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ENSO Modoki impact on the Southern Hemisphere storm track activity during extended austral winter

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[1] Impacts of the recently discovered ENSO Modoki phenomena on extended winter storm track activity in the Southern Hemisphere are examined using the observed rainfall, sea surface temperature, and reanalyzed upper air circulation data for the period 1979–2004. The partial correlation technique is utilized to distinguish the impact of ENSO Modoki events from those of the ENSO and Indian Ocean Dipole (IOD). El Niño Modoki events introduce an anomalous blocking over central eastern Australia, which suppresses the storm track activity from southwest till centraleast, reducing the storm-associated rainfall in southeastern tip and portions of the southeast. On the other hand, the storm track activity in central Argentina is enhanced owing to the strengthened upper air westerlies in this region. The impacts from the ENSO Modoki events are apparently stronger than the individual impacts from the ENSO and IOD events. **Citation:** Ashok, K., C.-Y. Tam, and W.-J. Lee (2009), ENSO Modoki impact on the Southern Hemisphere storm track activity during extended austral winter, *Geophys. Res. Lett.*, *36*, L12705, doi:10.1029/2009GL038847.

1. Introduction

[2] Much of the atmospheric variability in the midlatitudes is associated with the passage of cyclones/anticyclones which arise through baroclinic instability of the mean flow. These synoptic-scale baroclinic eddies propagating along midlatitude storm tracks form an important constituent of the climate system, and act to maintain the extratropical general circulation by transporting zonal angular momentum, sensible heat, and moisture poleward. The winter storms are very important for the midlatitudes of southern hemisphere (SH) [*Trenberth*, 1991; *Lee and Held*, 1993; *Berbery and Vera*, 1996; *Chang*, 1999; *Sinclair*, 1994; *Simmonds and Keay*, 2000; *Rao et al.*, 2002; *Nakamura and Shimpo*, 2004, hereinafter referred to as NS04; *Hoskins and Hodges*, 2005] (see NSO4, *Ashok et al.* [2007a] for associated details) as the rainfall during this season contributes a significant percentage of the annual rainfall in the midlatitudes, particularly in the Australian region where it can reach as much as 65% [*Ashok et al.*, 2003, 2007a]. During extended austral winter, unlike in summer, the main upper-level storm track over the South Pacific forms along the intense subtropical jet (STJ), which is located between 25°S–35°S over the eastern Indian Ocean and western Pacific in the southern hemisphere (see Figure 1a) [*Ashok et al.*, 2007a], with a sub-branch along a subpolar jet further south. In the core region of the STJ over the western Pacific, the eddy amplitude decreases downstream, reaching its minimum over the central Pacific; the associated low-level storm track activity, however, is modest. In addition to the other issue that affects the storm track activity (see NS04), several studies propose that the ENSO events can influence the SH storm track activity by changing the strengths and positions of the STJ and/or the polar frontal jet (PFJ) in response to anomalous convective activity in the Tropics [*Trenberth et al.*, 1998; *Bhaskaran and Mullan*, 2003; *Nakamura et al.*, 2004; *Ashok et al.*, 2007a]. The anomalous convection associated with ENSO can influence the STJ via an anomalous divergent wind [*Sardeshmukh and Hoskins*, 1985], whereas the PFJ tends to be influenced through stationary Rossby waves generated in response to anomalous tropical convection [*Kidson et al.*, 2002]. *Ashok et al.* [2007a], generalizing the 1997 case study of *Nakamura et al.* [2004] to include all ENSOs since late 1970s, show that during an El Niño event, the STJ in extended austral winter (June-October; JJASO, and henceforth referred to as "winter") tends to strengthen substantially, enhancing the jet bifurcation and thereby reducing storm track activity over the midlatitude South Pacific and to the south of Australia. They also show that during a positive Indian Ocean Dipole (IOD) [*Saji et al.*, 1999], the westerlies and storm track activity also tend to weaken over South Australia and portions of New Zealand, and that the impacts of the IOD are relatively more wide-spread in the region in comparison to those from ENSO.

