Weakened interannual variability of the contrast in rainfall between the eastern equatorial Pacific and equatorial Atlantic since 2000

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ABSTRACT
Recent studies suggest that the interannual variability in the tropical Pacific associated with the El Niño–Southern Oscillation has weakened since 2000. In this study, the authors report that the interannual variability of the contrast in rainfall between the eastern equatorial Pacific and equatorial Atlantic has also weakened remarkably since 2000, attributable to the weakened interannual variability in the zonal sea surface temperature gradient between the eastern equatorial Pacific and equatorial Atlantic and in the associated equatorial low-level zonal wind across South America linking the two ocean basins. Diagnosis of a column-integrated moisture budget indicates that the weakening in the interannual variability of the contrast in rainfall is primarily attributable to the changes in moisture convergence associated with vertical motion. The results highlight the clear weakened interannual variability in the coupled equatorial Pacific–Atlantic climate system since 2000, including the Pacific El Niño, Atlantic Niño, equatorial zonal wind across South America, and rainfall over the eastern equatorial Pacific and equatorial Atlantic.

1. Introduction
Rainfall is a critical component of Earth’s climate system, and the release of latent heat accompanied by rainfall plays a major role in the climate system. Understanding the variability in rainfall is thus of vital importance to understanding and predicting climate variability.

Wang (2006) revealed an anti-symmetric configuration between the rainfall over the eastern equatorial Pacific and equatorial Atlantic. This anti-symmetric rainfall pattern is considered to be closely associated with the variability of the zonal sea surface temperature (SST) gradient between the eastern equatorial Pacific and equatorial Atlantic, which is coupled with the overlying atmospheric wind across northern South America linking the two ocean basins (i.e. the Pacific and Atlantic). This rainfall anomaly pattern, with opposite signs over the eastern equatorial Pacific and equatorial Atlantic, has also been observed in a number of other studies (e.g. Enfield and Alfaro 1999; Giannini, Kushnir, and Cane 2000; Munnich and Neelin 2005). As suggested by Wang (2006), the interactions between the inter-Pacific–Atlantic zonal SST gradient and cross-South American zonal wind work in the equatorial Pacific–Atlantic climate system in the following way: The anomalous warming or cooling of the eastern equatorial Pacific and equatorial Atlantic can induce an inter-Pacific–Atlantic SST gradient variability, which can force low-level zonal wind anomalies across South America, and this cross-South American wind can further feed back to modulate the SST variability in the eastern equatorial Pacific and equatorial Atlantic through oceanic dynamics. As a consequence, a positive feedback process with interactions between the zonal inter-Pacific–Atlantic SST gradient and cross-South American zonal wind can be formed. The rainfall over the eastern equatorial Pacific and equatorial Atlantic...
Atlantic is an important component of the coupled equatorial Pacific–Atlantic climate system, which is itself an important but overlooked feature of tropical climate, as suggested by Wang (2006). Therefore, it is important to investigate the rainfall variability over these two regions, as it will help us to better understand the climatic variability of the coupled Pacific–Atlantic climate system.

Recently, the interannual variability in the tropical Pacific associated with the El Niño–Southern Oscillation (ENSO) was found to have weakened significantly since 2000 (Hu et al. 2013). This interdecadal shift since 2000 can be observed in changes in both the tropical atmosphere and ocean in the Pacific. A twenty-first century shift in ENSO characteristics has also been documented in a number of other studies (e.g. Horii, Ueki, and Hanawa 2012; McPhaden 2012; Lübbecke and McPhaden 2014; Guan and McPhaden 2016). Hu et al. (2013) proposed that the mean-state changes (mean thermocline slope and trade wind) in the Pacific since 2000 are responsible for the weakened interannual variability in ENSO. The combination of a steeper thermocline slope with stronger surface trade wind could inhibit the eastward migration of warm water in the Pacific, giving rise to reduced variability of the warm water volume in the Pacific and decreased ENSO amplitude since 2000.

