Oceanic Origin of A Recent La Niña-Like Trend in the Tropical Pacific

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ABSTRACT

Global ocean temperature has been rising since the late 1970s at a speed unprecedented during the past century of recordkeeping. This accelerated warming has profound impacts not only on the marine ecosystem and oceanic carbon uptake but also on the global water cycle and climate. During this rapid warming period, the tropical Pacific displays a pronounced La Niña-like trend, characterized by an intensification of west-east SST gradient and of atmospheric zonal overturning circulation, namely the Walker circulation. This La Niña-like trend differs from the El Niño-like trend in warm climate projected by most climate models, and cannot be explained by responses of the global water cycle to warm climate. The results of this study indicate that the intensification of the zonal SST gradient and the Walker circulation are associated with recent strengthening of the upper-ocean meridional overturning circulation.

Key words: tropical Pacific, warming trend, hydrological cycle, subtropical tropical cell


1. Introduction

Tropical Pacific Ocean–atmosphere circulation can regulate global climate profoundly through atmospheric teleconnections (Alexander et al., 2002; Yang and Li, 2005; Wu et al., 2010; Xiao et al., 2010). A long-standing debate has been focusing on the trend of tropical Pacific SST west–east gradient in global warming, i.e., a La Niña-like (enhanced zonal SST gradient) trend or an El Niño-like (reduced zonal SST gradient) trend (Cubasch et al., 2001; Collins et al., 2005; Cane, 2005). The potential change of the atmospheric Walker circulation is also associated with this trend (Vecchi et al., 2006; Vecchi and Soden, 2007). Climate-model projections and reconstructions have produced very diverse results, hindering the understanding of mechanisms and the ability to predict future tropical climate changes.

Several competing hypotheses have been proposed to explain potential shift of the coupled ocean–atmosphere circulation in warm climate, including effects of latent heat cooling (Knutson and Manabe, 1995), cloud cover, and albedo feedbacks (Meehl and Washington, 1996) favoring El Niño-like SST response, and oceanic dynamics favoring La Niña-like SST response (Clement et al., 1996; Seager and Murtugudde, 1997). Recent hypotheses have tended to link the tropical ocean–atmospheric circulation with changes in the global hydrological cycle induced by global warming (Held and Soden, 2006; Vecchi and Soden, 2007). The 21st-century simulations of the Intergovernmental Panel on Climate Change (IPCC) models demonstrate a weakening trend of the Walker circulation associated with an El Niño-like trend in the tropical Pacific. The cause of the slowing Walker circulation has been suggested to be the difference in the rate of increase of moistening and the rate of increase of precipitation in warm climates. A recent study attempted to unify these arguments (Karnauskas et al., 2009) by demonstrating that the potential mechanisms mentioned previously are at work but with relative strengths that vary seasonally. Therefore, these theories need not be inconsistent. While the cause of these trends remains elusive, the rapid warming of Earth’s climate...
and the accumulation of more reliable observational data during the past 30 years provide a unique opportunity to investigate possible mechanisms of the tropical ocean–atmosphere circulation responses to warm climate (Chen et al., 2002; Soden et al., 2005; Mitas and Clement, 2005; Fu et al., 2006). In this study, analysis of the trend of tropical Pacific Ocean atmosphere response in warmer climate between 1980 and 2006 has been based on series of observation datasets, reanalysis data products, and climate-model data outputs. Meanwhile, we sought to determine the unified response between ocean and atmosphere and its associated potential mechanisms during this period.

Available datasets are briefly described in the following section. The trend of response of tropical Pacific Ocean and its associated atmosphere variation in the past three decades (1980–2006) are analyzed in section 3. A discussion of the unified trend in both ocean and atmosphere (i.e., whether or not they can be explained by hydrological cycle changes) is presented in section 4. In the following section 5 a possible mechanism responsible for the tropical Pacific trend in recent warm climate is proposed. Discussion and summary are presented in section 6.

