Sensitivity of South American summer rainfall to tropical Pacific Ocean SST anomalies

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Received 21 September 2010; revised 24 October 2010; accepted 3 November 2010; published 5 January 2011.

[1] A suite of idealised ensemble experiments are used to investigate the sensitivity of the Southern Hemisphere atmospheric circulation to the location of SST anomalies over the tropical Pacific Ocean. Of particular interest is the response of South American rainfall during austral summer. The experiments reveal an approximately opposite response in rainfall over South America when the tropical SST forcing is applied over the western and eastern Pacific Ocean, respectively. The contrasting tropical rainfall conditions are due primarily to the displaced Walker circulation anomalies. Further south, the atmospheric circulation over the South American subtropics is modulated by teleconnection patterns that appear as a wave train. The resulting circulation manifests as an anomalous cyclone over central-eastern South America which in turn leads to a northward displacement of the westerly moisture transport when the SST forcing is located further west. The opposite pattern occurs when the SST forcing is applied to the eastern equatorial Pacific. Citation: Hill, K. J., A. S. Taschetto, and M. H. England (2011), Sensitivity of South American summer rainfall to tropical Pacific Ocean SST anomalies, Geophys. Res. Lett., 38, L01701, doi:10.1029/2010GL045571.

1. Introduction

[2] The tropical Pacific Ocean experiences a range of sea surface temperature (SST) anomalies over a variety of space and time scales. These anomalies can result from both small-scale stochastic processes such as tropical instability waves and weather-scale atmospheric forcing, through to large-scale climate modes of variability such as the El Niño South Oscillation (ENSO). In addition, there are large inter-event variations in the pattern of SST anomalies associated with ENSO phases and ENSO events. There is also the potential for climate change to alter the way that ENSO manifests in SST anomalies over the next century [e.g., Collins et al., 2010, and references therein]. The goal of this study is to evaluate the role of the longitudinal position of tropical Pacific SST anomalies in driving rainfall variations over South America.

[3] ENSO plays a fundamental role in regulating South American climate; for example during El Niño events, enhanced subsidence east of the anomalous Walker circulation suppresses rainfall across northeast Brazil [Ropelewski and Halpert, 1987]. This forms part of a dipole-like precipitation anomaly pattern with increased rainfall further south over subtropical South America, which is commonly seen during El Niño events [e.g., Grimm, 2003]. At these times the summer monsoon is weaker, leading to anomalously dry conditions over the north. It has been suggested that El Niño events also modulate the occurrence of extreme precipitation associated with intense convection in the South Atlantic Convergence Zone (SACZ) by displacing it northward [Carvalho et al., 2002]. In addition, during El Niño, warm moist air from the Amazon basin can be transported from the tropical latitudes to the subtropics along an enhanced northwesterly low-level jet east of the Andes [e.g., Marengo et al., 2004]. The presence of this low-level jet is conducive to enhanced rainfall over the La Plata basin and a weakened SACZ in southeastern Brazil [e.g., Herdies et al., 2002]. During La Niña events the rainfall conditions observed over South America are almost opposite to El Niño [Grimm et al., 2000]. For example, the summer monsoon is enhanced along with the rainfall and convection in the SACZ, while further south over the La Plata basin the rainfall is suppressed.

[4] The current understanding of the impact of different flavors of El Niño on South American rainfall is somewhat more limited. Silva and Ambrizzi [2006] showed observational evidence that the El Niño Modoki event of 2002/2003 displaced the position of the South American low-level jet, resulting in less moisture transport to the south compared to the classical 1997/1998 event. Numerical ensemble experiments forced by the tropical Pacific SST anomalies of these two types of El Niño events also show a northward displacement of the moisture fluxes, modifying the dipole precipitation between the two event types [Hill et al., 2009]. Following on from Hill et al. [2009] this study examines the role of the location of warm tropical Pacific SST anomalies in driving an atmospheric circulation response and rainfall variability over South America during austral summer.

2. Data Analysis and Atmospheric Model

[5] The model employed in this study is the National Centre for Atmospheric Research (NCAR) Community Atmosphere Model (CAM3), configured at T42 horizontal resolution (approximately 2.8° latitude-longitude) with 26 hybrid sigma-pressure vertical levels. For a detailed description of the model see Collins et al. [2006]. Four experiments consisting of a 50 member-ensemble were performed for 12 months, with an idealised +1°C warming anomaly imposed over different regions across the tropical Pacific (see Figure 1a). The SST anomalies were linearly damped to zero over a 10° latitude-longitude band; elsewhere the SST forcing is taken to be the climatological monthly mean. The control experiment is simply a 50 year integration forced by the 12-month climatology of global SST.