Considering the tight coupling between the eastern equatorial Pacific and equatorial Atlantic (e.g. Wang 2006), it is possible that the twenty-first century shift in ENSO variability could affect this Pacific–Atlantic coupling and the equatorial Atlantic climate, which has not been examined in previous studies. In this study, we report that the interannual variability of the contrast in rainfall between the eastern equatorial Pacific and equatorial Atlantic has also weakened remarkably since 2000, which highlights the clear weakened interannual variability in the coupled equatorial Pacific–Atlantic climate system since the turn of the century.

2. Data

The rainfall data, spanning the period 1979–2014, are from the Global Precipitation Climatology Project monthly precipitation analysis (Adler et al. 2003), which blends both satellite observations and rain gauge data. The SST data are from the Extended Reconstructed SST analysis (Smith et al. 2008). The atmospheric winds and specific humidity are from the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis (Kalnay et al. 1996).

Both the tropical Pacific and Atlantic exhibit an equatorial mode on the interannual time scale, referred to as the Pacific El Niño and Atlantic Niño, respectively. The Niño3 index is defined by the SST anomaly (SSTA) over (5°S–5°N, 150°–90°W), which is used to track the Pacific El Niño. The Atl3 index, defined by the SSTA over (3°S–3°N, 20°W–0°), is used to track the Atlantic Niño. According to Figure 4(b) in Wang (2006), we define the eastern equatorial Pacific rainfall index using the rainfall anomaly over (5°S–5°N, 180°–80°W) and the equatorial Atlantic rainfall index using the rainfall anomaly over (5°S–5°N, 40°W–10°E) (Figure 1(a)). Following Wang (2006), the inter-Pacific–Atlantic zonal SST gradient index is defined by the difference between the Niño3 index and Atl3 index. The equatorial cross-South American zonal wind index is defined by the 850-hPa zonal wind anomalies in the equatorial South America region of (5°S–5°N, 80°–40°W). The Pacific Decadal Oscillation (PDO) index is derived as the leading principal component of the North Pacific SST variability poleward of 20°N (http://research.jisao.washington.edu/pdo/PDO.latest).

The Atlantic Multidecadal Oscillation (AMO) index is calculated as the detrended SSTA of the North Atlantic, obtained from the Physical Sciences Division of the National Oceanic and Atmospheric Administration (http://www.esrl.noaa.gov/psd/data/timeseries/AMO/).

All the anomalies are calculated by removing the monthly-mean climatology based on the period 1979–2014. Statistical significance is determined based on two-tailed $P$ values using the Student’s t-test.

3. Results

Figure 1(b) presents the monthly time series for the eastern equatorial Pacific and equatorial Atlantic rainfall anomalies during January 1997–December 2014, both of which show pronounced interannual variation. The correlation coefficient between the monthly eastern equatorial Pacific rainfall and equatorial Atlantic rainfall anomaly is $-0.38$ during January 1997–December 2014, which is significant above the 95% confidence level. This significant anti-correlation supports the rainfall anomaly pattern of opposite sign over the eastern equatorial Pacific and equatorial Atlantic, as suggested in previous studies (e.g. Wang 2006). Next, we examine the contrast in rainfall, which is defined by the difference between the eastern equatorial Pacific rainfall and equatorial Atlantic rainfall. The contrast in rainfall also shows pronounced interannual variation (Figure 1(c)). Recently, Hu et al. (2013) documented that the interannual variability in the tropical Pacific associated with ENSO has weakened significantly since 2000. Here, we note that there is remarkable weakening in the variability of the contrast in rainfall between the eastern equatorial Pacific and equatorial Atlantic since 2000. During the pre-2000 period of 1979–1999, the standard deviation of the rainfall contrast is 2.35 mm d$^{-1}$; whereas, during the post-2000 period of 2000–2014, the standard deviation of the rainfall contrast reduces to 1.24 mm d$^{-1}$. Compared with
the standard deviation during 1979–1999, the standard deviation of the contrast in rainfall decreases by 47% during 2000–2014. The nine-year-running standard deviation also indicates a marked reduction in the variability of the contrast in rainfall after 2000 (Figure 1(d)).