2. Datasets

Various ocean datasets were used to assess recent tropical Pacific variability: Hadley Center Sea Ice and Sea Surface Temperature (HadISST) dataset (Rayner et al., 2003), Kaplan Extended SST data (Kaplan et al., 1998), the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST data (Smith et al., 2008), Simple Ocean Data Assimilation (SODA) subsurface temperature data (Carton and Giese, 2008), Ishii’s data (Ishii et al., 2006), and German contribution to the Estimating the Climate and Circulation of the Ocean assimilation effort (GECCO) data (Stammer et al., 2004). To evaluate the associated atmosphere response from 1980 to 2006, atmospheric datasets were also adopted: Global Precipitation Climatology Project (GPCP) product (Adler et al., 2003), global ocean–atmosphere flux data product developed recently by Woods Hole Oceanographic Institute (Yu and Weller, 2007), NCEP/NCAR Reanalysis product, and the ECWMF ERA40 Reanalysis product. Finally, 20th-century simulations from the IPCC Fourth Assessment Report (AR4) were also used for comparison with ob-

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![Fig. 1. Time series of global mean SST (black line) and 30-year running trend (gray line) in the commonly used datasets: (a) HadISST, (b) ERSST, and (c) Kaplan SST. Right panel shows the corresponding seasonal trend of the zonal SST gradient defined as the difference between west (5°S–5°N, 148°E–160°W) and east (5°S–5°N, 130°W–80°W) in the tropical Pacific in the past 30 years (1980–2006). Gray shading denotes 95% confidence intervals based on the nonparametric Sen median slope method (Sen, 1968; Thiel, 1950; Salini et al., 2002). Units for SST time series and trends are °C and °C (10 yr)^-1, respectively.](image-url)
3. La Niña-like warming trend in the Tropical Pacific

The nonuniform amplitudes of global warming during the 137 years of data gathering agree well across the three widely used datasets, with maximum warming evident after 1980 (Figs. 1a–c). Thirty years running trend further demonstrates that the warming after 1980 has a salient increasing velocity (Figs. 1a–c). The tropical Pacific trend during the rapid warming period (1980–2006) was considered with special regard to the anisotropy of warming time series.

To estimate the strength of the equatorial Pacific zonal SST gradient, the difference between SST averaged over the western equatorial Pacific Ocean (5°S–5°N, 148°E–160°W) and the eastern equatorial Pacific Ocean (5°S–5°N, 130°W–80°W), was computed as $\Delta_x$SST. The seasonal trend in the equatorial Pacific $\Delta_x$SST agrees well with the three datasets (Figs. 1d–f), with a significant strengthening every month. This indicates that tropical Pacific is characterized by a La Niña-like trend during the rapid warming period. However, a trend relating to the strong seasonal cycle, with positive peak in fall and negative peak in spring, is not significant between 1980 and 2006, which differs from the seasonality of the long-term trend proposed by Karnausus et al. (2009). In our study, the trend of peaks in winter is in phase with the seasonal development of a typical La Niña event, indicating that different origins dominate.

Next, we concentrated on the spatial distribution of SST trends. Global oceans underwent a general warming trend; these trends were stronger in the extratropical oceans, signifying the poleward amplification of global warming (Fig. 2). However, the eastern tropical Pacific underwent a cooling trend, leading to an enhanced zonal SST gradient. A close inspection found that the zonal SST gradient increases at a rate of $\sim 0.22$°C (10 yr)$^{-1}$.

