The Northward-Propagating Intraseasonal Oscillations in the Northern Indian Ocean during Spring–Early Summer

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ABSTRACT

The intraseasonal oscillations (ISOs) activate in the tropical Indian Ocean (IO), exhibiting distinct seasonal contrasts in active regions and propagating features. The seasonal northward migration of the ISO activity initiates in spring–early summer, composed of two stages. Strong ISO activity first penetrates into the northern Bay of Bengal (BoB) around mid-April, and then extends to the northern Arabian Sea (AS) by mid-May. The northward-propagating ISOs (NPISOs) during their initiation periods, which are referred to as the primary northward-propagating (PNP) events, are analyzed with regard to the BoB and the AS, respectively. In terms of the BoB PNP event, the northward branch could be observed only in the BoB, and the eastward movement is still clear as the winter ISOs. For the AS PNP event, a strong northward branch spreads across the wider northern IO, as obvious as the summer ISOs. The relative roles of the seasonal environmental fields in modulating the PNP events are diagnosed based on a 2.5-layer atmospheric model. The results indicate that the seasonal variations of the surface moisture dominantly regulate the BoB PNP event, while both the surface moisture and the vertical wind shear are necessary for the AS PNP event. Additionally, the leading BoB PNP event is hypothesized to potentially act as a precondition of the following AS PNP event in terms of their internal ISO reinitiation processes and in terms of creating a favorable easterly shear environment in the northern IO.

1. Introduction

The intraseasonal oscillation (ISO) is one of the dominant low-frequency signals in the tropical atmosphere (Madden and Julian 1971, 1972). This oscillation, consisting of large-scale coupled atmospheric circulation and deep convection, actively propagates in the warm Indian Ocean (IO) and Pacific Ocean. ISOs play fundamental roles in regulating the weather and climate systems both in the tropics and in the extratropics (Zhang 2013).

Seasonality is one of the salient features of ISOs, which are typically recognized by their two distinct modes. During the boreal winter, ISOs are active in the near-equatorial regions with maxima appearing south of the equator (Wang and Rui 1990; Bellenger and Duvel 2012). Those convective systems coupled with the strongest baroclinic circulation disturbances move eastward at approximately 5 m s⁻¹ in the Eastern Hemisphere (Zhang 2005) and prefer a zonal wavenumber-1 structure (Li and Zhou 2009). The winter mode potentially interacts with tropical cyclones (Maloney and Hartmann 2000), Australian summer monsoon (Hendon and Liebmann 1990), and El Niño (Kessler 2001). In the boreal summer, ISO activity migrates northward and maxima are found in the Asian monsoon regions. A prominent northward propagation appears over the northern IO and a northwestward propagation appears in the western North Pacific (Yasunari 1979; Wang and Rui 1990). The summer mode significantly influences the Asian monsoon (Qi et al. 2009) and tropical cyclone activity (e.g., Liebmann et al. 1994; Camargo et al. 2009; Hsu and Li 2011).

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The striking seasonality of ISOs is largely attributed to their distinct seasonal environmental modulations. In terms of the ISO dependence on environmental states, Zhang and Dong (2004) found strong ISO activities prefer those regions with low-level background westerlies and moisture convergence. Based on observations and model experiments, Wu et al. (2006) suggested the seasonal difference of the ISO meridional propagation is driven by the distinct contrasts of the background vertical wind shear and the static stability fields. Adames et al. (2016) further explained the eastward (northward) propagation of the ISO winter (summer) mode in relation to the seasonal mean states with a focus on low-level flows and moisture distributions. Using a 2.5-layer atmospheric model, Lu and Hsu (2017) argued that the seasonal variation in low-level moisture (vertical wind shear) is the key environmental factor affecting the ISO strength (propagation).

Now, how does the seasonal transition from the equatorial-trapped eastward-moving winter mode to the pronounced northward-propagating summer mode occur in the tropical IO? Here, spring appears impactful in terms of the ISOs characteristics. Bearing some resemblances to the winter mode (Fig. 1a), a significant eastward propagation exhibits in the tropical IO during spring, even though the ISO activity is very symmetric about the equator (Fig. 1b). Meanwhile, an evident northward bifurcation in the Bay of Bengal (BoB) shares many common features with, as well as some distinctions from, the summer mode, whose northward movement spreads not only to the BoB but also to the Arabian Sea (AS) (Fig. 1c).

