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Delayed Atmospheric Temperature Response to ENSO SST: Role of High SST and the Western Pacific

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ABSTRACT

Tropical zonally symmetric atmospheric warming occurs during ENSO's warm phase, and lags the equatorial east Pacific sea surface temperatures (SSTs) by 3–4 months. The role of the Indian and Atlantic oceans on the atmospheric delayed response has been pointed out by earlier studies. For 1951–2004, a regression analysis based on the observed SST data shows the western Pacific has a similarly important role as the Indian and Atlantic.

Nevertheless, there is time mismatch of around 1–2 months between the zonally averaged tropical SST anomalies and the atmospheric temperature anomalies. It is expected that the tropospheric temperature should be controlled by diabatic heating forcing, which is sensitive primarily to SST anomalies over regions of high climatological SST, rather than to the tropical mean SST anomalies. To describe this mechanism, we propose a parameterization scheme of diabatic heating anomalies dependant on SST anomalies and climatological SST.

The 1–2 month mismatch between tropical mean SST anomalies and air temperature anomalies is reconciled by the fact that the tropical mean heating anomalies are dominated by the SST anomalies over regions of high climatological SST, and lag the tropical mean SST anomalies by 1 month. The mechanism described by this parameterization scheme joins several physical processes of ENSO with reasonable time intervals. And the parameterized heating anomalies work better than the tropical mean SST anomalies for capturing the atmospheric temperature signal relative to ENSO.

Key words: ENSO, delayed atmospheric response, high SST Ocean, western Pacific

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1. Introduction

The El Niño-Southern Oscillation (ENSO) is the largest interannual climate signal. Tropical zonally symmetric warming of the free atmosphere occurs during ENSO's warm phase (e.g., Newell and Weare, 1976; Angell and Korshover, 1978; Pan and Oort, 1983; Reid et al., 1989). A significant characteristic of tropical atmospheric temperature response to ENSO is its lag relative to the tropical mid-eastern Pacific sea surface temperature anomaly (SSTA) forcing by 3–4 months (Newell and Weare, 1976; Angell and Korshover, 1978; Pan and Oort, 1983; Jones, 1989; Reid et al., 1989; Yulaeva and Wallace, 1994; Wigley, 2000; Trenberth et al., 2002; Kumar and Hoerling, 2003, hereafter KH03; Su et al., 2005, hereafter Su05).

Yulaeva and Wallace (1994) and Trenberth et al. (2002) interpreted this delayed response as a linear diabatic response to the changes of the surface energy balance during ENSO. Further, KH03 pointed out that the lagged response was tied to the peak of warming of the tropical Indian and Atlantic SSTs, which lag the Niño-3.4 warming peak by 3–4 months. Su05 emphasized that the time delay was determined by the mixed layer depth of ocean. In contrast to the Indian and Atlantic, the western Pacific was less emphasized

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because of its out-phase SSTA with the Niño-3.4 SSTA during ENSO's life cycle. Does the SSTA over the western Pacific have contributions to this delayed phenomenon?

On the other hand, the maximum regression of the zonally averaged tropical (20°S–20°N) SSTA onto the Niño-3.4 SSTA index occurs when the former lags by 2 months (Lau and Nath, 1996; Klein et al., 1999; Alexander et al., 2002; Trenberth et al., 2002). If we regard this zonally averaged SSTA as directly representative of the tropical diabatic heating anomalies, this 2-month lag plus an additional week to 15 days, the time scale of linear atmospheric response to diabatic heating forcing (Heckley and Gill, 1984; Jin and Hoskins, 1995; Bantzer and Wallace, 1996), is still shorter than 3–4 months, the observed lag of tropical tropospheric temperature relative to the Niño-3.4 SSTA. Thus, there must be a lag between the zonally averaged SSTA and the tropical zonal mean diabatic heating anomalies. To explain the time mismatch between SSTA and heating anomalies, KH03 proposed that the SSTA is most effective in forcing local enhancement of convection when the local climatological annual cycle of SST is warmest, in later winter. Yet, this explanation was found insufficient by Su05, in which the lag of tropospheric temperature response appears not to be sensitive to the local climatological annual cycle of SST.

The purpose of this study is to propose a mechanism to connect the Niño-3.4 SSTA, zonally averaged tropical SSTA, diabatic heating anomalies, and tropospheric temperature anomalies with reasonable time intervals. The datasets and methods are described in section 2. The role of the western Pacific is analyzed in section 3. Next in section 4, we propose a simple parameterization scheme of latent heating anomalies dependent on SSTA and climatological SST. The results of using parameterized latent heating anomalies are documented in section 5. Finally, a summary is presented in section 6.

