The unusual summer of 1994 in East Asia: IOD teleconnections

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[1] An extremely hot and dry summer of 1994 was reported in East Asian countries. Using observational data, we have demonstrated that the Indian Ocean Dipole (IOD) is at least one possible cause of the abnormal East Asian summer climate. An anomalous cyclonic circulation over the western Pacific and the southern China weakened the monsoonal northward flow in the lower troposphere. An anomalous anticyclonic circulation with the equivalent barotropic structure around Japan, Korea and the northeastern part of China caused the hot and dry summer of 1994. This accumulation of the lower potential vorticity in the Far East is related to the wave activity from the Mediterranean/Sahara region. The monsoon-desert mechanism connects a Rossby wave source with the IOD-induced diabatic heating around the Bay of Bengal. Another Rossby wave-train pattern was generated in the upper troposphere and propagates northeastward from the southern China. Both the Rossby wave patterns influenced the circulation changes over East Asia. *INDEX TERMS:* 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 9340 Information Related to Geographic Region: Indian Ocean; 9320 Information Related to Geographic Region: Asia; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 1620 Global Change: Climate dynamics (3309); 0312 Atmospheric Composition and Structure: Air/sea constituent fluxes (3339, 4504). **Citation:** Guan, Z., and T. Yamagata, The unusual summer of 1994 in East Asia: IOD teleconnections, *Geophys. Res. Lett.*, *30*(10), 1544, doi:10.1029/2002GL016831, 2003.

1. Introduction

[2] The East Asian summer monsoon has profound economical and societal impacts on the East Asian countries. Anomalous changes in the summer monsoon circulation can lead to either abnormally hot (and dry) or cold (and humid) summer in this region. In 1994, East Asian countries suffered from a record-breaking hot and dry summer climate. *Park and Schubert* [1997] examined the nature of this condition using some assimilated data from 1985 through 1994. Their conclusion is that "the anomalous circulation is primarily the result of an orographic forcing associated with zonal wind changes over Tibet". Here we show that the abnormal 1994 East Asian summer conditions are also related to an ocean-atmosphere coupled signal in the tropical Indian Ocean, which is now called the Indian Ocean Dipole (IOD).

[3] The term IOD was introduced as a basin-wide ocean-atmosphere coupled mode by *Saji et al.* [1999]. The positive IOD event is characterized by the strong positive sea surface temperature anomalies (SSTA) in the tropical western Indian Ocean (50°E–70°E, −10°S–10°N, denoted as region A) and the negative SSTA in the southeastern Indian Ocean (90°E–110°E, 10°S- equator, denoted as region B). An Indian Ocean Dipole Mode Index (IODMI) is defined as the zonal difference of SST anomaly of region A from that of region B. The IOD is seasonally phase-locked and it starts in around April and peaks in October. Studies on the dipole phenomenon using observational data, ocean general circulation models (OGCMs), and ocean-atmosphere coupled general circulation models (CGCMs) have demonstrated that IOD is an ocean-atmosphere coupled phenomenon [*Vinayachandran et al.*, 1999; *Behera et al.*, 1999; *Webster et al.*, 1999; *Iizuka et al.*, 2000; *Feng et al.*, 2001; *Rao et al.*, 2002; *Yamagata et al.*, 2002; *Gualdi et al.*, 2002].

[4] Using the SST data (GISST2.3b) from 1979 through 1999 [*Parker et al.*, 1995], we have calculated the SSTA for June–July–August (JJA) and its standard deviation (σ) for three different tropical regions and the IODMI (Table 1, lower line). The IODMI in 1994 shows the variance reaching about 2.6σ, which indicates that a very strong positive IOD event occurred in the summer of 1994. We also note that the NINO3 region (5°S–5°N, 150°W–90°W) showed the weak negative SST anomaly during summer of 1994.

[5] The IOD event in 1994 continued for more than 8 months from around March through October (not shown). The Indian summer monsoon is significantly influenced by the IOD. This does not exclude the possibility that the Indian summer monsoon influences the IOD during the evolution process. Our AGCM studies demonstrate that surplus summer monsoon rainfall over India can be induced by the IOD SSTA [*Ashok et al.*, 2001]. Using the 'All Indian Rainfall' derived from *in situ* observations [*Parthasarathy et al.*, 1995], it is found that India received good monsoon rainfall during June–July–August of 1994; it amounts to 265 mm per month by a value 19% above the climatological mean.