[6] The anomaly regions of Figure 1a were not selected to reflect the approximate position of anomalies associated with El Niño, La Niña and El Niño Modoki events. For
instance, one could argue that a better idealised representation of a La Niña event would be a cooling in the eastern Pacific coupled with a warming in the west. Here, the locations merely span the zonal extent of the Pacific Ocean and provide a broad means of comparing the resultant atmospheric circulation and rainfall impacts associated with warm SST anomalies in each region. The imposition of a +1°C warming anomaly is also highly idealised: for example, typical anomalies in the eastern Pacific can be of much larger magnitude than those in the west. Nonetheless, given the goal of this study is to better understand the impact of SST anomalies as a function of geographic location along the tropical Pacific, it is appropriate that a uniform SST anomaly be applied. Where possible, comparison will be made with the climate regime and atmospheric circulation observed during El Niño, La Niña, and El Niño Modoki events, but this is not the central goal of the study. Furthermore the focus of this paper is on austral summer, i.e., December, January and February (DJF), when South America experiences its monsoon season, and when warming events in the Pacific tend to have their greatest impact.

3. Results

[7] Figure 1b compares the simulated rainfall anomalies in the four ensemble experiments, averaged over the tropical...
Pacific (5°N–5°S), while the precipitation anomalies over South America are shown in Figures 1c–1f. The simulated moisture advection is illustrated through the vertically integrated moisture flux and convergence anomalies in Figures 1g–1j. The direct impact on the atmosphere from the tropical SST anomalies is examined via the Walker circulation, which is represented by the 200hPa velocity potential anomalies across the globe (Figure 2, right) and the vertical velocity anomalies across the tropics (Figure 1, right). The Southern Hemisphere low-level circulation anomalies are highlighted in Figure 3 (left), illustrating the 850hPa winds and sea level pressure (SLP) anomalies. The upper level circulation response is indicated by the 200hPa asymmetric streamfunction anomalies (Figure 3, right). As we are interested in both the direct forcing in the tropics (i.e., the Walker circulation anomalies) and the teleconnections into the subtropics (i.e., wave train anomalies) the following analysis will be stratified accordingly.

3.1. Tropical Response

[s] In the two western Pacific experiments (CW_PAC and W_PAC) there is reduced South American rainfall north of the equator and enhanced rainfall south to approximately 20°S (Figures 1c and 1d). These rainfall anomalies result from an enhanced summer-time circulation over the continent, i.e., from the southward progression of the summer monsoon into the Southern Hemisphere. This leaves the far north dry, while south of the Equator convection and precipitation increase, which is typical of La Niña conditions [Grimm, 2003]. The reduced rainfall north of the equator is associated with an anomalous anticyclonic circulation that leads to easterly flux and divergence of moisture over the continent, while to the south increased moisture in the monsoon to easterly flux and divergence of moisture over the continent. This anomalous circulation in the subtropics drives anomalous southeasterly (northerly) moisture flux acting associated with an anomalous southerly (northerly) moisture flux acting over the region and is similar to the classical El Niño response over South America. The winds converge over the northwest coast in this case (Figures 1i and 1j and Figures 3e and 3g) and in turn diverge over northeastern South America, where reduced rainfall occurs. In contrast, the SST anomaly and resultant uplift in the CE_PAC case is located further offshore, drawing with it the strongest subsidence and divergence of moisture. The weaker subsidence over South America allows more of the widespread climatological monsoonal uplift and precipitation to occur to the north, despite the offshore location of the SST anomalies, which can be seen in the plots of vertical velocity (Figure 2g). Further east of the uplift over northeastern South America, the subsidence appears to strengthen, resulting in a rainfall deficit. The velocity potential anomalies in CE_PAC exhibit a double Walker circulation structure (Figures 2e and 2f), which is a feature of El Niño Modoki events [Ashok et al., 2007].

3.2. Subtropical Response

[12] In the subtropics the rainfall anomalies are also opposite in sign between the western and eastern Pacific experiments. When SST warming is applied in the western (eastern) equatorial Pacific Ocean, rainfall is significantly reduced (enhanced) around 30°S, 50°W. These opposing subtropical circulation anomalies seem to be the result of a Pacific South America (PSA) [Mo, 2000, and references therein] teleconnection (Figure 3, right) emanating from the region of warm SST anomalies in the tropical Pacific [Grimm, 2003; Silva and Ambirizzo, 2006; Hill et al., 2009]. The teleconnection structure manifests as a mid-latitude wave train that originates in the upper troposphere by divergent outflow from strong tropical deep convection. This stationary Rossby wave shows an equivalent barotropic pattern seen by the asymmetric streamfunction in the upper troposphere and the low-level circulation anomalies in the southern subtropics (Figure 3). The teleconnection appears to modulate the South American mid-latitude circulation in the western (eastern) Pacific experiments via an anticyclonic (cyclonic) wind anomaly over the region (Figure 3, left). This anomalous circulation in the subtropics drives anomalous southeasterly (northwesterly) moisture flux acting to weaken (strengthen) the northwesterly low-level jet. Consequently, this circulation impacts further north, leading to an enhanced (suppressed) SACZ and higher (lower) precipitation due to the anomalous westerly (easterly) moisture advection.

