8B.3 THE RESPONSE OF THE EQUATORIAL PACIFIC OCEAN TO GLOBAL WARMING

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1. INTRODUCTION

The basic pattern of sea surface temperature (SST) in the equatorial Pacific Ocean is characterized by a vast warm pool in the west (~29°C, annual mean), and a relatively narrow tongue of cold surface water extending westward from the coast of South America (~25°C, annual mean). The result is an approximately linear zonal gradient of SST where the west is ~4°C warmer than the east. A persistent change of the zonal SST gradient 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 zonal SST gradient exhibits strong seasonality that is dominated by the seasonality of the eastern equatorial Pacific (i.e., the “cold tongue”) as SSTs in the west remain fairly constant. The cold tongue is weak during March (Fig. 1a) and strong during September (Fig. 1b), resulting in a strong seasonal cycle (Fig. 1c).

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” 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). 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, hence resulting in a stronger contrast with the west (Clement *et al.* 1996, Seager and Murtugudde 1997). Observational evidence has been presented in support of this theory as well (Cane *et al.* 1997, Cane 2005). Although it appears that the zonal atmospheric overturning circulation of the equatorial Pacific has been weakening since the mid–1800s (Vecchi *et al.* 2006), no consensus has been achieved to date regarding the change in the zonal SST gradient.

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2. DATA AND METHODOLOGY

Here the most recent versions of three widely used observational data sets of historical monthly SST are analyzed to determine 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 sea ice and temperature version 1 (HadISST1, Rayner *et al.* 2003), Kaplan Extended SST (Kaplan SST, Kaplan *et al.* 1998), and the National Oceanic and Atmospheric Administration Extended Reconstructed SST version 3 (NOAA ERSST v.3, Smith *et al.* 2008). The horizontal resolutions of HadISST1, Kaplan SST, and NOAA ERSST v.3 are 1°, 5°, and 2°, respectively. Our metric of the zonal SST gradient is the difference between SST averaged over the rectangular boxes in the western and eastern equatorial Pacific shown in Fig. 1. Given the strong seasonality of the equatorial Pacific zonal SST gradient (Fig. 1), we analyze trends separately for each calendar month.

Sea level pressure (SLP) is also analyzed in a similar fashion; here we use the U.K. Hadley Centre sea level pressure version 2 (HadSLP2, Allen and Ansell 2006), Kaplan sea level pressure (Kaplan SLP, Kaplan *et al.* 2000), and the NOAA Extended Reconstructed SLP (NOAA ERSLP, Smith and Reynolds 2004).

Trends and statistical significance are estimated using the median–slope approach (Sen’s method; Sen 1968, Thiel 1950), and the Mann–Kendall test (Mann 1945, Kendall 1975), both of which are nonparametric and resilient to outliers. Since 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 if a trend is significantly different from zero.

We also briefly comment on the agreement between the observed trends in the equatorial Pacific zonal SST and SLP gradients and those simulated by the coupled general circulation models included in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) and archived by the World Climate Research Program (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) Multi–Model Database. To compare with observations, we use the “Climate of the 20th Century” experiment, which is initialized at a stable pre–industrial 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 Database (BCC CM1), while two additional models have since been added to the Database (CSIRO MK3.5 [see http://www–pcmdi.llnl.gov/ipcc/model_documentation/CSIRO–Mk3.5.htm] and INGV ECHAM4 [see http://www–

pcmdi.llnl.gov/ipcc/model_documentation/INGV–SXG.htm]). Refer to Table 8.1 of the IPCC AR4 for complete references and basic model specifications.

3. RESULTS AND DISCUSSION

The seasonally–stratified trends in the equatorial Pacific zonal SST gradient are in good agreement across the three data sets (Fig. 2a–c) with a statistically significant strengthening of the equatorial Pacific zonal SST gradient from 1880–2005 for several months throughout boreal fall and winter. The multi–data set mean trend, averaged from June to January is 0.26°C per century, equivalent to 6.1% of the 1880–2005 June–January climatological mean gradient. During September, the multi–data set mean trend is 0.36°C (7.7%) per century. Throughout boreal spring, trends are approximately– or not significantly different from zero. Therefore, apart from the season when the zonal SST gradient is weakest, the equatorial Pacific zonal SST gradient 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 SST gradient 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 very closely the mean annual cycle (i.e., Fig. 1c), this implies a trend toward a stronger annual cycle of the zonal SST gradient.

