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# Regime shift in Indian summer monsoon climatological intraseasonal oscillations

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[1] Using a high resolution daily rainfall data over Indian continent between 1951 and 2004, summer monsoon climatological intraseasonal oscillations (CISO) and its regime shift around mid seventies is investigated. Explaining 20% −40% of intraseasonal oscillation (ISO) amplitude, the summer monsoon CISO represents a significant predictable component of the monsoon ISOs. Indian monsoon CISO is characterized by a dominant northward propagating episode in both pre-seventies (1951–75, pre75) and in the post-seventies (1979–04, post79). The dominant episode starts in the beginning of July during pre75 in contrast to beginning of June during post79 period. We find that the IAV of the initial phase of both the first and the second ISO episodes worked in tandem with the changes in the northward propagation speed in producing the phase locking for the second episode during pre75 while for the first episode during post79. Change in northward propagation speed is shown to be consistent with changes in easterly vertical shear and meridional gradient of low level humidity during the two climate regimes. **Citation:** Suhas, E., and B. N. Goswami (2008), Regime shift in Indian summer monsoon climatological intraseasonal oscillations, *Geophys. Res. Lett.*, *35*, L20703, doi:10.1029/2008GL035511.

## 1. Introduction

[2] Indian summer monsoon has vigorous intraseasonal oscillations (ISO) that manifest in the sub-seasonal active and break spells of monsoon rainfall. Long breaks of monsoon lead to large scale droughts [*Joseph et al.*, 2008]. Therefore, extended range prediction of monsoon ISO (namely, the active and break spells) is of utmost importance for water resource management of the country. Better understanding of the space-time characteristics of monsoon ISOs has led to development of Bayesian techniques for predicting these spells three to four weeks in advance [*Goswami and Xavier*, 2003; *Webster and Hoyos*, 2004; *Jones et al.*, 2004; *Chattopadhyay et al.*, 2008]. While these models have demonstrated useful skill for extended range prediction of monsoon ISOs, improvement of the skill is required for routine operational applications. Space-time characteristics of the monsoon ISOs include a fluctuating component with two dominant periodicities between 10–20 days and 30–60 days respectively with the 30–60 day mode propagating northward and eastward while the 10–20 day mode propagating westwards (see *Goswami* [2005a] for details). Even though there is considerable year-to-year variability of the monsoon ISOs, phase locking of some of these oscillations with the annual cycle leads to a climatological ISO (CISO) signal [*Lau et al.*, 1988; *Wang and Xu*, 1997; *Kang et al.*, 1999]. The CISO represents a predictable component of the monsoon ISO and could be exploited for improving skill of extended range prediction of the active and break spells.

[3] Any significant change in the character of the monsoon CISO would, therefore, result in change in predictability of the active-break spells. Both the convectively coupled monsoon ISOs and the annual cycle are modulated by the planetary scale background climate. Thus, any significant shift (or change) in the climate could influence the space-time characteristics of the ISOs as well as the monsoon annual cycle and hence could result in a shift (or change) in the monsoon CISO. A major shift in climate regime around mid seventies is well documented [*Zhang et al.*, 1997; *Deser et al.*, 2004; *Trenberth and Hurrell*, 1994; *Miller et al.*, 1994]. It has been shown [*Krishnamurthy and Goswami*, 2000; *Goswami*, 2004, 2005b] that the regional monsoon Hadley circulation and the Walker circulation have significant coherent variations with the interdecadal variability that results in the regime shift of Pacific climate in mid seventies. As a result of this significant change in the planetary scale climate during the two regimes, namely pre-seventies and post seventies, we may expect significant changes in the monsoon CISOs. In this study, we use a high resolution daily rainfall data set between 1951 and 2004 over India and investigate the change in character of the CISO during two 25-year periods, namely, 1951–1975 and 1979–2004 (hereafter referred to as pre75 and post79 respectively). We find that the average amplitude of CISO of Indian monsoon rainfall is as large as 35% of the dominant ISO amplitude. However, this predictable component has undergone major changes between the two regimes. Although the CISO is characterized by one major northward propagating episode in both regimes, it starts around 25 June in the southern tip of India and propagates to 28°N by 20 July during pre75. During post79, however, it starts around 1 June and reaches 28°N by 1 July. Reasons for this shift in phase locking is investigated and identified.

