Intraseasonal and Seasonal-to-Interannual Indian Ocean Convection and Hemispheric Teleconnections

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ABSTRACT

Deep tropical convection over the Indian Ocean leads to intense diabatic heating, a main driver of the climate system. The Northern Hemisphere circulation and precipitation associated with intraseasonal and seasonal-to-interannual components of the leading pattern of Indian Ocean convection are investigated for November–April 1979–2008. The leading pattern of Indian Ocean convection is separated into intraseasonal and seasonal-to-interannual components by filtering an index of outgoing longwave radiation at 33–105 days and greater than 105 days, yielding Madden–Julian oscillation (MJO)- and El Niño–Southern Oscillation (ENSO)-influenced patterns, respectively. Observations and barotropic Rossby wave ray tracing experiments suggest that Indian Ocean convection can influence the ENSO-related hemispheric teleconnection pattern in addition to the regional Asian teleconnection. Equivalent barotropic circulation anomalies throughout the Northern Hemisphere subtropics are associated with both seasonal-to-interannual Indian Ocean convection and ENSO. The hemispheric teleconnection associated with seasonal-to-interannual Indian Ocean convection is investigated with ray tracing, which suggests that forcing over the Indian Ocean can propagate eastward across the hemisphere and back to Asia. The relationship between the seasonal-to-interannual component of Indian Ocean convection and ENSO is investigated in terms of a gradient in sea surface temperatures (SST) over the equatorial western Pacific Ocean. When the western Pacific SST gradient is strong during ENSO, strong Maritime Continent precipitation extends further westward into the Indian Ocean, which is accompanied by enhanced tropospheric Asian circulation, similar to the seasonal-to-interannual component of Indian Ocean convection. Analysis of the three strongest interannual convection seasons shows that the strong Indian Ocean pattern of ENSO can dominate individual seasons.

1. Introduction

The Indian Ocean is a location of strong intraseasonal (e.g., Lau and Chan 1988; Ferranti et al. 1990; Hendon et al. 1999) and interannual (e.g., Chelliah and Arkin 1992; Nigam and Shen 1993; Kidson et al. 2002) convective variability during the boreal cold season of November–April. Stationary wave responses over Asia (e.g., Barlow et al. 2005) and the Northern Hemisphere (e.g., Knutson and Weickmann 1987; Ferranti et al. 1990; Kiladis and Weickmann 1992; Salby and Hendon 1994; Higgins and Mo 1997; Matthews et al. 2004) have been linked to intraseasonal Indian Ocean convection associated with the Madden–Julian oscillation (MJO). Interannual Indian Ocean convection associated with El Niño–Southern Oscillation (ENSO) has also been linked to stationary wave responses over Asia (e.g., Barlow et al. 2002) and the Northern Hemisphere (e.g., Trenberth et al. 1998). Previously, we examined the leading pattern of Indian Ocean precipitation and the associated regional circulation and thermodynamic forcing of precipitation over Asia during boreal winter at both intraseasonal and seasonal-to-interannual time scales (Hoell et al. 2012). Here, we examine the Northern Hemisphere circulation and precipitation variability associated with the intraseasonal and interannual contributions to convection.
specifically for the Indian Ocean domain during boreal winter.

Indian Ocean convection is associated with ENSO and MJO during boreal winter. ENSO and MJO vary on different time scales, are associated with varying magnitudes of Indo-Pacific convection, and are associated with different extratropical convection and precipitation variability. The Pacific Ocean SST anomalies during ENSO phases lead to convection modifications over the Indo-Pacific basin and convergence modifications over the subtropics. Conditions of ENSO are generally associated with circulation modifications over the North Pacific Ocean, North America, and the Atlantic Ocean (Trenberth et al. 1998; Diaz et al. 2001) in the Pacific–North American pattern (Horel and Wallace 1981) where La Niña and El Niño phases are opposing, yet nonlinear (Hoerling et al. 1997). Northern Hemisphere precipitation variability associated with ENSO can be extreme in some areas and is season and phase dependent (Ropelewski and Halpert 1986, 1987, 1989).

The MJO is a phenomenon characterized by eastward-propagating convective anomalies in the tropics with a time scale of approximately 30–90 days and has strongest magnitudes over the Indo-Pacific domain (Madden and Julian 1994). The phase speed of eastward propagation is approximately 5 m s⁻¹ associated with the MJO, so the MJO contributes to enhanced or reduced convection over the Indo-Pacific basin for weeks at a time. The regional circulation over Asia during MJO periods is primarily a single baroclinic Rossby wave (Barlow et al. 2005; Jeong et al. 2008), while throughout the Northern Hemisphere the circulation is essentially a wave train that extends over the North Pacific Ocean, North America, and the Atlantic Ocean (Knutson and Weickmann 1987; Ferranti et al. 1990; Kiladis and Weickmann 1992; Salby and Hendon 1994; Higgins and Mo 1997; Matthews et al. 2004). In addition to the modifications of global circulation associated with MJO, the MJO has been shown to influence precipitation over western Asia (Barlow et al. 2005), eastern Asia (Jeong et al. 2008), the western United States and California (Mo and Higgins 1998a,b; Jones 2000), Australia (Hendon and Liebmann 1990; Wheeler and Hendon 2004; Wheeler et al. 2009), India (Goswami et al. 2003) and Africa (Kijazi and Reason 2005; Mapande and Reason 2005; Pohl et al. 2007, 2009). The Northern Hemisphere circulation and precipitation patterns associated with interannual and intraseasonal convection over both the Indian and Pacific basins have been investigated in some detail; however, the specific role of the Indian Ocean is not yet fully understood.