2. Data and methods

We use the monthly National Oceanic and Atmospheric Administration (NOAA) optimum interpolation SST Version 2 data with a resolution of 2° × 2° (Reynolds et al., 2002), and observed monthly mean 200 hPa heights for 1951–2004 provided by the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis on a 2.5° × 2.5° grid (Kalnay, 1996). The data are pretreated to eliminate the annual cycle and remove linear trends. Because the areas of the eastern and western Pacific are much larger than the Indian and Atlantic Oceans (see Fig. 1), the eastern and western Pacific contribute more anomalous heating than the Indian and Atlantic Oceans given the same averaged SSTA. To emphasize the different contributions of SSTA over each ocean basin to the total tropical SSTA, traditional methods such as correlation, regression of regional mean SSTA, or regression of regional normalized SSTA cannot describe the role of each ocean basin. Therefore, we calculated the regional integral of the tropical ocean SSTA between 20°S and 20°N, and used the regression analysis rather than the correlation or regression of regional mean of SSTA (KH03; Su05). And the Niño-3.4 SSTA index is the averaged SSTA over the so-called Niño-3.4 region (5°S–5°N, 120°–170°W). All the selected dimensions of ocean basins are shown in Fig. 1. Thus, the unit of regression coefficient of regional integral SSTA onto the Niño-3.4 SSTA index is the resolution of SST data, 2° × 2° (e.g., Figs. 2 and 3). The tropical atmospheric height anomalies are averaged between 30°S and 30°N.

3. Role of the western Pacific

Figure 2 shows that in the eastern Pacific (east of the date line) the SSTA develops concurrently with the Niño-3.4 SSTA, while the Niño-3.4 SSTA leads the other in-phase SSTA over tropical ocean basins, such as the Indian by 4 months and the Atlantic by 6 months. This has been pointed out by many former researchers (e.g., Lau and Nath, 1996; Klein et al., 1999; Alexander et al., 2002; Trenberth et al., 2002). However, the integral SSTA over these three tropical ocean basins (eastern Pacific+Indian+Atlantic in Fig. 3) lags the Niño-3.4 SSTA just by 1 month. On the other hand, the integral SSTA over the entire Pacific

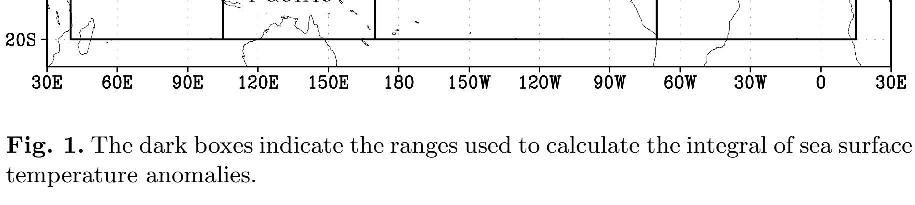

Fig. 1. The dark boxes indicate the ranges used to calculate the integral of sea surface temperature anomalies.

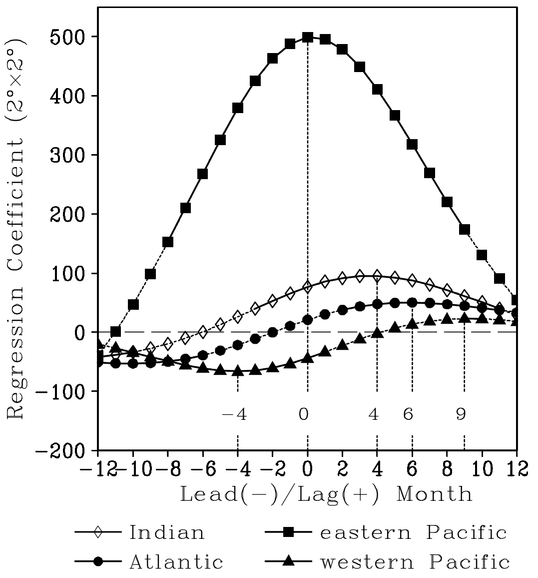

Fig. 2. Lead/lag regression coefficients of the regional integral SSTA over tropical (20°S–20°N) Indian, Atlantic, eastern Pacific, and western Pacific oceans onto the Niño-3.4 SSTA. Significant values above 95% confidence level from a two-tailed Student's *t*-test are solid. Units: $2° \times 2°$.

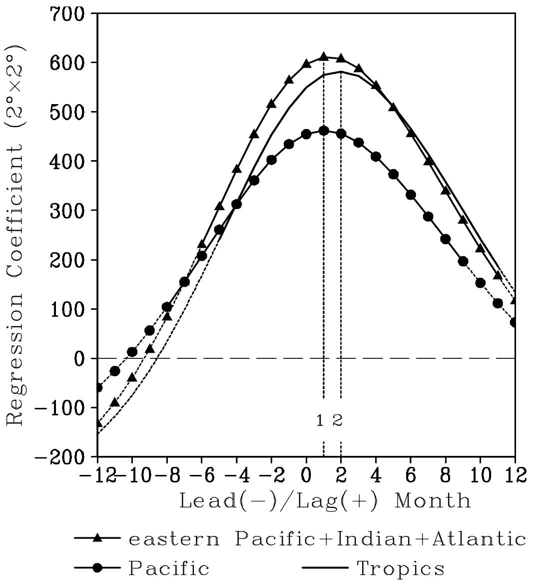

Fig. 3. Lead/lag regression coefficients of the regional integral SSTA over the sum of tropical (20°S–20°N) eastern Pacific, Indian and Atlantic oceans, for the entire tropical Pacific, and for the entire Tropics onto the Niño-3.4 SSTA. Units: $2° \times 2°$.