Considering the significance of summer ISOs, much attention has been paid to their northward-propagating mechanisms, of which the summer environmental fields are regarded as necessary controlling factors. Based on the summer mean dynamic and thermodynamic states, many northward-propagating mechanisms are proposed, including land–atmosphere interactions (Webster 1983), ocean–atmosphere interactions (Kemball-Cook and Wang 2001; Fu et al. 2003), and internal atmospheric dynamics.

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**Table 1. Selected parameters in the model.**

| Parameter                                      | Value      |
|------------------------------------------------|------------|
| Pressure at the top of the boundary layer (hPa) | 900        |
| Pressure at the top of the free atmosphere (hPa) | 100        |
| Rayleigh friction coefficient (s⁻¹)             | 1 x 10⁻⁶   |
| Newtonian cooling coefficient (s⁻¹)             | 1 x 10⁻⁶   |
| Dissipation coefficient in the boundary layer (s⁻¹) | 3.5 x 10⁻⁵ |
| Horizontal diffusion coefficient (m² s⁻¹)       | 8 x 10⁵    |
| Precipitation efficiency coefficient            | 0.85       |
| Mean static stability parameter at the middle level (m² s⁻² Pa⁻²) | 3 x 10⁻⁶ |
| Density scale height/water vapor density scale height | 3.45      |

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**Fig. 1.** RMSs of the intraseasonal OLR anomalies (W m⁻²) and the propagation vectors in (a) December, January, and February; (b) March, April, and May; and (c) June, July, and August. The propagation vectors, which are calculated based on 3-day lead-lag correlation maps of the intraseasonal OLR, represent the movement directions of localized OLR anomalies (Li 2014).

**Fig. 2.** Time–latitude cross sections of the 31-day running RMSs of the intraseasonal OLR anomalies (shaded, W m⁻²) along (a) the BoB section of 80°–100°E and (b) the AS section of 60°–75°E. The contours represent the vertical wind shear between 200 and 850 hPa (U200 – U850; contour interval is 8 m s⁻¹).
such as vertical-shear-induced meridional vorticity asymmetry (Jiang et al. 2004; Drbohlav and Wang 2005), meridional vorticity advection (Bellon and Sobel 2008), and convective momentum transport (Kang et al. 2010). However, compared with the northward-propagating ISOs (NPISOs) in summer, the events in their initiation periods of spring–early summer have received little attention so far. Indeed, the NPISOs in the initiation periods significantly modulate the monsoon onsets (Goswami 2005; Tong et al. 2009; Li et al. 2013; Wang et al. 2018) and tropical cyclones (Kikuchi et al. 2009; Li et al. 2016) in the Asian monsoon regions.

The present work aims to investigate the NPISOs during their initiation periods of spring–early summer and try to address the following questions: What are the characteristics of the NPISOs in the initiation period? What causes the initiation of the NPISOs in the northern IO? How can the stepwise northward propagation of the ISO, which first occurs in the BoB and further extends to the AS, be understood? The rest of the paper is organized as follows: The data and methods used in the analysis are described in section 2. Sections 3–5 provide the results of the three aforementioned scientific issues. A discussion and summary are presented in the last section.

2. Data and methods

The observed daily outgoing longwave radiation (OLR) (Liebmann and Smith 1996) from the National
Oceanic and Atmospheric Administration (NOAA) is adopted as a proxy for convection. The daily atmospheric fields, including horizontal winds, vertical pressure velocity, air temperatures at 850 and 200 hPa, and surface specific humidity are derived from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996). The temporal interval of the above data spans from 1979 to 2016. Based on the NCEP–NCAR reanalysis data, a low-frequency climatology is constructed in preparation for the model study. The original daily data are first processed with a 75-day low-pass filter to remove the high-frequency signals and then averaged according to the calendar date to yield the low-frequency climatology.

An intermediate atmospheric model, which consists of a two-level free atmosphere and a well-mixed boundary layer (Li and Wang 1994; Wang and Xie 1997), is employed to investigate the environmental modulations on the ISO. The model covers the global tropics between 40°S and 40°N with a spatial grid of 5° longitude × 2° latitude resolution. A salient feature of this simple model is that the model can be flexibly used to estimate the ISO response to a specified mean state. Table 1 illustrates some model parameters in the present study, and details of this model can be found in Wang and Xie (1997).