The Northern Hemisphere circulation response to ENSO conditions has been investigated in considerable detail, particularly for the recent La Niña event of 1998–2000. Atmospheric models indicate that high pressure and subsequent drought conditions throughout the Northern Hemisphere poleward of 20°N were forced by anomalously cold central Pacific Ocean SST and anomalously warm western Pacific Ocean SSTs during 1998–2002 (Hoerling and Kumar 2003). Pacific Ocean SST variations during 1998–2000 were also responsible for enhanced Indian Ocean convection, and Indian Ocean convection around the turn of the century was linked to baroclinic circulation and drought over much of Asia (Barlow et al. 2002).

Shaman and Tziperman (2005) investigated an eastward stationary barotropic Rossby wave propagation mechanism associated with ENSO conditions that spans the Northern Hemisphere. Using a Rossby wave ray tracing technique with origins over the tropical central Pacific and forced by the mean wintertime flow, Shaman and Tziperman (2005) showed that stationary barotropic waves propagate northeastward, reflect toward the equator off of the North American jet, and enter the North African–Asian jet, thereby passing through western Asia. Because ENSO contributes to interannual Indian Ocean convection, we will utilize Rossby wave ray tracing to assess whether Rossby rays with origins over the Indian Ocean can impact Northern Hemisphere circulation. Specifically, this method will help to answer the question raised by Barlow and Tippett (2008) of whether stationary waves originating over the Indian Ocean can travel eastward throughout the Northern Hemisphere and into Asia from the west, influencing the regional circulation.

The interaction of ENSO and the MJO has been shown to make further modifications to Indian Ocean, Maritime Continent, and western Pacific Ocean convection. Singular MJO events have been linked to both the initiation (McPhaden 1999) and demise (Takeyabu et al. 1999) of the 1997/98 El Niño episode as well as the beginning of the 2002/03 El Niño (McPhaden 2004). Once El Niño events have begun, MJO-related convection weakens considerably, as evidenced by August–October 2002 convection over the Indian and western Pacific Oceans during the 2002/03 El Niño event (McPhaden 2004). La Niña events suppress low-level intraseasonal flow over the central Pacific Ocean and enhance low-level intraseasonal flow over the western Pacific Ocean, as shown by Tam and Lau (2005) using reanalysis data and an ensemble of general circulation models. El Niño events have the opposite influence on the intraseasonal low-level wind. Tam and Lau (2005) also showed that MJO growth and decay is displaced westward during La Niña events as opposed to El Niño events. Overall, MJO activity is weaker during strong
El Niño warm events but is uncorrelated with El Niño otherwise (Hendon et al. 1999).

The global circulation and precipitation relationships associated with Indian Ocean precipitation have been primarily investigated in terms of the MJO and ENSO, but it is not clear whether this represents the main Indian Ocean convection influence. Previously, in Hoell et al. (2012), we examined the circulation and thermodynamic forcing of precipitation over Asia associated with the intraseasonal and seasonal-to-interannual components of the leading pattern of Indian Ocean convection during the boreal cold season of November–April 1979–2008. Here, we explore the Northern Hemisphere precipitation and circulation associated with intraseasonal and interannual components of Indian Ocean convection and compare the results with circulation and precipitation associated with the MJO and ENSO, respectively. The global circulation associated with seasonal-to-interannual Indian Ocean convection is investigated in terms of the three-dimensional structure, the relationship with stationary Rossby ray propagation, and the relationship to ENSO during western Pacific Ocean SST gradient occurrences. The data and methods used are described in section 2. Seasonal-to-interannual and intraseasonal contributions to Indian Ocean vertical motions are discussed in section 3. The modification of seasonal-to-interannual Indian Ocean vertical motions by the western Pacific Ocean SST gradient are examined in section 4. A summary is provided in section 5.

2. Data and methods

a. Intraseasonal and interannual tropical convection

Daily outgoing longwave radiation (OLR) was used as a proxy for deep tropical convection. With the seasonal cycle removed, OLR was obtained from the National Oceanographic and Atmospheric Administration/Cooperative Institute for Research in Environmental Sciences (NOAA/CIRES) Climate Diagnostics Center (Liebmann and Smith 1996) on a fixed 2.5° × 2.5° latitude–longitude grid for November–April 1979–2008.