## 2. Data and Approach

[4] A high resolution daily rainfall data over India has recently been available for the period between 1951 and 2004 [*Rajeevan et al.*, 2006]. Based on quality controlled daily rainfall data at 1803 stations well distributed over the country, a daily one degree latitude by one degree longitude analysis has been produced. Daily climatology of rainfall at each grid point is constructed separately for the two periods, 1951–75 and 1979–2004. CISO anomalies are constructed

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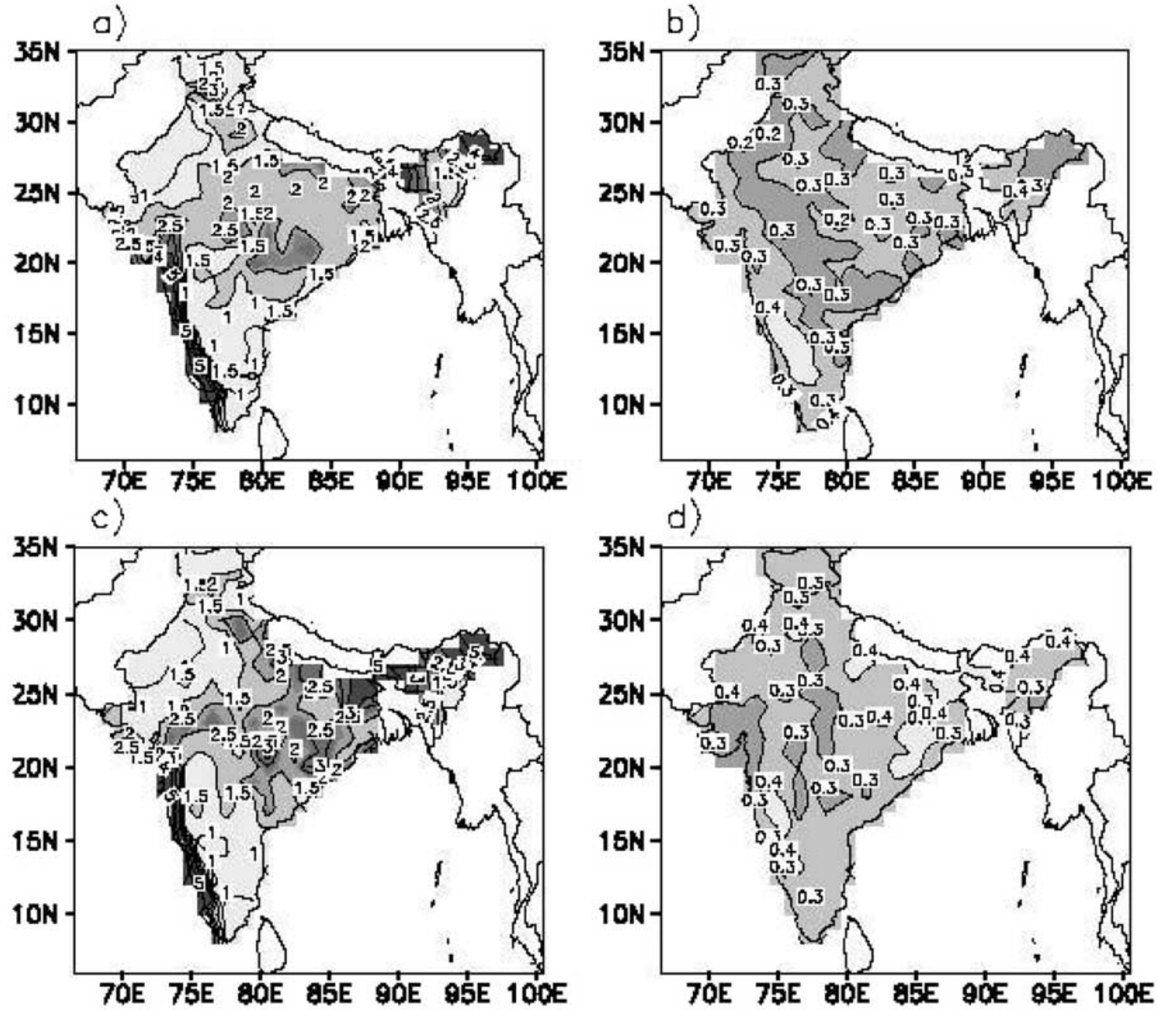