The observed ISO is represented by the 20–70-day bandpass-filtered OLR anomaly, and its intensity is indicated by the root-mean-square (RMS) of the OLR anomaly. To denote the intensity of the ISO in the model, the accumulated precipitation caused by the initial perturbation is used.

3. Composite characteristics of NPISOs in the initiation periods

As illustrated in Fig. 1, significant NPISOs are observed over the northern BoB in spring and are absent in the northern AS, except in summer. A further detailed analysis is conducted focusing on the sections along BoB (80°–100°E) and AS (60°–75°E) (Fig. 2). Note that strong ISO activity is observed along both sections throughout the year, exhibiting clearly seasonal evolutions. The seasonal northward migration (SNM) from the equatorial region is found during spring–early summer. As noted above, the SNM of ISO activity does not initiate concurrently in the wider southern Asian monsoon regions. In mid-April, strong ISO activity extends to the northern BoB (north of 10°N). This type of activity is then observed in the northern AS by approximately mid-May. Thus it suggests that the ISO events occurring between these two times behave differently from the summer events, which usually sweep northward to the wider southern Asian monsoon regions, including not only the BoB but also the AS. Considering the aforementioned uniqueness, the period of 10 April–15 May (AM; 36 days) is selected as the initiation period of the NPISOs in the BoB, during which the northward branches only appear in the BoB. Similarly, the period of 15 May–19 June (MJ; 36 days) is defined as the initiation period of the NPISOs in the AS. Next, the characteristics and mechanisms of the NPISOs will be addressed regarding the two initiation periods. An earlier hint of the difference may be observed in the vertical wind shear, which is regarded as a vital background condition for the northward propagation (e.g., Jiang et al. 2004). Compared with the BoB, SNM of ISO activity in the AS is more sensitive to the establishment of the easterly vertical shear (Fig. 2b). Additional discussion is presented in the next section.

The temporal and spatial evolutions of the ISO events in the initiation periods are extracted based on EOF analysis, which has been widely used in ISO studies (e.g., Matthews 2000; Huang et al. 2011). EOF analysis is performed on the 20–70-day bandpass-filtered OLR over the domains of 30°E–180° and 25°S–25°N for AM and MJ, respectively. The principal components (PCs) of the EOFs are normalized by one standard deviation of each component, and the standard deviations are multiplied to the corresponding spatial modes. The first two EOF modes display a quadrature phase relationship, representing a propagating wave phenomenon. Based on these two modes, the amplitude and phase of an ISO event can be expressed as \{PC1(t)^2 + PC2(t)^2\}^{1/2} and \tan^{-1}[PC2(t)/PC1(t)]\), respectively. A day when the amplitude is greater than 1 is defined as a strong ISO day. Then, the entire cycle of the ISO is constructed based on the strong ISO days and the eight phases described in Wheeler and Hendon (2004).

Figure 3 shows the patterns of the two leading EOF modes in AM and MJ. In both initiation periods, EOF1...
(Figs. 3a,b) exhibits significant convective anomalies over the tropical IO, explaining approximately 17% of the total variances of the filtered OLR. Although the EOF2 (Figs. 3c,d) explains similar amounts (approximately 9%) of the total variances in both periods, this function shows a striking difference in the spatial patterns, particularly in the southern Asian monsoon regions. In AM, a noticeable convective anomaly is mainly located in the BoB. However, at the start of MJ, the convective anomaly dominates a wider region, including the BoB, the AS, and the Indian subcontinent.

The lead–lag correlations between the PC1 and PC2 values (Figs. 3e,f) for both initiation periods are shown in Fig. 4. The maximum correlations occur when the PC1 leads/lags the PC2 by 8 days, wherein correlation coefficients reach approximately 0.6. Thus, the
oscillation period described by EOF1 and EOF2 should be approximately 32 days, and each phase lasts for 4 days.

Figure 5 illustrates the composite spatial–temporal evolutions of ISO events in the two initiation periods. For simplicity, the two life cycles are referred to as the primary northward-propagating (PNP) events in the BoB and AS. For both PNP events, the tropical IO is largely controlled by the suppressed convection in phase 1 and organized convection forms in phase 3. In phases 4–6, the convection strengthens and dominates the tropical IO, whereas the two events behave differently. For the BoB PNP event, the convection is generally trapped in the equatorial regions with notable eastward movement. A distinct northward branch is only observed in the BoB when the major convection arrives at the eastern IO. To a certain extent, the above evolution resembles the winter ISOs, except for the significant BoB convection. In contrast, the AS PNP event exerts more meridional propagating components and weak eastward movement. The distinct northward propagation of an elongated northwest–southeast convective band in the wider southern Asian monsoon regions has the major characteristics of the summer ISOs.

