The Leading Pattern of Intraseasonal and Interannual Indian Ocean Precipitation Variability and Its Relationship with Asian Circulation during the Boreal Cold Season

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ABSTRACT

The leading pattern of precipitation for the Indian Ocean, one of the most intense areas of rainfall on the globe, is calculated for November–April 1979–2008. The associated regional circulation and thermodynamic forcing of precipitation over Asia are examined at both intraseasonal and interannual time scales. The leading pattern is determined using both empirical orthogonal function analysis of monthly precipitation data and a closely related index of daily outgoing longwave radiation filtered into intraseasonal (33–105 days) and interannual (greater than 105 days) components.

The leading pattern has a maximum in the tropical eastern Indian Ocean, and is closely associated with the Madden–Julian oscillation at intraseasonal time scales and related to the El Niño–Southern Oscillation at interannual time scales. Both time scales are associated with baroclinic Gill–Matsuno-like circulation responses extending over southern Asia, but the interannual component also has a strong equivalent barotropic circulation. Thermodynamically, both time scales are associated with cold temperature advection and subsidence over southwest Asia, with advection of the mean temperature by the anomalous wind more important at lower and midlevels and advection of the anomalous temperature by the mean wind more important at upper levels.

For individual months, the intraseasonal variability can overwhelm the interannual variability. Enhanced Indian Ocean convection persisted for almost the entire 2007/08 season in association with severe drought over southwest Asia, but a strong intraseasonal signal in January 2008 reversed the pattern, resulting in damaging floods in the midst of drought.

1. Introduction

Deep tropical convection during November through April over the Indian Ocean results in some of Earth’s most intense rainfall (Xie and Arkin 1997; Adler et al. 2003). Latent heat release associated with deep tropical convection is a main driver of the global climate (Dickinson 1971a,b; Schneider 1977; Schneider and Lindzen 1977) and is capable of exciting large-scale stationary wave responses (Sardeshmukh and Hoskins 1988; Ting and Sardeshmukh 1993). Here we examine the leading pattern of Indian Ocean precipitation and the associated atmospheric circulation and thermodynamic influence over southern Asia at both intraseasonal and interannual time scales.

Some aspects of both intraseasonal and interannual precipitation over the Indo-Pacific region have been analyzed in considerable detail. The Indian and west Pacific Oceans are regions of strong precipitation activity on intraseasonal time scales during boreal winter (Wang and Rui 1990), and much of this precipitation is associated with the Madden–Julian oscillation (MJO) (Madden and Julian 1994; Ting and Sardeshmukh 1993). Here we examine the leading pattern of Indian Ocean precipitation and the associated atmospheric circulation and thermodynamic influence over southern Asia at both intraseasonal and interannual time scales.

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convection over the Indian Ocean, Maritime Continent, and west Pacific Ocean had the strongest variation relative to the rest of the globe based on the standard deviation of outgoing longwave radiation (OLR). The convective centers over these regions propagated eastward at a phase speed of 4°–5° of longitude per day. Lyons (1981) also showed a spatially coherent out-of-phase relationship, referred to as a “seesaw,” between convection over the Maritime Continent and an area including the eastern Indian and west Pacific Oceans, by correlating OLR at representative points over the regions, which has since been further examined (e.g., Murakami 1980; Lau and Chan 1988; Ferranti et al. 1990; Zhu and Wang 1993). The leading pattern of boreal cold-season intraseasonal convection (e.g., Lau and Chan 1988; Ferranti et al. 1990; Hendon et al. 1999) over both the Indian and Pacific basins together is concentrated in two areas. The first area is located over the eastern Indian Ocean and extends along the western edge of the Maritime Continent, and the second area is located over the west Pacific Ocean. The leading patterns of boreal cold-season interannual convection (e.g., Chelliah and Arkin 1992; Nigam and Shen 1993; Kidson et al. 2002) over the Indian and Pacific Oceans during the Northern Hemisphere cool season is concentrated in two areas, the Maritime Continent and the central Pacific Ocean, and is closely related to El Niño–Southern Oscillation (ENSO). Previous work for boreal winter has generally focused on the Indian and Pacific basins together. The leading pattern for the Indian Ocean alone, and the degree to which it is independent from the Pacific, has not yet been established.