**Figure 1.** (a) Standard deviation of CISO anomalies (mm/day) for the pre75 period. (b) Ratio between standard deviation of CISO anomalies to mean standard deviation of 20–70 day filtered ISO anomalies, for the pre75 period. (c) Same as Figure 1a but for the post79 period. (d) Same as Figure 1b but for the post79 period.

from 4–20 harmonics of the daily climatology. Sum of annual mean and first three harmonics of the daily climatology represent the 'annual cycle' while the higher harmonics represent contribution from fast annual cycle [*LinHo and Wang*, 2002] on daily climatology. To gain insight into the summer monsoon CISO as a physical entity, coupling between the rainfall CISO and those of large scale circulation and convection are also examined. For this purpose, daily circulation data from NCEP/NCAR reanalysis and daily NOAA interpolated OLR data (available from http://www.cdc.noaa.gov/cdc/data.interp_OLR.html) are used.

## 3. Results

[5] How large is the amplitude of the CISO in rainfall compared to the average amplitude of summer ISO? To answer this question, standard deviation (s.d.) of the CISO anomalies between May 1 and October 30 is calculated and compared to the 'average' s.d. of 20–70 day filtered ISO anomalies. The 'average' is calculated from s.d of ISO anomalies for the 25 years in each regime. The spatial pattern of s.d. of CISO anomalies during both the periods (Figures 1a and 1c) is similar to that of the dominant ISO mode (see Figure S5 of the auxiliary material).[1] It may also be noted that in most part of the country, the ratio between s.d. of the CISO and that of the ISO varies between 0.2 and 0.4 during pre75 period while during post79 period this ratio varies between 0.3 and 0.4. Thus, no major change is noted in the amplitude of the CISO between the two climate regimes (Figures 1a and 1c) except that the ratio between s.d of CISO and ISO has increased slightly over central India during the recent 25 years.

[6] A clear signal of regime shift is seen when we examine the temporal evolution of the CISO anomalies. Temporal evolution of the CISO anomalies averaged between 72°E–85°E as a function of latitude (Figure 2) shows that the CISOs in both 25 year periods are characterized by one dominant northward propagating episode of positive rainfall anomaly. While this episode starts around 1 June at 8°N and reaches 28°N by 1 July during post79, it starts around 25 June at 8°N and reaches 28°N quickly by 16 July

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL035511.

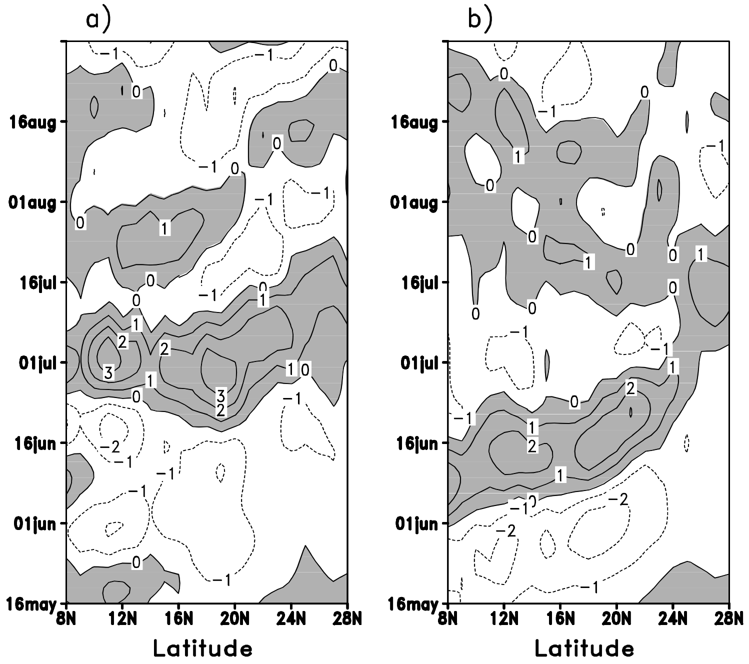

**Figure 2.** (a) Temporal evolution of longitudinally averaged (72°E–85°E) CISO anomalies (mm/day), for the pre75 period. (b) Same as Figure 2a but for the post79 period.

during pre75. Another major difference is that while a climatological break used to occur in August during pre75 no such climatological break occurs in August during post79. This regime shift of the CISO is expected to have a significant impact on the extended range predictability of the active-break cycle of the summer monsoon ISOs.

