Weakening of the biennial relationship between Central American and equatorial South American rainfall in recent decades

WANG Lei and WU Min-Min

Guangdong Province Key Laboratory for Coastal Ocean Variation and Disaster Prediction, College of Ocean and Meteorology, Guangdong Ocean University, Zhanjiang, China

ABSTRACT

There is a rainfall variability biennial relationship between Central America (CA) and equatorial South America (ESA) over the tropical western hemisphere, which is known to have arisen due to the combined effects of ENSO and tropical North Atlantic (TNA) SST. Here, the authors report that this biennial rainfall relationship between CA and ESA has weakened remarkably since 2000, with weakening in both in-phase and out-of-phase rainfall transitions. The observed decadal changes in the biennial relationship between CA and ESA rainfall can be attributed to changes in the effects of ENSO and TNA SST since 2000, which may be associated with more frequent occurrences of the central Pacific or ‘Modoki’ type El Niño. The weakening of the association with ENSO for CA rainfall since 2000 might have given rise to the weakening of the in-phase rain transition from CA rainfall to the following ESA rainfall. The weakened linkage between boreal-winter ESA rainfall and the subsequent boreal-summer TNA SST since 2000 may have resulted in the weakening of the out-of-phase rainfall transition from boreal-winter ESA rainfall to the subsequent boreal-summer CA rainfall.

1. Introduction

In the tropical western hemisphere, a biennial relationship exists between the interannual rainfall anomalies over Central America (CA) and equatorial South America (ESA) (Wu and Zhang 2010), which is analogous to the well-documented biennial rainfall relationship in the Indian–Australian monsoons involved in the tropospheric biennial oscillation (TBO) over the tropical eastern hemisphere (Meehl 1987, 1993, 1997; Meehl and Arblaster 2002). Understanding the behavior and mechanisms of such a biennial rainfall relationship has important applications, due to the importance of rainfall variability to agriculture, economies and society in these regions.

According to the results reported by Wu and Zhang (2010), this biennial rainfall relationship manifests as an in-phase transition from CA rainfall to ESA rainfall (i.e. strong rainfall over CA in boreal summer followed by strong rainfall over ESA in the following austral summer, and vice versa), and an out-of-phase transition from ESA rainfall back to CA rainfall in the following year (i.e. strong rainfall over ESA in boreal summer followed by weak rainfall over CA in the following boreal summer, and vice versa). Thus, these in-phase and out-of-phase transitions between CA and ESA rainfall are two key features of this biennial rainfall relationship, and are referred to as the ‘biennial rainfall transition’ in this study.

The biennial transitions between CA and ESA rainfall may form because of the combined effects of ENSO and tropical North Atlantic (TNA) SST (Wu and Zhang 2010), which involves interactions between the seasonal migration of convection in the northwest–southeast direction (Horel, Hahnmann, and Geisler 1989) and the underlying...
Pacific–Atlantic Ocean. It is very similar to the interactions between the seasonal migration of convection and the underlying Pacific–Indian Ocean in the biennial rainfall transitions of the TBO over the tropical eastern hemisphere (e.g. Li et al. 2006; Meehl 1987, 1993; Meehl, Arblaster, and Loschinger 2003; Wu 2008, 2009; Wu and Kirtman 2007; Yu, Weng, and Farrara 2003).

Prominent decadal variation has been observed in the biennial rainfall relationship over the tropical eastern hemisphere (e.g. Ashok et al. 2014; Meehl and Arblaster 2011; Pillai and Mohankumar 2010; Wu 2016). However, it remains necessary to determine if there are significant decal changes in the biennial rainfall relationship between CA and ESA over the tropical western hemisphere. In the present study, we report that the biennial relationship between CA and ESA has weakened remarkably since 2000.

2. Data

The rainfall data, spanning the period 1979–2016, are from the CMAP product (Xie and Arkin 1997); the SST data are from the ERSST analysis (Smith et al. 2008); and the wind fields are from the NCEP–NCAR reanalysis (Kalnay et al. 1996).

