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Teleconnections associated with the intensification of the Australian monsoon during El Niño Modoki events

A S Taschetto[1], R J Haarsma[2], A Sen Gupta[1], C C Ummenhofer[1] and M H England[1]

[1] Climate Change Research Centre, University of New South Wales, Sydney, NSW 2052 Australia
[2] Royal Netherlands Meteorological Institute, De Bilt, The Netherlands

E-mail: a.taschetto@unsw.edu.au

Abstract. In this study we investigate the teleconnection between the central-western Pacific sea surface temperature (SST) warming, characteristic of El Niño Modoki events, and Australian rainfall using observations and atmospheric general circulation model experiments. During Modoki events, wet conditions are generally observed over northwestern Australia at the peak of the monsoon season (i.e. January and February) while dry conditions occur in the shoulder-months (i.e. December and March). This results in a shorter but more intense monsoon season over northwestern Australia relative to the climatology. We show that, apart from the well-known displacement of the Walker circulation, the anomalous warming in the central-western equatorial Pacific also induces a westward-propagating disturbance associated with a Gill-type mechanism. This in turn generates an anomalous cyclonic circulation over northwestern Australia that reinforces the climatological mean conditions during the peak of the monsoon season. The anomalous circulation leads to convergence of moisture and increased precipitation over northern Australia. This response, however, only occurs persistently during austral summer when the South Pacific Convergence Zone is climatologically strengthened, phase-locking the Gill-type response to the seasonal cycle. The interaction between the interannual SST variability during El Niño Modoki events and the evolution of the seasonal cycle intensifies deep convection in the central-west Pacific, driving a Gill-type response to diabatic heating. The intensified monsoonal rainfall occurs strongly in February due to the climatological wind conditions that are normally cyclonic over northwestern Australia.

1. Introduction

The sea surface temperature (SST) variability of the tropical Pacific has important implications for climate worldwide, primarily associated with El Niño-Southern Oscillation (ENSO) events. The eastern Pacific warm water associated with El Niño episodes induces an anomalous Walker cell that leads to subsiding air and relative dry conditions over the maritime continent. When the maximum SST warming is located in the central Pacific instead, an anomalous double Walker cell is observed in the troposphere with the joint ascending branch over the warm anomaly and descending branches over the eastern Pacific and the Indonesian region [1]. This "flavour" of El Niño, termed El Niño Modoki, has been associated with climate impacts distinct from conventional El Niño events (e.g., [1, 2, 3, 4]). The Modoki phenomenon has become more frequent than traditional El Niños since the late 1970s [1].

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Over Australia, dry conditions are observed in December and March during El Niño Modoki events [5,6]. In addition, unusually wet conditions occur in northern Australia during the peak of the monsoon season, particularly in February [6]. As the positive rainfall anomaly in February counteracts the negative one in December, analysis of the averaged austral summer season therefore gives a false impression that Modoki does not affect the Australian monsoon. This behaviour is the opposite to that observed during traditional El Niño events and seems to be a robust feature across different datasets (figure 1).

Over northwestern Australia, this bi-modal rainfall anomaly behaviour in austral summer indicates that Modoki events tend to delay the normal monsoon onset and advance the monsoon retreat over the region. Modoki does not necessarily reduce the total amount of rainfall received in the year, but it leads to a rearrangement of the annual precipitation cycle in northwestern Australia, producing a shorter and more intense monsoon season.

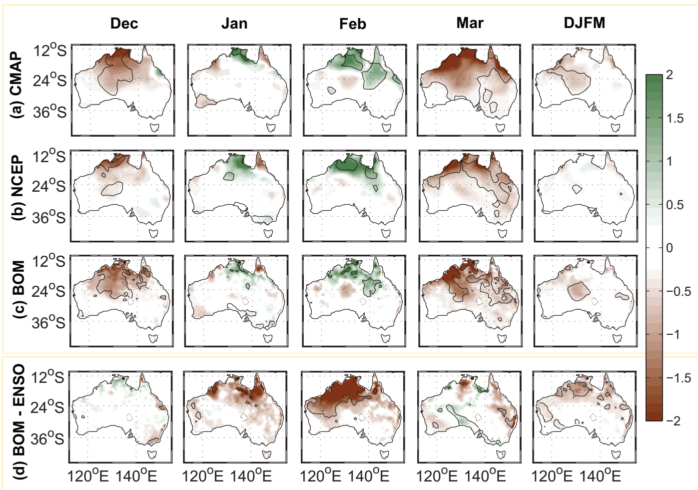

Figure 1. Composites of rainfall anomalies during Modoki (a-c) and conventional El Niño (d) events from December to March and for the December to March (DJFM) average using the (a) CMAP, (b) NCEP/NCAR Reanalysis and (c-d) BOM datasets. Modoki years based on Ashok et al. (2007): 1979/80, 1986/87, 1990/91, 1991/92, 1992/93, 1994/95, 2002/03, 2004/05. El Niño years: 1957/58, 1965/66, 1969/70, 1972/73, 1982/83, 1987/88, 1997/98. Units in mm day^{-1}. Areas within the thin black line are statistically significant at the 90% level according to a two-tailed t-test.

