

Observed Strengthening of the Zonal Sea Surface Temperature Gradient across the Equatorial Pacific Ocean*

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ABSTRACT

Decadal variations of very small amplitude [$\sim 0.3^{\circ}\text{C}$ in sea surface temperature (SST)] in the tropical Pacific Ocean, the genesis region of the interannual El Niño–Southern Oscillation (ENSO) phenomenon, have been shown to have powerful impacts on global climate. Future projections from different climate models do not agree on how this critical feature will change under the influence of anthropogenic forcing. A number of attempts have been made to resolve this issue by examining observed trends from the 1880s to the present, a period of rising atmospheric concentrations of greenhouse gases. A recent attempt concluded that the three major datasets disagreed on the trend in the equatorial gradient of SST. Using a corrected version of one of these datasets, and extending the analysis to the seasonal cycle, it is shown here that all agree that the equatorial Pacific zonal SST gradient has strengthened from 1880 to 2005 during the boreal fall when this gradient is normally strongest. This result appears to favor a theory for future changes based on ocean dynamics over one based on atmospheric energy considerations. Both theories incorporate the expectation, based on ENSO theory, that the zonal sea level pressure (SLP) gradient in the tropical Pacific is coupled to SST and should therefore strengthen along with the SST gradient. While the SLP gradient has not strengthened, it is found that it appears to have weakened only during boreal spring, consistent with the SST seasonal trends. Most of the coupled models included in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report underestimate the strengthening SST gradient in boreal fall, and show almost no change in the SLP gradient in any season. The observational analyses herein suggest that both theories are at work but with relative strengths that vary seasonally, and that the two theories need not be inconsistent with each other.

1. Introduction

The basic pattern of sea surface temperature (SST) in the tropical Pacific Ocean is characterized by a vast warm pool in the west ($\sim 29^{\circ}\text{C}$ annual mean SST), and a relatively narrow tongue of cold surface water extending westward from the coast of South America ($\sim 25^{\circ}\text{C}$ annual mean SST). The result is an approximately linear zonal gradient of SST between the western and eastern equatorial Pacific corresponding to a zonal SST difference ($\Delta_x\text{SST}$) of $\sim 4^{\circ}\text{C}$. A persistent change of $\Delta_x\text{SST}$ by

a fraction of a degree centigrade was enough to cause the Dust Bowl drought of the 1930s and other major droughts (Schubert et al. 2004; Schubert 2004; Seager et al. 2005; Kumar et al. 1999). The equatorial Pacific $\Delta_x\text{SST}$ exhibits strong seasonality that is dominated by the seasonality of the cold tongue because SSTs in the west remain fairly constant throughout the year. The cold tongue is weak (warm) during boreal spring and strong (cold) during boreal fall, resulting in a marked seasonal cycle of the equatorial Pacific $\Delta_x\text{SST}$ (Fig. 1).

Because of its importance in the global climate system, the past and future change of the equatorial Pacific zonal SST gradient, as well as the atmospheric circulation to which it is coupled, has been the subject of recent climate research. A weakening of the zonal SST gradient and atmospheric circulation has been termed “El Niño like,” and a strengthening thereof has been termed “La Niña like.” A theory has been proposed that global warming will result in an El Niño-like