4. Environmental modulations on the PNP event

The striking seasonality of the ISOs is largely due to the distinct seasonal environmental modulations. Among these, the vertical shear of zonal wind and the boundary layer moisture are considered to be the critical dynamic and thermodynamic environmental factors (e.g., Wang and Xie 1997; Wu et al. 2006; Lu and Hsu 2017). Next, the roles of the zonal wind and the boundary layer moisture, and those of some other environmental factors in modulating the PNP events, are investigated using a simple 2.5-layer atmospheric model (Wang and Xie 1997). The model has been used to examine the characteristics of ISOs in winter (Deng and Li 2016) and summer (Wang and Xie 1997; Jiang et al. 2004; Liu et al. 2016) and the equatorial wave dynamics (Wang and Chen 2016, 2017). First, we confirm the model’s performance in capturing the SNM of ISO activity (Fig. 2) and the major characteristics of the PNP events in the BoB and the AS (Fig. 5).

Under varying mean states, the same initial perturbations are specified to have a theoretical Kelvin wave structure (Fig. 6). The initial location is centered at 70°E on the equator. This point refers the place where the observed convection forms in the IO (phase 3; Fig. 5a). The initial wind is purely zonal and has a cosine shape with a zonal length of 4000 km. Although the perturbation has a pure Kelvin wave structure initially, it quickly develops into an ISO-like structure because of the convective heating generated in the midtroposphere. To represent the ISO intensity in the model, the accumulated precipitation induced by the initial perturbation is used. A sensitivity test shows the precipitation associated with the initial perturbation vanishes approximately 16 days afterward in our specific Asian monsoon regions (Fig. 7). Therefore, the precipitation accumulated in the first 16 days is used arbitrarily to represent the ISO intensity in the model experiments.

To assess the model’s ability to represent the SNM of ISO activity during spring–early summer, a series of model experiments are carried out at a pentad interval from March to June. The modeled ISO intensity is given in Fig. 8, wherein it is compared with the observations along the BoB and AS sections. Generally, the model results are quite similar to the observations in both the temporal and meridional directions for both sections. In the BoB, the SNM of ISO activity starts in April and the strongest activity appears in the central area around mid-May in the observations. These observational features are well reproduced in the model results (Fig. 8a).
For the AS section, the model also reproduces the observed SNM of ISO activity that starts in May, although few differences exist between the locations of the maximum intensities at the beginning of June from the model and those observed. Basically, the model successfully captures the two-step SNM of ISO activity in the northern IO during spring–early summer.

Further experiments are conducted to validate the model’s ability to resolve the features of the two PNP events, particularly their evolutions in the southern Asian monsoon regions. Figure 9 illustrates the simulated evolutions of the perturbations with regard to three different mean states: January, AM, and MJ. Given the initial Kelvin wave perturbation, the Kelvin–Rossby wave couplet associated with the ISO is clearly observed on day 2 with an equatorial Kelvin wave cell to the east and two off-equatorial Rossby wave cells to the west of the heat source. In the following days, the coupled Kelvin–Rossby wave packet generally propagates eastward along the equator, whereas distinct meridional contrasts appear because of the asymmetric developments of the two off-equatorial Rossby wave cells. Under the January mean state, the southern cell develops much stronger than its northern counterpart. A zonal rainband is generated between 10° and 20°S in the southern IO, while almost no precipitation is induced in the Asian monsoon regions. For the AM mean state, the two Rossby wave cells appear comparable in both hemispheres. Note that strong precipitation starts to be generated in the northern BoB when the major convection reaches the Maritime Continent on day 4. Over the subsequent days, the precipitation mainly develops in the BoB, and little emerges in the northern AS. This evolutionary pattern catches the salient features of the BoB PNP event. For the MJ mean state, the northern Rossby wave cell quickly develops to become stronger than its southern counterpart, and a northwest–southeast-oriented rainband forms in the southern Asian monsoon regions on day 4. The subsequent evolution of the rainband largely resembles the AS PNP event. Therefore, the above evidence suggests the model is capable of describing the general evolutionary features of the two PNP events in the northern IO.