Correlation analysis indicates significant positive correlation between the contrast in rainfall and the inter-Pacific–Atlantic zonal SST gradient (Table 1), during both the pre- and post-2000 periods. Significant negative correlations can also be observed between the contrast in rainfall and the cross-South American zonal wind (Table 1). These significant correlations support the modulation of the contrast in rainfall between the eastern equatorial Pacific and equatorial Atlantic by the zonal inter-Pacific–Atlantic SST gradient and cross-South American zonal wind, as suggested by Wang (2006). Physically, tropical rainfall change can be decomposed into a thermodynamic component and a dynamic component, based on the water vapor budget (e.g. Huang et al. 2013). The inter-Pacific–Atlantic SST gradient can modulate the low-level atmospheric moisture and humidity, thus influencing the thermodynamic component associated with rainfall change. At the same time, the cross-South American zonal wind, which is linked to the inter-basin Walker circulation (e.g. Wang

Figure 1. (a) Annual mean SST (color shading; units: °C), 850-hPa winds (vectors; units: m s⁻¹), and rainfall (contours; units: mm d⁻¹), during 1979–2014. The red box represents the domain used to define the cross-South American zonal wind. The two green boxes are the domains used to define the eastern equatorial Pacific rainfall and equatorial Atlantic rainfall, respectively. The two dashed grey boxes represent the domains used to define the Niño3 index and Atl3 index, respectively. (b) Time series for monthly rainfall anomalies over the eastern equatorial Pacific (red) and equatorial Atlantic (blue) during January 1979–December 2014. (c) Time series for the monthly contrast in rainfall between the eastern equatorial Pacific and equatorial Atlantic during January 1979–December 2014. (d) The nine-year-running standard deviation of the monthly contrast in rainfall between the eastern equatorial Pacific and equatorial Atlantic.
2006), can modulate the atmospheric vertical motion over the eastern equatorial Pacific and equatorial Atlantic, and thus influence the dynamic component associated with the rainfall change. Both the observed statistical correlations and the underlying physical mechanisms support the roles of the inter-Pacific–Atlantic SST gradient and cross-South American zonal wind in modulating the contrast in rainfall variation during both the pre- and post-2000 periods.

Next, we examine the changes in the variability of the inter-Pacific–Atlantic SST gradient and cross-South American zonal wind, to search for possible reasons for the observed weakened variability in the contrast in rainfall since 2000. A marked reduction in the variability of the inter-Pacific–Atlantic SST gradient after 2000 can be observed (Figure 2(a) and (b)). During 1979–99, the standard deviation of the inter-Pacific–Atlantic SST gradient is 1.12 °C; in contrast, the standard deviation of the inter-Pacific–Atlantic SST gradient reduces to 0.73 °C during 2000–2014. Compared with the standard deviation during 1979–1999, the standard deviation of this zonal SST gradient decreases by 35% during 2000–2014. Both the Niño3 and Atl3 indices contribute to the weakened variability of the inter-Pacific–Atlantic SST gradient. During 1979–1999, the standard deviation is 0.98 °C for the Niño3 index and 0.41 °C for the Atl3 index; in contrast, the corresponding value during 2000–2014 reduces to 0.66 °C for Niño3 and 0.33 °C for Atl3. Compared with the standard deviation during 1979–1999, the standard deviation decreases by 33% during 2000–2014 for Niño3 and by 20% for Atl3. Along with the changes in the variability of the inter-Pacific–Atlantic SST gradient, a decrease in the variability of the cross-South American zonal wind is also evident since 2000 (Figure 3(a) and (b)). Compared with the standard deviation during 1979–1999 (0.74 m s⁻¹), the standard deviation of the cross-South American zonal wind during 2000–2014 (0.61 m s⁻¹) decreases by 18%. Therefore, the weakened interannual variability of the contrast in rainfall between the eastern equatorial Pacific and equatorial Atlantic can be explained by the weakened interannual