[6] The Indian summer monsoon system interacts with the tropical Indian Ocean. The East Asian summer monsoon interacts with the Indian summer monsoon via the tropospheric jets, Tibetan high, and the westerly jet stream at about 40°N in the upper troposphere [e.g., *Lau and Li*, 1984; *Liang and Wang*, 1998; *Webster et al.*, 1998; *Wang and Fan*, 1999; *Wang et al.*, 2001; *Lu et al.*, 2002; *Enomoto et al.*, 2003]. When the circulation over South Asia changes anomalously, it is reasonable to expect that the summer monsoon circulation over East Asia will also change accordingly. We here discuss using the reanalysis data the

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Table 1. Averaged JJA SSTA in 1994 and the Standard Deviation From 1979 Through 1999 For Different Tropical Regions

Regions	IODMI	Box A	Box B	NINO3
SSTA	0.90	0.24	−0.65	−0.21
σ	0.35	0.32	0.31	0.85

way in which the atmospheric circulation was influenced by the IOD during the summer of 1994.

2. Anomalous Circulation Features

[7] Using the NCEP/NCAR reanalysis data [*Kalnay et al.*, 1996] from 1979 through 2001 and the CMAP precipitation data from 1979 through 1999 [*Xie and Arkin*, 1996], we have plotted the circulation anomalies during the summer months (JJA) of 1994 (Figures 1 and 2). Large positive air temperature anomalies are found over the northeastern and eastern China, Korea, and Japan in 1994 summer (Figure 1a). Some positive anomalies are also found above the Kuroshio Extension in the northwestern Pacific. The anomaly of thickness between 200 hPa and 850 hPa isobaric surfaces is also positive (not shown), indicating that the temperature of the air column is anomalouly high. Strong negative precipitation anomalies were observed in East Asia during summer of 1994 (Figure 1b). Water vapor anomalously diverges from this region, leading to a severe drought condition. This agrees well with those in *Park and Schubert* [1997]. It is known that this northeastern part of Asia was covered during the summer of 1994 by an anomalous anticyclonic circulation in the lower troposphere. The anomalous circulation can also be found in the upper troposphere over this region (Figure 2a), showing its equivalent barotropic structure. On the other hand, we find an anomalous cyclonic circulation elongating westward from the tropical western Pacific to the southern part of China (Figure 1a). This circulation facilitates the surplus rainfall in this region (Figure 1b) but it weakens the moist monsoonal southerly wind that blows northward from the Bay of Bengal and the South China Sea to the eastern part of China, Korea and Japan.

[8] The above anomalous cyclonic circulation along with the intensified monsoon trough over India appears to be linked directly with the tropical IOD event. As seen in Figure 1b, the distinctive IOD structure over the tropical Indian Ocean is manifested in rainfall anomalies (Figure 1b) and also in the velocity potential field (Figure 2b). The water vapor converges into the western Indian Ocean (Figure 1b), while it diverges in the southeastern Indian Ocean. An anomalous meridional circulation associated with the IOD connects the anomalous decent branch over the southeastern Indian Ocean and the anomalous ascent branch at about 20°N, as simulated by *Ashok et al.* [2001]. More precisely, the anomalous northwestward low-level winds from the eastern pole of the IOD reaches the Peninsula of India and then turns eastward (Figure 1a). Since just the opposite winds are seen in the upper troposphere (Figure 2a, 2b), the wind field in the tropics has a baroclinic structure. These results are in agreement with other results obtained from both data analysis and AGCM studies [*Behera et al.*, 1999; *Ashok et al.*, 2001].

3. Teleconnection Mechanisms

[9] The precipitation over India and the southern part of China is enhanced during the positive IOD event (Figure 1b). This rainfall-IOD connection is also reported in *Ashok et al.* [2001]. The northward branch of the meridional circulation excited by the eastern pole of the positive IOD leads to the anomalous updraft and the associated divergent flow in the upper troposphere over the Tibetan Plateau (Figure 2). This divergent flow emanating from India, the Bay of Bengal and the southern part of China acts as anomalous vorticity source in the upper troposphere (Figure 2b). To the northwest of this vorticity source region at 150 hPa, we observe an anticyclonic circulation (Figure 2a), which is generated as a result of the atmospheric response to the anomalous vorticity source as discussed by *Sardeshmukh and Hoskins* [1988] using a simple model.