Aspects of the links between South Asian circulation and Indian Ocean precipitation on intraseasonal and interannual time scales, as well as the thermodynamic budget on the intraseasonal time scale, have also been investigated. Early studies relating Asian circulation and Indo-Pacific convection during boreal winter were primarily performed on subseasonal time scales. The results of Liebmann (1987) showed that anticyclonic circulation over southwest Asia occurred during times of Maritime Continent convection through the correlation of OLR with upper-tropospheric wind data on subseasonal time scales. Beneath the anticyclonic circulation over southwest Asia, there is an out-of-phase relationship between Maritime Continent convection and west Asia convection as in seen Lau and Chan (1983) using OLR, and Chang and Lum (1985) using velocity potential during the 1983/84 season. In addition, the results of Lau and Boyle (1987) showed that extratropical circulations responded most to convection and heating over the Maritime Continent. More recently, stationary wave responses over Asia associated with Indo-Pacific convection have been studied using idealized global climate model experiments (Barlow et al. 2007), a linear model (Barlow et al. 2002), observational analysis during La Niña periods (Barlow et al. 2002; Mariotti 2007), MJO episodes (Barlow et al. 2005; Barlow 2012), and on decadal time scales (Meehl and Hu 2006). Associated with the MJO-related (intra-seasonal) convection over the tropical Indian Ocean, baroclinic stationary Rossby waves interact with the mean midtropospheric flow, resulting in thermodynamically forced subsidence and suppressed precipitation (Barlow et al. 2005, 2007) over the region centered over Afghanistan, Pakistan, and Iran (southwest Asia), consistent with the Rodwell–Hoskins hypothesis (Rodwell and Hoskins 1996, 2001). On interannual time scales, Kidson et al. (2002) found that the Pacific–North America pattern (Wallace and Gutzler 1981) and Asian Rossby wave responses are related to the leading patterns of Indo-Pacific convection. However, the relationship between the thermodynamic budget over Asia and the leading Indian Ocean convection at interannual time scales, as well as a comparison between interannual and intraseasonal Indian Ocean convection patterns, has not been performed.

Prolonged periods of suppressed wintertime precipitation over southwest Asia have a severe influence on yearly water supplies and crop harvests. Southwest Asia is a water-scarce region (Oki and Kanae 2006) and drought conditions have an increased potential to cause loss of life and property, requiring outside aid to the affected societies (Agrawala et al. 2001; Barlow et al. 2006). Drought periods during 1999–2001 (Barlow et al. 2002; Hoerling and Kumar 2003) and during 2007/08 have not only influenced water supplies, food supplies through crop growing, and quality of life, but also have contributed to decreased national security, particularly in Afghanistan, where the Taliban have an influence (Gall 2008). Southwest Asia is defined here as the region 20°–40°N, 40°–80°E (e.g., boxed region of Fig. 5), similar to Barlow et al. (2005), but modified slightly to reflect the relationship between Asian circulation and Indian Ocean precipitation variability (described in section 4); 74% of the yearly average precipitation falls during the boreal cold season over the western portions of southwest Asia (20°–40°N, 40°–70°E), using 1979–2008 as the climatology period. Wintertime southwest Asia precipitation is generally associated with eastward-moving synoptic storms through the region (Martyn 1992) associated with the subtropical upper-tropospheric westerlies (Krishnamurti 1961) overhead. In contrast, May–October is quite dry over most of southwest Asia, particularly during May and October, which only contribute 4.0% and 4.8% of the yearly average precipitation, respectively. Previous work has suggested potential predictability at
both intraseasonal (Barlow et al. 2005) and interannual time scales for precipitation (Tippett et al. 2003, 2005) and for river flows and vegetation (Barlow and Tippett 2008) in the region.

While the MJO and ENSO contributions to Indian Ocean precipitation and associated circulation have been studied in some detail, so far the analysis of patterns has largely been done for the much larger Indo-Pacific domain, and the leading pattern for the Indian Ocean alone is not yet known, as well as the relative importance of the two time scales. Both time scales of variability have been shown to influence precipitation over southwest Asia. For the MJO, the thermodynamic mechanisms appear to be important, but for ENSO and related interannual variability, the thermodynamic influence has not yet been examined. Here, we explore the leading precipitation pattern solely over the Indian Ocean and its intraseasonal and interannual contributions during the boreal cold season of November through April for the years of 1979–2008. EEOF analysis is used to determine the leading pattern of Indian Ocean monthly precipitation, and its intraseasonal and interannual contributions are obtained through filtering a related daily OLR-based index for periods of 33–105 days and greater than 105 days, respectively. Over Asia, we examine the circulation and thermodynamic forcing of precipitation in relation to the leading patterns of Indian Ocean precipitation and their intraseasonal and interannual contributions. The three-dimensional circulation and thermodynamic budget are also examined in terms of the interaction of anomalous features during intraseasonal and interannual convection periods with the mean climate. The data used are described in section 2. The leading pattern of Indian Ocean precipitation and its relationship with precipitation over southwest Asia is investigated in section 3. The associated three-dimensional circulation and thermodynamic budget at both intraseasonal and interannual time scales are examined in section 4. A summary is provided in section 5.

2. Data

a. Precipitation

Monthly precipitation was used from the Global Precipitation Climatology Project (GPCP) version 2 by the World Climate Research Programme (Adler et al. 2003) on a fixed 2.5° × 2.5° latitude–longitude grid for November–April 1979–2008. The GPCP dataset incorporates satellite-based precipitation estimates using infrared and microwave channels and global station data. All monthly precipitation calculations were also performed with the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) dataset (Xie and Arkin 1997), and all results were similar to the results obtained using the GPCP dataset. Subseasonal precipitation analyses were performed using the GPCP pentad precipitation dataset version 1 (Xie et al. 2003) on a 2.5° × 2.5° latitude–longitude grid for November–April 1979–2008. GPCP pentad means were constructed by adjusting the CMAP pentad precipitation dataset against the GPCP monthly means.