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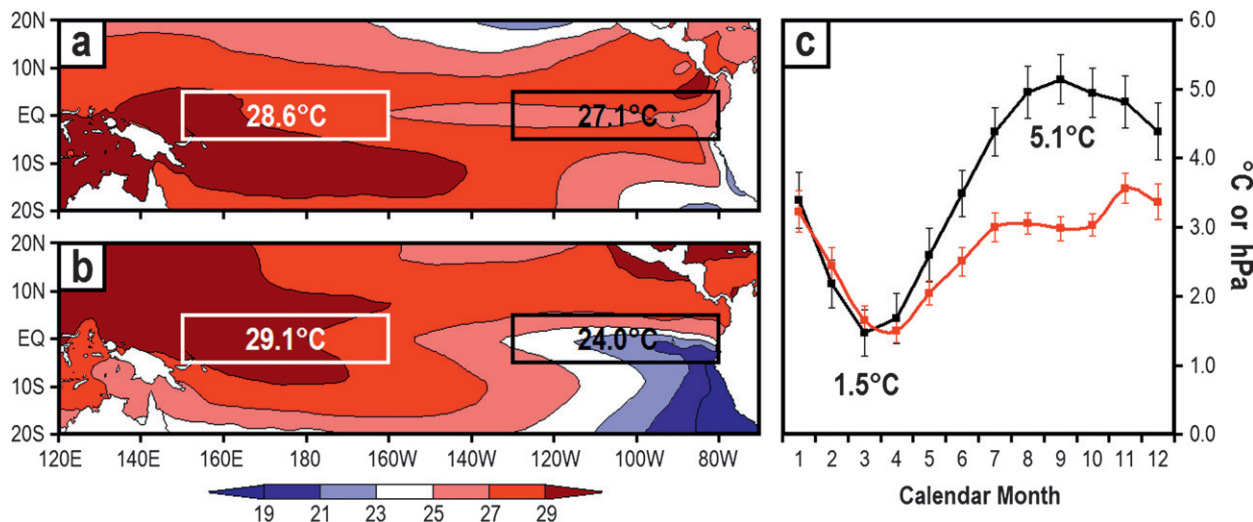


FIG. 1. Observed tropical Pacific SST ($^{\circ}\text{C}$) in (a) March and (b) September averaged over the modern satellite era (1982–2007) from the NOAA Optimal Interpolation (OI) SST version 2 dataset (Reynolds et al. 2002). The white (black) rectangles represent the western (eastern) equatorial Pacific. (c) Observed annual cycle of equatorial Pacific Δ_x SST (black, $^{\circ}\text{C}$) and Δ_x SLP (HadSLP2; red, hPa) averaged over the same period. Error bars represent ± 2 standard errors of the mean.

response, including a weakened zonal atmospheric overturning circulation and SST gradient, based on the mass and energy balances of the atmosphere (Held and Soden 2006; Vecchi and Soden 2007). Recent analysis of observed trends in annual mean sea level pressure (SLP) in the Indo-Pacific sector seem to support this theory (Vecchi et al. 2006), although some of the weakening appears as a strong shift in the 1970s. A more ocean-centric theory has also been proposed, wherein global warming will result in a La Niña-like response, because the strong upwelling in the cold tongue should dilute the warming in that region, resulting in a stronger contrast with the west (Clement et al. 1996; Seager and Murtugudde 1997; Sun and Liu 1996). Observational evidence has been presented in support of this theory as well (Cane et al. 1997; Cane 2005). While the zonal atmospheric overturning circulation of the equatorial Pacific may have weakened since the mid-1800s (Vecchi et al. 2006), no consensus has been achieved to date regarding the change in the zonal SST gradient.

2. Data and methodology

Here the most recent versions of three widely used observational datasets of historical monthly SST are analyzed to estimate the change in the zonal SST gradient in the period of adequate, overlapping coverage (1880–2005). Included in the present analysis are the U.K. Hadley Centre Global Sea Ice and Sea Surface Temperature version 1 (HadISST1; Rayner et al. 2003), the Kaplan Extended SST (Kaplan SST; Kaplan et al.

1998), and the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST version 3 (ERSST v3; Smith et al. 2008). The horizontal resolutions of HadISST1, Kaplan SST, and NOAA ERSST v3 are 1° , 5° , and 2° , respectively. To estimate the strength of the equatorial Pacific zonal SST gradient, we compute the difference between SST averaged over the rectangular boxes in the western and eastern equatorial Pacific Ocean shown in Fig. 1. This proxy index of the equatorial Pacific zonal SST gradient is hereafter called Δ_x SST. Given the strong seasonality of the eastern tropical Pacific, we analyze trends separately for each calendar month.

SLP is also analyzed in a similar fashion; here we use the U.K. Hadley Centre Sea Level Pressure version 2 (HadSLP2; Allan and Ansell 2006), Kaplan SLP (Kaplan et al. 2000), and the NOAA Extended Reconstructed SLP (NOAA ERSLP; Smith and Reynolds 2004). The calculated zonal SLP difference is hereafter called Δ_x SLP.

