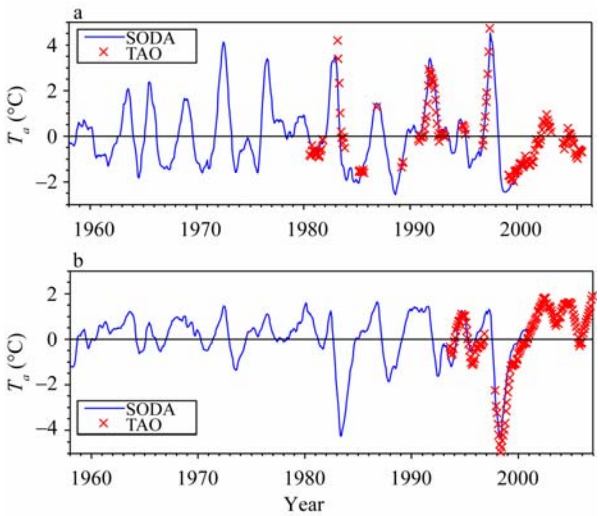

Fig.3 Time series of subsurface (100 m) temperature anomalies at (a) 0°N, 110°W and (b) 0°N, 180°E from TAO (x-mark) and SODA (solid line) data

The time series are 9-month running smoothed

180°W) in 1998 exceeds –4°C in both the SODA and TAO. The positive subsurface temperature anomalies at (0°, 110°W) during 1982–1983, 1991–1992 and 1997–1998 are also matched quite well. This adds the confidence to use the SODA data for the skewness analysis.

A notable feature from a zonal-depth section of the temperature skewness along the equator (Fig.4a) is that a positive (negative) skewness appears below (above) the climatological mean thermocline, represented by the annual mean 20°C isotherm, over the most of the ocean basin (west of 120°W). Significant negative skewness occurs in the upper 150 m, above the thermocline, in the western-central Pacific, from 145°E to 135°W. Below the thermocline, a positive skewness shows up in the entire Pacific basin, with a vertical extension of about 100 m. As the thermo cline shoals toward the east, the depth of the positive skewness center also shifts upward. In the far eastern Pacific (east of 110°W), the positive skewness below the thermocline is well connected to the positive surface temperature skewness. When shown on the climatological depth of 20°C (not shown), the values of skewness are smaller than that shown on the fixed depth level (Fig.1b). This can readily be indicated by the vertical pattern of skewness along the equator (Fig.4a), where the skewness is primarily zero along the main thermocline.

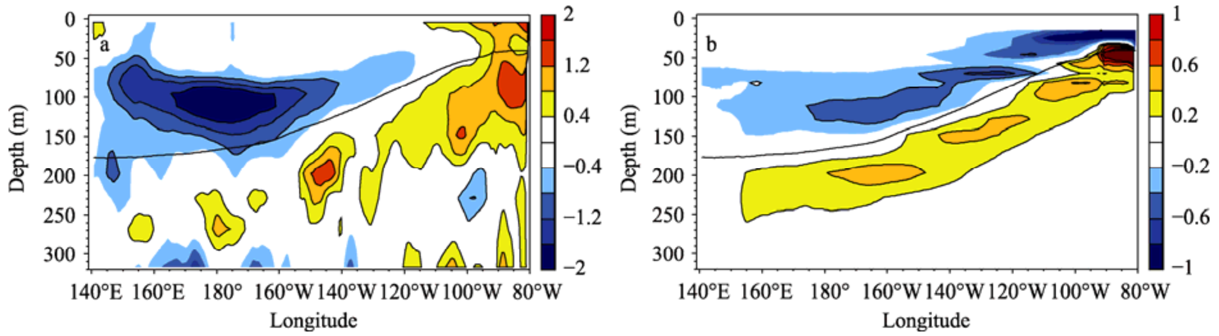

Fig.4 Longitude-depth section of (a) the temperature skewness and (b) $\partial^2 T/\partial^2 z$ (unit: 10^{-3} °C m^{-1}) along the equator (within ±3°)

The shadings with black (white) contour lines indicate positive (negative) values; the heavy black line denotes the depth of 20°C isotherm

4 PHYSICAL INTERPRETATION

In the previous section we illustrate the observed asymmetric characteristic of the subsurface ocean temperature anomalies in the equatorial Pacific. Because the dominant subsurface process associated with the ENSO variability is the vertical displacement of the thermocline (Li, 1997), in the following a strategy is developed in which we examine how the subsurface ocean temperature responds to the upward and downward shifts of the thermocline. A fundamental question related to the temperature asymmetry is that given the equal amount of the thermocline (upward or downward) displacement, does the temperature respond symmetrically? In the below, we argue that the temperature response is asymmetric, even though the thermocline variation is symmetric, due to the distinctive vertical structure of the ocean temperature profile.