The leading pattern of convection over the Indian Ocean, as determined by the first empirical orthogonal function (EOF) of monthly November–April 1979–2008 precipitation over 20°S–40°N and 40°–120°E, is most concentrated over the eastern Indian Ocean region of 15°S–5°N and 80°–110°E (Hoell et al. 2012). A daily convection index, which is closely related with the leading pattern of Indian Ocean convection, was constructed by averaging OLR over the region 15°S–5°N and 80°–110°E. The intraseasonal and seasonal-to-interannual components of the daily convection index were obtained through filtering for periods of 33–105 days and greater than 105 days, respectively, using a Lanczos filter with 201 weights, as in Hoell et al. (2012).

The intraseasonal and seasonal-to-interannual components of the leading pattern of Indian Ocean convection were related to SST, tropospheric streamfunction, and global OLR through linear regression and to continental precipitation through correlation. Significance testing was performed using a Student’s $t$ test. Values displayed on all regressions and correlations plots are significant to $p < 0.05$.

b. ENSO variation and SST

Daily SSTs, with the seasonal cycle removed, were drawn from the NOAA Optimum Interpolation SST, version 2 (OISST2; Reynolds et al. 2007), on a fixed 0.25° × 0.25° latitude–longitude grid for November–April 1982–2008. Daily ENSO variability during the 1982–2008 period was studied using area-averaged SST over the Niño-3.4 region, 5°S–5°N and 170°–120°W.

Variability of ENSO was related to tropospheric streamfunction, OLR, and SST through linear regression and continental precipitation through correlation. The similarities in the westward extent of Maritime Continent convection patterns associated with ENSO and seasonal-to-interannual Indian Ocean convection were investigated in terms of a gradient in SST over the equatorial western Pacific Ocean. The daily-average magnitude of the SST gradient over the region 5°S–5°N and 140°–150°E was calculated. The regression between ENSO and SST, OLR, and tropospheric streamfunction were calculated for the top 20% (strong gradient), the top 40% (moderate gradient), and top 60% (weak gradient) of western Pacific SST gradient occurrences. The modifications to the western Pacific SST gradient, and therefore related changes to the atmospheric response, are examined in terms of ENSO magnitude. The magnitude of ENSO is measured by the magnitude of the Niño-3.4 index. The regression between ENSO and SST, OLR, and tropospheric streamfunction were calculated for the top 20% (strong ENSO), the top 40% (moderate ENSO), and top 60% (weak ENSO) of ENSO occurrences. Significance testing was performed using a Student’s $t$ test. Values displayed on all regressions and correlations plots are significant to $p < 0.05$.

c. MJO estimates

The phase and amplitude of the MJO for November–April 1979–2008 were obtained from the all-season real-time multivariate MJO (RMM) index of Wheeler and Hendon (2004). The MJO indices are derived from the first two principal components of a combined EOF of
global OLR, zonal wind at 850 hPa and zonal wind at 200 hPa, averaged meridionally between 15°S and 15°N. Prior to the calculation of the combined EOF, the seasonal cycle and components of the annual cycle were removed for each of the input variables. The first two principal components, named RMM1 and RMM2, vary mostly on the intraseasonal time scale and therefore describe the MJO. The phase of the MJO is determined as a point in two-dimensional space according to the RMM1 and RMM2 indices, and the amplitude of the MJO is derived from the magnitude of the RMM1 and RMM2 indices.

Concomitant relationships between the global climate and MJO were obtained by regressing the MJO amplitude to OLR, SST, and tropospheric streamfunction. The OLR composites indicate that phases 2–5 of the MJO correspond to enhanced eastern Indian Ocean convection while phases 6–8 and 1 correspond to reduced eastern Indian Ocean convection (Wheeler and Hendon 2004). Therefore, the MJO amplitude was assigned a positive value during phases 2–5 and a negative value otherwise prior to regression and correlation analyses. Because the MJO amplitude is obtained from the magnitude of the first two leading EOF components of OLR, this regression is a measure of the variance explained by the first two leading EOF components over the domain. Significance testing was performed using a Student’s $t$ test. All regression and correlation plots are significant to $p < 0.05$.

d. Atmospheric circulation

Daily streamfunction was used to assess the atmospheric circulation. Stream function, with the seasonal cycle removed, was derived from the 6-hourly 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 grid for November–April 1979–2008.

Barotropic Rossby wave ray tracing, using the method of Shaman and Tziperman (2005), was utilized to test whether Indian Ocean convection can force stationary Rossby waves that travel around the Northern Hemisphere when guided by the upper tropospheric–mean flow during November–April. Using the dispersion relation for the perturbation streamfunction on a Mercator projection, Shaman and Tziperman (2005) integrated the equations for the path of a ray and for changing zonal and meridional wavenumbers, as performed earlier by Karoly (1983). Rays were initiated with a zonal wavenumber $k$ at a particular forcing site. Initial meridional wavenumbers $l$ were determined from the dispersion relation at the initial point in the ray path assuming wave stationarity (zero frequency). The November–April 1979–2008 climatological NCEP–NCAR reanalysis winds were used as the time-mean fields and were smoothed using a low-pass Butterworth filter.

e. Global precipitation

Daily continental precipitation, with the seasonal cycle removed, was drawn from the Climate Prediction Center Gauge-Based Analysis of Global Daily Precipitation (Chen et al. 2008) on a fixed 0.5° × 0.5° latitude–longitude grid for November–April 1979–2008. Two versions make up this dataset: a retrospective version that covers 1979–2005 and a real-time version that extends from 2006 onward. The spatial coverage of stations used to construct the dataset varies by geographic location, so the reliability of the dataset over certain regions is limited.