Temporal trends and their statistical significance are estimated using the median slope approach (Sen 1968; Thiel 1950; Salmi et al. 2002), and the Mann–Kendall test (Mann 1945; Kendall 1975; Salmi et al. 2002), both of which are nonparametric and resilient to outliers. Because we do not assume trends of a given sign a priori, we use the more stringent two-tailed test for assessing levels of significance and determining whether a trend is significantly different from zero.

We also briefly comment on the agreement between the observed trends in the equatorial Pacific Δ_x SST and

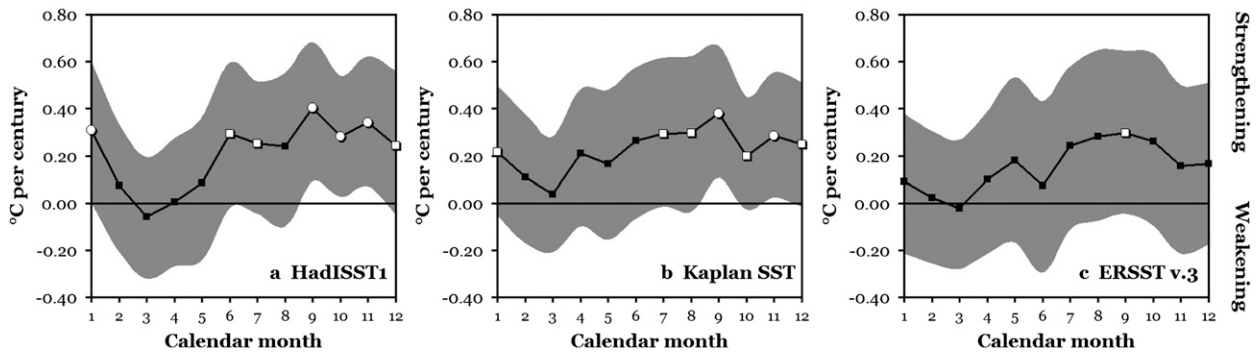


FIG. 2. Trends of observed equatorial Pacific Δ_x SST ($^{\circ}\text{C century}^{-1}$) from 1880 to 2005 as a function of calendar month from (a) HadISST1, (b) Kaplan SST, and (c) NOAA ERSST v3. Gray shading denotes 95% confidence intervals based on the nonparametric Sen median slope method. White circles (squares) represent trends significant at the 5% (10%) level based on the nonparametric Mann-Kendall test.

Δ_x SLP and those simulated by the coupled general circulation models included in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) and archived by the World Climate Research Program (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel database. We analyze the “Climate of the Twentieth Century” experiment, which is initialized at a stable preindustrial state, and forced by the historical record of greenhouse gases, aerosols, volcanoes, and solar forcing. Included in our analysis are 24 models; one of the models included in the IPCC AR4 was not archived by the CMIP3 database [i.e., the Beijing Climate Center (BCC) Climate Model 1 (CM1)], while two additional models have since been added to the database [Commonwealth Scientific and Industrial Research Organisation Mark version 3.5 (CSIRO Mk3.5; information online at http://www-pcmdi.llnl.gov/ipcc/model_documentation/CSIRO-Mk3.5.htm) and Istituto Nazionale di Geofisica e Vulcanologia (INGV) ECHAM4 (information online at http://www-pcmdi.llnl.gov/ipcc/model_documentation/INGV-SXG.htm)]. Refer to Table 8.1 of the IPCC AR4

(Solomon et al. 2007) for complete references and basic model specifications.

3. Results and discussion

The seasonally stratified trends in the equatorial Pacific Δ_x SST are in good agreement across the three datasets (Figs. 2a–c), with a statistically significant strengthening from 1880 to 2005 for several months throughout boreal fall and winter. The multidataset mean trend, averaged from June to January, is $0.26^{\circ}\text{C century}^{-1}$, which is equivalent to 6.1% of the 1880–2005 June–January climatological mean Δ_x SST. During September, the multidataset mean trend is $0.36^{\circ}\text{C (7.7%)} \text{ century}^{-1}$. Throughout boreal spring, the trends are approximately zero. For visual assessment, time series of the September Δ_x SST from all three datasets are shown in Fig. 3. Even in the face of a marked decadal shift in the 1970s toward an El Niño-like Pacific and a very strong El Niño event in the late 1990s, the multidataset mean trend is positive and significant at the 99% confidence level. The level of statistical significance of the observed