lags the Niño-3.4 SSTA by 1 month, too (Pacific in Fig. 3), the same lag as for eastern Pacific+Indian+Atlantic. For the entire tropical ocean, including the Indian, Atlantic, eastern Pacific, and western Pacific (west of the date line), the lag time of the entire zonal integral tropical SSTA (Tropics in Fig. 3) relative to Niño-3.4 SSTA extends to 2 months.

This shows that the SSTA over the western Pacific can play a role as important as that over the Indian and Atlantic on the atmospheric delayed response, and put off the entire tropical oceanic heating anomalies by 1 month. Because the variation of SSTA over the western Pacific is out of phase with the Niño-3.4 SST, hardly any attention has been paid to its role.

Though the SSTA over the western Pacific develops out of phase against the Niño-3.4 SSTA, the biggest negative western Pacific SSTA doesn't occur when the Niño-3.4 SSTA peaks in the ENSO warm phase, as shown in Fig. 2 (Barnett et al., 1991; Tourre and White, 1995; Zhang and Levitus, 1996; Giese and Carton, 1999; Meinen and McPhaden, 2000; Smith, 2000). Actually, the maximum negative correlation between the western Pacific SSTA and the Niño-3.4 SSTA occurs when the former leads by 3 months, and the maximum positive correlation between these occurs when the former lags by 9 months. Thus, the SSTA over the western Pacific decreases the zonal integral tropical SSTA before the Niño-3.4 SSTA peak, and increases the zonal integral after that. And the 9-month lag of western Pacific SSTA relative to the Niño-3.4 SSTA is much more than that for the Indian and Atlantic, though its amplitude is less. Therefore, the importance of the western Pacific is comparable to the Indian and Atlantic in the atmospheric delayed response to El Niño.

4. Parameterization of diabatic heating anomalies

Even when including the SSTA over western Pacific, the entire zonal integral tropical SSTA just lags the Niño-3.4 SSTA by 2 months (Fig. 3). As pointed out in section 1, if we regard this zonal integral SSTA as directly representative of the tropical diabatic heating anomalies, this 2-month lag time plus a week to 15 days required by linear response is still shorter than the observed 3–4 month delay of the atmospheric response relative to the Niño-3.4 SSTA. Therefore, there must be a delay between the SSTA and the diabatic heating anomalies. In other words, the SSTA cannot directly be regarded as indicative of the diabatic heating anomalies, at least in the context of the delayed atmospheric response discussed here.

The relationship between diabatic heating anomalies and underlying SSTA is very complex. Using numerical models including the relationship between SSTA and diabatic heating anomalies via surface moisture, Su et al. (2003) proposed a function that describes the relationship between SSTA and tropospheric temperature response. They argued that there is larger latent heating forcing and tropospheric temperature response to the same SSTA in regions of high climatological SST than elsewhere. In some simple linear atmospheric models, the external heating forcings were often assumed to be linearly related to evaporation anomalies, while the evaporation anomalies were approximated by linearizing the Clausius-Clapeyron relation about the climatological SST (e.g., Zebiak, 1982, 1986). Similar to Zebiak (1982), we present a relationship between heating anomalies and underlying SSTA as follows:

$$Q' \propto T'(ab\overline{T}^{-2})\exp[a(1-b/\overline{T})]\ , \qquad (1)$$

where Q' is the heating anomaly, T' is SSTA, and $\overline{T}$ is the climatological SST. Values of $a = 19.85$ and $b = 273.15°C$ are the canonical parameters in the Clausius-Clapeyron equation (e.g., Holton, 2004). The underlying assumption is that warm SSTA should initially cause positive evaporation anomalies from the sea surface, and thus positive boundary layer moisture anomalies. The associated increased conditional instability will induce the increase of cumulus convection and atmospheric heating (Zebiak, 1982). Of course, this heating parameterization considering only evaporation is crude. In fact, the atmospheric heating anomalies also depend on the low-level horizontal moisture convergence and wind. However, this assumption is reasonable and appropriate for this planetary scale conceptional model (e.g., Zebiak, 1982, 1986).

In addition, using monthly mean data Graham and Barnett (1987) and Waliser et al. (1993) concluded that deep convection occurs where there is high underlying SST. Based on this observational convection-SST relationship, Wang and Li (1993) proposed a switch-on SST-dependent conditional heating parameter in a simple tropical atmosphere model. A similar climatological precipitation-threshold SST anomaly mechanism has been proposed by Sobel et al. (2002) to study the ENSO signal in tropical tropospheric temperature.