[10] An anomalous cyclonic circulation to the east of the vorticity source region is also found (Figure 2a). A Rossby wave train is excited by the vorticity source (the divergent flow), propagating northeastward from the southern China. This pattern is reminiscent of the Pacific-Japan (PJ) teleconnection pattern as put forward by *Nitta* [1987] but the location is a little shifted westward in the present case.

[11] The IOD-induced divergent flow in the upper troposphere near India also progresses westward and converges over the Mediterranean/Sahara region (Figure 2b). The zonal section averaged between 25°N and 35°N captures the vertical circulation (Figure 2c); the anomalous convection over India, which is induced by the IOD SSTA, is linked to the anomalous decent in the Mediterranean/Sahara region, as expected by *Rodwell and Hoskins* [1996] in a somewhat different context.

[12] To examine mechanisms behind the above circulation changes in more detail, we show in Figure 3 the heat budget anomalies during the summer of 1994 in terms of thermodynamic equation. Over the northern as well as eastern part of China, the anomalous diabatic heating is responsible for the abnormally hot summer (Figure 3c). Over Japan and Korea, however, the dynamic heating due to the anomalous descent of air is dominant, which cancels the anomalous negative horizontal advection of temperature. Around the Sea of Okhotsk, the anomalous positive horizontal advection of temperature balances the dynamic cooling (Figure 3b). The observed diabatic cooling around Japan and the Sea of Okhotsk suggests that the strong positive SSTA around Japan in 1994 (not shown) is not the primary cause of the hot summer. Rather, it is the result of the hot and dry summer condition although it may have feedback to the circulation

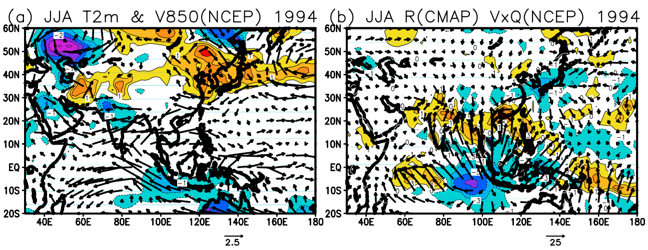

Figure 1. (a) The JJA mean anomalous air temperature at 2 m above the earth surface (contour intervals: 0.5°C), along with the wind at 850 hPa (in $m \cdot s^{-1}$) during 1994. (b) The anomalous precipitation (contour intervals: 1 $mm \cdot d^{-1}$) and the anomalous water vapor flux (in $Kg \cdot m^{-1} \cdot s^{-1}$) which is vertically integrated from the earth surface up to 300 hPa (shown with vectors).

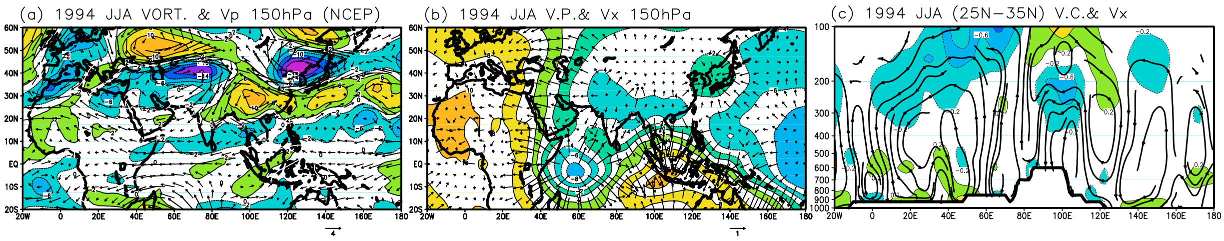

Figure 2. (a) JJA mean anomalous vorticity (to be multiplied by $1 \times 10^{-6}\ s^{-1}$) along with the rotational wind ($m \cdot s^{-1}$) at 150 hPa in 1994. (b) JJA mean velocity potential along with the divergent wind ($m \cdot s^{-1}$) at 150 hPa in 1994. The contour interval is $4 \times 10^{-5}\ m^2 \cdot s^{-1}$. (c) JJA mean zonal-vertical circulation averaged over (25°N–35°N). The contours denote the zonal component of the divergent wind with contour interval of $0.2\ m \cdot s^{-1}$.

changes in these regions. We note that the present results are in agreement with *Park and Schubert* [1997].