By definition, the thermocline is where the vertical temperature gradient reaches its maximum (i.e., $\partial^2 T/\partial^2 z=0$), and the mixed layer is a layer where the vertical temperature gradient nearly vanishes. In the equatorial central Pacific, the mean thermocline depth is about 150 m, well separated from the mixed layer (typically 40–50 m deep). Above (below) the mean thermocline, the temperature gradient decreases (increases) with increased z (here z is defined upward), thus $\partial^2 T/\partial^2 z$ (second derivative of temperature with respect to z) being negative (positive) (Fig.4b).

Assuming due to the interannual wind forcing, the thermocline depth experiences a downward and an upward shift, with the equal magnitude in both directions. First, we consider the temperature changes at a location above the thermocline, say, at point A_0 (Fig.5a). The black curve represents the observed climatological mean thermal structure in the central equatorial Pacific. In the case of an upward shift of the thermocline, the water at A_0 will be replaced by the water below, say, A_1. Thus the temperature at A_0 is changed from $T(A_0)$to $T(A_1)$, and a negative temperature anomaly, $T(A_1)-T(A_0)$, represented by $\overline{A_1'A_0}$ is induced. Similarly, a positive temperature anomaly of $T(A_2)-T(A_0)$,

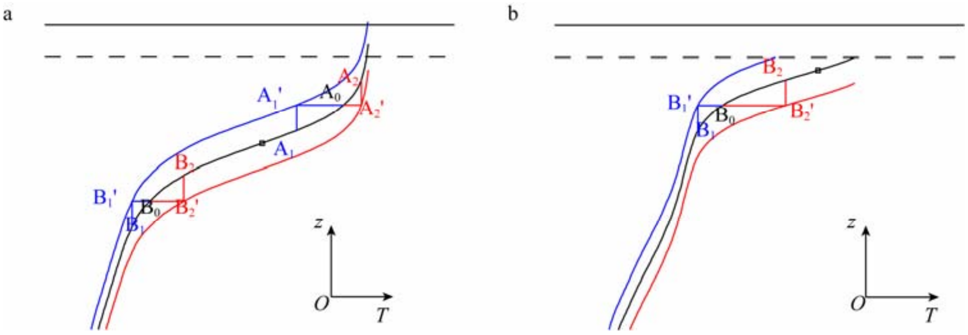

Fig.5 Schematic diagrams for the upward and downward thermocline displacement and associated temperature changes for the case of (a) the central equatorial Pacific and (b) the far eastern equatorial Pacific

The dot denotes the location of the maximum vertical temperature gradient or depth of the climatological mean thermocline; the dashed black line represents the base of the surface mixed layer

represented by $\overline{A_2'A_0}$, is induced in the case of a downward thermocline shift.

The temperature skewness depends on the amplitude difference between the temperature anomalies in the two cases. Obviously, the amplitude of the temperature anomaly in the upward shift case ($\overline{A_1'A_0}$) is greater than that in the downward shift case ($\overline{A_2'A_0}$), owing to the characteristic vertical temperature profile above the thermocline (i.e., the temperature gradient decreases with increased z). As a result, negative temperature skewness occurs there. Note that $[T(A_1)\text{-}T(A_0)]+[T(A_2)\text{-}T(A_0)]$ measures the difference of the temperature anomaly in the upward and downward shift cases, and is mathematically identical to $\partial^2 T/\partial^2 z$. Since $\partial^2 T/\partial^2 z$ is negative above the thermocline, the temperature skewness at point A_0 should be negative. This can be easily inferred based on the length difference between line segments of $\overline{A_1'A_0}$ and $\overline{A_2'A_0}$ in Fig.5a.