3. Intraseasonal and seasonal-to-interannual teleconnections

Previously, we examined the circulation and thermodynamic forcing of precipitation over Asia associated with the intraseasonal and seasonal-to-interannual components of the leading pattern of Indian Ocean convection (Hoell et al. 2012). Here, we examine the Northern Hemisphere circulation, SST, and Indo-Pacific convection associated with the intraseasonal and seasonal-to-interannual components of the leading pattern of Indian Ocean convection. Additionally, we compare these findings with two leading climate modes, MJO and ENSO.

a. Leading climate modes and Indian Ocean convection

Intraseasonal Indian Ocean convection is related to a strong OLR signal concentrated south of the equator, extending around the western edge of the Maritime Continent (Fig. 1b), which resembles the leading pattern of Indian Ocean precipitation during November–April (Hoell et al. 2012) and the variance of boreal cold-season Indo-Pacific OLR (e.g., Lau and Chan 1988; Hendon et al. 1999). An OLR signal of the opposite sign over the western Pacific Ocean is also observed in Fig. 1b. Throughout the tropical and extratropical Indian and Pacific Oceans a weak SST relationship is observed, relative to the seasonal-to-interannual case (Fig. 3a, described in greater detail below), in relation to intraseasonal Indian Ocean convection (Fig. 1a). Intraseasonal Indian Ocean convection is related to an upper-tropospheric Rossby wave across Asia located near 25°N (Fig. 1c). Hoell et al. (2012) indicated that the Rossby wave over Asia is baroclinic and is similar to a Gill–Matsuno response to tropical forcing modified
by the mean wind (Barlow 2011). While the Rossby wave over Asia is the most dominant feature over the Northern Hemisphere as it relates to intraseasonal Indian Ocean convection, other features are observed in the upper troposphere. A subtropical cyclone is present over the central Pacific Ocean as well extratropical features over the Mediterranean and North Pacific. The upper-tropospheric circulation over the Northern Hemisphere related to intraseasonal Indian Ocean convection strongly resembles the leading patterns of intraseasonal upper-tropospheric circulation during boreal winter presented by Knutson and Weickmann (1987).

There is a close resemblance between the MJO response (Fig. 2) and the response to intraseasonal Indian Ocean convection (Fig. 1) with respect to SST, convection patterns (as observed through OLR), and upper-tropospheric circulation. The tropical OLR responses over the Indian and western Pacific Oceans and the OLR response over southwestern Asia are nearly identical. The subtropical and extratropical Rossby waves over Asia are very similar as they are both baroclinic, oriented near the same latitude, have the same zonal extent through Asia, and are centered over southwestern Asia. In addition, the global upper-tropospheric circulation over the entire Northern Hemisphere is also similar.

The SST relationships with seasonal-to-interannual Indian Ocean convection (Fig. 3a) and ENSO (Fig. 4a) are similar, as they display a distinct cold tongue of SST located over the tropical central and eastern Pacific Ocean and a warm SST area that extends from the western Pacific northeastward into the extratropical central Pacific Ocean. Despite strong spatial SST similarities, the correlation between monthly-average seasonal-to-interannual Indian Ocean convection and the Niño-3.4 index is only $-0.55$.

Seasonal-to-interannual Indian Ocean convection (Fig. 3b) and ENSO (Fig. 4b) are related to a similar OLR seesaw between the Maritime Continent and central Pacific Ocean. The peak OLR magnitudes are present in the far northeast (over the Philippines) and far southwest (over the extreme southeastern Indian Ocean) portions of the Maritime Continent OLR signal. The OLR patterns related to the ENSO case (Fig. 4b) closely resemble OLR associated with La Niña conditions displayed in Kidson et al. (2002). The westward extent into the eastern Indian Ocean of the Maritime Continent OLR pattern is a significant difference between the patterns associated with ENSO (Fig. 4b) and seasonal-to-interannual Indian Ocean convection (Fig. 3b). The OLR associated with seasonal-to-interannual Indian Ocean convection extends further into the eastern Indian Ocean.