[3] Recently, *Ashok et al.* [2007b] identified a phenomenon in the tropical Pacific, apparently distinct and different from the canonical ENSO [e.g., *Rasmusson and Carpenter*, 1982], which *Ashok et al.* [2007b] name as ENSO Modoki (Pseudo-ENSO). El Niño Modoki (seven events, since 1979, are 1986, 1990, 1991, 1992, 1994, 2002 and 2004), the positive phase, is characterized by warm sea surface temperature anomaly in the central tropical Pacific flanked by colder than normal SSTA on its eastern and western sides. The warmest SSTA persists in the central tropical Pacific instead of amplifying and propagating to the eastern tropics, as in case of canonical El Niños such as that during 1997/98. The Modoki events are seen to occur since 1980s with increased intensity and frequency (see *Ashok et al.* [2007b] for further details). These events also have an anomalous distinct twin-cell Walker circulation structure, with rising motion in the central tropical Pacific that subsides to its east and west, and hence its teleconnections are different from those of canonical ENSO [*Ashok et al.*, 2007b]; the impact of Modoki events are particularly stronger and more widespread in Australia during austral

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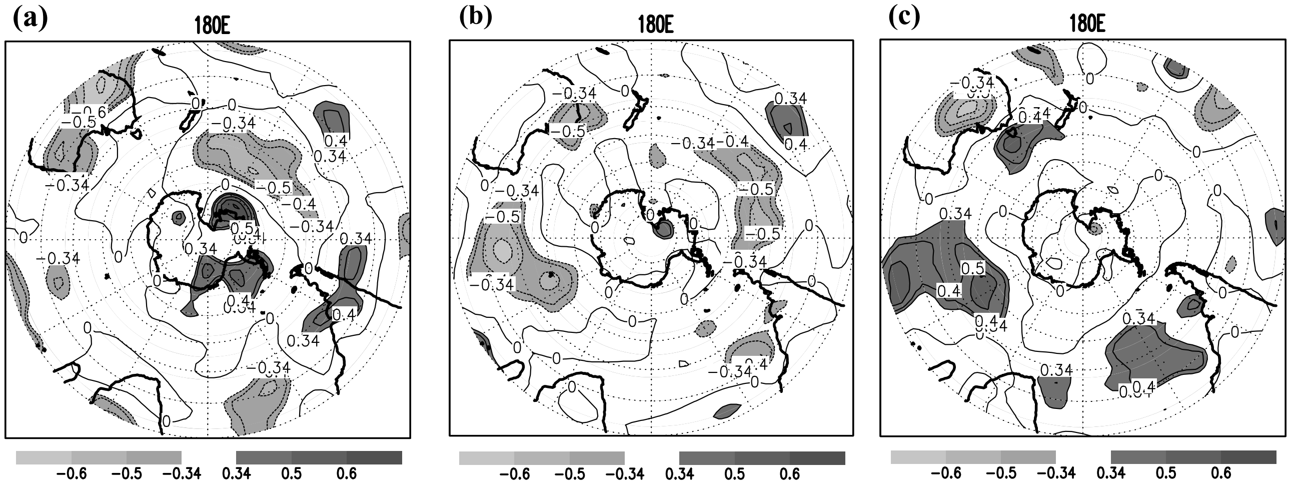

Figure 1. Partial correlations of the storm track index at 300 hPa with (a) EMI, (b) NINO3 index, and (c) IODMI.

winter, and opposite to those of the ENSO in most regions of the American continents [*Ashok et al.*, 2007a, 2009; *Weng et al.*, 2007; *Wang and Hendon*, 2007; *Taschetto and England*, 2009]. *Wang and Hendon* [2007] note that SSTAs in the west-central Pacific are particularly important to Australian rainfall. *Drosdowsky and Chambers* [2001] have also examined the importance of the different modes of the SSTA in tropical Pacific for Australian rainfall.

[4] In this paper, we examine the difference in impacts of the IOD, ENSO and Modoki events on the southern hemisphere winter storm tracks, and propose a possible mechanism for the Modoki impacts.

2. Data and Methodology

[5] In the present study, we use the GPCP's observed rainfall data [*Adler et al.*, 2003] and Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) [*Rayner et al.*, 2003] data. We use the 6-hourly NCEP/NCAR global reanalysis data [*Kalnay et al.*, 1996] to derive systematic storm track statistics for the period 1979–2004. As an index for storm track activity at every grid point, we compute the "envelope function" (Z_e [after *Nakamura and Shimpo*, 2004]), defined as

$$Z_e = \left(\sqrt{2^*\overline{Z'^2}}\right)^*(\sin(45°\mathrm{S})/\sin(\mathrm{latitude})), \quad (1)$$

where Z' denotes the 8-day high-pass-filtered 300-hPa height and the overbar the smoothing with an 8-day low-pass filter. The quantity Z_e thus represents local instantaneous amplitude of 300-hPa height fluctuations with periods shorter than 8 days in terms of geostrophic streamfunction. The monthly anomaly fields are defined as monthly departures from their corresponding climatological-mean fields for a given calendar month for the period of 1979–2004.