Daily anomalies of OLR were also used as a proxy for precipitation to allow considerations of submonthly variability. The National Oceanic and Atmospheric Administration–Cooperative Institute for Research in Environmental Sciences (NOAA–CIRA) Climate Diagnostics Center (Liebmann and Smith 1996) dataset was used on a fixed 2.5° × 2.5° latitude–longitude grid for November–April 1979–2008.

b. Extratropical circulation and thermodynamic budget

Stream function, horizontal wind velocity, vertical wind velocity, temperature, and the terms of the hydrostatic thermodynamic energy equation were derived from the 4-times-daily data from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis fields (Kalnay et al. 1996) on a fixed 2.5° × 2.5° latitude–longitude pressure-level grid for November–April. Daily and monthly anomalies were computed using averages of the 4-times-daily anomalies.

3. The leading pattern of Indian Ocean precipitation

The leading pattern of boreal winter Indian Ocean precipitation is shown as shaded contours in Fig. 1 in terms of the leading EOF of November through April 1979–2008 monthly precipitation anomaly over the domain 20°S–40°N, 40°–120°E. The first EOF (EOF1), which explains 16% of the total variance, was calculated using a covariance matrix and has units of millimeters per day.

The precipitation pattern is only slightly sensitive to domain choice in the meridional direction over the Indian Ocean, but is sensitive to significant domain changes in the zonal direction. Increasing the domain westward into Africa has little influence on the leading pattern, but increasing the domain eastward into the west and central Pacific Ocean shifts the main signal over the Indian Ocean eastward by about 5° and emphasizes the ENSO signal over the Pacific. Increasing the domain of the leading pattern past the date line yields a standard ENSO pattern over the Indo-Pacific.
with less precipitation signal over the Indian Ocean. Since the primary focus here is the Indian Ocean, a zonal domain that includes only the Indian Ocean basin was chosen. The leading pattern is not strongly dependent on the precipitation dataset used, as the leading EOFs of both GPCP (Fig. 1) and CMAP precipitation (not shown) datasets are very similar over the Indian Ocean. Furthermore, the leading pattern is not sensitive to the number of years analyzed, as the pattern in Fig. 1a is closely reproduced even if as few as 7 yr are included.

The leading pattern of Indian Ocean precipitation (Fig. 1a) resembles intraseasonal Indo-Pacific OLR (Lau and Chan 1988; Hendon et al. 1999; Barlow et al. 2002) and west Pacific ENSO patterns (Barlow et al. 2002) with a strong signal concentrated over the eastern Indian Ocean (15°S–5°N, 80°–110°E). The eastern extent of the main precipitation area skirts the Maritime Continent, indicating that precipitation is weaker over this region relative to the Indian Ocean (Zhu and Wang 1993). The area of eastern Indian Ocean precipitation anomaly extends northward into the Bay of Bengal and westward into the central Indian Ocean. A much weaker center of opposite-signed anomaly appears over the western Indian Ocean, with some similarities to the

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**Fig. 1.** (a) Leading pattern of November–April 1979–2008 monthly precipitation anomaly over the plotted domain in mm day^{-1} and 300-hPa wind regression in m s^{-1}. The variance explained by the leading pattern is 16%. (b) Leading pattern time series in mm day^{-1} (bar; left ordinate) and Niño-3.4 index in K (line; right ordinate). The monthly correlation coefficient between the leading pattern and Niño-3.4 is −0.40, and the seasonally averaged correlation coefficient is −0.75.
When averaged by month, Indian Ocean OLR departures maximum precipitation anomaly in the leading pattern. which coincided with the strongest El Niño in the 1979–2008 record. OLR departures were spatially averaged over the region over this domain are closely related to the leading Indian Ocean precipitation pattern, with a correlation coefficient of −0.87. Intraseasonal and interannual contributions to Indian Ocean convection were separated using a Lanzcos filter with 201 weights for periods of 33–105 days and greater than 105 days, respectively. These filtering bands were chosen to be consistent with a power spectrum of November–April 1979–2008 OLR anomaly (not shown) and for consistency with the literature (e.g., Izumo et al. 2010). Monthly averages of both the intraseasonal and interannual components are moderately related to the leading pattern, as demonstrated by correlation coefficients of −0.64 and −0.68, respectively. The intraseasonal and interannual components of the index were spatially regressed to OLR in Fig. 2 to assess the associated patterns of convection but for a larger area that includes both the Indian and central Pacific Oceans to consider relationships with the large scale.

The sensitivity of the averaging area to size over the Indian Ocean was assessed by reducing the domain to 10°–5°S, 95°–105°E, which encompasses the 2.25 mm day⁻¹ contour of the leading pattern in Fig. 1. Spatial averages of daily precipitation were computed, filtered for intraseasonal and interannual periods, and regressed to OLR and 300 hPa wind to obtain the intraseasonal and interannual convection patterns; the same method as calculating Fig. 2 of the manuscript. These results (not shown) are very similar to Fig. 2, and our sensitivity analysis indicates that the size of the intraseasonal and interannual precipitation patterns associated with the leading Indian Ocean precipitation pattern are not sensitive to the domain size. The sensitivity of the filtered intraseasonal and interannual daily precipitation indices and their related convection patterns were explored by calculating the leading patterns via EOF analysis of filtered intraseasonal and interannual Indian Ocean precipitation. The leading patterns of intraseasonal and interannual Indian Ocean precipitation (not shown) are also very similar to Fig. 2.