A large Rossby wave, extending across all of southern Asia, is related to seasonal-to-interannual Indian Ocean convection (Fig. 3c) and ENSO (Fig. 4c). The Rossby wave over Asia is mixed between baroclinic (India and China) and equivalent barotropic (southwestern Asia and to the north and west) in the case of seasonal-to-interannual Indian Ocean convection, as described by Hoell et al. (2012). A zonally symmetric streamfunction signal, extending throughout much of the Northern Hemisphere, from the North Pacific Ocean eastward to Europe, passing through the United States and the Atlantic Ocean, is related to both seasonal-to-interannual Indian Ocean convection (Fig. 3c) and ENSO (Fig. 4c). There are strong similarities between the upper-tropospheric circulation associated with seasonal-to-interannual Indian Ocean convection (Fig. 3c) and the circulation associated with La Niña conditions displayed in Kidson et al. (2002).

b. Peak seasons

Seasonally averaged amplitudes of the leading pattern of monthly Indian Ocean precipitation for November–April 1979–2008 indicates that the three strongest Indian Ocean precipitation seasons during that period in ascending order were 2007/08, 1999/00, and 1983/84 (Hoell et al. 2012). November–April-averaged OLR anomalies for each of these strong seasons are displayed in Fig. 5. Seasonal OLR anomalies over the Indo-Pacific domain during 2007/08, 1999/00, and 1983/84 are similar and closely resemble seasonal-to-interannual Indian Ocean convection (Fig. 3b). Because each of these November–April seasons were characterized by SST consistent with La Niña, this indicates that the strong Indian Ocean pattern of ENSO can dominate individual seasons. Negative Maritime Continent OLR anomalies, consistent with enhanced precipitation and convection, for each of these three seasons were strong and extended a considerable distance westward into the Indian Ocean, similar to the seasonal-to-interannual OLR patterns described in Fig. 3b. Positive western-central Pacific OLR anomalies, consistent with reduced precipitation, were confined primarily west of the international date line and east of 150°E and are also similar to the seasonal-to-interannual OLR patterns described in Fig. 3b.

c. Seasonal-to-interannual Indian Ocean convection and hemispheric teleconnections

Stationary barotropic Rossby waves with initial wavenumbers of 4 and 5 and origins over various central Pacific Ocean longitudes at $5^\circ$N in the context of the mean December–February flow at 200 hPa can propagate throughout the Northern Hemisphere and reach
Asia from the west (Shaman and Tziperman 2005). The origins of these stationary barotropic Rossby waves were chosen because of their possible association with ENSO. Here, we investigate the existence of stationary Rossby waves propagating through the Northern Hemisphere with origins over the Indian Ocean and the structure of the circulation during seasonal-to-interannual eastern Indian Ocean convection.

The regression of seasonal-to-interannual Indian Ocean convection to the 200- and 700-hPa streamfunction anomaly are shown in Figs. 6a and 6b for the Northern Hemisphere, respectively. Also plotted in Fig. 6a are stationary barotropic Rossby rays with initial zonal wavenumbers $k = 3$ (solid line) and $k = 5$ (dashed line) forced by the 200-hPa November–April 1979–2008 background flow originating at 5°N and 92.5°E using the method of Shaman and Tziperman (2005). A range of other wavenumbers and origins over the Indian Ocean and Maritime Continent forced by the upper-tropospheric flow at and above 300-hPa yield similar results to those that are shown in Fig. 6a.

Away from Asia, the circulation throughout the extratropical Northern Hemisphere is generally equivalent barotropic, as evidenced by positive streamfunction values at 200 (Fig. 6a) and 700 hPa (Fig. 6b) in a meridional band between 20° and 50°N extending across the
North Pacific Ocean, United States, North Atlantic, from Europe into the Middle East, and western Asia. To test whether the appearance of equivalent barotropic features in the extratropical circulation are related to stationary Rossby wave propagation, Rossby rays were traced with initial locations, wavenumbers, and background flow described previously. Rossby wave propagation in Fig. 6a takes one of two routes, through the extratropics or through the subtropics. Rays with smaller wavenumbers travel with the Northern Hemisphere’s extratropical jet between 30° and 40°N and reach western Asia after 15 days of propagation. Rays with larger wavenumbers are initially reflected off of the East Asian jet toward the subtropics, similar to the case considered by Shaman and Tziperman (2005), except those waves reflect off of the North American jet. After 15 days of propagation, these waves reach western Asia. This analysis shows that extratropical circulation influenced by seasonal-to-interannual Indian Ocean convection over the Northern Hemisphere is equivalent barotropic. The eastern Indian Ocean convection seen in a seasonal-to-interannual pattern and in La Niña events like 1998–2000 (Shabbar and Yu 2009) may be dynamically important to the hemispheric circulation.

d. Indian Ocean convection and global precipitation

Both intraseasonal and seasonal-to-interannual Indian Ocean convection are related to substantial subtropical Northern Hemisphere circulation modifications. Because convection modifications are often intimately tied to the

![Fig. 2. As in Fig. 1, but for daily MJO amplitude.](image-url)
large-scale circulation, we assess whether intraseasonal and seasonal-to-interannual Indian Ocean convection is related to precipitation over the Indian Ocean rim. Furthermore, the relationships between continental precipitation and intraseasonal and seasonal-to-interannual convection are compared with the MJO and ENSO, respectively. Correlation plots for Asia are shown in Fig. 7 (intraseasonal and MJO) and Fig. 8 (seasonal to interannual and ENSO) and are displayed when significant to $p < 0.05$.