[7] To gain further insight into the space-time character of the CISOs during the two periods, EOF analysis of CISO anomalies during the two periods are carried out separately (see Figure S1 for EOF patterns and Figure S2 for PCs). The dominant CISO (Figure S1) has strong projection on spatial pattern of some phases of the canonical monsoon ISO (see Figure S3). The quadrature relationship between the first two PCs of CISO (Figure S2) during the initial phase (between 15 May and 31 July) indicates northward propagation of the CISO during this phase. The temporal evolution of CISO anomalies averaged over central India (72°E–85°E, 15°N–25°N, Figure S4) is closely related to that of the PC1 of CISO. The climatological break in August during pre75 period is clear while conspicuous by its absence during post79 (Figure S4).The first three EOFs of CISO for the pre75 period (Figure S1a–S1c) have great similarity to spatial patterns of three northward propagating phases of the summer monsoon ISO (see Figure S3) [see also *Chattopadhyay et al.*, 2008; *Krishnamurthy and Shukla*, 2007]. For the post79 period, however, only EOF1 is similar to EOF1 of CISO of the previous period and the other two EOFs do not show any coherent northward propagating phases. This indicates that while several phases of the monsoon ISO were phase locked with the annual cycle to give similar CISO phases during pre75, only one phase of the ISO appears to be phase locked with the annual cycle in post79 period. Further, the dominant peak in both the PCs in the early part of the season indicates the predominance of one oscillation during both periods as consistent with Figure 2.

[8] As daily rainfall over Indian continent during the summer season has large day-to-day fluctuations, it is not surprising to have some residual variability in the daily climatology based on 25 year average. Therefore, it may be natural to ask, is the observed CISO a result of simple statistical averaging or represents a physical mode of variability? If it were simply result of statistical averaging, we would not expect any coherent relationship between the CISO of rainfall and those of large scale convection and circulation. In order to try to answer this question, we constructed CISO of 850 hPa and 200 hPa winds from NCEP/NCAR reanalysis for both the periods and that of OLR for the post79 period. As OLR observation is unavailable during the pre75 period to derive a climatology, we examine the vertical pressure velocity from NCEP/NCAR reanalysis to gain insight regarding coupling of low level and upper level winds. Correlation of PC1 of rainfall CISO with CISO of 850 hPa and 200 hPa winds and OLR for the post79 period and with CISO of 850 hPa, 200 hPa winds and 500 hPa vertical pressure velocity for the pre75 period (Figure S4) show very coherent and significant relationship between winds, convection and rainfall. Relationship between circulation and rainfall associated with CISO (Figure S5) indicates that CISO is a convectively coupled oscillation with approximate first baroclinic vertical structure as in the case of the dominant ISO [*Goswami*, 2005a]. Thus, the rainfall CISO of Indian summer monsoon appears to be a physical mode of variability.

[9] The onset of Indian monsoon over Kerala is usually followed by a northward propagating episode of ISO [*Sikka and Gadgil*, 1980; *Krishnamurti and Subrahmanyam*, 1982]. It appears from Figure 2 that the first ISO episode following the onset (beginning of June) was phase locked