The observed strengthening of the zonal SST gradient has important consequences. The magnitude of the observed change in the zonal SST gradient over a period of 100 yr (e.g., 0.36°C for September) is comparable in magnitude to those associated with Pacific decadal variability (~0.24°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 zonal SST gradient seems in conflict with the observed weakening of the zonal atmospheric overturning circulation (Vecchi *et al.* 2006). We turn to observational data sets of SLP from each of the three institutions that provide the SST data sets analyzed above. Based on the zonal SLP gradient, two out of the three data sets indeed suggest a significant weakening of the zonal atmospheric overturning circulation during boreal spring (Fig. 3a–b). During boreal fall, however, each of the three data sets show trends in SLP gradient that are not significantly different from zero– which is when the zonal SST gradient is a climatological maximum and has been strengthening. Since the mean annual cycle of the zonal SLP gradient is in phase with that of the zonal SST gradient, it is a valid interpretation of Fig. 3a–c that, amidst 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 multi–model database, 20 models faithfully reproduce the observed seasonal climatology of the equatorial Pacific zonal SST gradient, although few sustain the SST gradient into boreal winter (Fig. 4a). Using that subset of models, the multi–model ensemble mean trend 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. 4b). 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 exhibit a reasonable climatological zonal SLP gradient (Fig. 4c). Using that subset of models, the multi–model ensemble mean trend of the zonal SLP gradient is in good agreement with observations during boreal summer and fall, but fails to reproduce the observed weakening trend in boreal spring (Fig. 4d).

Despite their obvious errors simulating the climatology and trends of tropical Pacific climate, the models do suggest that that it is possible, according to the physics within these models, for the zonal SST gradient to strengthen but for the SLP gradient to remain largely unchanged. Such a change contrasts 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 may be distinct from those of tropical Pacific climate 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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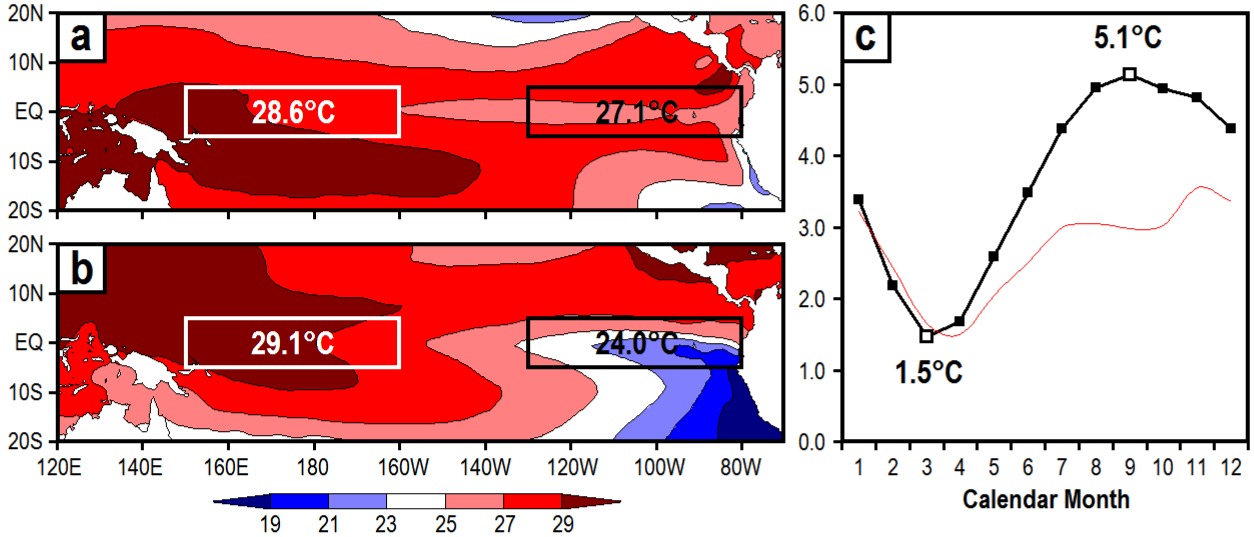

Figure 1. Observed tropical Pacific SST (°C) in March (a) and September (b) averaged over the modern satellite era (1982–2007) from the NOAA OI v.2 SST data set (Reynolds *et al.* 2002). The white (black) rectangles represent the western (eastern) equatorial Pacific. Observed annual cycle of the equatorial Pacific zonal SST (black, °C) and SLP (HadSLP2, red, hPa) gradients averaged over the same period (c). Open squares highlight March and September.