Following Wu and Zhang (2010), we define a CA rainfall index using the rainfall anomalies over (7.5°–22.5°N, 110°–80°W), and an ESA rainfall index using the rainfall anomalies over (7.5°S–7.5°N, 70°–40°W). To represent the intensity of ENSO, we use the Niño3.4 index, which is defined by the SST anomalies averaged over (5°S–5°N, 170°–120°W). A TNA SST index is defined by the SST anomalies averaged over (10°–20°N, 80°–30°W), following Wu and Zhang (2010).

Anomalies are calculated by first removing the long-term trend, and then the mean seasonal cycle, for the period 1979–2016. The level of statistical significance is determined based on the two-tailed P-value using the Student’s t-test.

3. Results

To elucidate possible decadal changes in the biennial rainfall transition between CA and ESA, we perform an 11-year sliding correlation analysis between the CA rainfall index during boreal summer (June–July–August; JJA) and the ESA rainfall index during the austral summer (December–January–February; DJF) for the period 1979–2016 (Figure 1(a) and (b)). The correlation coefficients between the JJA CA rainfall index and the following DJF ESA rainfall index are positive throughout the analysis period (Figure 1(a)), which indicates that the expected in-phase transition from strong (weak) CA rainfall to strong (weak) ESA rainfall dominates the time series. These positive sliding correlations are statistically significant at the 95% confidence level during nearly the entire analysis period, except for the year 2003. The values of the positive correlations between JJA CA rainfall and DJF ESA rainfall decrease after 2000 (Figure 1(a)), with a mean 11-year sliding correlation of 0.79 during the pre-2000 period (1979–1999), and 0.66 during the post-2000 period (2000–2016). A similar sliding analysis between the DJF ESA rainfall index and the subsequent JJA CA rainfall index shows negative correlation throughout the analysis period (Figure 1(b)), which indicates the expected out-of-phase transition from ESA rainfall to the following boreal-summer CA rainfall. The negative correlations are statistically significant at the 90 or 95% confidence level during ~1990–2000, but become non-significant after 2000. It is interesting to note that the minimum value of the positive sliding correlations (0.47) occurs in 2003 (dip in Figure 1(a)) and the maximum value of the negative sliding correlations (−0.13) in 2004 (peak in Figure 1(b)). This analysis indicates that the biennial rainfall transition between CA and ESA rainfall may have weakened since 2000.

To quantitatively assess the strength of the biennial rainfall relationship between CA and ESA rainfall, we define a biennial relationship index (BRI) as follows:

\[
BRI = (-1) \times Cor1 \times Cor2,
\]

(1)

where Cor1 is the 11-year sliding correlation coefficient between the JJA CA rainfall index and the subsequent DJF ESA rainfall index, and Cor2 is the 11-year sliding correlation coefficient between the DJF ESA rainfall index and the subsequent JJA CA rainfall index. The factor −1 is included in Equation (1) considering the fact that the biennial rainfall relationship is a combination of an in-phase transition (i.e. a positive correlation coefficient) and an out-of-phase transition (i.e. a negative correlation coefficient) between CA and ESA rainfall. Thus, the larger the BRI value, the stronger the biennial relationship between CA and ESA rainfall. The BRI values calculated from the 11-year sliding correlations between CA and ESA rainfall (Figure 1(c)) show prominent decadal variation. After 2000, the BRI values tend to be smaller than the long-term mean value (0.33) of the BRI during the whole analysis period. On the contrary, the BRI values before 2000 are generally greater than the long-term mean value. These results suggest that the biennial relationship between CA and ESA rainfall has weakened remarkably since 2000. A regime shift index, calculated following Rodionov (2004), further confirms the occurrence of a regime shift around 2000 for the BRI between JJA CA rainfall and DJF ESA rainfall. This weakening of the biennial rainfall relationship since 2000 may have been contributed by both the weakening of the in-phase rain transition (i.e. the value of positive correlation coefficients decreasing after 2000) and the weakening of the out-phase rain transition (i.e. the negative correlation coefficients becoming non-significant after 2000).
Figure 1. (a) The 11-year sliding correlation coefficients between JJA CA rainfall and the following DJF ESA rainfall during 1979–2016. (b) As in (a) but for DJF ESA rainfall and the subsequent JJA CA rainfall. The red (yellow) dots in (a) and (b) represent correlations that are significant at the 95% (90%) confidence level. (c) The BRI between JJA CA rainfall and DJF ESA rainfall based on the 11-year sliding correlations.