Below the thermocline, say, at point B_0, the magnitude of the temperature anomaly in the upward shift case ($\overline{B_1'B_0}$) is less than that in the downward shift case ($\overline{B_2'B_0}$). This results in a positive skewness, which is in accordance with positive $\partial^2 T/\partial^2 z$.

The mechanism discussed above applies for the most of the ocean basin except in the far eastern equatorial Pacific (east of 110°W) where the thermocline is so shallow that the water above the thermocline connects directly to the surface mixed layer (Fig.4b). Due to the closeness of the mixed layer base and the thermocline, strong in-situ vertical mixing alters the shape of the temperature profile above the thermocline. As a result, the temperature responds to the thermocline variation differently. However, this mechanism still applies to the subsurface temperature changes below the thermocline (Fig.5b), where significant positive temperature skewness occurs (Fig.4a). In the surface layer, positive rather than negative temperature skewness occurs in the far eastern Pacific (Fig.4a). We hypothesized that this positive skewness in the surface layer is at least partially attributed to the vertical advection of anomalous temperatures by strong mean upwelling at the base of the mixed layer. A heat budget analysis is needed to confirm this hypothesis. The result implies a possible new paradigm for El Niño and La Niña amplitude asymmetry in the eastern Pacific.

5 DISCUSSION AND CONCLUSION

The ocean subsurface temperature variability in the equatorial Pacific shows a significant asymmetry between the east and west. Positive (negative) temperature skewness appears in the equatorial eastern (western and central) Pacific. There is also a vertical asymmetry in the ocean temperature skewness above and below the climatological mean thermocline over the most of the ocean basin, this is, a positive (negative) skewness appears below (above) the thermocline in the central-western Pacific. The distinctive vertical asymmetry of the temperature skewness is proposed to be attributed to the asymmetric temperature response to upward and downward thermocline displacement in the presence of the observed upper-ocean vertical thermal structure. Because of the positive (negative) $\partial^2 T/\partial^2 z$ below (above) the thermocline, an upward and downward shift of the thermocline with equal strength would lead to a negative temperature skewness above the thermocline but a positive skewness below the thermocline. The result above points out a positive correlation between the temperature skewness and $\partial^2 T/\partial^2 z$.

The process differs in the far eastern equatorial Pacific where the thermocline is close to the base of the mixed layer. Due to the strong mixing at the base of the mixed layer, the shape of the upper-ocean vertical temperature profile cannot be kept. Thus, the local temperature response to the thermocline change would be different. On the other hand, the process associated with the subsurface temperature changes below the thermocline is essentially same. This is confirmed by positive temperature skewness there. The positive surface temperature skewness in the far eastern Pacific is possibly attributed to the subsurface impact in association with anomalous vertical temperature advection by mean upwelling.

The skewness is primarily about zero along the main thermocline. This does not mean that there is no temperature variability near the thermocline. In fact, significant temperature anomalies were observed to form and propagate along the main thermocline during the ENSO cycle (McPhaden, 1999; McPhaden et al., 1999). The small skewness along the thermocline indicates that the amplitude of positive temperature anomalies near the thermocline is close to that of negative temperature anomalies there. Above the thermocline, negative temperate anomalies tend to have larger amplitude than positive anomalies, which are apparent in the western-central Pacific.

In this study we focus on the observed feature of the subsurface temperature skewness in the equatorial Pacific. Given the strong east-west contrast of the subsurface temperature skewness, one may infer that the skewness in the subsurface may make a contribution to the surface skewness. Over the central and eastern Pacific, the anomalies of the subsurface waters tend to entrain into the surface mixed layer (by climatological mean upwelling) and then affect the SST. Hence, the positive (negative) subsurface skewness in the far eastern (central) Pacific may favor positive (negative) SST skewness. This is consistent with the observational fact that more La Niña (El Niño) occur in the central (eastern) Pacific.

A fixed upper-ocean thermal structure is assumed when we examined the thermocline-induced subsurface temperature change. However, in reality, the upper-ocean thermal structure does change with time and space and other processes such as horizontal temperature advection may also affect ocean temperatures. The real wind stress and ocean waves may be also asymmetric during ENSO cycle, which can lead to asymmetric variability of the thermocline depth. A further investigation with a model that contains sophisticated ocean dynamics and mixed layer physics is needed for qualitatively examining the subsurface ocean temperature changes.

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