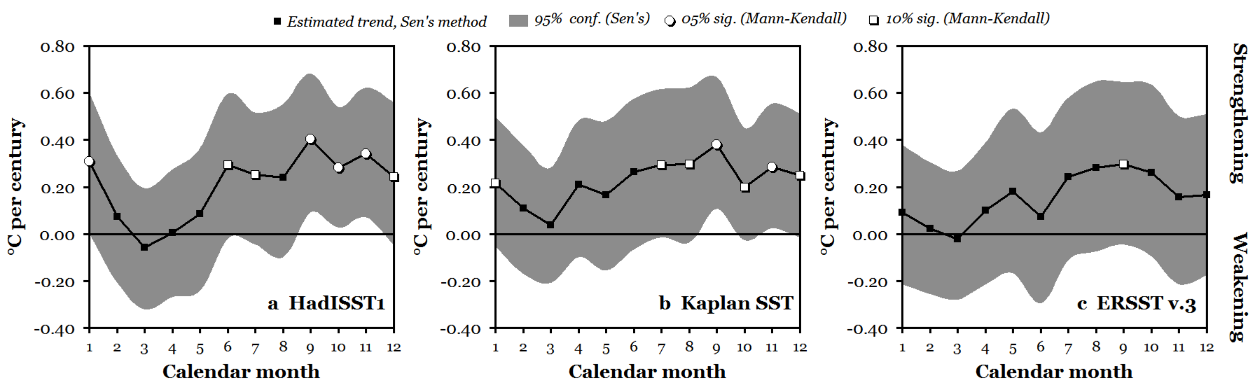

Figure 2. Trends of observed zonal SST gradient (west–east difference, °C per century) from 1880–2005 as a function of calendar month from HadISST1 (a), Kaplan SST (b), and NOAA ERSST v.3 (c). Gray regions denote 95% confidence intervals. Trends and confidence intervals calculated using the nonparametric Sen's median slope method. White circles (squares) represent trends significant at the 5% (10%) level based on the Mann–Kendall test.

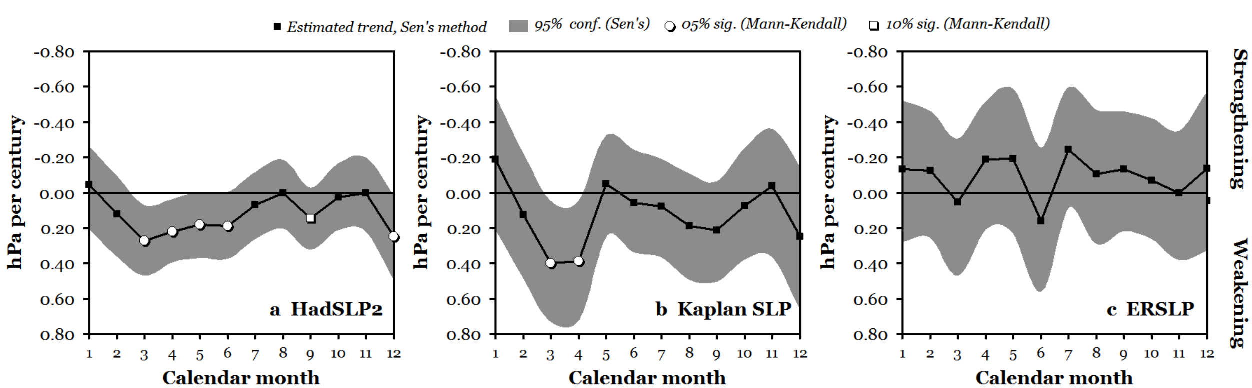

Figure 3. As in Fig. 2, but for SLP from HadSLP2 (a), Kaplan SLP (b), and NOAA ERSLP (c).