Note: The dashed line represents the long-term mean value (0.33) of the BRI during the analysis period.
But why did the in-phase rain transition between JJA CA rainfall and the following ESA rainfall weaken around 2000? The in-phase rainfall transition may have been induced by the direct effects of ENSO (Wu and Zhang 2010), in which anomalous convection over the eastern equatorial Pacific associated with warm (cold) ENSO events generate anomalous descent (ascent) and suppress (enhance) rainfall over both CA and ESA. The 11-year sliding correlation between the JJA CA rainfall index and the following DJF Niño3.4 index shows prominent weakening from 2000, although no such changes are observed for the correlation between the DJF ESA rainfall index and the simultaneous Niño3.4 index (not shown). For the correlation between CA rainfall and the Niño3.4 index, the mean value of the 11-year sliding correlation is −0.82 for the pre-2000 period and −0.65 for the post-2000 period. In contrast, the corresponding value for the correlation between ESA rainfall and the Niño3.4 index is −0.92 for the pre-2000 period and −0.91 for the post-2000 period. Therefore, the weakening of the association with ENSO for CA rainfall might have given rise to the weakening of the in-phase rain transition from JJA CA rainfall to the following DJF ESA rainfall.

Since 2000, changes in the characteristics and variability of ENSO have been observed (e.g. Hu et al. 2013; Lübbecke and McPhaden 2014; McPhaden 2012). In particular, central Pacific (CP) or ‘Modoki’ El Niño events, with the center of SST anomalies shifted westward (e.g. Lübbecke and McPhaden 2014; McPhaden 2012), have occurred more frequently. The weakening of the relationship between CA rainfall and ENSO since 2000 may be closely associated with this twenty-first century shift in ENSO characteristics. During the pre-2000 period (1979–1999), very similar distribution patterns are observed in the correlations with equatorial Pacific SST for both JJA CA rainfall and DJF ESA rainfall (Figure 2(a)), which supports the prominent in-phase rainfall transition between JJA CA rainfall and the following DJF ESA rainfall under the same influence from the equatorial Pacific SST anomalies. Significant negative correlations are observed with DJF SST in both the central and eastern equatorial Pacific from 174°E to 80°W for both CA rainfall and ESA rainfall during the pre-2000 period (Figure 2(a)). In contrast, remarkable changes can be found for CA rainfall in the correlation distribution with equatorial Pacific SST during the post-2000 period (2000–2016), with significant negative correlation located in the central equatorial Pacific from 170°E to 144°W (Figure 2(b)). The correlation between JJA CA rainfall and the following DJF SST in the eastern equatorial Pacific (east of 144°W) becomes non-significant during the post-2000 period (Figure 2(b)). These results suggest that CA rainfall during the post-2000 period might have been influenced more by CP or ‘Modoki’ El Niño events, with the center of SST anomalies in the central equatorial Pacific. This change for CA rainfall since 2000 may be closely associated with more the frequent occurrences of CP or ‘Modoki’ El Niño during recent decades (e.g. Lübbecke and McPhaden 2014; McPhaden 2012). For DJF ESA rainfall, significant negative correlation is still observed, with simultaneous SST in the central and eastern equatorial Pacific east of 174°E during the post-2000 period (Figure 2(b)). The different distribution patterns in the correlation with equatorial Pacific SST for JJA CA rainfall and DJF ESA rainfall (Figure 2(b)) weakens the in-phase rainfall transition between CA and ESA.