As mentioned previously, the model performances shown in Figs. 8 and 9 give us confidence to conduct further analyses regarding the mechanisms of PNP events, that is, how and to what extent certain environmental fields cause the PNP events. There are five environmental fields prescribed in the model, that is, the horizontal winds \((u, v)\) at the upper and lower levels, vertical wind \(w\) and air temperature \(T\) at the middle troposphere, and moisture \(q\) at the sea surface. Their relative importance is assessed through model experiments, including three control runs and a series of sensitivity runs (Table 2). Here, three control runs are designed under the mean state of January, AM, and MJ (Fig. 10). The January run (CR1), in which the ISO behavior as that of the winter mode, is selected as a reference experiment. Additionally, the control runs for the mean states of AM (CR2) and MJ (CR3) represent the PNP events in the BoB and AS, respectively. The sensitivity runs of SR1–SR5 (SR6–SR10) attempt to clarify the relative roles of the individual environmental field in inducing the ISO transitions from the winter mode to the PNP event in the BoB (AS). In the
sensitivity runs, one of the environmental fields is set as the January mean (Jan), while the other four match those of the corresponding control run. Therefore, by comparing the ISO intensity of the sensitivity run with that of the corresponding control run, one can estimate the importance of a certain environmental field in causing the PNP event.

As demonstrated in Fig. 11, when the ISO behaves as does the winter mode in January, its intensity is very weak in the BoB and AS regions. During AM (MJ), the ISO intensity suddenly increases over the BoB (AS) when the PNP event occurs. Given the above transition in the BoB, the moisture effect can be inferred to play a dominant role because the ISO intensity in AM would substantially decrease by approximately 70% when we fix the surface moisture to the January mean (SR1). The zonal wind effect is secondary but appears to be much weaker. The ISO intensity in AM decreases by only approximately 30% when we fix the zonal wind to the January mean (SR2). In the AS, the moisture effect also dominates the PNP event. The ISO intensity in MJ significantly decreases by approximately 70% when we fix the surface moisture to the January mean (SR6). Distinct from the BoB, the zonal wind effect acts comparably to that of the moisture effect in terms of the PNP event in the AS. The ISO intensity in MJ decreases by approximately 60% when we fix the zonal wind to the January mean (SR7). Generally, the other three environmental fields seem to be less effective for controlling the occurrences of PNP events in both regions.

The above model results suggest that the boundary layer moisture and the zonal wind are critical environmental fields for causing the ISO seasonal transition. The AS PNP event is sensitive to both fields, while the BoB PNP event is predominantly sensitive to the moisture field. Indeed, it is the vertical shear of the zonal wind that significantly modulates the ISO activity through tropical wave dynamics. An easterly shear environment could enhance the lower-tropospheric Rossby wave response (Wang and Xie 1996), leading to greater perturbation growth through convection–circulation–moisture feedback (Li 2006; Ge et al. 2007). The increase in mean
moisture, as well as its eastward gradient, is found to be favorable for the ISO growth (Hsu and Li 2012; Sobel and Maloney 2013; Zhao et al. 2013; Liu and Wang 2016). In January (Fig. 10a), the moisture concentrates in the Indo-Pacific warm regions with high values located slightly south of the equator. The easterly shear dominates the zonal band as far as 15°S, spanning the IO–western Pacific. Thus, while the major convection moves eastward along the equator, abundant moisture together with the favorable easterly shear induce a convective tail associated with the southern Rossby wave cells (Fig. 9a). In AM (Fig. 10b), the surface moisture significantly increases in the southern Asian monsoon regions, and a high center clearly forms in the northern BoB. Though the easterly shear is still confined to the south of 10°N at this time, the abundant moisture supply itself is enough to excite the northern Rossby wave cell through surface friction–induced moist convergence (Lawrence and Webster 2002), resulting in strong convection within the northern BoB (Fig. 9b). However, in the northern AS, an unfavorable shear effect and an insufficient moisture supply suppress the Rossby wave development. In MJ (Fig. 10c), high moisture contents are already available in the Asian monsoon regions, particularly in the AS and BoB. Additionally, the easterly shear covers the wide monsoon regions with its northern bound shifting to 20°N. Under these favorable environmental fields, the Rossby wave cell is substantially activated in the northern IO, and a clear northwest–southeast-oriented rainband is induced in the wider southern Asian monsoon regions (Fig. 9c).