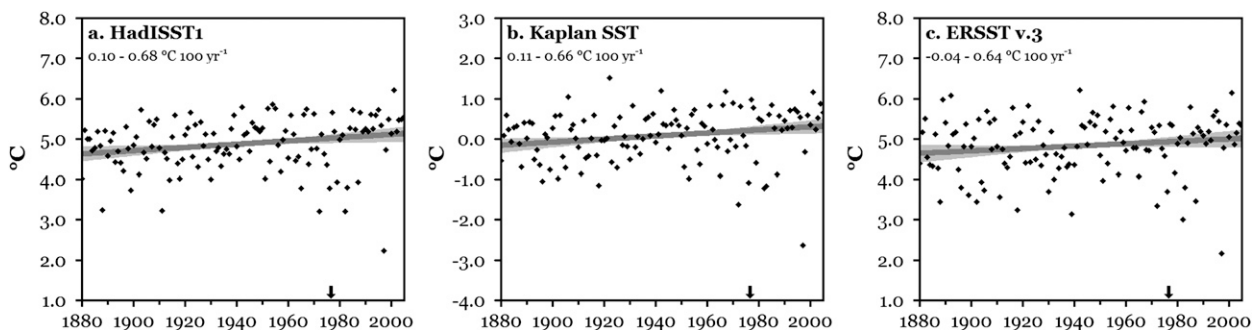


FIG. 3. Time series of observed September Δ_x SST ($^{\circ}\text{C}$) from 1880 to 2005 from (a) HadISST1, (b) Kaplan SST, and (c) NOAA ERSST v3. Dark gray lines represent the estimated linear trend and light gray shading represents the 95% confidence intervals of each trend. Small arrows along time axis mark 1976/77.

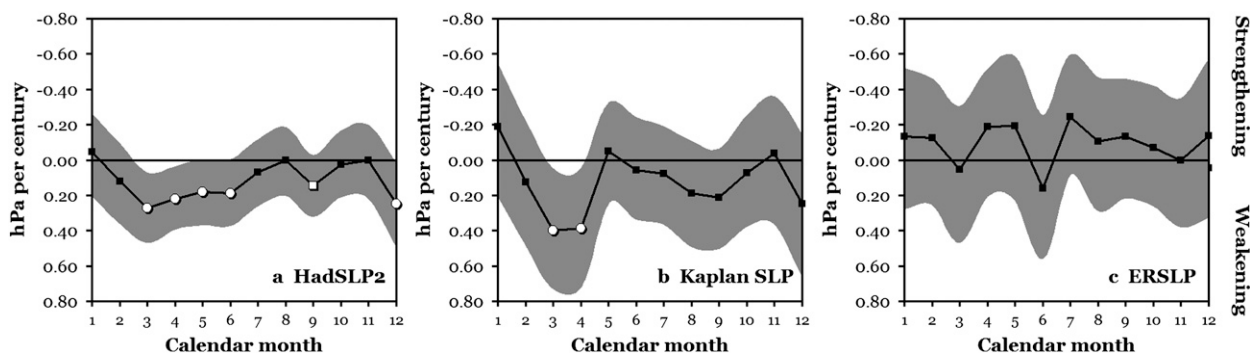


FIG. 4. Same as Fig. 2, but for $\Delta_x\text{SLP}$ based on (a) HadSLP2, (b) Kaplan SLP, and (c) NOAA ERSLP. Note the vertical scale is inverted so that up corresponds to a strengthening of the SLP gradient ($\Delta_x\text{SST}$), and vice versa.