But why did the out-phase rain transition between DJF ESA rainfall and the subsequent JJA CA rainfall weaken around 2000? The TNA SST anomalies in response to ENSO-generated ESA rainfall/convection anomalies were likely the main contributor to this out-of-phase rainfall transition (Wu and Zhang 2010). Warm (cold) TNA SST anomalies can give rise to above-normal (below-normal) rainfall over CA through a Gill-type response (e.g. Wang, Lee, and Enfield 2008; Wu and Zhang 2010). Remarkable weakening is observed in the linkage between DJF ESA rainfall and the subsequent JJA TNA SST since 2000 (Figure 3). For the correlation between DJF ESA rainfall and the subsequent JJA TNA SST, the mean value of the 11-year sliding correlation is −0.77 for the pre-2000 period, which is significant at the 95% confidence level; however, the correlation for the post-2000 period is −0.42, which is not significant at the 90% confidence level. Regression analysis (Figure 4) also indicates that strong ESA rainfall during boreal winter may have caused cold TNA SST anomalies during the subsequent JJA in the pre-2000 period; however, such associations weakened greatly during the post-2000 period. During boreal spring, cold SST anomalies are apparent in the TNA region during both the pre-2000 (Figure 4(b)) and post-2000 (Figure 4(e)) periods. These cold TNA SST anomalies persist throughout the following boreal summer during the pre-2000 period (Figure 4(b) and (c)), which may suppress the JJA CA rainfall anomalies through a Gill-type response and thus contribute to the out-of-phase rainfall transition from DJF ESA rainfall to JJA CA rainfall. In contrast, the cold TNA SST anomalies decay in JJA during the post-2000 period (Figure 4(f)). Therefore, the significant weakening of the effects from the TNA SST anomalies may have weakened the out-phase rainfall transition during the post-2000 period, as shown in Figure 1(b). These changes in the TNA SST anomalies should be closely associated with different characteristics of the Pacific SST anomalies associated with the evolution of ENSO. Compared with the pre-2000 period, the maximum SST anomalies in the tropical Pacific during the post-2000 period move westward (Figure 4(d) and (e)), making them more likely to be the CP or ‘Modoki’ type of ENSO. Moreover, the warm SST anomalies in the eastern equatorial Pacific occur in boreal summer during the post-2000 period (Figure 4(f)), suggesting
Figure 2. The zonal distributions of correlation coefficients between rainfall indices (JJA CA rainfall and DJF ESA rainfall) and DJF equatorial Pacific SST averaged between 5°S and 5°N for (a) the pre-2000 period (1979–1999) and (b) the post-2000 period (2000–2016). Notes: The horizontal dashed lines show the 95% confidence levels. The red dots in (a) and (b) represent correlations that are significant at the 95% confidence level.

Figure 3. The 11-year sliding correlation coefficients between DJF ESA rainfall and the subsequent JJA TNA SST during 1979–2016. Note: The red dots represent correlations that are significant at the 95% confidence level.
a faster biennial phase transition in ENSO. Wang and Ren (2017) also suggested that the dominant period of ENSO has tended to be more biennial since 2000. This fast ENSO phase transition from the cold to warm phase may be the root cause for the observed weaker persistence in the cold TNA SST anomalies from boreal spring to boreal summer during the post-2000 period. It is interesting to note that the cold SST anomalies in the tropical Indian Ocean also persist from boreal spring to boreal summer during the pre-2000 period (Figure 4(b) and (c)), but not during the post-2000 period (Figure 4(e) and (f)), which is similar to the evolution of the cold TNA SST anomalies. These different evolutionary characteristics in TNA and Indian Ocean SST anomalies are closely associated with differing ENSO evolution during the pre- and post-2000 periods.

Figure 4. Regressions of SST anomalies (color shading) and 850-hPa winds (vectors) with respect to DJF ESA rainfall from DJF to the following JJA during (a–c) the pre-2000 period (1979–1999) and (d–f) the post-2000 period (2000–2016). Notes: Only the values at the 90% confidence level or higher are shown. The red box in (c) and (f) represents the domain of the TNA SST index.