Fig. 2. La Niña-like trend in the tropical Pacific. (a) Linear trend of global SST. (b, c) Vertical-longitudinal profile of mean (white contours) and linear trend (shaded) of equatorial temperature in the SODA and Ishii’s data. (d) Mean (shaded) and linear trend of equatorial upwelling in GECCO data. Units for temperature and upwelling trends are °C and $10^{-4}$ cm s$^{-1}$ (10 yr)$^{-1}$, respectively. The analyzed period is 1980 to 2006.
The La Niña-like trend was also revealed in the changes of equatorial subsurface temperate from different reanalysis datasets, including the SODA (Carton and Giese, 2008) and the Ishii data (Ishii et al., 2006). In spite of differences in magnitudes, both data clearly show deepening and shoaling of the equatorial thermocline in the west and the east, respectively (Figs. 2b, c). The maximum warming and cooling collocates with the mean thermocline, roughly around the isothermal of 20°C. The coherence of temperature trends in both surface and subsurface suggests a potential role of thermocline dynamics in the La Niña-like trend. This is further demonstrated by changes of equatorial upwelling from independent GECCO reanalysis data (Stammer et al., 2004). Overall, the upwelling intensified in the central equatorial Pacific and the eastern equatorial Pacific but decreased in the western equatorial Pacific during this period, which led to a strengthening of the equatorial thermocline (Fig. 2d).

Consistent with the La Niña-like trend, the atmospheric circulation is characterized by a strengthening of the Walker Circulation. The sea-level pressure (SLP) data shows a reduction in the west and intensification in the east at a rate of ~ 0.2 hPa (10 yr)$^{-1}$ (Fig. 3a). The seasonal trend also exhibits a maximum trend of zonal SLP gradient peaks during winter (Fig. 4a), consistent with the SST seasonality. The enhanced surface convergence in the west corresponds to the SST increase, which led to an intensification of deep convection. This is demonstrated by the upward velocity at 500 hPa, which was enhanced at a rate of ~ 0.004 Pa s$^{-1}$ (10 yr)$^{-1}$ over the warm pool region (Fig. 3a). In the east, the cooling trend corresponds to an enhancement of downward velocity and surface divergence. The intensification of the Walker Circulation coupled with the La Niña-like SST trend can be also inferred from changes of the precipitation (Fig. 3b). The precipitation from the Global Precipitation Climatology Project (GPCP) data product (Adler et al., 2003) clearly displays an intensification trend with a magnitude of ~ 0.2 mm d$^{-1}$ (10 yr)$^{-1}$ over the warm pool region, as a result of local warming. Compared

Fig. 3. Atmospheric circulation and precipitation trend. (a) Linear trend of sea level pressure [contours, units: hPa (10 yr)$^{-1}$] and vertical velocity (positive upward) at 500 hPa [shaded, units: 1/15 Pa s$^{-1}$ (10 yr)$^{-1}$]. (b) Linear trend of precipitation [units: mm d$^{-1}$ (10 yr)$^{-1}$].

Fig. 4. Trends of observed equatorial Pacific zonal (a) sea level pressure, (b) vertical velocity (positive upward), and (c) precipitation gradient from 1980 to 2006 as a function of calendar month. Gray shading denotes 99% confidence intervals based on the nonparametric Sen median slope method. Units for sea level pressure, vertical velocity and precipitation trend are hPa (10 yr)$^{-1}$, Pa s$^{-1}$ (10 yr)$^{-1}$, and mm d$^{-1}$ (10 yr)$^{-1}$, respectively.
Table 1. Fractional increase of Precipitation \((P)\), moisture \((q)\), surface temperature \((T)\) from 1980 to 2006. The fractional increase of moisture is calculated based on WHOI OAflux data for global ocean, and the ECWMF ERA40 Reanalysis product \((1980-2002)\) for global ocean and land, respectively. Levels at 90% confidence are given for each quantity.

<table>
<thead>
<tr>
<th></th>
<th>(\Delta P/P) (%)</th>
<th>(\Delta q/q) (%)</th>
<th>(\Delta T) ((^\circ)C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Ocean</td>
<td>2.54(\pm)1.6</td>
<td>3.35(\pm)1.7</td>
<td>0.30(\pm)0.16</td>
</tr>
<tr>
<td>Global ocean and land</td>
<td>1.81(\pm)1.4</td>
<td>4.42(\pm)2.6</td>
<td>0.41(\pm)0.2</td>
</tr>
</tbody>
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with SST trend seasonality, the trend in peak of vertical velocity associated with precipitation displays some lags, implicating the passive response of atmosphere circulation (Figs. 4b-c).