trends in $\Delta_x\text{SST}$ depends on the use of a robust method for slope estimation. For example, the trend in Fig. 3a, as estimated by least squares regression, is $0.29^\circ\text{C century}^{-1}$ with 95% confidence limits of -0.02° and $0.61^\circ\text{C century}^{-1}$. Therefore, apart from the season when $\Delta_x\text{SST}$ is weakest, robust statistical methodology shows that the equatorial Pacific $\Delta_x\text{SST}$ has been strengthening since 1880. If the observed changes arose as a response to rising greenhouse gases, then this seasonal dependence of the forced change in $\Delta_x\text{SST}$ is consistent with a model prediction that emphasizes the ability of upwelling of cold water in the eastern equatorial Pacific, which maximizes in summer and fall, to offset warming forced by increased downward longwave radiation (Clement et al. 1996). Since the trend as a function of calendar month matches the mean annual cycle very closely (i.e., Fig. 1c), this implies a trend toward a stronger annual cycle of $\Delta_x\text{SST}$.

An observed strengthening of the equatorial Pacific $\Delta_x\text{SST}$ has important consequences. The magnitude of the observed change in $\Delta_x\text{SST}$ over a period of 100 yr (e.g., 0.36°C for September) is comparable in magnitude to those associated with Pacific decadal variability ($\sim 0.24^\circ\text{C}$), which strongly influences global precipitation patterns and drought.

According to well-established theory (Bjerknes 1966), a stronger SST gradient should be coupled to a stronger SLP gradient, and therefore the robust strengthening of the equatorial Pacific $\Delta_x\text{SST}$ seems in conflict with the observed weakening of the zonal atmospheric overturning circulation (Vecchi et al. 2006). We turn to observational datasets of SLP from each of the three institutions that provide the SST datasets analyzed above. Based on our computed equatorial Pacific $\Delta_x\text{SLP}$, two out of the three datasets indeed suggest a significant weakening of the zonal atmospheric overturning circulation during boreal spring (Figs. 4a,b). During boreal fall, however, each dataset shows a trend in $\Delta_x\text{SLP}$

that is not significantly different from zero, which is when $\Delta_x\text{SST}$ is a climatological maximum and has been strengthening. Because the mean annual cycle of $\Delta_x\text{SLP}$ is in phase with that of $\Delta_x\text{SST}$, it is a valid interpretation of Figs. 4a–c that, amid a general weakening, the seasonality of the zonal atmospheric overturning circulation has also been strengthening, consistent with the observed change in the seasonality of the equatorial ocean surface.

Of the 24 coupled general circulation models archived by the WCRP CMIP3 multimodel database, 20 grossly reproduce the observed seasonal climatology of the equatorial Pacific $\Delta_x\text{SST}$, although few maintain a strong enough $\Delta_x\text{SST}$ into boreal winter (Fig. 5a). Using that subset of 20 models, the multimodel ensemble mean trend in $\Delta_x\text{SST}$ is positive (strengthening) all year long, but fails to reproduce the observed seasonality of the trends, including an underestimation of the strengthening trend in boreal fall and winter (Fig. 5b). Also, the models do not reproduce the reduced strengthening trend in boreal spring, which may be attributable to a wide range of model deficiencies simulating tropical climatology. A smaller proportion of the models exhibits a reasonable climatology of $\Delta_x\text{SLP}$ (Fig. 5c). Using that subset of models, the multimodel ensemble mean trend in $\Delta_x\text{SLP}$ is in good agreement with observations during boreal summer and fall, but fails to reproduce the observed weakening trend in boreal spring (Fig. 5d).

It is necessary to keep in mind that complex climate models are not necessarily closer to nature in all aspects than simpler models. While the overall performance of a complex climate model may be better, some important processes, such as water vapor and cloud feedbacks, are not yet entirely understood. Because the actual heating resulting from rising greenhouse gases felt by the ocean will depend on such feedbacks, there are still many uncertainties in projections based on complex models. Despite their obvious errors simulating the climatology