The reason why Australia experiences dry conditions with a warm anomaly in the equatorial Pacific is already known to be due to Walker circulation changes and the anomalous subsiding air that inhibits convection, the formation of clouds and thus reduces rainfall. An explanation for the opposite rainfall response during the peak of the monsoon season has been proposed by [6]. Using observations and numerical experiments, the authors have shown that northwestern Australian rainfall is enhanced in February due to an increase in moisture convergence caused by an anomalous cyclonic circulation over the region. However, the mechanisms responsible for generating the anomalous cyclonic circulation were not established. More recently, [7] suggested that this circulation anomaly is a remote response to anomalous heating in the tropical Pacific as developed in the Gill-Matsuno theory.

In this study we address the physical link between the warm Pacific SST anomalies associated with Modoki events and the anomalous cyclonic circulation that causes enhanced rainfall in northwestern Australia during February. This study complements [7] by considering the mean wind state and by examining the initialization of the air-sea process in the AGCM that leads to a Gill-Matsuno response.

2. Data and methods

2.1. Data sets and climatologies

In this study we use the rainfall datasets from the Australian Bureau of Meteorology (BOM; [8]), the CPC Merged Analysis of Precipitation (CMAP; [9]), and the National Center for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) Reanalysis [10]. In addition, the global SST analysis from the Hadley Centre (HadISST1; [11]), the outgoing longwave radiation

(OLR) from the NOAA Interpolated OLR [12] and horizontal winds from the NCEP/NCAR reanalysis are also used here. The use of different datasets corroborates the analysis of [7] that is based on the NCEP/NCAR Reanalysis only.

We focus our analysis on the period for which more reliable global data exists, and on the period when Modoki events are more frequent, i.e. 1979 to 2006. The El Niño Modoki years used here are the same as those selected by [1]: 1979/80, 1986/87, 1990/91, 1991/92, 1992/93, 1994/95, 2002/03 and 2004/05. The Modoki year starts in June and ends in May of the following year.

2.2. Numerical experiments

A series of four experiments generated with the NCAR Community Atmospheric Model (CAM3) was performed by [6] to test the sensitivity of the Australian rainfall to the location of the SST warming along the equatorial Pacific. Each experiment consisted of 50 members integrated for 12 months. A 1°C anomaly was superimposed onto the SST seasonal cycle around 10°S-10°N over four locations: eastern, central-eastern, central-western and western Pacific. The authors concluded that Australian rainfall is more sensitive to the warm SST anomaly in the central-western Pacific, suggesting that the dateline is a key region for the Modoki forcing. Here we make use of this experiment, hereinafter referred to as the central-western Pacific experiment.

3. Results

3.1. Seasonality of the atmospheric response: Observations

The fact that the northern Australian rainfall anomalies during Modoki events change sign during the peak of the monsoon for the same tropical Pacific SST signature suggests that this response is phase-locked to the mean seasonal cycle. Figure 2(a-f) shows the long-term monthly mean rainfall, the regions with strong convective activity (via low OLR values) and the location of the maximum SST in the southern latitudes. The intensification of the precipitation rate and the broadening of the deep convection in the southern latitudes are most pronounced in January and February, indicating the strengthening of the South Pacific Convergence Zone (SPCZ).

To assess the seasonality of the atmospheric response during Modoki years, we show in figure 2(g-i) the composite seasonal cycle for Modoki years and long-term mean seasonal climatology for the southern tropical Pacific region around the dateline. This region is chosen as it contains the warm SST anomalies in the key central-western Pacific region as suggested by [6], and also because it exhibits strong convective and rainfall responses from the seasonally strengthened SPCZ. Although Modoki events are associated with a statistically significant warming of the SST compared to the mean state, the responses in precipitation and OLR are only significantly different from the climatology from November to February. This demonstrates the seasonality in the interaction between the interannual anomalies from Modoki events and the mean state of the atmosphere.