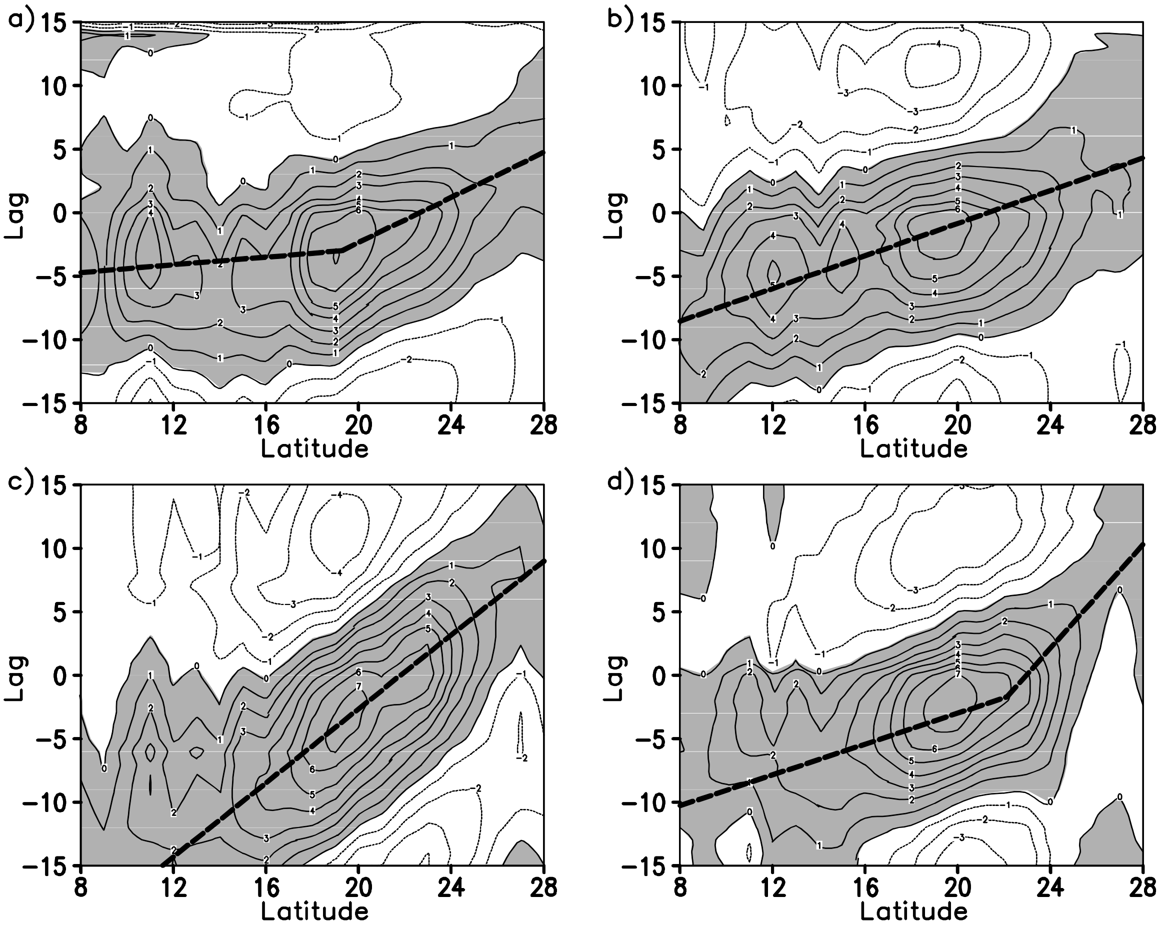

**Figure 3.** Latitudinal propagation of ISO anomalies around the first ISO episode (1 May to 30 June) for (a) pre75 period and for (b) post79 period based on longitudinally averaged (72°E–85°E) lag composites of 20–70 day filtered anomalies (mm/day) with respect to a reference time series averaged over central India. Same as Figures (c) 3a and (d) 3b but for the period around the second ISO pulse (1 July to 31 August).

with the annual cycle while none of the subsequent ISO were phase locked during post79 period. During pre75 period, however, it appears that first episode was not phase locked while the second ISO episode starting in the beginning of July was phase locked with the annual cycle. What is responsible for change in phase locking with the annual cycle and shift in the major northward propagating CISO event? If monsoon ISO had a fixed period with a constant speed of northward propagation, the phase at a given latitude and time would be entirely dependent on the interannual variability of the initial phase. However, it gets more complicated as the speed of northward propagation changes from episode to episode within a season and from year to year. Slow northward propagation is favorable for phase locking while fast northward propagation would lead to large phase mixing in different years due to interannual variation (IAV) in the initial phase. Assuming that variability of the initial phase is small, we explore the possibility of change in northward propagation speed of the monsoon ISO to be responsible for this shift in phase locking seen in Figure 2. Thus, during the first episode we expect the northward propagation speed to be faster during pre75 period while slower during post79 period. To test this, lag composites of 20–70 day filtered anomalies during between 1 May and 30 June with respect to a reference time series of the filtered anomalies averaged over central India (72°E–85°E, 15°N–25°N). The lag composites for the two periods averaged between 72°E and 85°E as a function of latitudes (Figures 3a and 3b) show that indeed the average northward propagation during pre75 was larger (2.8° lat./day) compared to that during post79 (1.5° lat/day). On the other hand, during the second episode of ISO, we would expect the reverse to occur. Similar lag composites constructed for the second episode period (1 July to 31 August) shows (Figures 3c and 3d) that indeed the speed of northward propagation during the pre75 period was much slower (0.7° lat/day) compared to that during the post79 period (1.2° lat/day).