Introducing a similar switch-on SST-dependent heating parameter δ into Eq. (1), we propose the following parameterization scheme of heating anomalies dependent on SSTA and climatological SST:

$$Q' = \alpha T'(ab\overline{T}^{-2})\exp[a(1-b/\overline{T})]\delta\ , \qquad (2)$$

where α is a constant coefficient and δ is the switch-on parameter:

$$\delta = \begin{cases} 1\ , & \text{if } \overline{T} \geqslant 27°\text{C}\ , \\ (\overline{T}-25)/2\ , & \text{if } 27°\text{C} \geqslant \overline{T} \geqslant 25°\text{C}\ . \\ 0\ , & \text{otherwise}\ . \end{cases} \qquad (3)$$

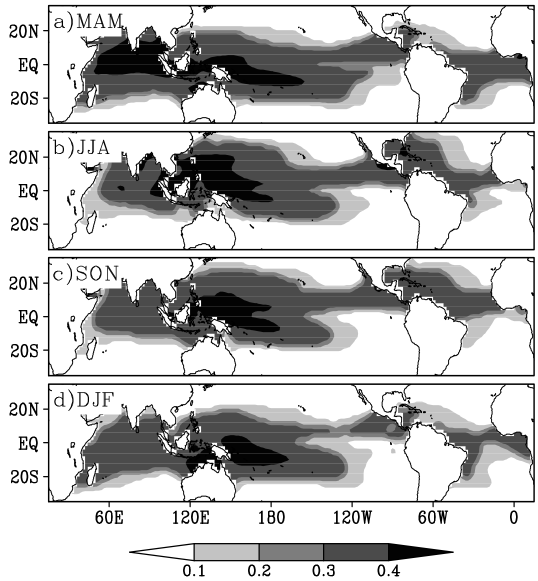

Fig. 4. The weight coefficient of the parameterization scheme for (a) March–April–May (MAM), (b) June–July–August (JJA), (c) September–October–November (SON), and (d) December–January–February (DJF).

The parameters in Eq. (3) are based on Wang and Li (1993) and Waliser et al. (1993). Thus, the parameterization of diabatic heating anomalies presented in Eq. (2) includes two thermodynamic processes: (1) the relationship between heating anomalies and SSTA is deduced from the Clausius-Clapeyron equation, and that (2) the deep convection is infrequent over low underlying SST.

The $T'(ab\overline{T}^{-2})\exp[a(1-b/\overline{T})]\delta$ also can be called a weighted SSTA (w-SSTA) similar to the concept of a P-threshold or P-weighted SST as in Sobel et al. (2002), where the $(ab\overline{T}^{-2})\exp[a(1-b/\overline{T})]\delta$ is the weight coefficient. The difference between w-SSTA and actual heating anomalies Q' is just the constant coefficient α, which has no influence on the lead/lag response time of atmospheric temperature relative to the Niño-3.4 SSTA discussed here. Thus, we will make use of w-SSTA to represent both the weighted SSTA and the parameterized heating anomalies Q', without loss of generality in on our focus problem.

In this scheme, we choose the climatological SST, not the climatological precipitation like Sobel et al. (2002), as the threshold. One reason is the lack of precipitation data before 1979. Another is that according the study of Su et al. (2003), "The diabatic heating more directly constrains the relationship between tropospheric temperature and SST, while the tropical mean precipitation anomalies are best thought of as a by-product of tropical atmosphere reaction to the SST forcing."

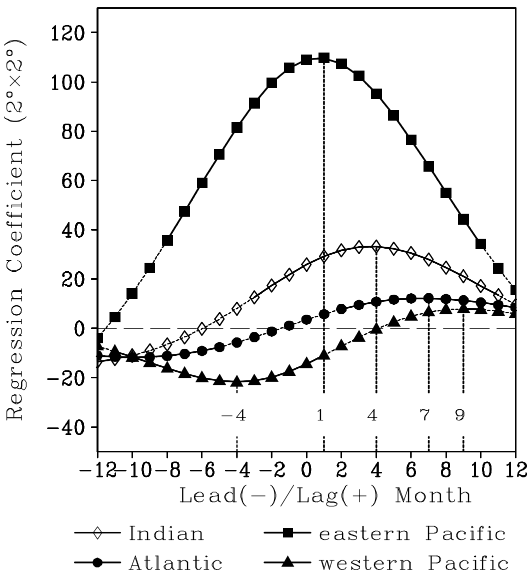

Fig. 5. Same as Fig. 2, but for weighted SSTA.

Figure 5 shows the seasonally averaged weight coefficient for the Tropics. The profile of weight coefficient is similar to the climatological SST. There are high weight coefficients over the Indian, the western and middle Pacific, and the western Atlantic, while the weight over the southeastern Pacific is low. But compared with the climatological SST, the differences between high and low weights are much more distinct. The weights over high climatological SST areas are greater than 0.3, while the weights over low climatological SST are less than 0.1.