The correlation of 5-day lagged precipitation and intraseasonal Indian Ocean convection (left) and the MJO (right) are displayed for November–April in Fig. 7. Negative (positive) correlations indicate that enhanced (diminished) Indian Ocean convection is related with suppressed (enhanced) continental precipitation. The largest negative correlations in both the intraseasonal convection and MJO cases are observed over the domain $20^\circ$–$40^\circ$N and $40^\circ$–$80^\circ$E, which is consistent with the results using monthly time scales of Barlow et al. (2005) and Barlow (2011). While there are strong similarities between the MJO and intraseasonal Indian Ocean convection relationships with Asian, African, and Indian precipitation, the intraseasonal convection relationship is stronger over central and southwestern Asia during all months of the boreal cold season. These results indicate that intraseasonal Indian Ocean convection may be a better predictor of central and

Fig. 3. As in Fig. 1, but for seasonal-to-interannual Indian Ocean convection.
southwestern Asian precipitation than the amplitude of the MJO.

Correlation of precipitation and seasonal-to-interannual Indian Ocean convection (left) and ENSO (right) are displayed for November–April in Fig. 8. Lagged correlations display similar results to the lag-0 case and are therefore not shown. Seasonal-to-interannual Indian Ocean convection and ENSO are related to precipitation increases over India and decreases throughout eastern Africa and the entire zonal extent of Asia within a meridional band that extends from 20° to 40°N. The largest negative correlations are observed over western Asia during the months of January, February, and March, but they are also of considerable magnitude during each of the other months throughout Asia. Significant correlations of these magnitudes using daily data, particularly over southwestern Asia, are similar to the results presented using a different dataset with monthly observations in Hoell et al. (2012). Seasonal-to-interannual Indian Ocean convection and ENSO have similar relationships with continental precipitation over these regions; however, the precipitation relationships are stronger with the seasonal-to-interannual case, particularly during January and February. The results presented here suggest that seasonal-to-interannual Indian Ocean convection may be a better predictor of the interannual component of precipitation over eastern Africa and Asia than ENSO.

**Fig. 4.** As in Fig. 1, but for Niño-3.4 index.
4. ENSO and the western Pacific SST gradient

In section 3, we found that the Maritime Continent convection patterns associated with seasonal-to-interannual Indian Ocean convection (Fig. 3b) and ENSO (Fig. 4b) are similar, except for their westward extent into the Indian Ocean. Stronger convection associated with seasonal-to-interannual Indian Ocean convection extends farther westward into the Indian Ocean than during ENSO. Barlow et al. (2002) showed that ENSO periods associated with a strong western Pacific Ocean warm pool, where the western Pacific Ocean SST anomaly opposed the central Pacific Ocean SST anomaly, were linked to a westward extension of strong Maritime Continent precipitation departures into the Indian Ocean. The presence of opposing western and central Pacific Ocean SST anomalies implies that an SST gradient exists in the western-central Pacific Ocean. Here, we assess whether an enhanced gradient between the western and central Pacific Oceans over the region of 140°–150°E is related to a modified ENSO response with closer correspondence to seasonal-to-interannual Indian Ocean convection.

During strong western Pacific SST gradient occurrences, the convection response to ENSO (Fig. 9a) over the Maritime Continent extends farther westward into the Indian Ocean than the total case (Fig. 4b). This is evidenced by the presence of the −9 W m⁻² OLR contour at 90°E in the strong gradient case as opposed to 115°E in the total case. During the moderate (Fig. 9c) and weak gradient (Fig. 9e) occurrences, larger OLR values do not penetrate as far into the Indian Ocean during ENSO. The area-averaged OLR regression to ENSO over the eastern Indian Ocean region of 15°S–5°N and 80°–110°E is displayed as the blue curve in Fig. 10 as a function of western Pacific SST gradient strength. Also shown in Fig. 10 are the area-averaged OLR regressions to seasonal-to-interannual Indian Ocean convection (green line) and to ENSO for all days (red line). The OLR regression to ENSO for the top 15% of western Pacific SST gradient occurrences are not significant to \( p < 0.05 \) over the Indian Ocean and are therefore not shown in Fig. 10. Area-averaged eastern Indian Ocean OLR associated with ENSO has the largest magnitudes during the strongest western Pacific Ocean SST gradient occurrences. Eastern Indian Ocean OLR is strong for the top 40% of western Pacific SST gradient occurrences but decreases considerably in the range of 40%–70%. This analysis indicates that Indian Ocean convection is enhanced during ENSO periods when the western Pacific SST gradient is strong.
Modifications to both the Northern Hemisphere circulation and extratropical vertical motions over Asia are observed during instances of strong western Pacific SST gradients associated with ENSO (Fig. 9). During strong western Pacific SST gradient occurrences, Asian tropospheric subsidence strengthens, as evidenced by increases in positive OLR values of 5 W m$^{-2}$ over the region 25$^\circ$–40$^\circ$N and 40$^\circ$–70$^\circ$E (Fig. 9a) relative to the total case (Fig. 4c). The magnitude of 200-hPa streamfunction during the strong western Pacific SST gradient occurrences strengthens considerably over Northern Africa, the Middle East, and Asia and maintains the zonally symmetric Northern Hemisphere circulation pattern (Fig. 9b) relative to when all western Pacific SST gradient occurrences are considered (Fig. 4c). When the selection criteria for the western Pacific SST gradient is relaxed, for example, during the moderate and weak cases, the magnitudes of Northern Hemisphere 200-hPa streamfunction (Fig. 9d,f) are weaker relative to the strong western Pacific SST gradient case (Fig. 9b). Thus, the strength of the western Pacific Ocean SST gradient is also a link between the influences of ENSO and the global circulation.