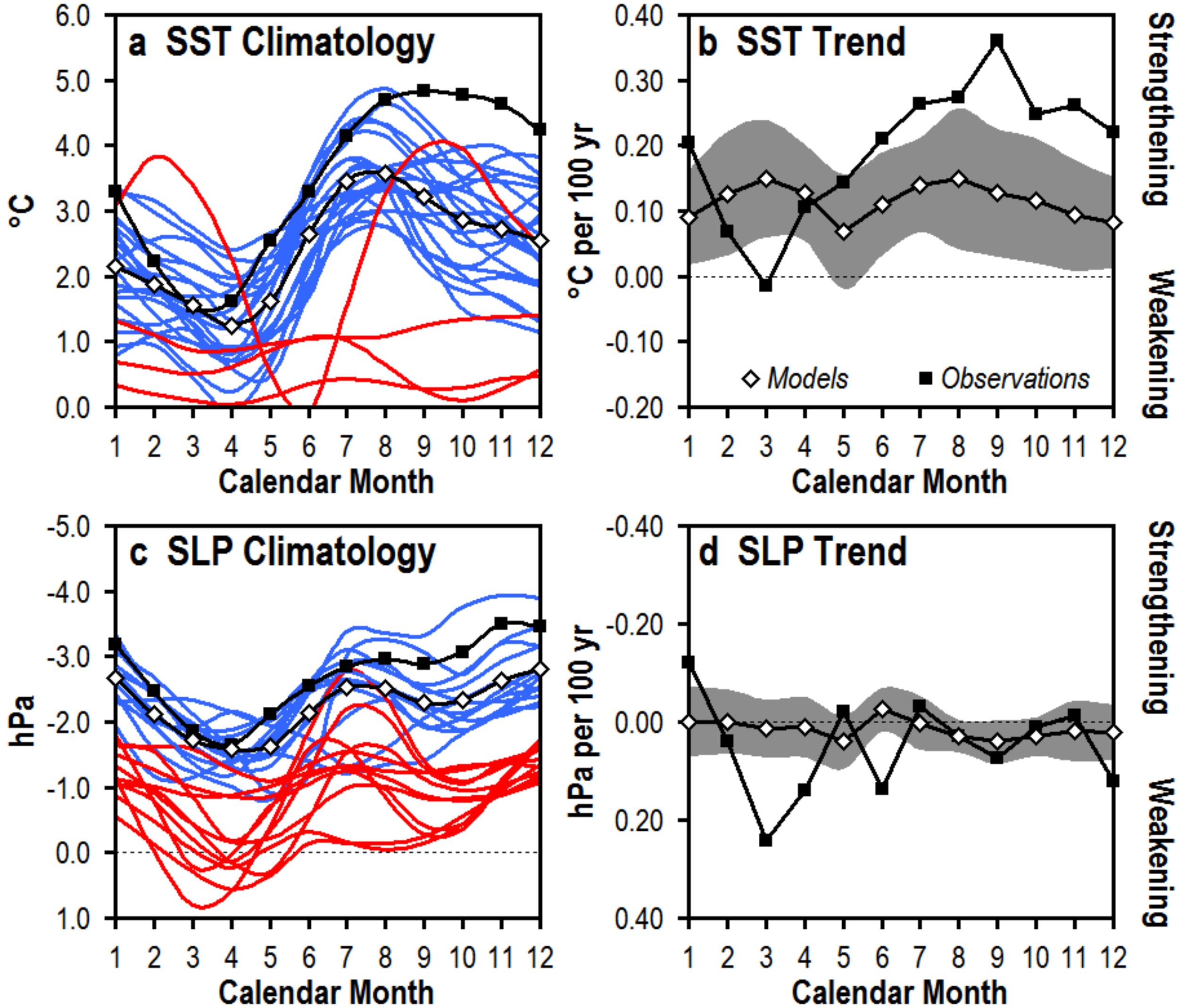

Figure 4. Annual cycle of the equatorial Pacific zonal SST gradient (western minus eastern) computed over the "Climate of the 20th Century" experiments (~1880–2000) for 24 coupled GCMs (a). A subset of models is easily distinguishable as having an unrealistic SST gradient and/or annual cycle (red lines). The black line with open diamonds represents the multi–model ensemble mean of the blue lines. The black line with closed squares represents the observations (multi–data set mean, 1880–2005). Multi–model (blue lines) ensemble mean (open diamonds) and observed (multi–data set mean, closed squares) linear trend in the west–east SST difference as a function of calendar month (b). Trends calculated using the nonparametric Sen's median slope method. The gray shading represents ±2 standard errors of the multi–model (blue lines) ensemble mean trends. Panels c and d as in a and b, but for SLP.