Figure 5. Comparison of the power spectrum during the pre-2000 (P1) and post-2000 (P2) periods for (a) DJF ESA rainfall, (b) JJA CA rainfall, and (c) JJA TNA SST. Note: The dashed lines denote the 95% confidence interval against red noise.
4. Conclusions

In this paper, we present a weakened biennial relationship between CA and ESA rainfall since 2000. Both the in-phase rainfall transition (from JJA CA rainfall to the following DJF ESA rainfall) and out-phase rainfall transition (from DJF ESA rainfall back to the subsequent JJA CA rainfall) have weakened since the turn of the twenty-first century.

The observed decadal changes in the biennial relationship between CA and ESA rainfall can be attributed to the changes in the effects of ENSO and TNA SST since 2000, which are closely associated with the twenty-first century shift in ENSO characteristics (i.e. the more frequent occurrence of CP or ‘Modoki’ El Niño events and the more biennial tendency for ENSO since 2000). The changes in the correlation of CA rainfall with equatorial Pacific SST anomalies associated with the development of ENSO since 2000 have weakened the in-phase rainfall transition between CA and ESA. The weakening of the out-of-phase rainfall transition between ESA and CA is attributable to the weakened linkage between boreal-winter ESA rainfall and the subsequent TNA SST since 2000.

Wang and Ren (2017) suggested that the dominant period of ENSO shortened from quasi-quadrennial to quasi-biennial (QB) after 2000. Therefore, it is also instructive to compare the power spectra of ESA and CA rainfall before and after 2000. The results show that an enhanced QB band (e.g. 2–3 years) since 2000 can be observed for DJF ESA rainfall (Figure 5(a)), which is consistent with the enhanced QB band for ENSO since 2000 (Wang and Ren 2017). In contrast, the QB band for JJA CA rainfall is suppressed after 2000 (Figure 5(b)), which may be partly influenced by the suppressed QB band in JJA TNA SST since 2000 (Figure 5(c)). The reasons why the QB band of JJA TNA SST is suppressed after 2000 need to be investigated in detail in future studies.

Acknowledgments

We thank the two anonymous reviewers for their comments and suggestions, which helped to greatly improve the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was funded by the National Natural Science Foundation of China [grant number 41776031], the Guangdong Natural Science Foundation [grant number 2015A030313796], the National Program on Global Change and Air-Sea Interaction [grant number GASI-IPOVAI-04], the Strategic Priority Research Program of the Chinese Academy of Sciences [grant number XDA11010104], the program for scientific research start-up funds of Guangdong Ocean University, and the Foundation for Returned Scholars of the Ministry of Education of China.

ORCID

WANG Lei  http://orcid.org/0000-0002-9015-5422

References

Ashok, K., C. Nagaraju, A. S. Gupta, and D. S. Pai. 2014. “Decadal Changes in the Relationship Between the Indian and Australian Summer Monsoons.” Climate Dynamics 42: 1043–1052.

Hored, J. D., A. N. Hahnmann, and J. C. Geisler. 1989. “An Investigation of the Annual Cycle of Convective Activity over the Tropical Pacific.” Journal of Climate 2: 1388–1403.

Hu, Z.-Z., A. Kumar, H.-L. Ren, H. Wang, M. L’Heureux, and F.-F. Jin. 2013. “Weakened Interannual Variability in the Tropical Pacific Ocean since 2000.” Journal of Climate 26: 2601–2613.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, et al. 1996. “The NCEP/NCAR 40-Year Reanalysis Project.” Bulletin of the American Meteorological Society 77 (3): 437–471.

Li, T., P. Liu, X. Fu, B. Wang, and G. A. Meehl. 2006. “Spatiotemporal Structures and Mechanisms of the Tropospheric Biennial Oscillation in the Indo-Pacific Warm Ocean Regions.” Journal of Climate 19: 3070–3087.

Lübbecke, J. F., and M. J. McPhaden. 2014. “Assessing the Twenty-First-Century Shift in ENSO Variability in Terms of the Bjerknes Stability Index.” Journal of Climate 27: 2577–2587.