[13] Over India and the Bay of Bengal, the net anomalous diabatic heating is found (Figure 3c), which balances the negative anomalies of dynamic cooling due to the anomalous upward motion (Figure 3b). On the other hand, the net diabatic cooling is found over the Mediterranean/Sahara region (Figure 3c). The negative anomalies of the horizontal advection of temperature are also found in this region (Figure 3a). Both the diabatic and dynamic cooling are compensated by the anomalous dynamic heating due to the decent of air. Based on this heat budget diagnosis along with the vertical circulation shown in Figure 2c, the relationship between the IOD/monsoon and the anomalous circulation changes over the Mediterranean/Sahara region can be established. The present view confirms the monsoon-desert mechanism put forward by *Rodwell and Hoskins* [1996]; they suggested that the diabatic heating due to convective activities in the Indian region could induce an anticyclonic Rossby wave pattern that covers west Asia and northern part of Africa. The adiabatic decent induced by the remote thermal forcing from the Asian summer monsoon intensifies the decent induced by radiative cooling over the Mediterranean/Sahara region.

[14] The IOD-induced dynamic warming due to the decent of the air over the Mediterranean/Sahara region and its vicinity must steadily perturb the mid-latitude westerly. The lateral adiabatic cooling as manifested by the Maestro and Etesian may also generate disturbances. Since the mid-latitude westerly acts as a Rossby waveguide [*Hoskins and Ambrizzi*, 1993], the wave energy propagates along the westerly eastward to East Asia, periodically intensifying the aforementioned anomalous anticyclonic and cyclonic circulations around East Asia and the Western Pacific (Figure 2a). This scenario can be properly checked by examining the wave activity flux (WAF) introduced by *Plumb* [1986]. Figure 4a actually shows that the wave activity fluxes at 200 hPa are much larger along the Asian westerly jet than those over other regions. The WAF converges around the Sea of Japan, indicating the accumulation of wave energy in this area. The longitude-height cross-section (Figure 4b) shows that the anomalous wave energy propagates upward into the upper troposphere around the regions of the Mediterranean Sea, the Caspian Sea, and the East Asia (around 120°E) along the westerly jet stream. To the north of the Asian jet, we observe very weak Rossby wave propagation; this suggests that the 1994 East Asian summer climate is not directly related to variations in higher latitudes. The upward propagating wave energy in the eastern flank of the Tibetan Plateau (around 120°E) suggests that orographic forcing also plays an important role in 1994, as suggested by *Park and Schubert* [1997].

4. Summary

[15] We have examined the East Asian summer climate condition in 1994 condition using the NCEP/NCAR reanalysis data. Main results can be summarized as follows.

[16] The anomalous anticyclonic circulation over Japan, Korea, the eastern as well as northeastern part of China was associated with the abnormally hot and dry summer in 1994. The anomalous cyclonic circulation over the southern part of China and the western Pacific weakened the monsoonal northward wind from the Bay of Bengal, the South China

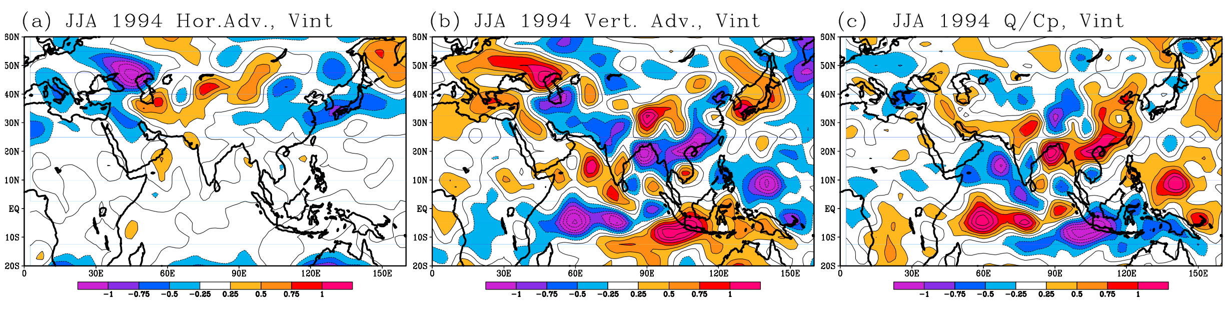

Figure 3. JJA mean vertically integrated quantities for 1994. (a) The anomalous horizontal advection of temperature, (b) the anomalous vertical advection of potential temperature, and (c) the anomalous diabatic heating rate. All these quantities are vertically averaged over pressure from surface to 100 hPa. The unit is $°C \cdot d^{-1}$.