4. Can this trend be explained by global hydrological cycle changes during this period?

A La Niña-like trend from 1980 to 2006 in the tropical Pacific has been confirmed. Can this trend be explained by changes in the global hydrological cycle during this period? To quantify hydrological cycle, we used the global ocean–atmosphere flux data product developed recently by Woods Hole Oceanographic Institute (Yu and Weller, 2007). During this period over the global ocean, the evaporation increased by an average of \(\sim 6.45\% \,(\Delta E/E)\) and precipitation increased by an average of \(\sim 2.54\% \,(\Delta P/P)\) (Fig. 5a). If the fractional increase in evaporation is further decomposed into the fractional increases in wind speed \((U)\) and humidity \((q)\) as

\[
\Delta E/E = \Delta U/U + \Delta q/q,
\]

the evaporation increases due to wind speed change (based on NECP/NCAR Reanalysis data) is \(\sim 3.1\% \,(\Delta U/U)\), and the humidity increases \(\sim 3.35\% \,(\Delta q/q = \Delta E/E - \Delta U/U = 6.45\% - 3.1\% )\). During this period, the global SST increases \(\sim 0.3^\circ\)C, therefore, the rate of moistening \((\Delta q/q/\Delta T = \Delta E/E/\Delta T - \Delta U/U/\Delta T)\) increases \(\sim 10^\circ\)C, and precipitation \((\Delta P/P/\Delta T)\) increases \(\sim 8^\circ\)C. During this period the rate of moistening increase slightly exceeded the rate of the precipitation increase. The difference is amplified if land data are included (Table 1).

The difference in the rate of increase of moistening and the rate of increase of precipitation from 1980 to 2000 is also captured by climate model simulations of 20th century (20C3M) organized by the program for Climate Model Diagnosis and Intercomparison (PCMDI) for the IPCC AR4. The models were forced by well-mixed greenhouse gases, aerosols, etc. All models showed an increase in surface air temperature (SAT) with considerable variability from 1980 to 2000 (Fig. 5b). In spite of a wide range of precipitation changes, these models display a strong coupling...
between precipitation changes and temperature changes. The magnitude of the precipitation increase is roughly 1% K\(^{-1}\)-2% K\(^{-1}\). The fractional increase in total column water vapor is linearly proportional to the SAT increase, with a rate of \(\sim 7\%\) K\(^{-1}\), which resembles that expected from Clausius–Clapeyron (C–C) thermodynamic scaling.

Although observations and climate models consistently indicate a greater rate of moistening increase than the rate of precipitation increase, the tropical Pacific responses do not show an El Niño-like response. Observations indicate a La Niña trend in the tropical Pacific (red dot in Fig. 5c), while climate models show either El Niño-like or La Niña-like response without preference (Fig. 5c). Therefore, the tropical Pacific Ocean–atmosphere circulation changes may not be directly regulated by the global hydrological cycle responses to warm climate during this short period.

5. Ocean origin (STC) of La Niña-like warming trend

The recent La Niña-like trend in the tropical Pacific is associated with acceleration of upper-ocean shallow meridional overturning circulation. In the subtropical and tropical Pacific Ocean, water masses subduct into the thermocline in the eastern subtropics of both hemispheres, enter into the equatorial thermocline through western boundary current and interior path, upwell to the surface in the eastern equatorial Pacific, and return to the subtropics through surface Ekman flow. These shallow, subtropical–tropical cells (STCs; McCreary and Lu, 1994; Liu et al., 1994) have been suggested to play an important role in the tropical climate variations (Gu and Philander, 1997; Kleeman et al., 1999).