Table 1. Correlations between the monthly anomalies of the contrast in rainfall between the eastern equatorial Pacific and equatorial Atlantic, inter-Pacific–Atlantic zonal SST gradient, and equatorial cross-South American zonal wind, during the whole period (1979–2014), the pre-2000 period (1979–1999), and the post-2000 period (2000–2014).

|                        | 1979–2014 | 1979–1999 | 2000–2014 |
|------------------------|-----------|-----------|-----------|
| Contrast in rainfall and zonal SST gradient | 0.77      | 0.81      | 0.58      |
| Contrast in rainfall and cross-South American wind | −0.39     | −0.38     | −0.36     |
| Zonal SST gradient and cross-South American wind | −0.42     | −0.42     | −0.37     |

Note: All coefficients are above the 95% confidence level.

Figure 2. (a) Time series of the monthly inter-Pacific–Atlantic zonal SST gradient during January 1979 to December 2014. (b) The nine-year-running standard deviation of the monthly inter-Pacific–Atlantic zonal SST gradient.
variability in the inter-Pacific–Atlantic zonal SST gradient and the cross-South American wind since 2000.

To develop a better understanding of the physical processes that cause the weakening of the interannual variability in the contrast in rainfall, we examine a column-integrated moisture budget following the analysis method used in previous studies (e.g., Seager, Naik, and Vecchi 2010; Hsu et al. 2012, 2013; Chou et al. 2013). The changes
in horizontal moisture advection, moisture convergence, and surface evaporation are presented in Figure 4. The results indicate that the weakening of the interannual variability in the contrast in rainfall since 2000 is primarily attributable to changes in moisture convergence associated with vertical motion, whereas the horizontal moisture advection and surface evaporation have little effect.

But why has the interannual variability of the inter-Pacific–Atlantic SST gradient weakened since 2000? The inter-Pacific–Atlantic SST gradient is determined by the contrast between the El Niño (i.e. Niño3 index) and Atlantic Niño (i.e. Atl3 index). The weakened interannual variability in El Niño is considered to be due to the mean-state changes (mean thermocline slope and trade wind) in the Pacific since 2000 (Hu et al. 2013). For the Atlantic Niño, the weakened variability may possibly be due to the mean-state changes in the Atlantic, or due to the influences from the Pacific via Pacific–Atlantic interactions. Results from Svendsen, kvamsto, and Keenlyside (2014) indicate that a weakening Atlantic meridional overturning circulation (AMOC) can change the mean background state of the tropical Atlantic surface conditions and enhance equatorial Atlantic variability. The warm phase of the AMO corresponds to a strengthening of the AMOC (Wang and Zhang 2013). Therefore, a positive phase of the AMO tends to weaken equatorial Atlantic variability, according to Svendsen, Kvamsto, and Keenlyside (2014). However, mean-state changes in the Atlantic associated with the AMO occur in the early-1990s, with the AMO index changing from a negative to positive value. The time transition points are not consistent between the Atlantic mean-state changes (early-1990s) and the variability changes observed in this study (around 2000). On the other hand, it is noted that the mean-state changes in the Pacific associated with the PDO occur around the late-1990s and early-2000s, with the PDO index changing from a positive to negative phase. The consistency in the time transition point leads us to associate the observed weakened interannual variability in this study with the mean-state changes in the Pacific since 2000. Considering that the eastern equatorial Pacific and equatorial Atlantic could be tightly coupled (e.g. Wang 2006), it is possible that the weakened interannual variability in El Niño due to the mean-state changes in the Pacific since 2000 could influence the interannual variability in the equatorial Atlantic via their interactions. Significant negative correlation is apparent between the inter-Pacific–Atlantic SST gradient and cross-South American zonal wind (Table 1), which supports the close association between the two. The weakening of interannual variability in the El Niño variability since 2000 due to the mean-state changes in the Pacific could modulate the inter-Pacific–Atlantic SST gradient variability and then influence the variability of cross-South American zonal wind. As suggested by Wang (2006), the cross-South American zonal wind anomalies could extend eastwards to the equatorial Atlantic and influence the equatorial Atlantic SST (i.e. the Atlantic Niño and Atl3 index) through oceanic dynamics. Due to the coupled feedback process, the weakened variability of the equatorial Pacific due to the mean-state changes in the Pacific since 2000 could give rise to the corresponding weakened interannual variability in the Atlantic Niño and cross-South American zonal wind.

