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Extension of potential predictability of Indian summer monsoon dry and wet spells in recent decades

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An understanding of the limit on potential predictability is crucial for developing appropriate tools for extended-range prediction of active/break spells of the Indian summer monsoon (ISM). The global low-frequency changes in climate modulate the annual cycle of the ISM and can influence the intrinsic predictability limit of the ISM intraseasonal oscillations (ISOs). Using 104-year (1901–2004) long daily rainfall data, the change in potential predictability of active and break spells are estimated by an empirical method. It is found that the potential predictability of both active and break spells have undergone a rapid increase during the recent three decades. The potential predictability of active spells has shown an increase from one week to two weeks while that for break spells increased from two weeks to three weeks. This result is interesting and intriguing in the backdrop of recent finding that the potential predictability of monsoon weather has decreased substantially over the same period compared to earlier decades due to increased potential instability of the atmosphere. The possible role of internal dynamics and external forcing in producing this change has been explored. The changes in energy exchange between the synoptic and ISO scale and the different ISO modes as evidenced by energetics computations in frequency domain also support the increased potential predictability of ISO. Our finding provides optimism for improved and useful extended-range prediction of monsoon active and break spells. Copyright © 2010 Royal Meteorological Society

Key Words: Intraseasonal oscillations; potential predictability; Indian summer monsoon

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1. Introduction

The theoretical limit of predictability or potential predictability is the extent to which the future state in any scale can be reliably predicted with ideal models (Lorenz, 1969). Predictability of the tropical atmosphere in weather time-scales is mainly governed by the fast-growing convective instabilities, and hence is limited to a few days. Whereas on the seasonal to interannual time-scales the tropical atmospheric variability and hence predictability is controlled by the slowly varying boundary conditions such as sea-surface temperature (SST), resulting from the low-frequency planetary-scale variability of the atmosphere–ocean coupled system and has a longer predictability than the weather scales (Charney and Shukla, 1981; Shukla, 1981). Between the chaotic weather and the more predictable boundary-forced seasonal mean state, the tropical ocean–atmosphere climate system exhibits an important mode of variability in the form of intraseasonal oscillations (ISOs: Lau and Waliser, 2005). The amplitude of intraseasonal variability (ISV) in the Tropics is much larger than that of the interannual variability and is almost as large as the annual cycle (Waliser, 2005; Goswami *et al.*, 2010). The large amplitude, coupled with the fact that the dominant ISV is quasi-periodic with dominant periodicity around 45 days, indicates that tropical ISV should possess significant potential predictability beyond the limit of weather predictability. The tropical ISV, being governed by both the internal dynamics of the atmosphere and the boundary conditions, has a complex character. and assessing its predictability is a challenge in itself.

During boreal summer, over the Indian monsoon domain, ISOs have two preferred modes, the 30–60-day northward propagating oscillations with larger planetary scale and the 10–20-day westward propagating oscillations with a smaller regional scale (Goswami, 2005). The monsoon ISO's have a dual influence on the tropical weather and climate. While on one hand they affect tropical weather by clustering of monsoon lows and depressions (Goswami *et al.*, 2003), on the other the frequency of occurrence and strength of the active and break spells in rainfall significantly influence the seasonal mean monsoon and its interannual variability (Goswami and Ajayamohan, 2001). Longer breaks or untimely active spells are disastrous for agriculture. The duration and frequency of active/break spells determine the occurrence of flood or drought and affect the life and living of a very large population. Thus, notwithstanding the importance of the seasonal mean monsoon rainfall, the prediction of active or break spells is very vital for agricultural planning and disaster mitigation. Hence, there has been a constant effort towards the extended-range prediction of these active break cycles 20–30 days ahead. For effective prediction of these events, an understanding of their potential predictability is essential. In a warming global atmosphere, increased potential instability leads to increased amplitude and higher frequency of occurrence of extreme rain events (Goswami *et al.*, 2006). Cascading of errors from the intense high-frequency regime could affect the intrinsic predictability of lower frequencies. It has been demonstrated recently that the potential predictability of monsoon weather has decreased significantly during the past couple of decades as compared to earlier periods (Mani *et al.*, 2009). In light of the importance of predicting monsoon active and break spells and the above findings, it is important to quantify any changes in the potential predictability of monsoon active/break spells during recent years compared to earlier decades.