The intraseasonal component is related to a strong eastern Indian Ocean signal that extends along the western edge of the Maritime Continent (Fig. 2a), and resembles both the leading pattern of Indian Ocean precipitation during November–April (Fig. 1a) and the variance of boreal cold-season Indo-Pacific OLR (e.g., Lau and Chan 1988; Hendon et al. 1999). An OLR signal to the east of the Maritime Continent has the opposite sign of the OLR signal over the eastern Indian Ocean, with magnitudes that are 40% weaker, consistent with previous analyses of the MJO. OLR signals over Saudi Arabia, Afghanistan, Pakistan, and Iran associated with intraseasonal Indian Ocean convection are much smaller
than the tropical maximum but are important locally (Barlow et al. 2005; Barlow 2012). In terms of circulation, there is an anticyclone across South Asia, centered near 20°N at 300 hPa (vectors in Fig. 2a), and resembles patterns observed during MJO periods (Barlow et al. 2005; Barlow 2012). Tropospheric circulation associated with intraseasonal Indian Ocean convection will be further investigated in the following sections.

Interannual Indian Ocean convection is related to an OLR seesaw between the Maritime Continent and central Pacific Ocean, resembling the leading pattern of interannual Indo-Pacific OLR (Chelliah and Arkin 1992), which is related to ENSO. A large anticyclone at 300 hPa, centered about 25°N and extending across much of Asia (Fig. 2b), is related to interannual contributions to Indian Ocean convection. In addition, a small yet noticeable circulation center is also located east of the Mediterranean on the northwest flank of the South Asian anticyclone. The most noticeable difference between circulations associated with interannual convection and the leading precipitation pattern is the circulation to the north and west of the broad south

![Fig. 2. Regression between (a) intraseasonal and (b) interannual Indian Ocean convective variability and OLR anomaly in units of W m$^{-2}$ (shaded) and 300-hPa wind anomaly in units of m s$^{-1}$ (vectors) for November–April 1979–2008. Indian Ocean convective variability is captured by calculating spatial averages of daily OLR anomaly over the domain 15°–5°N, 80°–110°E (boxed in Fig. 1a) and filtering for periods of 33–105 days (intraseasonal) greater than 105 days (interannual).]
Asian Rossby waves. Tropospheric circulation associated with interannual Indian Ocean convection will be further investigated in the following sections.

November through April OLR patterns over the eastern Indian Ocean and over Afghanistan, Pakistan, and Iran are inversely related during intraseasonal and interannual Indian Ocean convection periods, consistent with previous research. To compare these links between intraseasonal and interannual variability, we define southwest Asian precipitation as 20°–40°N, 40°–80°E. This domain was chosen as it encompasses the largest areas of subsidence associated with the leading patterns of Indian Ocean precipitation discussed in the following sections. The inverse relationship between the leading pattern of Indian Ocean precipitation and southwest Asian precipitation is explored in Fig. 3 for each month of the boreal cold season. The monthly leading pattern of Indian Ocean precipitation has an important influence on area-averaged southwest Asia precipitation during November–February, as evidenced by correlations of stronger than −0.50 for each of the 4 months. The relationship during March and April is somewhat weaker, averaging correlations of −0.42 for the 2 months. The difference between early and late cold-season relationship does not appear to be linked to the magnitudes of Indian Ocean and southwest Asia precipitation. The monthly percent contribution of yearly precipitation over the strong Indian Ocean precipitation region of 15°S–5°N, 80°–110°E for November, December, January, February, March, and April is 10.1, 9.3, 10.3, 8.5, 8.3, and 8.6, respectively, whereas over

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**Fig. 3.** Leading pattern time series of November–April 1979–2008 precipitation anomaly (Fig. 1b) separated into months (bar; left ordinate) and area-averaged precipitation anomaly over the region 20°–40°N, 40°–80°E (line; right ordinate). Both the leading pattern and area-averaged precipitation have units of mm day$^{-1}$. The correlation coefficients between monthly EOF1 and area-averaged precipitation are displayed in the plot titles. All monthly correlations are significant to $p < 0.05$ except for March.
southwest Asia the monthly percent contribution is 6.6, 13.0, 15.4, 15.9, 18.1, and 9.8, respectively. As a percentage of yearly precipitation, Indian Ocean precipitation remains roughly constant throughout the boreal cold season, while southwest Asia precipitation increases to a maximum during the middle to latter parts of the cold season.

The daily intraseasonal and interannual Indian Ocean convection time series were averaged by month and correlated to area-averaged southwest Asia precipitation (Table 1). Enhanced interannual Indian Ocean convection is also related to precipitation decreases over southwest Asia. The largest correlations, similar to the relationship between the leading pattern of Indian Ocean precipitation and southwest Asian precipitation, occur during November, January, and February. During March, however, correlations are much larger for the interannual component alone than for the leading pattern of Indian Ocean precipitation. The relationship between intraseasonal Indian Ocean convection and southwest Asian precipitation is much weaker on the monthly time scale. However, the monthly intraseasonal correlations for February ($r = -0.50$) are significant to $p < 0.05$. The leading pattern of Indian Ocean precipitation and interannual Indian Ocean convection has strong monthly to seasonal relationships with southwest Asian precipitation. Even on monthly time scales, intraseasonal Indian Ocean variability has some influence, particularly during February, although it is not clear why the intraseasonal link to southwest Asia precipitation is so much weaker than the interannual, given that the intraseasonal and interannual have roughly equal contributions to monthly variability of the leading pattern.