The SST associated with ENSO as a function of the western Pacific Ocean SST gradient is displayed equatorially (Fig. 11d) and in the aggregate (Figs. 11a–c) over the Indo-Pacific Ocean. Strong SST modifications are observed over the western Pacific Ocean and over the warm water flanks to the northwest and southwest of the central Pacific cold tongue (Figs. 11a–c). Over the central Pacific, there is very little change in ENSO-related SST patterns and magnitudes (Figs. 11a–c). Over the equatorial western Pacific, centered near 140$^\circ$E, there are large changes in SST as a function of the western Pacific SST gradient (Fig. 11d), whereas elsewhere the changes are minimal. Therefore, modifications to the western Pacific SST gradient, which serve as a link between ENSO and seasonal-to-interannual Indian Ocean convection, are driven primarily by SST over the western Pacific, particularly near 140$^\circ$E.

We test whether ENSO magnitude alone is responsible for a westward extension of the ENSO-related Maritime Continent precipitation into the Indian Ocean (Fig. 12). For ENSO events in the aggregate, as opposed to the daily analysis performed here, Hoell and Funk (2013, manuscript submitted to J. Climate) showed that strong departures in SST over the eastern-central Pacific and strong magnitudes of the western Pacific SST gradient are not mutually inclusive. Therefore, events characterized by a strong western Pacific gradient need not be a strong ENSO as measured by area-averaged SST departures over the tropical Pacific. Modifications to the ENSO-related tropical Indo-Pacific convection and upper-tropospheric circulation are observed as a
FIG. 7. Correlation between 5-day lagged precipitation and (left) intraseasonal Indian Ocean convection and (right) the amplitude of the MJO. Significance was assessed using a Student’s t test and insignificant correlations ($p > 0.05$) are shaded in gray.
FIG. 8. Correlation between precipitation and (left) seasonal-to-interannual Indian Ocean convection and (right) Niño-3.4 index. Significance was assessed using a Student’s $t$ test and insignificant correlations ($p > 0.05$) are shaded in gray.
function of ENSO magnitude. Strong ENSO magnitudes are associated with a stronger Indo-Pacific convection seesaw between the Maritime Continent and central Pacific (Fig. 12a,c,e) and a stronger and more continuous upper-tropospheric teleconnection over Asia, North America, Northern Africa, and the Middle East (Fig. 12b,d,f). While the magnitude of Maritime Continent convection response increases as a function of stronger ENSO, the western edge of convection does not extend westward into the Indian Ocean (Fig. 12a) as during the case of a strong western Pacific SST gradient (Fig. 9a). Therefore, the relationship between ENSO events with an enhanced western Pacific SST gradient and the westward extension of the Maritime Continent convection anomalies in the Indian Ocean is primarily caused by the SST gradient rather than ENSO magnitude for individual days.

5. Summary and discussion

Vigorous deep tropical convection over the Indo-western Pacific Ocean during November–April leads to intense diabatic heating, a main driver of the climate system (Dickinson 1971a,b; Schneider 1977; Schneider
and Lindzen 1977). November–April Indian Ocean convection has been primarily investigated in terms of the leading climate modes, MJO and ENSO, for the Indo-Pacific domain as a whole. To isolate the influence of Indian Ocean convection on the regional climate, Hoell et al. (2012) examined the Asian circulation and thermodynamic forcing of precipitation associated with the intraseasonal and seasonal-to-interannual components of the leading Indian Ocean convection pattern during November–April. Here, we expanded on our previous analysis and examined the Northern Hemisphere precipitation and circulation associated with the leading patterns of intraseasonal and seasonal-to-interannual Indian Ocean convection and compared those results with the circulation and precipitation associated with the MJO and ENSO, respectively, during November–April.

The correspondence between intraseasonal Indian Ocean convection (Fig. 1) and the MJO (Fig. 2) is strong with respect to tropical Indo-Pacific convection patterns and the hemispheric circulation. Over the tropical Indo-Pacific, the convection patterns for both intraseasonal Indian Ocean convection (Fig. 1a) and the MJO (Fig. 1b) are heavily concentrated over the eastern Indian Ocean, resembling the leading pattern of Indian Ocean precipitation for November–April (Hoell et al. 2012). Over Asia, the Rossby wave responses are subtropically oriented and baroclinic in form associated with the MJO (Barlow et al. 2005) and intraseasonal Indian Ocean convection (Hoell et al. 2012). Over the entire Northern Hemisphere, the upper-tropospheric circulation associated with intraseasonal Indian Ocean convection (Fig. 1c) and the MJO (Fig. 2c) are also very similar.