4. Summary and Conclusions

[13] This study investigates the sensitivity of the circulation over South America to the location of a uniform +1°C
SST anomaly imposed along the tropical Pacific Ocean. In response to the progressive displacement of the SST anomalies across the experiments, the large-scale circulation is also displaced throughout the atmosphere. The shifted circulation anomalies are highlighted by the regions of uplift in the vertical velocity (Figure 2) and by the quadrupole pattern straddling the equator in the 200hPa asymmetric streamfunction anomalies (Figure 3, right), as in the Gill-Matsuno response to diabatic heating imposed on the equator.

Due to the westward location of the SST anomalies in WPAC and CWPAC, these two ensemble sets show similarities to La Niña impacts in terms of the average tropical Pacific response (Figure 1b). Yet both central Pacific experiments (CWPAC and CE PAC) exhibit a more Modoki-like atmospheric circulation across the equatorial Pacific, with a clear double Walker circulation, particularly in the CE PAC case (Figures 2e and 2f). However, the South American rainfall response in the CE PAC and CWPAC experiments is almost opposite in sign, revealing a very different teleconnection to South American rainfall when SST anomalies are applied either side of the dateline. The EPAC case exhibits the most El Niño-like circulation and rainfall response over South America, even though the SST anomaly of +1°C is relatively modest and only extends as far west as 120°W, compared to the dateline in observed intense El Niño events. Finally we note that the difference between the atmospheric response of the WPAC and CWPAC experiments is relatively small, which is due primarily to the sensitivity to the warm underlying SSTs where these two idealised anomalies are applied.

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**Figure 2.** (left) Anomalous velocity potential at 200hPa and (right) anomalous vertical velocity averaged between 5°N–5°S for the (a, b) WPAC, (c, d) CWPAC, (e, f) CE PAC and (g, h) EPAC experiments sets. Units in Figure 2 (left) are 10^6 m^2 s^-1 and 10^-2 m s^-1 in Figure 2 (right). Vertical velocity is upwards for negative values (blue shaded regions). The dashed line indicates statistical significance at the 95% level according to a two-tailed student t-test.
that can occur over the tropical Pacific Ocean during El Niño events. The eastern Pacific can experience much larger variations in SST than the central and western Pacific; for example, the 1997/1998 El Niño saw SST anomalies of up to 2.4°C in the eastern Pacific during DJF. In contrast, the 2002/2003 El Niño Modoki showed average maximum SST anomalies of just 1.2°C over the central Pacific during austral summer. This does not necessarily mean that the impact of Modoki events is, a priori, weaker than traditional ENSO episodes; they can have significant impacts around the globe [e.g., Ashok et al., 2007; Weng et al., 2007; Wang and Hendon, 2007; Taschetto et al., 2009].

Overall the simulated tropical rainfall anomalies over South America reveal a predominantly opposite spatial distribution between the eastern and western Pacific experiments. This is particularly the case for rainfall over eastern South America in the SACZ region. Here, in the WPAC and CW PAC experiments, there is a normal-to-enhanced austral summer circulation, including increased monsoon convection and precipitation plus westerly moisture advection, favouring higher precipitation. In contrast, in the eastern Pacific experiments (CE PAC and EPAC), the monsoon is suppressed with weakened moisture advection into the SACZ region.

Further south in the subtropics the rainfall response also shows a reversal in sign between the WPAC/CW PAC and the CE PAC/EPAC experiments. This anomaly reversal occurs not only due to the modified anomalies in the tropics but it is also enhanced by the modified trajectory of the PSA-like wave train that emanates from the region of maximum SST anomaly in each experiment. This has important implications for interannual rainfall variability over South America.

Figure 3. (left) Anomalous SLP (mb) and 850hPa wind anomalies (m s\(^{-1}\)) and (right) 200hPa asymmetric streamfunction anomalies (m\(^2\) s\(^{-1}\)) for the (a, b) WPAC, (c, d) CW PAC, (e, f) CE PAC and (g, h) EPAC ensemble sets. The dashed line in Figure 3 (right) indicates statistical significance at the 95% level according to a two-tailed student t-test. The maximum anomalous wind vector scale is in m s\(^{-1}\) below Figure 3g.
In addition, there may also be implications, for future climate if global warming results in a non-uniform temperature transformation of the tropical Pacific.

[18] Acknowledgments. This study was supported by the Australian Research Council. The model simulations were conducted on the Australian National Computational Infrastructure (NCI) supercomputing facility.

References

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