3.2. The Gill-Matsuno mechanism: Modelled response in February

We assess the simulated atmospheric response to the SST warming in the central-western Pacific for February in figure 3. The positive SST anomaly changes the local surface flux balance via enhanced evaporation. A zone of low pressure forms over the underlying warm waters, driving a convergence of low-level winds over the central-western Pacific (figure 3a).

At the same time the anomalous SST forcing drives additional diabatic heating to the troposphere via enhanced air-sea heat fluxes. In the equatorial regions, any available potential energy generated by diabatic heating is immediately converted to kinetic energy. Therefore, rising motion is also intensified by the convergence of low level winds (via continuity) and by enhanced diabatic heating (via thermodynamics). The anomalous positive vertical velocity transports moisture from the convective mixing layer to the mid troposphere, favouring the development of deep convective clouds.

Deep convection eventually leads to disturbances in the high troposphere generating a Gill-Matsuno-type response [13, 14] in the central-west Pacific and a remote response in the atmosphere via excitation of equatorial waves. The remote response to the SST forcing is seen over Australia with a center of low pressure and anomalous cyclonic circulation (figure 3a). The cyclonic circulation anomaly is also seen in the vertically integrated moisture flux from the surface to 500hPa (figure 3b), indicating anomalous convergence of moisture over northern Australia. The anomalous convergence of moisture and cyclonic circulation enhance the normal atmospheric conditions during the monsoon season over Australia, i.e. a cyclonic circulation in February (figure 2m) and low pressure over the continent, generating intensified convection and increased monsoonal rainfall over the northwest region. Note that only during January and February is the mean circulation cyclonic over northwestern Australia (figure 2l-m). The anomalous cyclonic circulation then reinforces the background state, generating enhanced monsoonal rainfall during the peak of the Australian monsoon.