[6] In this study, each of the monthly indices and anomaly fields of the atmospheric circulation and precipitation for a particular year is further averaged over a period from JJASO. This period includes early austral spring to capture the robust influence of IOD events that tend to peak in November. The climatological characteristics of storm tracks over the SH Indo-Pacific sector remain qualitatively the same throughout this winter period [*Nakamura and Shimpo*, 2004]. Partial correlation technique is employed to distinguish the respective impacts of the IOD, Modoki, and ENSO by removal of the impacts of the other two [see *Ashok et al.*, 2007b] (see also auxiliary material for details).[1]

[7] The ENSO events are represented by the NINO3 index (area-averaged SSTA over 5°N–5°S, 150°W–90°W). The Indian Ocean Dipole Mode Index (IODMI) is defined as the area-averaged SSTA difference between the tropical western Indian Ocean (50°E–70°E, 10°S–10°N) and the tropical southeastern Indian Ocean (90°E–110°E, 10°S-equator).We have adapted the ENSO Modoki index (EMI) [after *Ashok et al.*, 2007b], as:

$$\mathrm{EMI} = [SSTA_{BOX-A}] - 0.5 * [SSTA_{BOX-B}] - 0.5 * [SSTA_{BOX-C}] \quad (2)$$

[8] The square bracket in equation (2) represents the area-averaged SSTA over each of the regions A (165°E–140°W, 10°S–10°N), B (110°W–70°W, 15°S–5°N), and C (125°E–145°E, 10°S–20°N), respectively. We also use the linearized Rossby Wave Source analysis [*Sardeshmukh and Hoskins*, 1988].

3. Modoki Impacts on Winter Stormtracks

[9] NS04 demonstrate that the STJ with its strongest core at 300 hPa plays an important role in modulating the storm track activity in the South Pacific. Despite its relatively shallow vertical core in westerlies and associated modest storm track activity, the seasonally enhanced winter STJ traps the upper-level eddy activity and makes the association among the midlatitude storm track [*Nakamura and Sampe*, 2002], the PFJ, and the oceanic subarctic frontal

[1]Auxiliary materials are available in the HTML. doi:10.1029/2009GL038847.

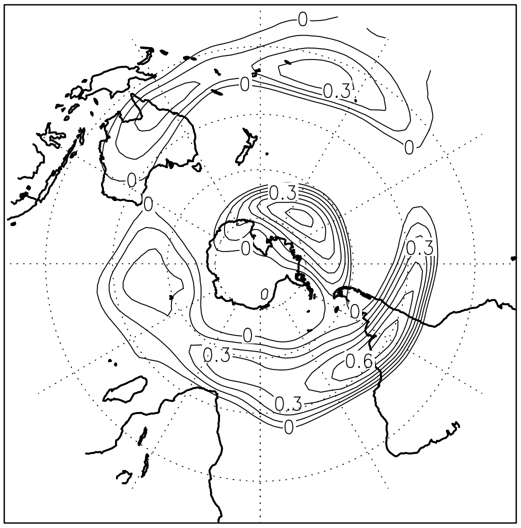

Figure 2. Partial correlations of Z300 with EMI for JJASO.

zone less robust over the Southern Pacific, unlike the case over the South Atlantic and Indian Oceans [*Nakamura et al.*, 2004]. NS04 and *Ashok et al.* [2007a] also show that in the regions of large interannual variability in U_{300} and Z_e, such as those over the midlatitude South Pacific and Atlantic Oceans, the local correlation between the two variables is generally and significantly positive. The correlation is particularly high over the South Pacific and part of the Indian Ocean, and also over the southern rim of continental Australia. Based on these earlier findings, we can speculate that that one plausible way for the Modoki events to influence the winter climate over the midlatitude SH is by influencing the strength of the STJ and thereby the storm track activity.