McPhaden, M. J. 2012. “A 21st Century Shift in the Relationship Between ENSO SST and Warm Water Volume Anomalies.” Geophysical Research Letters 39: L09706. doi:10.1029/2012GL051826.

Meehl, G. A. 1987. “The Annual Cycle and Interannual Variability in the Tropical Pacific and Indian Ocean Region.” Monthly Weather Reviews 115: 27–50.

Meehl, G. A. 1993. “A Coupled Air-sea Biennial Mechanism in the Tropical Indian and Pacific Regions: Role of the Ocean.” Journal of Climate 6: 31–41.

Meehl, G. A. 1997. “The South Asian Monsoon and Tropospheric Biennial Oscillation.” Journal of Climate 10: 1921–1943.

Meehl, G. A., and J. M. Arblaster. 2002. “The Tropospheric Biennial Oscillation and Asian–Australian Monsoon Rainfall.” Journal of Climate 15: 722–744.

Meehl, G. A., and J. M. Arblaster. 2011. “Decadal Variability of Asian–Australian Monsoon–ENSO–TBO Relationships.” Journal of Climate 24: 4925–4940.

Meehl, G. A., J. M. Arblaster, and J. Loschinger. 2003. “Coupled-Ocean-Atmosphere Dynamical Processes in Tropical Indian and Pacific Oceans and the TBO.” Journal of Climate 16: 2138–2158.

Pillai, P. A., and K. Mohankumar. 2010. “Effect of Late 1970’s Climate Shift on Tropospheric Biennial Oscillation–Role of Local Indian Ocean Processes on Asian Summer Monsoon.” International Journal of Climatology 30: 509–521.

Rodionov, S. N. 2004. “A Sequential Algorithm for Testing Climate Regime Shifts.” Geophysical Research Letters 31: L09204. doi:10.1029/2004GL019448.

Smith, T. M., R. W. Reynolds, T. C. Peterson, and J. Lawrimore. 2008. “Improvements to NOAA’s Historical Merged Land–Ocean Surface Temperature Analysis (1880–2006).” Journal of Climate 21: 2283–2296.
Wang, R., and H.-L. Ren. 2017. “The Linkage Between Two ENSO Types/Modes and the Interdecadal Changes of ENSO around the Year 2000.” Atmosperic and Oceanic Science Letters 10 (2): 168–174. doi:10.1080/16742834.2016.1258952.

Wang, C., S. K. Lee, and D. B. Enfield. 2008. “Climate Response to Anomalously Large and Small Atlantic Warm Pools during the Summer.” Journal of Climate 21: 2437–2450.

Wu, R. 2008. “Possible Role of the Indian Ocean in the In-Phase Transition of the Indian-to-Australian Summer Monsoon.” Journal of Climate 21: 5727–5741.

Wu, R. 2009. “Possible Role of the Indian Ocean in the Out-of-Phase Transition of the Australian to Indian Summer Monsoon.” Journal of Climate 22: 1834–1849.

Wu, R. 2016. “Possible Roles of Regional SST Anomalies in Long-Term Changes in the Relationship Between the Indian and Australian Summer Monsoon Rainfall.” Theoretical and Applied Climatology 124: 663–677.

Wu, R., and B. P. Kirtman. 2007. “Role of the Indian Ocean in the Biennial Transitions of the Indian summer Monsoon.” Journal of Climate 20: 2147–2164.

Wu, R., and L. Zhang. 2010. “Biennial relationship of rainfall variability between Central America and equatorial South America.” Geophysical Research Letters 37: L08701. doi:10.1029/2010GL042732.

Xie, P., and P. A. Arkin. 1997. “Global Precipitation: A 17-Year Monthly Analysis Based on Gauge Observations, Satellite Estimates, and Numerical Model Outputs.” Bulletin of American Meteorological Society 78: 2539–2558.

Yu, J. Y., S. P. Weng, and J. D. Farrara. 2003. “Ocean Roles in TBO Transition of Indian-Australian Monsoon System.” Journal of Climate 16: 3072–3080.