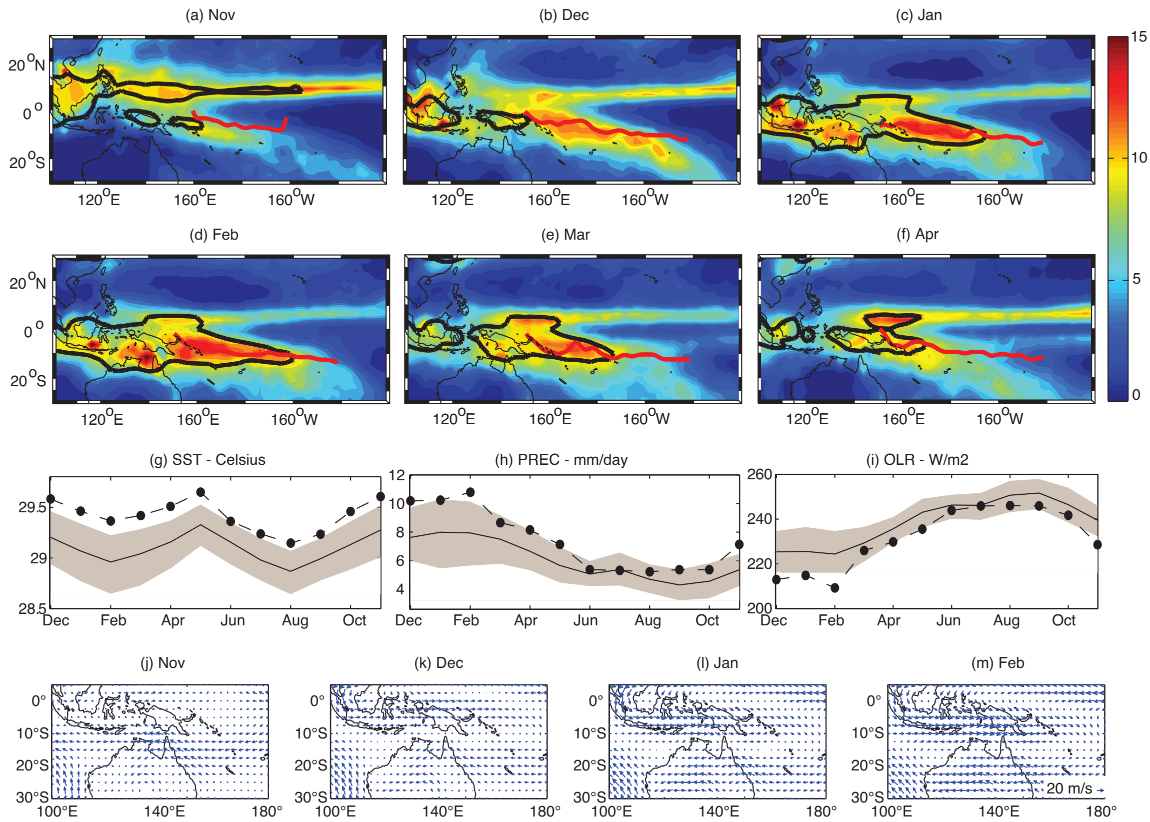

Figure 2. (a-f) Long term monthly mean precipitation (shaded, mm day^{-1}), OLR<220W/m^2 (black line) and maximum SST location (red line, °C) from November to April. (g-i) Annual cycles of SST, precipitation (from CMAP) and OLR based on 1979-2006 mean (solid line) and Modoki years (dashed-circle line) for the averaged southern tropical Pacific region around the dateline, i.e. 0°-10°S, 160°E-160°W. The gray areas represent the 95% confidence level based on a Monte Carlo test. (j-m) Long term monthly mean winds at 850hPa from November to February.

The remote response, based on the Gill-Matsuno theory, is most clearly seen in the simulated streamfunction anomaly fields (figure 3d-e). A horizontal quadrupole vortex structure, consistent with [13], appears at the upper levels of the atmosphere with negative anomaly over Australia. An opposing positive anomaly occurs at low levels over Australia, consistent with the anomalous cyclonic circulation and low sea level pressure anomaly. This indicates a simulated baroclinic response in the tropics during Modoki events. In addition to the return flow west of the heat forcing, the model simulates an anomalous Walker circulation with upward motion in the central-western Pacific in response to the warm equatorial SST (figure 3f). Mass conservation requires a compensating downward motion, which occurs over the Indian Ocean. Interestingly, Australia lies in between the ascending and descending Walker cell anomalies (figure 3f), which allows the Gill return flow to freely influence the rainfall over the continent.