These results suggest that the mean-state changes in the Pacific since 2000 may cause chain effects in the coupled equatorial Pacific–Atlantic climate system. Since 2000, the mean-state changes in the Pacific could cause the weakening of the interannual variability in the tropical Pacific associated with ENSO (Hu et al. 2013). This change in El Nino since 2000 could influence the SST gradient and then further influence the cross south-American zonal wind. The cross south-American zonal wind could further influence the Atl3 SST via ocean dynamics, further enhancing the SST gradient with a positive feedback process between the SST gradient and cross-South American zonal winds. Therefore, weakened interannual variability since 2000 can also be found for the SST gradient and the cross South American zonal wind. These changes in the SST gradient and cross-South American zonal wind could further modulate the contrast in rainfall, giving rise to the weakening in the interannual variability of the contrast in rainfall between the eastern equatorial Pacific and equatorial Atlantic, as observed in Figure 1. As a consequence, clear weakened interannual variability since 2000 can be observed in the coupled equatorial Pacific–Atlantic climatic system, including the Pacific El Niño, Atlantic Niño, equatorial zonal wind across South America, and rainfall over the eastern equatorial Pacific and equatorial Atlantic.

4. Conclusions and discussion

In this paper, we present a weakened interannual variability in the contrast in rainfall between the eastern equatorial Pacific and equatorial Atlantic since 2000. Diagnosis of a column-integrated moisture budget indicates that this weakening is primarily attributable to changes in moisture convergence associated with vertical motion. The weakened interannual variability of the contrast in rainfall is closely associated with the weakened interannual variability in the inter-Pacific–Atlantic zonal SST gradient and in the associated equatorial cross-South American wind linking the two ocean basins since 2000. As suggested by Hu et al. (2013), the interannual variability in the tropical Pacific associated with ENSO has weakened significantly since 2000, due to the mean-state change in the Pacific. In
this study, we find that the weakened interannual variability since 2000 is not confined to the Pacific; rather, there is clear weakened interannual variability in the coupled Pacific–Atlantic climate system. These results highlight a clear weakened interannual variability in the coupled Pacific–Atlantic climate system since 2000, including the Pacific El Niño, Atlantic Niño, equatorial zonal wind across South America, and rainfall over the eastern equatorial Pacific and equatorial Atlantic.

Recently, the zonal tropical SST gradient between the Indian Ocean and western Pacific was found to be a possible cause for the recent intensification of the contrast in rainfall between the South and East Asian monsoons (Yun, Lee, and Ha 2014). In this study, we suggest that the inter-Pacific–Atlantic zonal SST gradient is important for the recent change in the contrast in rainfall between the eastern equatorial Pacific and equatorial Atlantic. The influences of the zonal SST gradient between different ocean basins (Indian, Pacific, and Atlantic) on global rainfall variability need to be examined in a more systematic way in future work.

Global warming has largely stalled since around the late-1990s and early-2000s, a phenomenon that has been dubbed the global warming ‘hiatus’ (e.g. Meehl et al. 2011; Kosaka and Xie 2013). It is also possible that there are some associations between the changes of the contrast in rainfall observed in this study and the global warming ‘hiatus’, both of which could be linked with mean-state changes in the Pacific around the late-1990s. The influences of the global warming ‘hiatus’ on tropical rainfall variability need to be investigated in more detail in future studies.

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