4. Regional dynamic and thermodynamic processes

Barlow et al. (2005, 2007) and Barlow (2012) showed that stationary baroclinic Rossby waves over southwest Asia can be directly linked to MJO convection during its peak phase in the eastern Indian Ocean. The warm core Rossby wave in the midtroposphere intersects the mean wind, resulting in cold temperature advection, subsidence, and precipitation decreases over southwest Asia, consistent with the Rodwell and Hoskins desert monsoon hypothesis (Rodwell and Hoskins 1996, 2001).

Here we will assess whether the leading pattern of Indian Ocean precipitation and the intraseasonal and interannual components of Indian Ocean convection are linked to southwest Asia precipitation through the same dynamical forcing mechanisms as seen in the case of the MJO. Specifically, we will investigate the changes to the thermodynamic budget throughout the troposphere and the contributions of horizontal temperature advection from the mean and anomalous terms.

a. Rotational circulation

The leading pattern of Indian Ocean precipitation is associated with anticyclonic circulation in the 300-hPa streamfunction field across southern Asia (Fig. 4a), and extends westward into southwest Asia, the Middle East, northern Africa, and northward into the Mediterranean and Caspian region. There are two circulation centers within this large anticyclone, the first located over the Middle East and southwest Asia and the second located over India and China. At 500 hPa (Fig. 4d), the anticyclonic circulation is strongest over northern Africa, the Middle East, and the Caspian region, extending eastward into southwest Asia. A very weak signal is present over subtropical China, and cyclones straddle the equator poleward and westward of the precipitation signal. At 700 hPa (Fig. 4g), a similar pattern to the 500-hPa signal exists; anticyclonic circulation is again concentrated over northern Africa, the Middle East, and the Caspian region, extending eastward toward southwest Asia and cyclones straddle the equator. One different feature between the 500- and 700-hPa streamfunction plots is that cyclonic circulation is present at 700 hPa over China, India, and the easternmost portions of southwest Asia. The tropical circulation response to the leading pattern of Indian Ocean precipitation during the cold season is similar to Gill–Matsuno circulation (Matsuno 1966; Gill 1980) with some modifications by the mean wind (Barlow 2012). The extratropical response associated with the leading pattern of Indian Ocean precipitation consists of an anticyclone with two centers. Anticyclonic flow throughout the depth of the troposphere over northern Africa, the Middle East,
and the Caspian region extending eastward toward southwest Asia indicates an equivalent barotropic feature. A low-level cyclone and an upper-level anticyclone over China and India indicate a baroclinic structure consistent with a Gill–Matsuno-like response. The area of largest precipitation change, southwest Asia, is located within both the equivalent barotropic and baroclinic response regions. The atmospheric response of the leading pattern of Indian Ocean precipitation has a different midlevel response from the MJO variability analyzed by Barlow et al. (2005).

The extratropical circulation response to the intraseasonal component of Indian Ocean convection is associated with an anticyclone at 300 hPa (Fig. 4b) located along the 25°N parallel. The zonal extent of the Rossby wave is large, extending from Saudi Arabia eastward to the Pacific Ocean. The circulation is centered over southern portions of southwest Asia. The vertical structure of the circulation relationship to intraseasonal Indian Ocean convection indicates that this Rossby wave is baroclinic (Figs. 4b,e,h). At 700 hPa, the circulation is cyclonic over Asia (Fig. 4h) and the sign of the circulation reverses with increasing tropospheric height. Contrary to the circulation response associated with the leading pattern of Indian Ocean precipitation over Asia, the rotational response associated with intraseasonal Indian Ocean convection is primarily baroclinic and strongly resembles the circulation response to MJO conditions noted by Barlow et al. (2005) at upper-tropospheric levels.

The extratropical circulation response to the interannual component of Indian Ocean convection strongly

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**FIG. 4.** Regression between streamfunction anomaly and (a),(c),(e) the leading pattern of Indian Ocean precipitation, (b),(e),(h) intraseasonal convective variability, and (c),(f),(i) interannual convective variability for November–April 1979–2008 in units of m² s⁻¹; 300-hPa plots are contoured every 5.0 × 10⁵ m² s⁻¹, 500-hPa plots are contoured every 3.0 × 10⁵ m² s⁻¹, and 700-hPa plots are contoured every 2.0 × 10⁵ m² s⁻¹.
resembles the extratropical circulation response to the leading pattern of Indian Ocean precipitation during November–April. The anticyclonic Asian circulation pattern is mixed between baroclinic (India and China) and equivalent barotropic (southwest Asia and to the north and west) shown in Figs. 4c,f,i. In the baroclinic region over China, cyclonic circulation is observed at 700 hPa and transitions to anticyclonic with increasing height through the troposphere. In the equivalent barotropic region over the Middle East, the circulation is anticyclonic throughout the troposphere. Southwest Asia is located within both the equivalent barotropic and baroclinic Rossby waves associated with the interannual component of Indian Ocean convection.

b. Thermodynamic balance

The interaction between anomalous circulations and the mean climate, and the resulting modifications to the thermodynamic budget and the related changes to vertical velocity and hence the potential forcing of precipitation are investigated. The hydrostatic thermodynamic energy equation (Holton 2004) used to investigate the thermodynamic balance is

$$\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T = S_p \omega + \frac{J}{c_p},$$  (1)

where $T$ is temperature, $\mathbf{V}$ is the horizontal wind vector, $S_p$ is the static stability parameter, $\omega$ is the vertical velocity in pressure coordinates, $c_p$ is the specific heat of dry air, and $J$ is the diabatic heating. We have verified that the static stability term is approximately constant in the horizontal in this analysis (Fig. 6a), so changes in the horizontal distribution of this term are primarily due to vertical velocity changes. Diabatic heating is calculated as a residual.