[10] The winter distribution of the partial correlation between 300-hPa Z_e and the EMI shows (Figure 1a) strong negative correlations in the shape of a large swathe over the Australian continent. It covers southwest Australia, which receives 65% of its annual rainfall in winter- the El Niño Modoki events apparently weaken the stormtrack activity anomalously in this region- and extend northeast through Queensland. Further, the impact on the storm tracks in the continent is broader and stronger in magnitude as compared to those of IOD (Figure 1c), and not limited to Tasmania as in the case of ENSO (Figure 1b). Southeast of New Zealand in the far southern part of the Pacific, the storm tracks are suppressed during the positive ENSO Modoki phase. Interestingly, the El Niño Modoki events are apparently also associated with increased stormtrack activity in the midlatitude South America (Figure 1a), where the relative magnitude of the impacts associated with the other two phenomena is weaker. It is noteworthy that the partial correlation maps of Ze based on the IODMI and NINO3 indices (Figures 1b and 1c) strongly resemble those given in A07a (with a base period of 1979–2003), in which only these latter two indices were used in calculating the partial correlations. This attests to the robustness of the relationships, and implies that each of these Indo-Pacific climate phenomena has its own unique impact on the winter storm tracks in SH.

[11] To obtain an overview of the impact of ENSO Modoki on the time mean circulation during the austral winter, the partial correlation between the winter geopotential height at 300 hPa with the EMI is computed after partialling out the linear correlations with IODMI and NINO3. The result is given in Figure 2, which shows significant positive height field anomalies over a few broad regions in SH: from southwestern to northeastern Australia and extending into subtropical South Pacific, over the Southern Ocean to the south of the Pacific, and in midlatitude South America extending into the South Atlantic and Southern Indian Ocean. It is noteworthy that, over the same Australia region, storm tracks are also suppressed during the positive phase of ENSO Modoki (see Figure 1a). This strongly suggests that during El Niño Modoki events, the

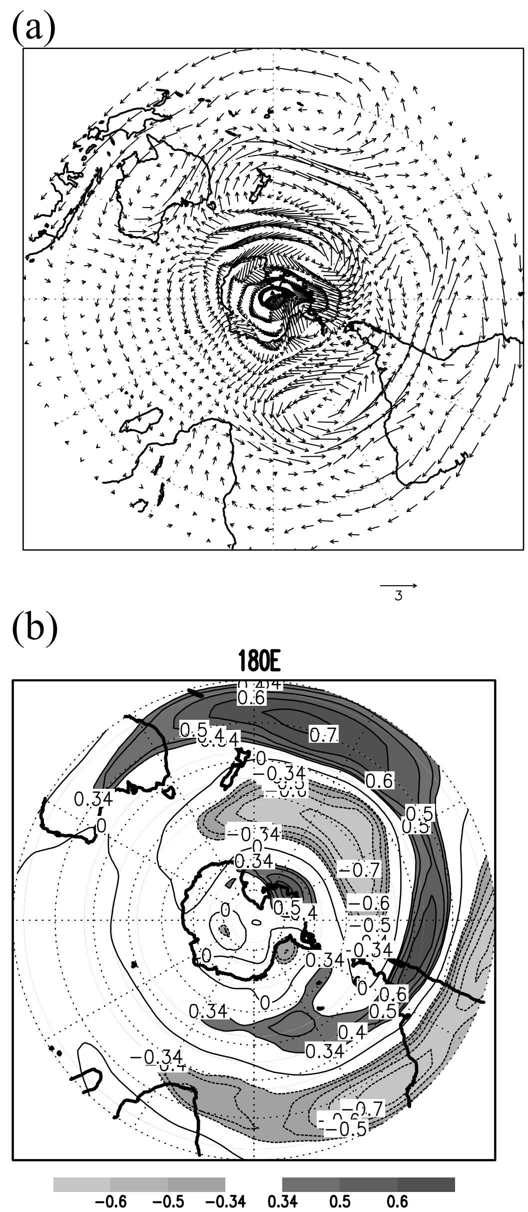

Figure 3. (a) Composite JJASO 300 hPa wind anomalies during the 7 El Niño Modoki events. (b) Same as Figure 2 but with U300 (m/s).

anomalous high pressure system over Australia blocks SH winter storms away from the continent.