5. Role of oceans with high climatological SST

For comparing with the above analysis about SSTA, the Niño-3.4 SSTA is also chosen as the time reference mark in the following analysis about w-SSTA. Comparing Fig. 4 with Fig. 2, we can see that the w-SSTA (parameterized diabatic heating anomalies) over the eastern Pacific and Atlantic basins have around 1 month more lag than SSTA itself, relative to the Niño-3.4 SSTA respectively. These different lagged times are listed in Table 1.

For the eastern Pacific, the ENSO key region, the regional integral of w-SSTA over the basin lags the Niño-3.4 SSTA by 1 month. That is, it lags the eastern Pacific SSTA by 1 month, as there is no lead/lag between the SSTA of the eastern Pacific and Niño-3.4. It means that if we were to use actual SST over the eastern Pacific but climatological SST outside this region in an external forcing of a simple linear model, and regard the w-SSTA as the heating anomalies induced by the underlying SSTA, there must be around a 1-month lagged atmospheric temperature response relative to the Niño-3.4 SSTA occurring. This conceptual result confirms one unexplained numerical model result simulated by Su05. In Su05, using the actual eastern Pacific SST with climatological SST outside this ENSO SST region forced a 1-month lagged atmospheric temperature response relative to the SSTA over and eastern Pacific, in an atmospheric general circulation model (AGCM) without atmosphere-ocean coupling. We suggest an explanation of this result is that the SSTA of the mid-eastern Pacific lags the Niño-3.4 SSTA by 1 month, and also the mid-eastern Pacific has high climatological SST. Thus, the total heating anomalies over the eastern Pacific are dominated by the SSTA over the mid-eastern Pacific, and lag the eastern Pacific SSTA (and equally the Niño-3.4 SSTA) by 1 month. Therefore, using the actual eastern Pacific SST and climatological SST outside that basin will force around a 1-month lagged atmospheric response.

Figure 6 shows that the maximum regression of regionally integrated w-SSTA over the entire Pacific onto the Niño-3.4 SSTA occurs when the w-SSTA lags by 2 months, same as for the integral of w-SSTA over the Indian, Atlantic, and eastern Pacific. Compared with the analysis about the role of the western Pacific based on SSTA in section 3 (Fig. 3), the role of the western Pacific is still as important as the Indian and Atlantic based on w-SSTA, though the lag time extends to 2-month.

According to the parameterization scheme, the SSTA over low climatological SST regions (<25°C) have been erased, and these over higher climatological SST regions are multiplied with higher weights. Therefore, comparing the SSTA over corresponding ocean basins (Fig. 2), the magnitude of the w-SSTA over

Table 1. The months of lag time of regional mean SSTA and w-SSTA over different ocean basins when the maximum (and also the minimum for western Pacific) correlations between SSTA/w-SSTA and the Niño-3.4 SSTA index occur. Unit: months.

	eastern Pacific	western Pacific	Indian	Atlantic	eastern Pacific +Indian+Atlantic	Pacific	Tropics
SSTA	0	−4, 9	4	6	1	1	2
w-SSTA	1	−4, 9	4	7	2	2	3

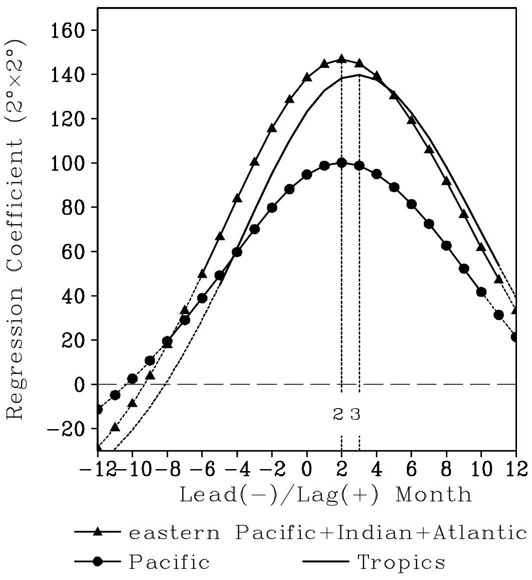

Fig. 6. Same as Fig. 3, but for weighted SSTA.

the eastern Pacific and Atlantic decrease around 50%, while these over the Indian and western Pacific decrease less than 20% (Fig. 4). Thus, the role of the Indian and western Pacific on the heating anomalies relatively increases, because there are high climatological SSTs over these basins. This means that the lag time of w-SSTA over the Indian (4 months) and western Pacific (9 months) play a more important role in delaying the response in the form of zonally averaged atmospheric temperature anomalies.

Since the key tropical eastern Pacific w-SSTA lags by 1 month more than the corresponding SSTA, relative to the Niño-3.4 SSTA, and the role of the Indian and western Pacific relatively increases, the zonal integral of tropical w-SSTA causes a delay in atmospheric responses of 1 month more also. Thus, the zonally integrated tropical w-SSTA lags the Niño-3.4 SSTA by around 3 months, as shown in Fig. 6. Considering the response time in a linear atmospheric model is around a week to 15 days, the tropospheric temperature response should lag the Niño-3.4 SSTA by 3–4 months. This lag time coincides with the observational result (KH03; Su05).