The relationship between the leading pattern of November–April Indian Ocean precipitation (Fig. 1) and the vertically integrated 200–700-hPa terms of the thermodynamic energy equation is shown in Fig. 5. The local change in temperature term (Fig. 5a) is an order of magnitude less than the three other terms. A strong diabatic heating signal exists over the eastern tropical Indian Ocean (Fig. 5d) in association with the strong precipitation signal. A much weaker diabatic heating of the opposite sign occurs over the western Indian Ocean, associated with the out-of-phase precipitation there. The diabatic heating is in close balance with convection over the tropics, as expected (Fig. 5c). The leading pattern can occur with either sign, so while we frame our discussion in terms of enhanced precipitation in the eastern Indian Ocean, the reverse also occurs.

Cold temperature advection occurs over much of southwest Asia (Fig. 5b), associated with the leading pattern of Indian Ocean precipitation, extending from Saudi Arabia eastward into China. The magnitude of vertically integrated cold temperature advection is strongest over southwest Asia throughout the troposphere. Cold temperature advection is largely balanced by downward vertical motions from Saudi Arabia eastward to India, as shown by a strong signal in the vertical term (Fig. 5c) as well as the relative smallness of the extratropical residually calculated diabatic heating term over Asia (Fig. 5d). The boxed region in Fig. 5 that spans the area 20°–40°N, 40°–80°E (southwest Asia) was defined based on the changes in subsidence. The diabatic cooling over southwest Asia is consistent with precipitation decreases over that region, but it may also be related to radiational cooling associated with changes in cloudiness.

c. Horizontal temperature advection contributions

To further investigate temperature advection, we compared contributions from mean temperature advection by the anomalous wind and anomalous temperature advection by the mean wind. Monthly data are used for mean and anomalies and for comparison to the monthly leading pattern. We have verified that these two monthly terms are the main contributors to the total change in temperature advection.

Associated with the leading pattern of Indian Ocean precipitation, there is an anomalous warm temperature area (shading in Fig. 6a) present over China and India, collocated with the baroclinic Rossby wave described in Fig. 4a and residing within the mean wintertime jet near 25°N at 300 hPa (vectors in Fig. 6a). The result is cold anomalous temperature advection by the mean wind (Fig. 7a) to the west of the maximum anomalous temperature signal throughout much of subtropical Asia, with the strongest magnitudes over southern portions of southwest Asia within the baroclinic regime described previously. In the anomalous wind field (vectors in Fig. 6b), two separate anticyclones are present over subtropical Asia. The eastern anticyclone resides over India and China, while the western anticyclone resides over Saudi Arabia and western portions of southwest Asia. Both of these features can be seen in the streamfunction relationship in Fig. 4a as well. The northerly flow separating the two anticyclones blows across the mean meridional cold season temperature gradient (shading in Fig. 6b), resulting in cold mean temperature advection by the anomalous wind (Fig. 7b) over northern and central portions of southwest Asia within the equivalent barotropic regime described previously. Therefore, at 300 hPa over southwest Asia, both the anomalous temperature advection by the mean wind and the mean temperature advection by the anomalous wind are contributors to
cold temperature advection but contribute over different areas, and they are associated with the differing equivalent barotropic and baroclinic Rossby waves. The vertical distribution of horizontal temperature advection averaged over southwest Asia that is related to the leading pattern of Indian Ocean precipitation is shown in Fig. 8a. As already seen in Fig. 5, the horizontal temperature advection and the vertical term of the thermodynamic equation are approximately in balance in a tropospheric average. Pressure vertical velocity is displayed instead of the vertical term of the thermodynamic equation to stress subsidence throughout the troposphere over southwest Asia. Anomalous temperature advection by the mean wind above 400 hPa (the level of maximum subsidence) is strongly negative as a result of the interaction of Rossby wave warm temperature anomalies and the westerlies. Cold temperature advection is balanced by subsidence in a similar fashion to Barlow et al. (2005). The intersection of the westerlies and warm temperature anomalies leads to the downward deflection of isentropic flow, subsidence, and precipitation reduction, as in Rodwell and Hoskins (1996, 2001). Cold horizontal temperature advection below 400 hPa is supported primarily by mean temperature advection by the anomalous wind. Anomalous temperature advection by the mean wind in the midtroposphere is generally weak, but it also competes against the mean temperature advection by the anomalous wind term. Below 400 hPa, cold anomalous temperature advection is weak in the absence of anomalous temperature areas.