Empirical and model-based techniques have been developed to quantify the potential predictability of tropical ISOs. One such model-based technique is the anomaly correlation coefficient method (Hollingsworth *et al.*, 1980) in which the pattern correlations between control and forecasts were calculated to determine the predictability limit. In another method, the ratio of signal to forecast error was determined from identical twin experiments to estimate potential predictability (Waliser *et al.*, 2003). Other than model-based techniques, an empirical method was devised to estimate the potential predictability of active and break spells from the observed data (Goswami and Xavier, 2003). Using an ISO index based on 10–90-day filtered precipitation, the active and break phases were identified and predictability limits for active and break phases were determined from the divergence of evolution of different phases and finding when this divergence of evolution (error) reaches the level of the signal (Goswami and Xavier, 2003).

All these techniques give consistent estimates for potential predictability of ISOs. It has been shown that the monsoon breaks are intrinsically more predictable (20–25 days, depending on the variable) than the active conditions (10–15 days) (Goswami and Xavier, 2003; Waliser *et al.*, 2003). Longer predictability estimates obtained with ocean–atmosphere coupled models than the atmosphere-only models (Fu *et al.*, 2007) implies the importance of atmosphere–ocean coupling on the predictability of monsoon ISOs. For characterizing the intrinsic predictability of ISOs using perfect-model experiments, it is necessary that the model produces accurate simulations of the ISOs and also captures the intraseasonal variability of SST.

Even though the monsoon ISOs exhibit interannual variability, there exists some components of the ISO phase-locked to the annual cycle, which constitute the climatological intraseasonal oscillations (CISO) (Wang and Xu, 1997; Kang *et al.*, 1999). They represent the regular component of ISOs. In a recent study, Suhas and Goswami (2008) showed that the contribution of CISO to the total ISO variance of Indian summer monsoon (ISM) rainfall during the period after the mid-seventies has increased compared to that before the mid-seventies. It provides scope for improved potential predictability of ISM ISOs. In the present study, using 104-year high-resolution rainfall data (Rajeevan *et al.*, 2008), we examine the changes in predictability of ISM rainfall ISOs using the Goswami and Xavier (2003) method. The possible effect of internal dynamics and boundary conditions on the error growth and potential predictability has been explored. The synoptic–ISO energy exchanges were also examined to bring out the influence of synoptic-scale errors on ISO predictability.

A brief description of the methodology and the results obtained from rainfall and 850 hPa vorticity fields are presented in section 2. In section 3, we examine the fundamental aspects of potential predictability. Changes in initial error and error growth characteristics are examined in 3.1, variability in evolution characteristics are discussed in 3.2, in section 3.3 the role of internal dynamics and boundary forcing is discussed, and the implications of increased phase-locking of ISO modes are discussed in section 3.4. The influence of synoptic scales on ISO predictability is discussed in section 4 and the results of the nonlinear energy exchange computations are given in section 4.1. Finally the conclusions and discussions are presented in section 5.

2. Estimation of potential predictability of ISO

The potential predictability estimates of ISO are made using the India Meteorological Department (IMD) 1° × 1° high-resolution daily gridded rainfall dataset for 1901–2004 (Rajeevan *et al.*, 2008), based on daily accumulated rainfall from about 1384 rain-gauge stations. Compared to satellite-derived variables such as outgoing long-wave radiation (OLR), precipitation etc. and reanalysis products, the ground-based rainfall data provide a better representation of the monsoon ISOs. Earlier estimates of active and break predictability were based on either satellite data or model output. It has been reported that the NCEP reanalysis data underestimate the intraseasonal convective activity by a factor of 2–3 (Shinoda *et al.*, 1999) and most of the present-day global models do not fully capture the ISV and convectively coupled equatorial waves (Lin *et al.*, 2006), signalling the importance of good empirical techniques for predictability estimation. Monsoon rainfall time series gives the end product of the interaction between the large-scale circulation and convective fields, and the ISOs manifest themselves through wet and dry spells in rainfall. This makes rainfall a suitable variable for estimating the potential predictability of monsoon ISOs.