In the above analysis, because the Niño-3.4 SSTA is the origin of the El Niño signal, it was used as the time reference mark to research the time processes of the delayed response from the Niño-3.4 SSTA index of the eastern Pacific SSTA, the zonal average tropical SSTA, the zonal average tropical w-SSTA, and the atmospheric temperature anomalies. Following this, the atmospheric signal related to ENSO will now be used as the time reference mark to check these results documented above.

We choose the 200 hPa height to stand for the vertically averaged temperature from the surface to the tropopause, similar to KH03. Figure 7 shows the standardized time series of zonally averaged tropical 200 hPa height anomalies, SSTA, and w-SSTA for 1951–2004. In Fig. 7, it can be seen that the w-SSTA doesn't lead or lag the height anomalies and coincides with the latter well, while the SSTA leads the height anomalies by around 1 month. Notably, the w-SSTA is better than the SSTA for capturing the 200 hPa atmospheric height anomalies in the largest El Niño events such as 1972/73, 1987/88, and 1997/98.

The lead or lag correlation coefficients between zonally averaged tropical 200 hPa height anomalies and the Niño-3.4 SSTA, the tropical SSTA, and tropical w-SSTA (Fig. 8) clearly describe these different time properties between SSTA and w-SSTA. There is no lead or lag between w-SSTA and the 200 hPa height anomalies, while the SSTA leads the height anomalies by around 1–2 months. In other words, there actually is a time mismatch between the zonally averaged tropical SSTA and tropospheric temperature anomalies, but time mismatch doesn't exist between w-SSTA and temperature anomalies. This result confirms the above analysis based on the Niño-3.4 SSTA as the time reference mark. Thus, it can be concluded that the parameterization scheme of heating anomalies describes an appropriate mechanism to connect the Niño-3.4 SSTA, zonal average tropical SSTA, diabatic heating anomalies, and tropospheric temperature anomalies, and reasonably explains these time mismatches among these variables.

Comparing this w-SSTA approach (climatological SST threshold SSTA) with the climatological precipitation threshold SST in KH03, we can see that the w-SSTA is better for explaining the lagged atmospheric response relative to the Niño-3.4 SSTA. In KH03, the precipitation threshold SST lags the Niño-3.4 SST by 1 month too, and hardly differs from the total SST anomalies.

6. Summary

Zonally averaged tropospheric atmospheric temperature anomalies are delayed with respect to the Niño-3.4 SST by 3–4 months during ENSO's life cycle, and this has been well documented in earlier studies. And also, the role of SSTs over the Indian and Atlantic has been pointed out. However, results of observational analysis show that the integral SSTA over the Indian, Atlantic, and eastern Pacific just lag the Niño-3.4 SST by 1 month. On the other hand, including the western Pacific, the SSTA over the entire Pacific lags the Niño-3.4 SST by 1 month, too. And the SSTA over the western Pacific can extend the lagged time to

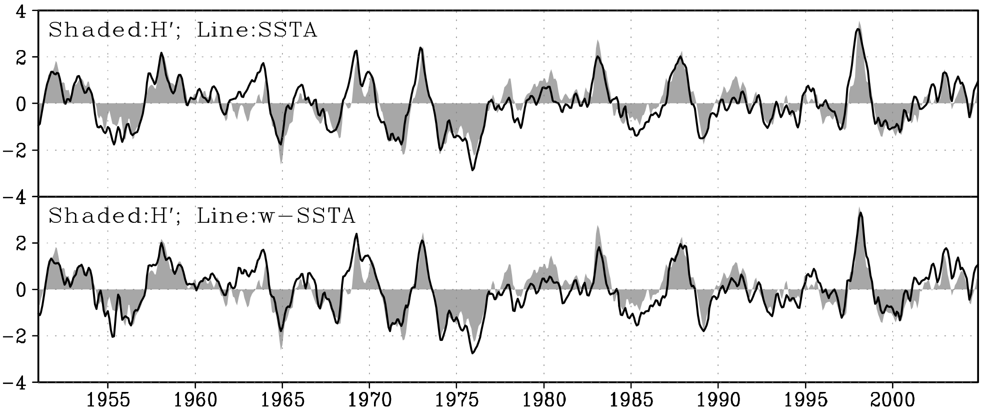

Fig. 7. The time series of the zonally averaged tropical 200 hPa height anomalies (top and bottom, shaded) and tropical SSTA (top, line), tropical w-SSTA (bottom, line) for 1951–2004. All of these have had their linear trends removed and have been standardized.