[10] Next, we examined whether IAV of the initial phases could also contribute to the phase locking of the ISO episodes. Monsoon onset over Kerala (MOK) define the initial phase of the first episode of northward propagating ISO. Therefore, IAV of MOK can contribute to the phase mixing of the first episode. Variability of MOK as defined by *Ananthakrishnan and Soman* [1988] indeed show a regime shift in mid seventies (Figure S6). The standard deviation (s.d.) of MOK during pre75 is found to be 8.9 days while that for the post79 period is 6.2 days. Hence, a higher (lower) IAV of the initial phase of the first episode of ISO

during the pre75 (post79) contributed constructively to the faster (slower) northward propagation speed in producing the observed lack of phase locking (strong phase locking) of the first episode during the two climate regimes. As compared to the initial phase of the first episode, an objective delineation of the initial phase of the second episode of monsoon ISO is not currently available. By examining the time-latitude plot of 20–70 day filtered precipitation anomalies averaged between 75°E and 85°E after July 1 every year, the initial phase of the second episode is defined as the date when 2 mm/day anomaly crosses 8N and persists for 5 days. It is found that the s.d. of initial phase of the second episode during pre75 is 8 days while that for post79 is 12 days. Thus, even for the second episode the IAV of the initial phase seems to have worked in tandem with changes in northward propagating speed to produce the phase locking of ISO during pre75 period while phase mixing during post79 period.

## 4. Conclusions and Discussions

[11] Phase locking of monsoon intraseasonal oscillations (ISOs) with the annual cycle leads to climatological intraseasonal oscillation (CISO). Using a high resolution daily rainfall data over Indian continent between 1951 and 2004, general character of monsoon CISO in rainfall and its regime shift around mid seventies is investigated. With CISO representing 20% −40% of ISO amplitude, the monsoon CISO represents a significant predictable component of the monsoon ISOs. Generally, monsoon CISO is characterized by a dominant northward propagating episode in the pre75 as well as in the post79 periods. However, the dominant episode starts in the beginning of July during pre75 period in contrast to beginning of June during post79 period. Also, a climatological 'break' occurs during August by the phase locking in the pre75 period while such a climatological break is not created in August during the post79 period. It is proposed that the regime shift in the phase locking may be partly due to change in the northward propagation speed of the monsoon ISO during the first ISO pulse following the monsoon onset (May–June) and the second ISO pulse (July–August). It is shown that during the onset pulse the northward propagating speed was indeed much faster during pre75 era compared to that during post79 era. Similarly, during the second ISO pulse, the northward propagation speed was much slower in the pre75 era compared to that in the post79 era. It is further shown that the IAV of the initial phase of both the first and the second episode of ISO worked in tandem with the changes in the northward propagation speed in producing the phase locking for the second episode during pre75 while for the first episode during post79.

[12] Northward propagation of summer monsoon ISO depends on easterly vertical shear over the monsoon region and the north-south gradient of mean humidity [*Jiang et al.*, 2004; *Wang*, 2005]. In order to investigate whether changes in these large scale circulation fields could explain the changes in propagation speed shown in Figure 3, we examined the 200 hPa minus 850 hPa zonal winds averaged over 50°–90°E, 0°–15°N (Figure S7a) and difference of 850 hPa humidity between a north box (50°–90°E,0°–10°N) and a south box (50°–90°E, 10°S–0°) during May–June period (Figure S7b). Changes in both easterly shear and north–south gradient low level humidity are consistent with faster northward propagation during pre75 period as compared to that during the post79 period. During the second ISO pulse (July–August), the easterly shear (Figure S7c) does not show significant change between pre75 and post79 periods. However, the north–south gradient of low level humidity shows a significant decreasing trend during pre75 era and a strong increasing trend during post79 era. It appears that a change in north–south humidity gradient is largely responsible for faster meridional propagation during post79 period compared to that in the pre75 period. Thus, regional manifestation of large scale multi-decadal variability of climate leads to shift in the phase locking of the summer ISO with the annual cycle leading to a regime shift of the monsoon CISO.

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## References

Ananthakrishnan, R., and M. K. Soman (1988), The onset of the southwest monsoon over Kerala: 1901–1980, *Int. J. Climatol.*, *8*, 283–296.

Chattopadhyay, R., A. K. Sahai, and B. N. Goswami (2008), Objective identification of nonlinear convectively coupled phases of monsoon intraseasonal oscillation: Implications for prediction, *J. Atmos. Sci.*, *65*, 1549–1569.