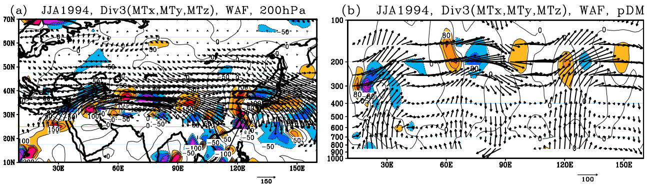

Figure 4. (a) The wave-activity flux (in $m^2 \cdot s^{-2}$) along with the 3-dimensional divergence (to be multiplied by 1.0×10^{-6} $m \cdot s^{-2}$) at 200 hPa. (b) The wave-activity flux and the 3-dimensional divergence in zonal-vertical section, which have been averaged over (35°N–45°N). The vertical component of wave-activity flux is arbitrarily enlarged before plotting. The high frequency components in the time-series have been removed by using a 5-day running mean. Shown in red is for positive values while in blue for negative values.

Sea, and the tropical Western Pacific, preventing the subtropical East Asia from receiving the normal water vapor from the tropical regions. The anomalously hot summer climate over East Asia is explained as a result from the anomalous dynamic heating around Japan, and diabatic heating over the northeastern as well as eastern part of China.

[17] The IOD induced the circulation changes over East Asia during the summer of 1994 at least in two ways. One is that a Rossby wavetrain was excited in the upper troposphere by the IOD-induced vorticity source (the divergent flow) over India, the Bay of Bengal, and the southern China. The wavetrain propagates northeastward from the southern part of China. This pattern looks similar to the PJ teleconnection pattern described by *Nitta* [1987]. Another is that the IOD-induced diabatic heating around India and the Bay of Bengal excited a Rossby wave pattern to the west of the heating. Through the Monsoon-desert mechanism proposed by *Rodwell and Hoskins* [1996], the circulation change over the Mediterranean/Sahara region is linked to the IOD/monsoon variations. The westerly jet acts as a wave-guide to link this circulation change around the Mediterranean Sea with the anomalous circulation change over East Asia. This connection may be called the "Silk Road process" as discussed by *Enomoto et al.* [2003] for explaining the formation of the equivalent barotropic 'Bonin High'.

[18] We also note that the East Asian summer climate was influenced by the IOD during other typical IOD years such as 1961 in a similar way. Besides the IOD, some other factors possibly affected the East Asian summer climate conditions in 1994. *Park and Schubert* [1997] suggest that the anomalous circulation in East Asia is primarily the result of an orographic forcing associated with zonal wind changes over Tibet. They also suggest that the local high SSTA around Japan might have feedback to the circulation changes during summer of 1994. Moreover, the East Asian summer climate could also be influenced by the SSTA in the central equatorial Pacific through atmospheric circulation changes. All those possibilities deserve further investigations.

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References

Ashok, K., Z. Guan, and T. Yamagata, Impact of the Indian Ocean Dipole on the Decadal Relationship between the Indian Monsoon Rainfall and ENSO, *Geophys. Res. Lett.*, *28*, 4499–4502, 2001.

Behera, S. K., R. Krishnan, and T. Yamagata, Unusual Ocean-Atmosphere conditions in the tropical Indian Ocean during 1994, *Geophys. Res. Lett.*, *26*, 3001–3004, 1999.

Enomoto, T., B. J. Hoskins, and Y. Matsuda, The formation of the Bonin high in August, *Q. J. R. Meteorol. Soc.*, *587*, 157–178, 2003.

Feng, M., M. Gary, and W. Susan, Interannual upper ocean variability in the tropical Indian Ocean, *Geophys. Res. Lett.*, *28*, 4151–4154, 2001.

Gualdi, S., E. Guilyardi, A. Navarra, S. Masina, and P. Delecluse, The interannual variability in the tropical Indian Ocean as simulated by a coupled GCM, *Climate Dynamics*, accepted, 2002.

Hoskins, B. J., and T. Ambrizzi, Rossby wave propagation on a realistic longitudinally varying flow, *J. Atmos. Sci.*, *38*, 1179–1196, 1993.