Fig. 5. Vertically integrated 200–700-hPa regression between terms of the thermodynamic energy equation and the leading pattern of November–April 1979–2008 Indian Ocean precipitation (Fig. 1) in units of K day$^{-1}$. The boxed region spans 20°–40°N, 40°–80°E.
FIG. 6. Variables that contribute to anomalous terms of horizontal temperature advection at 300 hPa in association with the leading pattern of Indian Ocean precipitation, intraseasonal Indian Ocean convection, and interannual Indian Ocean convection for November–April 1979–2008. (left) Mean wind vectors and anomalous temperature contribute to anomalous temperature advection by the mean wind, (right) while anomalous wind vectors and mean temperature contribute to mean temperature advection by the anomalous wind. Mean wind vectors (vectors in left panels with units of m s$^{-1}$) and mean temperature contours (shading in right panels with units of K) are means of the respective variables. Anomalous temperature (shading in left panels with units of K) and anomalous wind vectors (vectors in right panels with units of m s$^{-1}$) are calculated as a regression between the leading pattern of Indian Ocean precipitation, intraseasonal Indian Ocean convection, and interannual Indian Ocean convection, and the respective variables.
whereas cold mean temperature advection is strong as a result of northerly flow across the mean meridional temperature gradient (not shown) similar to the pattern at 300 hPa (Fig. 6). Overall, cold horizontal temperature advection is balanced by precipitation-suppressing descent throughout the entire troposphere over southwest Asia and reaches maximum values at 400 hPa.

Associated with intraseasonal Indian Ocean convection is an anomalous warm temperature area at 300 hPa (shading in Fig. 6c), present throughout the
The zonal extent of Asia at 25°N associated with the upper-tropospheric baroclinic Rossby wave (Fig. 4b). The warm temperature area intersects the mean wintertime jet (vectors in Fig. 6c), which results in cold (warm) anomalous temperature advection by the mean wind west (east) of India, shown in Fig. 7c. Cold anomalous temperature advection by the mean wind is strong over southern portions of southwest Asia. The anomalous wind field (vectors of Fig. 6d) shows the baroclinic Rossby wave centered between 20° and 25°N previously described. The contours associated with the mean meridional temperature gradient are not purely zonal (shading in Fig. 6d), and the results include the westerly flow on the northern portion of the Rossby wave and cold mean temperature advection by the anomalous wind over eastern Asia (Fig. 7d). There is also another area of cold mean temperature advection by the anomalous wind over northern portions of southwest Asia (Fig. 7d) as weak northerly flow on the northwest flank of the Rossby wave blows across the mean meridional temperature gradient at 300 hPa. Both the anomalous temperature advection by the mean wind and the mean temperature advection by the anomalous wind as a result of a baroclinic Rossby wave over Asia are contributors to cold temperature advection over southwest Asia, but in different areas.

The vertical distribution of horizontal temperature advection averaged over southwest Asia that is related to intraseasonal Indian Ocean convection is shown in Fig. 8b. When averaged over southwest Asia, anomalous temperature advection by the mean wind is the main contributor to cold temperature advection near the top of the troposphere. Similar to the vertical profiles of temperature advection related to the leading pattern of Indian Ocean precipitation, mean temperature advection by the anomalous wind is the primary contributor to cold temperature advection through the mid- and lower troposphere. Anomalous temperature advection by the

**Fig. 8.** Regression area-averaged over 20°–40°N, 40°–80°E between the leading pattern of Indian Ocean precipitation, intraseasonal contributions to Indian Ocean convection, and interannual contributions to Indian Ocean convection for November–April 1979–2008. Displayed are temperature advection (red), mean temperature advection by the anomalous wind (blue), anomalous temperature advection by the mean wind (green), and anomalous vertical velocity (orange). All vertical profiles are in units of K day⁻¹.

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**EOF1**

**Intraseasonal**

**Interannual**

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mean wind below 400 hPa makes virtually no contribution to temperature advection as a result of very small temperature anomalies (not shown). Temperature advection is therefore a direct result of mean temperature advection by the anomalous wind below 400 hPa. The anomalous wind vectors over much of Asia are directed southward on the western flank of the cyclonic circulation at 700 hPa of the baroclinic Rossby wave (i.e., Figure 4h) and blow across the mean meridional temperature gradient, resulting in cold temperature advection throughout southwest Asia. However, in the case of intraseasonal Indian Ocean convection, it is the interaction of the baroclinic Rossby wave with the mean climate that supports both the anomalous temperature advection by the mean wind and the mean temperature advection by the anomalous wind throughout the troposphere. Cold tropospheric temperature advection is balanced by subsidence over southwest Asia, and subsidence has maximum magnitudes around 300 hPa.