The similarities between seasonal-to-interannual Indian Ocean convection (Fig. 3) and ENSO (Fig. 4) are substantial, but noticeable differences are apparent in the Maritime Continent component of Indo-Pacific convection. Over the Maritime Continent, the magnitude and patterns of seasonal-to-interannual Indian Ocean

![Graph](https://example.com/graph.png)

**FIG. 10.** Area-averaged OLR regression over 15°S–5°N and 80°–110°E to (blue) ENSO as a function of western Pacific SST strength, (green) seasonal-to-interannual Indian Ocean convection, and (red) the Niño-3.4 index.

![Graph](https://example.com/graph2.png)

**FIG. 11.** Regression between daily Niño-3.4 index and (a),(b),(c) SST regression. (d) SST regression averaged over 5°S–5°N. The longitude region of the western Pacific SST gradient magnitude used to determine the strong, moderate, and weak days described in Fig. 9 is shaded. Significance was assessed using a Student’s *t* test and insignificant regressions (*p* > 0.05) are shaded in white.
convection (Fig. 3b) and ENSO-related convection (Fig. 4b) are similar; however, seasonal-to-interannual convection extends considerably farther westward into the Indian Ocean by 20°. The leading pattern of Indian Ocean precipitation, as calculated by the first EOF of November–April 1979–2008 precipitation, indicates that the three strongest precipitation seasons during that period were 2007/08, 1999/00, and 1983/84 (Hoell et al. 2012). Seasonal OLR anomalies over the Indo-Pacific during each of these three strong seasons (Fig. 5) are similar and closely resemble seasonal-to-interannual Indian Ocean convection (Fig. 3b). Because each of these November–April seasons were characterized by SST consistent with La Niña, this indicates that the strong Indian Ocean pattern of ENSO can play the primary role in determining the anomaly pattern of individual seasons.

Barlow et al. (2002) showed that ENSO-related Maritime Continent precipitation anomalies shift westward into the Indian Ocean in the presence of a strong western Pacific Ocean warm pool, where the sign of the western and central Pacific Ocean SST oppose one another. The presence of strongly opposed SST anomalies between the western and central Pacific Ocean implies the presence of an enhanced SST gradient. Here, we tested whether an enhanced zonal SST gradient over the region 140°–150°E during ENSO was linked to modifications in the location of Maritime Continent convection and in global circulation. When the SST gradient was enhanced over 140°–150°E, ENSO-related Maritime

Fig. 12. As in Fig. 9, but during occurrences of the Niño-3.4 index. Strong, moderate, and weak occurrences of the Niño-3.4 index include days in which the index falls into the top 20%, 40%, and 60% of days on record.
 Continent convection extended farther westward into the Indian Ocean (Fig. 9a,c,e), and there were noticeable increases in the magnitude of Northern Hemisphere Rossby waves (Fig. 9b,d,f). The physical and dynamical influences of an enhanced western Pacific SST gradient during ENSO have yet to be fully investigated. Characterizing ENSO events through western Pacific SST gradient magnitudes may have implications for tropical and extratropical circulation predictability.

Over southern Asia, a large Rossby wave is related to seasonal-to-interannual Indian Ocean convection (Fig. 3c) and ENSO (Fig. 4c). Over the rest of the Northern Hemisphere, a zonally symmetric equivalent barotropic streamfunction signal (Fig. 6), extending throughout much of the Northern Hemisphere from the North Pacific Ocean eastward to Europe and passing through the United States and the Atlantic Ocean, is related to both seasonal-to-interannual Indian Ocean convection (Fig. 3c) and ENSO (Fig. 4c). ENSO conditions are related to modifications of the Northern Hemisphere circulation (e.g., Hoerling et al. 1997; Trenberth et al. 1998) and Rossby ray propagation (Shaman and Tziperman 2005) during winter. In light of the similarities between the circulation relationships related to both ENSO and seasonal-to-interannual Indian Ocean convection, a stationary Rossby wave propagation mechanism with origins over the eastern Indian Ocean and Maritime Continent was investigated. Using the Rossby wave ray tracing method of Shaman and Tziperman (2005), stationary Rossby rays forced by the November–April climatological upper-tropospheric flow at 200 hPa originate over the eastern Indian Ocean and Maritime Continent, propagating throughout the Northern Hemisphere in paths either over the extratropics or subtropics (Fig. 6a).

Regional precipitation modifications over Asia and eastern Africa are related to intraseasonal and seasonal-to-interannual Indian Ocean convection. Intraseasonal (Fig. 7) and seasonal-to-interannual (Fig. 8) Indian Ocean convection are related to precipitation over Asia, eastern Africa, and portions of India and may be a better predictor of precipitation than the MJO and ENSO, respectively.

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