5. Possible links between the two PNP events

From the occurrence of the PNP event in the BoB to that in the AS one month later, how do we understand the stepwise evolution of NPISOs? In this section, we try to clarify the intrinsic relationship between the two events. First, one can be inferred from the succession of ISO events. A time lag of 1 month is generally in agreement with the period of the spring ISOs (32 days; Fig. 4); that is, the AS PNP event may be in the ensuing neighborhood of the BoB PNP event because of ISO reinitiation. Second, the BoB PNP event may precondition the subsequent AS PNP event by creating favorable environmental conditions, such as an easterly vertical shear in the northern IO.

To verify the first assumption, the spring ISO events along the BoB and the AS sections are examined each year from 1979 to 2016 (Fig. 12). The green ellipses (purple parallelograms) approximately signify the first significant NPISOs in the BoB (AS) in each year. Generally, in most years (the 27 years enclosed by blue boxes in the upper-left corner of the panels in Fig. 12), the BoB PNP events clearly lead the AS PNP events, and the ensuing events appear concurrently with the AS PNP events. Considering the previous ISO event may influence the initiation of the following event through dynamic and thermodynamic processes (Jiang and Li 2005;
Zhao et al. (2013), the above observations imply the underlying relationship between the two PNP events.

To reveal the second possible link, both the model experiments and observations are used in the analysis. In AM, when the PNP event occurs in the BoB, the convection is very weak in the northern AS compared with that for the MJ mean state. Now, for the transition from AM to MJ, which environmental fields play the major role in enhancing the ISO convection in the northern AS? Similar to the technique used in the previous section, five sensitivity runs (SR11–SR15) are conducted based on the 2.5-layer model. From the results shown in Fig. 13, it can be inferred that the zonal wind effect plays a dominant role because the ISO intensity in the MJ period would substantially decrease by approximately 50% when we fix the zonal wind to the AM mean (SR12). In AM, the easterly shear is confined to those regions south of 10°N; thus, the ISO convection is dramatically suppressed in the northern AS until the easterly shear dominates the wider southern Asian monsoon regions during MJ. Therefore, the significant northward expansions of the easterly shear during the two periods are primarily responsible for the occurrence of the PNP event in the AS region. Next, we will show that the creation of the easterly shear in the northern IO is closely associated with the BoB PNP event.

The NPISOs have been shown to act as the critical trigger of southwest monsoon flows in the BoB (e.g., Wang 2006, 61–62; Li et al. 2013). The composite based on the BoB PNP events in Fig. 12 further deepens this understanding. As illustrated in Fig. 14, the westerly winds burst and extend northward to 20°N accompanied by the convective phase of the BoB PNP event. Around this time, the convection along the AS section is still confined to the equatorial regions (10°S–10°N). Actually, the wind response to the convection occurs in the wider northern IO instead of within the local BoB. The easterly shear builds in the northern IO concurrently with the BoB PNP event (Fig. 15). When the new convection initiates at about day 30, the favorable environment induces a significant northward propagation in the wider northern IO (i.e., the AS PNP event occurs).

For the climatological two-step evolution of NPISOs in the northern IO during spring–early summer, the underlying physical links are revealed using observations and model experiments. The results suggest that the leading BoB PNP event may drive the following AS PNP event through internal ISO reinitiation processes and by creating a favorable easterly shear environment. During spring, the seasonal increase of the surface moisture in the northern BoB acts as the primary environmental factor in exciting the Rossby wave cell...
associated with the equatorial convection, and thereby induces the occurrence of the BoB PNP event. This convective disturbance interacts with the complex land–ocean–atmosphere conditions and triggers the BoB southwestern monsoon flows as well as the easterly shear in the wider northern IO. Therefore, when the subsequent ISO event is generated in the equatorial region because of some reinitiation processes, the favorable environment substantially activates the northern Rossby wave cell, and strong convection is caused in the northern IO, including the AS region.

6. Summary and discussion

Pronounced seasonality is one of the fundamental features of tropical ISOs. In the tropical IO, the ISO...
events are dominated by an equatorially trapped eastward-propagating mode in winter and a distinct northward-propagating mode in summer. This paper focuses on the mode transition from winter to summer in the northern IO. Climatologically, the SNM of ISO activity initiates in spring–early summer composed of two stepwise stages. Strong ISO activity first penetrates into the northern BoB around mid-April and then extends to the northern AS by mid-May. The ISO events in the two initiation periods, which are referred to as the PNP events, are analyzed for their characteristics, mechanisms, and possible links.