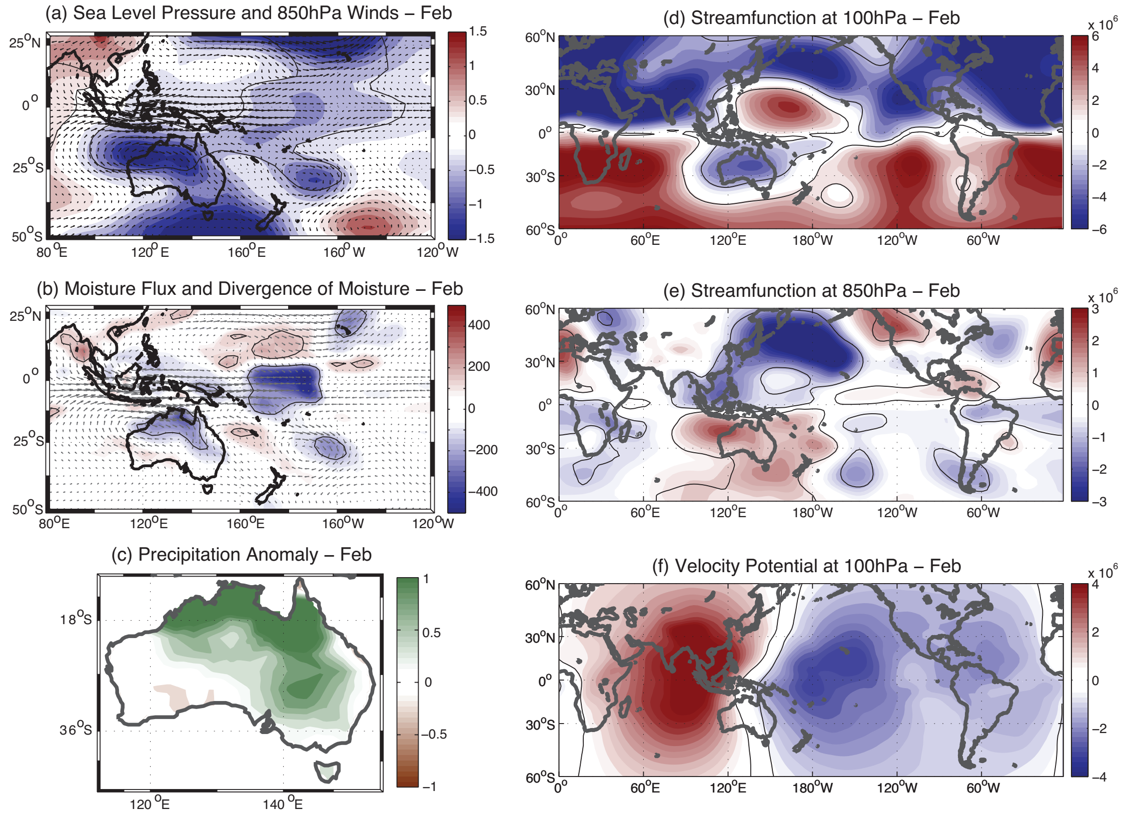

Figure 3. Simulated anomalies in February for the idealized experiment forced with 1°C SST warming in central-western equatorial Pacific (10°S-10°N, 160°E-160°W). (a) Sea level pressure (hPa) and wind anomalies at 850hPa (m s^{-1}). (b) Vertically integrated moisture flux (kg $m^{-1}s^{-1}$) anomaly from the surface to 500hPa and the associated divergence (kg s^{-1}). (c) Precipitation anomaly (mm day^{-1}). (d) Streamfunction anomaly at 100hPa (m^2s^{-1}). (e) Streamfunction anomaly at 850hPa (m^2s^{-1}). (f) Velocity potential anomaly at 100hPa (m^2s^{-1}). Adapted from [7].

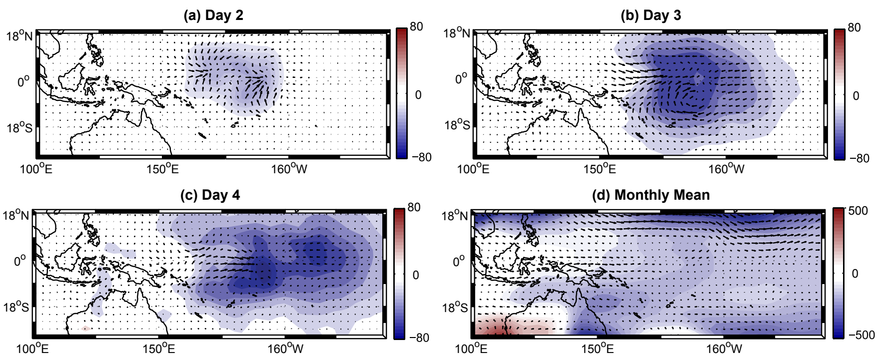

Figure 4. Evolution of the anomalies of sea level pressure and winds at 850hPa on (a) day 2, (b) day 3, (c) day 4, and (d) over 30-60 days average representing the February anomaly.

A preliminary analysis of the daily response to the simulated SST warming in the equatorial Pacific confirms the initialisation of the mechanism described here. Figure 4 shows the sea level pressure and low-level wind anomalies for the first three days of the simulation, after the Modoki-like SST perturbation is superimposed on the surface SST forcing on January 1st. The anomaly plotted in figure 4 is based on a single simulation and as such should be viewed with certain caution. However the response for the first few days is not expected to vary considerably given the predictability of the atmosphere to an initial SST forcing. The 30-60 days mean (representative of February) exhibits a similar solution as that presented in figure 3a based on the 50-member ensemble monthly mean.

4. Conclusions

Northern Australia generally experiences dry conditions during both canonical El Niño and El Niño Modoki events. This results from changes in the Walker circulation that drives anomalous subsidence, weakened convection and reduced rainfall over the continent. However, during El Niño Modoki events, when the location of the maximum SST anomaly is centered on the dateline, at the peak of the monsoon season, an increase in rainfall over northwestern Australia generally occurs. The teleconnection between the warm SST anomaly over the central-western Pacific and the intensified monsoonal rainfall over northwestern Australia can be explained by the Gill-Matsuno theory and the interaction between this interannual response and the climatological mean circulation state.

The short-lived rainfall increase only occurs in January-February phase-locked to the strengthening of the South Pacific Convergence Zone (SPCZ). The intensification of the SPCZ in the southern summer months is conducive to the development of increased deep convection and heavy rainfall in the central-west Pacific. During Modoki years, the warmer than normal SST in the central-west Pacific decreases the local pressure, causing anomalous wind convergence at low levels and a consequent rising motion. In addition, the warm SST anomaly also enhances the supply of latent heat flux to the moist mixing layer. This anomalous configuration during Modoki events, conspires to enhance the convection that occurs during the normal SPCZ intensification during austral summer. Enhanced vertical transport of moisture from the convective mixing layer to the mid troposphere drives intense deep convection over the southern latitudes of the central-western tropical Pacific. Moist convection and enhanced rainfall generates anomalous diabatic heating that eventually leads to disturbances in the high troposphere akin to a Gill-Matsuno-type response. The Gill-Matsuno response is associated with a remote cyclonic circulation over northwestern Australia. The anomalous circulation reinforces the mean cyclonic winds over the region during January and February, thus enhancing the monsoon. As a consequence, there is increased convergence of moisture and enhanced rainfall over the region.

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