[12] To further understand the mechanisms governing the circulation changes during ENSO Modoki events, we have composited the wind anomalies at 300 hPa during 7 El Niño Modoki winters; the typical signature of El Niño Modoki can be seen (Figure 3a) in the tropical Pacific with upper-level anomalous easterlies (westerlies) in tropical western (eastern) Pacific. This is owing to the ascending anomalous vertical velocity in the central tropical Pacific that diverges at upper levels and descends in to the tropical eastern and western Pacific [*Ashok et al.*, 2007b]. An anomalous anticyclone is found over the western Pacific, indicative of an upper-level Gill-type response to anomalous heating in the central to western Pacific [*Gill*, 1980]. Anticyclonic circulation covering the Australian continent can also be discerned. To understand the mechanism sustaining this upper-level ‘‘blocking high’’ over Australia, we have computed the composite divergent wind and (linearized) Rossby wave source over the seven Modoki winters. Inspection of the upper-level flow shows a strong divergence signal over the northwestern Australia (see Figure S1a of the auxiliary material). We suspect that this is induced by the sinking motion over the Borneo region, the latter of which is consistent with suppressed convection in that region. Figure S1b of the auxiliary material confirms that, indeed, the divergent flow leads to strong positive Rossby wave source over western Australia, which is the combined result of anomalous divergence and advection of absolute vorticity by divergent wind. The strong wave source is thus responsible for the large-scale rotational flow over the Australian sector.

[13] It can also be seen that the high pressure systems over Australia and South America (see also Figure 2) act to increase the upper-level westerlies in the subtropics to mid latitudes. The impact of ENSO Modoki on the SH jet streams is illustrated in Figure 3b, which shows the partial correlations of the 300 hPa zonal wind with EMI. Westerly flow is found to be enhanced in the subtropical western Pacific and mid-latitude South America around Argentina, reinforcing the climatological subtropical jet in SH. On the other hand, there is negative zonal wind anomaly over the far southern part of the Pacific during El Nino Modoki. Compared with the partial correlation map of Ze based on EMI (see Figure 1a), it can be seen that the regions of positive zonal wind anomalies over Argentina (negative over South Pacific southeast of New Zealand), are collocated with enhanced (suppressed) storm track activity in the same locations. In other words, the storm tracks in these regions are modulated by ENSO Modoki through its influence on the strength of the local upper-level westerlies, in accordance with linear theory.

[14] To further confirm that El Niño Modokis weaken the winter storm track activities in SH, we define an ENSO-Modoki related storm track index by area-averaging the Z_e over (140°E–150°E, 21°S–35°S), a region where the magnitude of partial correlations between the storm tracks and the EMI is maximum. The partial correlations of this index with the rainfall anomalies during winter, after regressing out the associations with the NINO3 index and IODMI, are compared with similar partial correlations of the EMI with the rainfall anomalies (Figure S2a). The tropical signatures, as expected, show the Modoki signature. Along with this, we can see negative correlations from southwest Australia as well as in Eastern Australia and adjoining regions, which receive significant percentage of annual rainfall during JJASO [*Ashok et al.*, 2007a]. The association between the two sets of significant correlations, particularly in the southwest tip and portions in the southeast where the winter storm track activity in Australia is maximized [NS04; *Ashok et al.*, 2007a], confirms that the El Nino Modoki events weaken the rainfall in these regions of Australia by weakening the storm tracks (also see Figure S2b), except in northeast where the storm track activity is weak.

[15] Similar negative signatures can also be seen in the midlatitude South America, along with positive correlations to immediate south.

4. Concluding Remarks

[16] Using observed rainfall and SST datasets and reanalyzed upper air data for the period 1979–2004, we examine the possible impacts of the recently discovered ENSO Modoki events on the storm track activity in southern hemisphere during austral winter. An anomalous blocking high forms over the Australian continent, likely as part of a Rossby wave train response to anomalous heating in subtropics during the El Niño Modoki events. Due to the presence of this anomalous blocking high, storm track activity over Australia is significantly reduced across the continent from southwest through central east, with rainfall reduction in storm-prone regions of the southwestern trip and portions in southeast. In south America, the storm track activity is anomalously enhanced over central Argentina while further north, in eastern Brazil, a tendency for the storm track activity to weaken is observed during the El Nino Modoki events. The current study is limited by the rather short span of data and any associated potential sampling errors. Nevertheless, as the signatures of the tropical phenomena such as ENSO and IOD on the storm track activity in southern hemisphere are reasonably robust to sampling [*Ashok et al.*, 2007a], and because the impacts of Modoki events, particularly in Australia, are stronger, it is reasonable to assume that the impacts attributed to Modoki are also robust. The robustness issue will be examined through GCM experiments in near future.

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