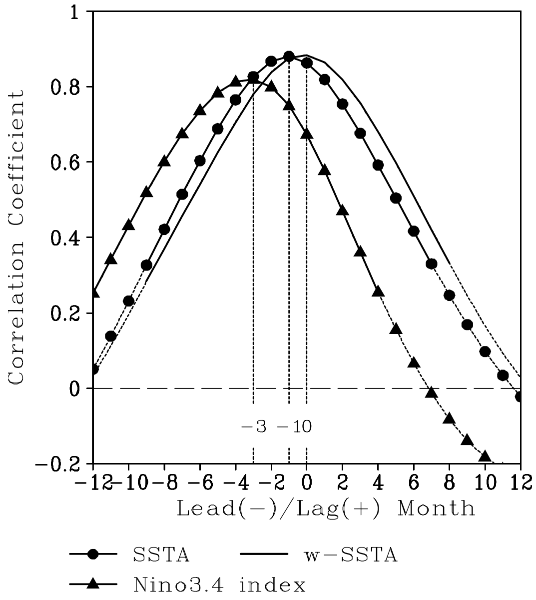

Fig. 8. Lead/lag correlation coefficients between zonally averaged tropical 200 hPa height anomalies and tropical SSTA, tropical w-SSTA, and the Niño-3.4 SSTA. Significant values above 95% confidence level from a two-tailed Student's t-test are solid.

2 months based on the 1 month lag of SSTA over the Indian, Atlantic, and eastern Pacific relative to the Niño-3.4 SSTA. This shows that the western Pacific plays the same important role as the Indian and Atlantic in this delayed atmospheric response phenomenon. This is because the maximum negative correlation between the western Pacific SSTA and the Niño-3.4 SSTA occurs when the Niño-3.4 SSTA lags by 4 months, and there are related positive anomalies occurring over the western Pacific 9 months after the Niño-3.4 SSTA peaks. The results of analysis using w-SSTA confirm this point.

Nevertheless, the integral SSTA over the entire Tropics lags the Niño-3.4 SSTA by just by 2 months, and this is much less than the observed result of 3–4 months. Because the atmosphere reacts immediately to the heating forcing, the problem of the time mismatch between tropical mean atmospheric temperature anomalies and the tropical mean SSTA can be transformed to the analysis of the mismatch between heating anomalies and SSTA. To explain this mismatch, we propose a parameterization scheme to describe the relationship between the diabatic heating anomalies and underlying SSTA, depending on the SSTA and the climatological SST. This parameterization scheme includes two physical processes: (1) the relationship between evaporation anomalies and SST deduced from the Clausius-Clapeyron equation, and (2) the relationship that deep convection is infrequent over low underlying SST. This parameterized diabatic heating anomalies is also called weighted SSTA (w-SSTA).

Based on the parameterization scheme of heating anomalies, the integral w-SSTA over the eastern Pacific lags the Niño-3.4 SSTA index (i.e., the eastern Pacific SSTA) by 1 month. Thus, the actual eastern Pacific SST and climatological SST outside this region can force a 1-month lagged atmospheric response, conceptually. This conceptual result confirms the simulated result in Su05 using AGCM. We suggest the explanation of this result is that the mid-eastern Pacific SSTA lags the Niño-3.4 SSTA by 1-month, and dominates the heating anomalies induced by eastern Pacific SSTA because of the high climatological SST over the mid-eastern Pacific.

Additionally, this parameterization scheme increases the importance of the Indian and western Pacific because of high climatological SST over these regions, while the importance of the eastern Pacific and

Atlantic are decreased relatively. Because the role of the Indian (with 4-month lags) and western Pacific (with 9-month lags) are emphasized, and there is around 1-month more lag for w-SSTA than SSTA over the eastern Pacific, the zonal integral w-SSTA lags the Niño-3.4 SSTA by 3–4 months. This lag time coincides with the observational result. Using the 200-hPa atmospheric height anomalies as the time reference mark, we gain the corroborative result that there is no lead or lag between zonally averaged w-SSTA and height anomalies.

Therefore, the physical mechanism described by this parameterization scheme is appropriate for connecting the variations of Niño-3.4 SSTA index, the tropical eastern Pacific SSTA, the zonally averaged tropical SSTA, the diabatic heating anomalies, and the atmospheric response during ENSO's life cycle, with reasonable time lags. And the time mismatch between the zonally averaged tropical SSTA and the atmospheric response can be explained by this mechanism. In this physical mechanism, the importance of ocean basins with high climatological SST is emphasized, and the SSTA over these basins domain the tropical heating anomalies rather than the tropical mean SSTA.

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REFERENCES

Alexander, M. A., I. Blade, M. Newman, J. R. Lanzante, N.-C. Lau, and J. D. Scott, 2002: The atmospheric bridge: The influence of ENSO teleconnections on air-sea interaction over the global oceans. *J. Climate*, **15**, 2205–2231.

Angell, J. K., and J. Korshover, 1978: Estimate of global temperature variations in the 100–30 mb layer between 1958 and 1977. *Mon. Wea. Rev.*, **106**, 1422–1432.

Bantzer, C. H., and J. M. Wallace, 1996: Intraseasonal variability in tropical mean temperature and precipitation and their relation to the tropical 40–50 day oscillation. *J. Atmos. Sci.*, **53**, 3032–3045.