The interannual component of Indian Ocean convection and the leading pattern of Indian Ocean precipitation are associated with similar anomalous temperature advection by the mean wind (Fig. 7e), mean temperature advection by the anomalous wind (Fig. 7f), and the contributing anomalous temperature (Fig. 6e) and wind terms (Fig. 6f). As described previously, the leading pattern of Indian Ocean precipitation and interannual convection share the same spatial circulation throughout the troposphere shown in Fig. 4 with zonally oriented barotropic and baroclinic Rossby waves. This is also the case for upper-tropospheric temperature anomalies within the baroclinic Rossby wave over China and India. The main differences between the two modes are the magnitudes of the associated circulation and temperature features. Since interannual Indian Ocean convection is related to slightly weaker circulation and upper-tropospheric temperature anomalies, weaker temperature advection anomalies throughout the troposphere result. The marginally weaker temperature advection anomalies are balanced by weaker subsidence (Fig. 8c).

d. Subseasonal influences during 2007/08

For individual months, intraseasonal contributions can overwhelm interannual contributions to Indian Ocean convection. Here, we consider an example: the flooding of January 2008, which occurred during the drought season of 2007/08. Based on the leading pattern of Indian Ocean precipitation for 1979–2008 (Fig. 1), 2007/08 was the third largest precipitation deficit within that period; 2007/08 was also the third most intense drought season over southwest Asia for the period. November 2007/April 2008 average precipitation and 300-hPa streamfunction departures are displayed in Fig. 9a. The 2007/08 cold season over the Indian Ocean was dominated by precipitation increases to the immediate west of the Maritime Continent in addition to the extreme west Pacific Ocean, just east of the Maritime Continent. The west-central Pacific, as a result of La Niña conditions, was an area of strong seasonally averaged precipitation deficits. Over western Asia and the Middle East, observed seasonally averaged precipitation was well below the 1979–2008 climatology. Anticyclonic circulation dominated the upper troposphere during 2007/08 over Asia.

Despite overall persistent precipitation decreases during the 2007/08 season, both positive and negative precipitation extremes were observed over both the Indian Ocean and southwest Asia. The precipitation extremes between both regions were inversely related. The seasonal evolution of area-averaged southwest Asia (blue) and Indian Ocean (brown) precipitation are displayed in Fig. 9b using the boxed regions of the same color in Fig. 9a. For the majority of the 2007/08 cold season, specifically mid-January through mid-March and mid-November through mid-December, positive Indian Ocean and negative southwest Asian precipitation departures occurred simultaneously. Precipitation departures during those times dominated the seasonal average. However, between 25 December 2007 and 14 January 2008 (shaded region in Fig. 9b), or January 2008 as a monthly average, the sign of Indian Ocean precipitation reversed and convection was reduced as a result of MJO conditions. MJO phases 5, 6, and 7, according to the multivariate MJO index (Wheeler and Hendon 2004), persisted from 27 December 2007 through 14 January 2008. Southwest Asia precipitation was also reversed during that time, becoming positive and resulting in copious precipitation during an otherwise intense drought season. Averaged precipitation and 300-hPa streamfunction departures between 25 December 2007 and 14 January 2008 are displayed in Fig. 9c. Very dry conditions over the eastern Indian Ocean and very wet conditions over southwest Asia were observed, having the opposite sign of the seasonal average (Fig. 9a). The 300-hPa circulation over western Asia and the Middle East was also reversed from the seasonal average as cyclonic circulation dominated.

5. Summary and discussion

The leading pattern of Indian Ocean monthly precipitation and its intraseasonal and interannual components are examined for November–April 1979–2008, as well as the associated three-dimensional circulation and thermodynamics over the Indian Ocean and southern Asia. The thermodynamic influence over Asia associated
with interannual Indian Ocean precipitation is similar to the previously analyzed intraseasonal Indian Ocean precipitation, but it has an additional barotropic circulation response. Although intraseasonal and interannual variability contribute about equally to the leading pattern, the intraseasonal component is less important with respect to southwest Asia precipitation in terms of monthly averages. However, for individual months, the intraseasonal component can occasionally dominate the interannual component and lead to flooding in the midst of drought conditions.

The predictive capabilities of southwest Asian precipitation associated with the intraseasonal and interannual components of Indian Ocean convection may be of considerable value since prolonged precipitation extremes, such as during the 2007/08 season, are responsible for many negative socioeconomic impacts (Gall 2008). At interannual time scales, Indian Ocean convection explains more than 25% of southwest Asian precipitation variance for November–March. While intraseasonal Indian Ocean convection does not explain a large percentage of southwest Asian precipitation variance for individual months, our analysis demonstrates that there is a clear link between Indian Ocean convection and southwest Asian precipitation associated with MJO extremes that last for weeks at a time.

**Fig. 9.** (a) Standardized precipitation anomaly and 300-hPa streamfunction anomaly contoured every $5.0 \times 10^5$ m$^2$ s$^{-1}$ averaged for November 2007–April 2008. (b) Standardized area-averaged pentad precipitation anomaly for southwest Asia (blue) and eastern Indian Ocean (brown). (c) Standardized precipitation anomaly and 300-hPa streamfunction anomaly contoured every $2.0 \times 10^5$ m$^2$ s$^{-1}$ averaged for 25 December 2007–14 January 2008.
The dynamical reasons for an additional barotropic circulation response over northern Africa, the Middle East, and the Caspian region associated with the interannual component and the leading pattern of Indian Ocean precipitation are not yet clear. We are currently investigating the behavior of transients on interannual time scales associated with Indian Ocean convection or a potential global teleconnection with origins over the Indo-Pacific domain associated with ENSO (Shaman and Tziperman 2005). The possible global circulation variability linked with the intraseasonal and interannual components of Indian Ocean convection also suggests further analysis, especially the link with ENSO. We are also investigating the role of the west Pacific Ocean SST gradient in the link between ENSO and Indian Ocean precipitation.

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