Deser, C., A. S. Phillips, and J. W. Hurrell (2004), Pacific interdecadal climate variability: Linkages between the tropics and North Pacific during boreal winter since 1900, *J. Clim.*, *17*, 3109–3124.

Goswami, B. N. (2004), Interdecadal change in potential predictability of the Indian summer monsoon, *Geophys. Res. Lett.*, *31*, L16208, doi:10.1029/2004GL020337.

Goswami, B. N. (2005a), South Asian monsoon, in *Intraseasonal Variability of the Atmosphere-Ocean Climate System*, edited by W. K. M. Lau and D. E. Waliser, chap. 2, pp. 19–61, Springer, Berlin.

Goswami, B. N. (2005b), The Asian monsoon: Interdecadal variability, in *The Asian Monsoon*, edited by B. Wang, chap. 7, pp. 295–327, Springer, New York.

Goswami, B. N., and P. K. Xavier (2003), Potential predictability and extended range prediction of Indian summer monsoon breaks, *Geophys. Res. Lett.*, *30*(18), 1966, doi:10.1029/2003GL017810.

Jiang, X., T. Li, and B. Wang (2004), Structures and mechanisms of the northward propagating boreal summer intraseasonal oscillation, *J. Clim.*, *17*, 1022–1039.

Jones, C., D. E. Waliser, K. M. Lau, and W. Stern (2004), The Madden–Julian Oscillation and its impact on Northern Hemisphere weather predictability, *Mon. Weather Rev.*, *132*, 1462–1471.

Joseph, S., A. K. Sahai, and B. N. Goswami (2008), Eastward propagating MJO during boreal summer and Indian monsoon droughts, *Clim. Dyn.*, doi:10.1007/s00382-008-0412-8.

Kang, I. S., C. H. Ho, Y. K. Lim, and K. M. Lau (1999), Principal modes of climatological seasonal and intraseasonal variations of the Asian summer monsoon, *Mon. Weather Rev.*, *127*, 322–340.

Krishnamurthy, V., and B. N. Goswami (2000), Indian monsoon-ENSO relationship on inter decadal time scales, *J. Clim.*, *13*, 579–595.

Krishnamurthy, V., and J. Shukla (2007), Intraseasonal and seasonally persisting patterns of Indian monsoon rainfall, *J. Clim.*, *20*, 3–20.

Krishnamurti, T. N., and D. Subrahmanyam (1982), The 30–50 day mode at 850mb during MONEX, *J. Atmos. Sci.*, *39*, 2088–2095.

Lau, K. M., G. Yang, and S. Shen (1988), Seasonal and intraseasonal climatology of summer monsoon rainfall over east Asia, *Mon. Weather Rev.*, *116*, 18–37.

LinHo and B. Wang (2002), The time-space structure of the Asian-Pacific summer monsoon: A fast annual cycle view, *J. Clim.*, *15*, 2001–2019.

Miller, A. J., D. R. Cayan, T. P. Barnett, N. E. Graham, and J. M. Oberhuber (1994), The 1976–77 climate shift of the Pacific Ocean, *Oceanography*, *7*(1), 21–26.

Rajeevan, M., J. Bhate, J. D. Kale, and B. Lal (2006), High resolution daily gridded rainfall data for Indian region: Analysis of break and active monsoon spells, *Curr. Sci.*, *9*(3), 296–306.

Sikka, D., and S. Gadgil (1980), On the maximum cloud zone and the ITCZ over Indian longitudes during the southwest monsoon, *Mon. Weather Rev.*, *108*, 1840–1853.

Trenberth, K. E., and J. W. Hurrell (1994), Decadal atmosphere-ocean variations in the Pacifc, *Clim. Dyn.*, *9*, 303–319.

Wang, B. (2005), Theory, in *Intraseasonal Variability of the Atmosphere-Ocean Climate System*, edited by W. K. M. Lau and D. E. Waliser, chap. 10, pp. 307–351, Springer, Berlin.

Wang, B., and X. Xu (1997), Northern Hemisphere summer monsoon singularities and climatological intraseasonal oscillation, *J. Clim.*, *10*, 1071–1085.

Webster, P. J., and C. Hoyos (2004), Prediction of monsoon rainfall and river discharge on 15–30 day time scales, *Bull. Am. Meteorol. Soc.*, *85*(11), 1745–1765.

Zhang, Y., J. M. Wallace, and D. S. Battisti (1997), ENSO-like interdecadal variability: 1900–93, *J. Clim.*, *10*, 1004–1020.

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