Barnett, T. P., M. Latif, E. Kirk, and E. Roeckner, 1991: On ENSO physics. *J. Climate*, **5**, 487–515.

Giese, B. S., and J. A. Carton, 1999: Interannual and decadal variability in the tropical and midlatitude Pacific Ocean. *J. Climate*, **12**, 3402–3428.

Graham, N., and T. P. Barnett, 1987: Observations of sea surface temperature and convection over tropical oceans. *Science*, **238**, 657–659.

Heckley, W. A., and A. E. Gill, 1984: Some simple analytical solutions to the problem of forced equatorial long waves. *Quart. J. Roy. Meteorol. Soc.*, **110**, 203–217.

Holton, J. R., 2004: *An Introduction to Dynamic Meteorology*. 4th ed., Academic Press, 535pp.

Jin, F.-F., and B. J. Hoskins, 1995: The direct response to tropical heating in a baroclinic atmosphere. *J. Atmos. Sci.*, **52**, 307–319.

Jones, P. D., 1989: The influence of ENSO on global temperatures. *Climate Monitor*, **17**, 80–89.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.

Klein, S. A., B. J. Soden, and N. C. Lau, 1999: Remote sea surface temperature variations during ENSO: Evidence for a tropical atmospheric bridge. *J. Climate*, **12**, 917–932.

Kumar, A., and M. P. Hoerling, 2003: The nature and causes for the delayed atmospheric response to El Niño. *J. Climate*, **16**, 1391–1403.

Lau, N. C., and M. J. Nath, 1996: The role of the "atmospheric bridge" in linking tropical Pacific ENSO events to extratropical SST anomalies. *J. Climate*, **9**, 2036–2057.

Meinen, C. S., and M. J. McPhaden, 2000: Observations of warm water volume changes in the equatorial Pacific and their relationship to El Niño and La Niña. *J. Climate*, **13**, 3551–3559.

Newell, R. E., and B. C. Weare, 1976: Factors governing tropospheric mean temperature. *Science*, 194, 1413–1414.

Pan, Y. H., and A. H. Oort, 1983: Global climate variations connected with sea surface temperature anomalies in the eastern equatorial Pacific ocean for the 1958–73 period. *Mon. Wea. Rev.*, **111**, 1244–1258.

Reid, G. C., K. S. Gage, and J. R. McAfee, 1989: The thermal response of the tropical atmosphere to variations in equatorial Pacific sea surface temperature. *J. Geophys. Res.*, **94**, 14705–14716.

Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang, 2002: An improved in situ and satellite SST analysis for climate. *J. Climate*, **15**, 1609–1625.

Smith, T. M., 2000: Tropical Pacific sea level variations (1948–1998). *J. Climate*, **13**, 2757–2769.

Sobel, A. H., I. M. Held, and C. S. Bretherton, 2002: The ENSO signal in tropical tropospheric temperature. *J. Climate*, **15**, 2702–2706.

Su, H., J. D. Neelin, and J. E. Meyerson, 2003: Sensitivity of tropical tropospheric temperature to sea surface temperature forcing. *J. Climate*, **16**, 1283–1301.

Su, H., J. D. Neelin, and J. E. Meyerson, 2005: Mechanisms for lagged atmospheric response to ENSO SST forcing. *J. Climate*, **18**, 4195–4215.

Tourre, Y. M., and W. B. White, 1995: ENSO signals in global upper-ocean temperature. *J. Phys. Oceanogr.*, **25**, 1317–1332.

Trenberth, K. E., J. M. Caron, D. P. Stepaniak, and S.

Worley, 2002: Evolution of El Niño-Southern Oscillation and global atmospheric surface temperatures. *J. Geophys. Res.*, **107**, 4065.

Waliser, D. E., N. E. Graham, and C. Gautier, 1993: Comparison of the highly reflective cloud and outgoing longwave radiation datasets for use in estimating tropical deep convection. *J. Climate*, **6**, 331–353.

Wang, B., and T. Li, 1993: A simple tropical atmosphere model of relevance to short-term climate variations. *J. Atmos. Sci.*, **50**, 260–284.

Wigley, T. M. L., 2000: ENSO, volcanoes, and record-breaking temperatures. *Geophys. Res. Lett.*, **27**, 4101–4104.

Yulaeva, E., and J. M. Wallace, 1994: The signature of ENSO in global temperature and precipitation fields derived from the microwave sounding unit. *J. Climate*, **7**, 1719–1736.

Zebiak, S. E., 1982: A simple atmospheric model of relevance to El Niño. *J. Atmos. Sci.*, **39**, 2017–2027.

Zebiak, S. E., 1986: Atmospheric convergence feedback in a simple model for El Niño. *Mon. Wea. Rev.*, **114**, 1263–1271.

Zhang, R.-H., and S. Levitus, 1996: Structure and evolution of interannual variability of the tropical Pacific upper ocean temperature. *J. Geophys. Res.*, **101**, 20501–20524.