Based on EOF analyses, the evolutionary characteristics of the two PNP events are constructed. For the BoB PNP event, the convection is generally trapped in the equatorial regions with a remarkable eastward movement. A distinct northward branch is only observed in the BoB when major convection arrives in the eastern IO. Generally, the evolution resembles that of the winter ISOS, except for the significant BoB convection. On the other hand, the AS PNP event has many meridional propagation components and a weak eastward movement. After the organized convection forms in the central IO, a striking northward propagation of an elongated northwest–southeast convective band in the wider southern Asian monsoon regions takes on the major characteristics of the summertime ISOS.

The roles of the seasonal environmental fields in modulating the PNP events are diagnosed based on a 2.5-layer atmospheric model. The model results show that, in comparison with the winter states, the changes in the surface moisture and the zonal wind are critical factors for causing the ISO seasonal transition. The AS PNP event is sensitive to both fields, while the BoB PNP event is predominantly sensitive to the moisture field. During AM, the surface moisture significantly increases. A high center clearly forms in the northern BoB region. Though the easterly shear is still confined to south of 10°N, the abundant moisture supply itself is enough to excite the northern Rossby wave cell associated with the eastward-moving convection, thereby causing strong precipitation in the northern BoB. However, in the northern AS, the unfavorable vertical shear and the insufficient moisture supply suppress the Rossby wave development of this region. During MJ, high moisture concentrations are already found in the northern AS and BoB regions, and the easterly shear covers the wider monsoon regions such that its northern bound shifts to 20°N. Given these environmental fields, the Rossby wave cell associated with the equatorial convection is substantially activated in the northern IO, and a clear northwest–southeast-oriented rainband is induced in the wider southern Asian monsoon regions.

Finally, the possible intrinsic processes regulating the two-step evolution of NPISOs in the northern IO are documented. One link between the two PNP events lies in the internal ISO reinitiation processes. In most years (approximately 70% during 1979–2016), the AS PNP events appear concurrently with the ensuing ISO events of the BoB PNP events. Thus, a BoB PNP event may influence the initiation of an AS PNP event through internal dynamic and thermodynamic processes. Additionally, the BoB PNP event may precondition the subsequent AS PNP event by creating favorable
environmental conditions. The easterly shear field in the northern IO, which dramatically limits the convection development in the AS, extends sharply northward to approximately 20°N accompanied by the BoB PNP event. Therefore, when the subsequent ISO event is generated in the equatorial region because of reinitiation processes, the favorable environments of the northern IO substantially activate the northern Rossby wave cell, and strong convection extends to the northern AS.

The current understanding of the characteristics, mechanisms, and physical links of the two PNP events would potentially benefit from the study of the summer monsoon onset in southern Asia. Except for aforementioned close relationship between the BoB PNP events and the local summer monsoon onset (Fig. 14), the AS PNP events are also regarded as the critical triggers of the Indian summer monsoon onset (Fig. 13). In most years (except for 1982, 1998, 2002, 2004, 2007, 2010, 2012, and 2016), the Indian monsoon onset is concurrent with the AS PNP events. Climatologically, the monsoon onset in the Indian subcontinent lags the BoB by approximately 1 month (Wang and LinHo 2002). To a large extent, this time interval can be interpreted via the occurrence times of the two physically linked PNP events. In view of the recent advances in the prediction skill of ISOs (e.g., Fu et al. 2007; Neena et al. 2014), the present understanding of PNP events can be used to better predict the onset of the Asian summer monsoon. Considering some deficiencies in the simple intermediate model, the current findings require further modeling validation based on a better full-physics atmospheric GCM, such as ECHAM (Wang et al. 2017).

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**FIG. 15.** Composite time–longitude cross sections of the 20–70-day bandpass-filtered OLR anomalies (shaded, W m⁻²) at 10°–20°N in relation to (a) the zonal wind at 850 hPa (contours, m s⁻¹) and (b) the vertical wind shear (U₂₀₀ − U₈₅₀; contours, m s⁻¹). The time axis is the same as that in Fig. 14.
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