Iizuka, S., T. Matsuura, and T. Yamagata, The Indian Ocean SST dipole simulated in a coupled general circulation model, *Geophys. Res. Lett.*, *27*, 3369–3372, 2000.

Kalnay, E., et al., The NCEP/NCAR 40 year Reanalysis Project, *Bull. Amer. Meteorol. Soc.*, *77*, 437–471, 1996.

Lau, K.-M., and M.-T. Li, The monsoon of East Asia and its global associations-A survey, *Bull. Amer. Meteorol. Soc.*, *65*, 114–125, 1984.

Liang, X.-Z., and W.-C. Wang, Associations between China monsoon rainfall and tropospheric jets, *Q. J. R. Meteorol. Soc.*, *124*, 2597–2623, 1998.

Lu, R.-Y., J.-H. OH, and B.-J. Kim, A teleconnection pattern in upper-level meridional wind over the North African and Eurasian continent in summer, *Tellus*, *54A*, 44–55, 2002.

Nitta, T., Convective activities in the tropical Western Pacific and their impact on the Northern Hemisphere summer circulation, *J. Meteorol. Soc. Japan*, *65*, 373–390, 1987.

Park, C.-K., and S. D. Schubert, On the nature of the 1994 East Asian summer drought, *J. Clim.*, *10*, 1056–1070, 1997.

Parker, D. E., C. K. Folland, and M. Jackson, Marine surface temperature: Observed variations and data requirements, *Climate Change*, *31*, 559–600, 1995.

Parthasarathy, B., A. A. Munot, and D. R. Kotawale, Monthly and seasonal rainfall series for all-India homogeneous regions and Meteorological subdivisions: 1871–1994, *Res. Rep. No. 65*, (Indian Institute of Tropical Meteorology, Pune, India, 1995), 1995.

Plumb, R. A., Three-dimensional propagation of transient quasi-geostrophic eddies and its relationship with the eddy forcing of the time-mean flow, *J. Atmos. Sci.*, *43*, 1657–1678, 1986.

Rao, S. A., S. K. Behera, Y. Masumoto, and T. Yamagata, Interannual subsurface variability in the tropical Inidan Ocean with a special emphasis on the Indian Ocean dipole, *Deep Sea Res. II*, *49*, 1549–1572, 2002.

Rodwell, M. J., and B. J. Hoskins, Monsoons and the dynamics of deserts, *Q. J. R. Meteorol. Soc.*, *122*, 1385–1404, 1996.

Saji, N. H., B. N. Goswami, P. N. Vinayachandran, and T. Yamagata, A dipole mode in the tropical Indian Ocean, *Nature*, *401*, 360–363, 1999.

Sardeshmukh, P. D., and B. J. Hoskins, The generation of global rotational flow by steady idealized tropical divergence, *J. Atmos. Sci.*, *45*, 1228–1251, 1988.

Vinayachandran, P. N., N. H. Saji, and T. Yamagata, Response of the equatorial Indian Ocean to an anomalous wind event during 1994, *Geophys. Res. Lett.*, *26*, 1613–1616, 1999.

Yamagata, T., S. K. Behera, S. A. Rao, Z. Guan, K. Ashok, and N. H. Saji, The Indian Ocean dipole: A physical entity, *CLIVAR EXCHANGES*, *24*, 1–6, 2002.

Wang, B., and Z. Fan, Choice of South Asian summer monsoon indices, *Bull. Amer. Meteorol. Soc.*, *80*, 629–638, 1999.

Wang, B., R. Wu, and K.-M. Lau, Interannual variability of the Asian summer monsoon: Contrasts between the Indian and the Western North Pacific-East Asian monsoons, *J. Clim.*, *14*, 4073–4090, 2001.

Webster, P. J., V. O. Magana, T. N. Palmer, J. Shukla, R. A. Tomas, M. Yanai, and T. Yasunari, Monsoons: Processes, predictability, and the prospects of prediction, *J. Geophys. Res.*, *103*(C7), 14,451–14,510, 1998.

Webster, P. J., A. Moore, J. Loschnigg, and M. Leban, Coupled ocean-atmosphere dynamics in the Indian Ocean during 1997–98, *Nature*, *40*, 356–360, 1999.

Xie, P., and P. A. Arkin, Analyses of global monthly precipitation using gauge observations, satellite estimates and numerical model predictions, *J. Climate*, *9*, 840–858, 1996.

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