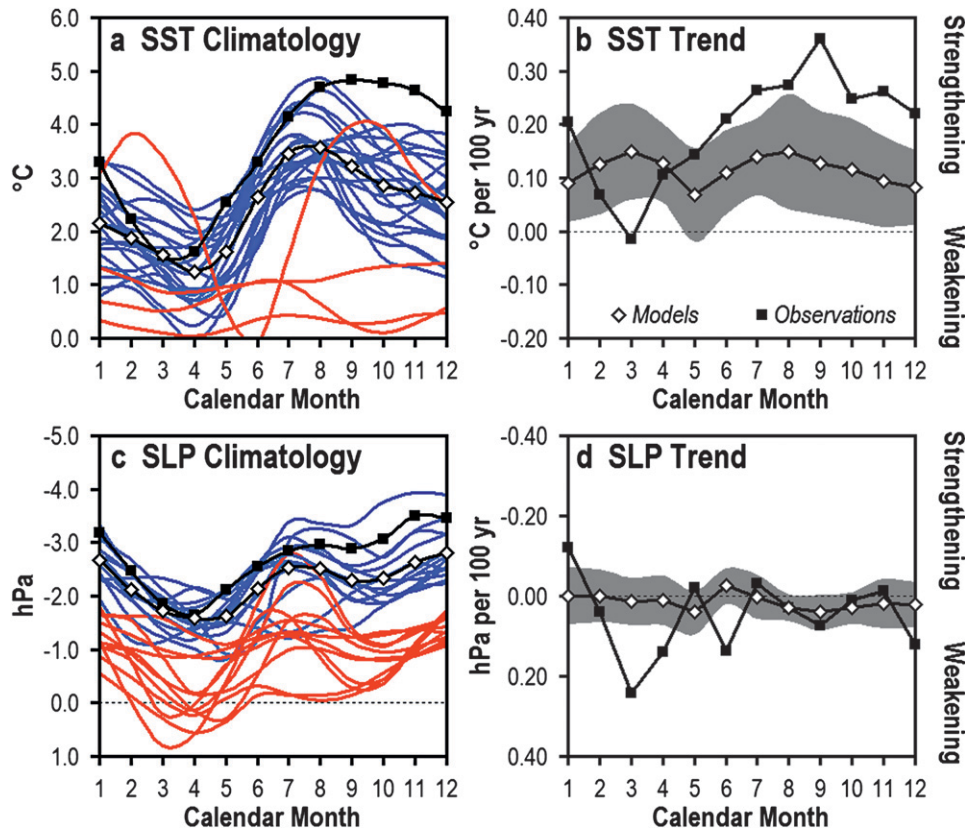


FIG. 5. Annual cycle of equatorial Pacific (a) $\Delta_x \text{SST}$ and (c) $\Delta_x \text{SLP}$ computed over the “Climate of the Twentieth Century” experiments for 24 coupled GCMs. A subset of models is easily distinguishable as having an unrealistic annual mean and/or seasonality of $\Delta_x \text{SST}$ (red lines). The black line with open markers represents the multimodel ensemble mean of the blue lines. The black line with closed markers represents the observations (multidataset mean, 1880–2005). Multimodel ensemble mean (blue models only; open markers) and observed (multidataset mean; closed markers) linear trend in (b) $\Delta_x \text{SST}$ and (d) $\Delta_x \text{SLP}$ as a function of calendar month. Gray shading represents ± 2 standard errors of the multimodel ensemble mean trends.

and trends of tropical Pacific climate, however, the models do suggest that it is possible, according to the physics built into the models, for the annual mean $\Delta_x \text{SST}$ to strengthen while the annual mean $\Delta_x \text{SLP}$ remains unchanged. Such changes contrast with the coupled fluctuations of the strength of the SST and SLP gradients that occur during ENSO events, suggesting that the mechanisms of tropical Pacific climate change associated with global warming may be distinct from those of known interannual variability. It has been shown that, even with fixed winds, the equatorial SST gradient can strengthen in response to positive radiative forcing because of an increase in the ocean’s thermal stratification (Seager and Murtugudde 1997). Therefore, if this effect is sufficiently strong, it is possible that an increased SST gradient can result, even if the SLP gradient and associated zonal winds weaken as a consequence of changes in the atmospheric energy and

moisture budget (Vecchi et al. 2008). Future explanations of the response of the tropical Pacific climate system to radiative forcing will need to account for the full range of mechanisms that couple the tropical Pacific atmosphere and ocean, their relative strengths, and their seasonal cycles. This understanding is required to determine how this key region of the global climate system will respond to anthropogenic climate forcing and how this will impact climate worldwide.

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