The equatorward mass convergence of STC was measured by total transport across 9°N and 9°S in both hemispheres based on the SODA and GECCO Ocean Reanalysis data (Schott et al., 2007; Schott et al., 2008). Analyses of both datasets indicate that the equatorial Pacific SST gradient displays a significant correlation with the STC strength: a stronger STC corresponds to an intensification of the zonal SST gradient, and a weaker STC corresponds to a weakening of the zonal SST gradient (Fig. 6a). A stronger STC can pump more cold subtropical water into the equatorial thermocline, leading to cold surface anomalies in the eastern equatorial Pacific cold tongue and thus strengthening the zonal SST gradient. A weaker STC can pump less cold subtropical water into the equatorial thermocline, leading to warm surface anomalies in the eastern equatorial Pacific cold tongue and thus weakening the zonal SST gradient. Analysis of both SODA and GECCO data indicates that 1 Sv (10\(^6\) m\(^3\))
s$^{-1}$) increase of STC mass transport corresponds to a $\sim 0.15^\circ$C increase of the equatorial zonal SST gradient.

In addition to year-to-year variability, an acceleration trend of STC was also revealed in the analysis of the two datasets, although there are some notable differences between the datasets (Fig. 6b). The total equatorward transport across 9$^\circ$N/S has an increasing trend of $1.4\pm1.1$ S$^{-1}$ (10 yr)$^{-1}$ and $2.0\pm1.3$ S$^{-1}$ (10 yr)$^{-1}$ in SODA and GECCO during 1980–2006, which may correspond to $0.2^\circ$C$\pm0.16^\circ$C (GECCO) or $0.3^\circ$C$\pm0.2^\circ$C (SODA) increase of the equatorial zonal SST gradient (10 yr)$^{-1}$. This is close to the trend observed [0.22$^\circ$C$\pm0.17^\circ$C (10 yr)$^{-1}$] in the equatorial Pacific.

What drives a recent intensification of the STC? The direct forcing for the STC is the trade winds in both hemispheres that are associated with the atmospheric meridional overturning circulation, namely Hadley circulation. Both NCEP/NCAR and ERA-40 atmospheric reanalysis data show an intensification of Hadley circulation during the past several decades (Quan et al., 2004; Tanaka et al., 2004; Mitas and Clement, 2005), although most climate models show either a negligible or a decreasing trend (Mitas and Clement, 2006). Although the discrepancies between atmospheric reanalysis and climate-model simulations and bias in both satellite observations and models raise uncertainties about the Hadley circulation changes in the past several decades, the La Niña-like SST trend and the acceleration of oceanic meridional overturning circulation may be indicative of the acceleration of the Hadley cell.

6. Summary

The tropical Pacific SST trend of recent rapid warming from 1980 to 2006 was analyzed based on various observations, reanalysis products, and IPCC models. The tropical Pacific was found to exhibit a La Niño-like trend characterized by warming in the west and cooling in the east. The strengthened zonal SST gradient, coupled with intensified atmosphere Walker circulation, may be explained by acceleration of upper-ocean shallow meridional overturning circulation, without an apparent link to the changes in the global hydrological cycle during this period. Whether the current trend is a part of natural multimodal variations or is a result of forcing by elevation of greenhouse gases, the mechanisms outlined here shed light on the processes and dynamics of tropical ocean-atmosphere circulation changes in response to global warming.

Zhang and McPhaden (2006) argued that tropical SST, characterized by an El Niño-like trend using the ERSST dataset and the corresponding interior STC, has weakened in recent 50 years. Although both the study of Zhang and McPhaden (2006) and our study emphasize the influence of the ocean bridge (STC) on tropical climate change, they differ with regard to studied time range. Indeed, the tropical Pacific SST trend during the past 50 years show great differences among different datasets, with an El Niño-like pattern in the ERSST data and an La Niña-like pattern in the HadISST and Kaplan SST datasets. The period and scale dependence of the tropical Pacific trend indicate that the associated mechanism may include many aspects, with different dominating factors during different periods and therefore across datasets. As revealed by Seager and Murtugudde (1997), even with fixed winds, the equatorial SST gradient can be strengthened by uniformly positive radiative forcing because of an increase in the ocean’s thermal stratification. Therefore, it is possible that an increased SST gradient can be a consequence of changes in the atmospheric energy and moisture budget, even if the SLP gradient and associated zonal winds are weakened (Vecchi et al., 2006). Further observations and multi-model comparisons are clearly necessary to improve our understanding of climate changes in the tropical Pacific.

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