To quantify the changes in predictability of active and break spells, predictability estimates were made for each 15-year sliding window starting from 1901. Following the Goswami and Xavier (2003) method, we define a normalized ISO index using 10–90-day filtered rainfall anomalies. The data were pre-processed by removing the mean and first three harmonics, and the anomalies were filtered to get the ISO variability. A normalized index for each 15-year sliding window is constructed by averaging the anomalies over the monsoon trough region (70.5°E–90.5°E, 15.5°N–25.5°N) and then dividing by its own standard deviation. Deviating slightly from Goswami and Xavier (2003), the active and break spells were identified as when the normalized index was $\geqslant +1.0$ or $\leqslant -1.0$ for three or more consecutive days. This provides a better criterion for the identification of active and break days. The peak of each event was identified and signal and error estimates were made, starting from these peaks up to 30 days lead time. For each of the 15-year windows, about 45–50 active or break peaks were obtained, giving a good sample for estimation of evolution of divergence of trajectories. Corresponding to each lead day the signal (amplitude of the ISO) is found as the variance of 50 days starting from that particular lead day (covering approximately one complete ISO event) and averaged over all events. 'Error' is defined as the variance among the different active/break events corresponding to each lead day. For example, the variance between all peak active (break) days may be considered 'initial error' for the active-to-break (break-to-active) transitions. The predictability limit for evolutions starting from active/break peaks is found from the lead time when the 'error' grows and becomes as large as the signal.

Figure 1(a) shows the changes in potential predictability of break conditions and Figure 1(b) shows the estimates for active conditions. The active as well as break predictability shows a steady increasing trend after the seventies. Prior to the seventies the predictability of active conditions show a steady value around 7–8 days and after the seventies it increased to 14 days. For the case of break predictability, the increase is even more dramatic. Until the mid-eighties, it was around 10–14 days and the value has gone up to 26 days during recent years. Hence it can be surmised that both active and break predictability has been extended by about one week. Whether such a change is in response to the natural atmospheric variability or the consequence of some global change is debatable. What is responsible for such an increase in the intrinsic predictability of ISOs in recent years? Is it entirely forced by internal dynamics of the atmosphere or forced by some slowly varying external forcing? We shall attempt to explore some answers to these questions in the subsequent section.

2.1. *Potential predictability from vorticity fields*

Considering the large-scale convectively coupled nature of the monsoon ISOs, the signature of such predictability changes should also be evident in large-scale circulation parameters as well. Choosing low-level vorticity as the representative variable, the predictability analysis was repeated. Vorticity at 850 hPa (1951–2004) was computed from National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay *et al.*, 1996) U wind and V wind at 850 hPa. The ISO index was constructed from 10–90-day filtered daily relative vorticity anomalies at the 850 hPa level, area-averaged over the central Indian domain (70°E–90°E, 15°N–25°N) and normalized by its own standard deviation. Figure 2(a) shows the estimates of predictability for active-to-break transition using the 15-year sliding window during 1951–2004, and Figure 2(b) shows the same for break-to-active transition. It is seen that the vorticity field also gives the same predictability changes as that observed in rainfall time series. The potential predictability of breaks has increased from 10 days to 22 days and that for actives has increased from 9 days to 14 days. The occurrence of rapid increase in predictability around 1980 is consistent with the estimates from rainfall. Evidence obtained from these two closely linked parameters provides confidence in the estimated increased potential predictability of ISO in recent decades.

3. Factors influencing ISO potential predictability

The wet and dry spells over the Indian monsoon domain coincide with the north–south excursions of the intertropical convergence zone (ITCZ). The growing convective instabilities and their interaction with the large-scale circulation field determine the occurrence of dry and wet spells (Goswami and Shukla, 1984). In general, the atmospheric predictability in any scale is determined by the initial error field and the growth rate of initial errors. In contrast to weather, in which the perturbations are solely controlled by the internal atmospheric dynamics, the error growth in ISO scales is influenced by both internal dynamics as well as boundary-induced changes. These aspects and their changes over the hundred-year period are examined using the rainfall data.

3.1. *Initial error and error growth characteristics*

The potential predictability of any event is sensitively dependent on the error in estimating the initial conditions as well as the strength of the signal. In the present analysis, we define initial error as the event-to-event variability of the initial phase. The method computes the ISO signal and the event-to-event variability of different ISO phases. Whether the signal and error variability over the hundred years are consistent with the observed increase in ISO potential predictability, needs to be examined. The ISO signals computed for evolutions starting from peak active or break conditions are quite close and give more-or-less a constant value for the 30 days of evolution considered. They do not show any significant change over the hundred years. Figure 3(a) shows the mean and variance of different phases in the evolution starting from peak active and break days for a 15-year period. As noted in Goswami and Xavier (2003), the 'initial error' associated with the peak active phase is much larger than that for the peak break phase. It can also be seen that in general, for evolution starting from peak active phases, the error initially decreases to a

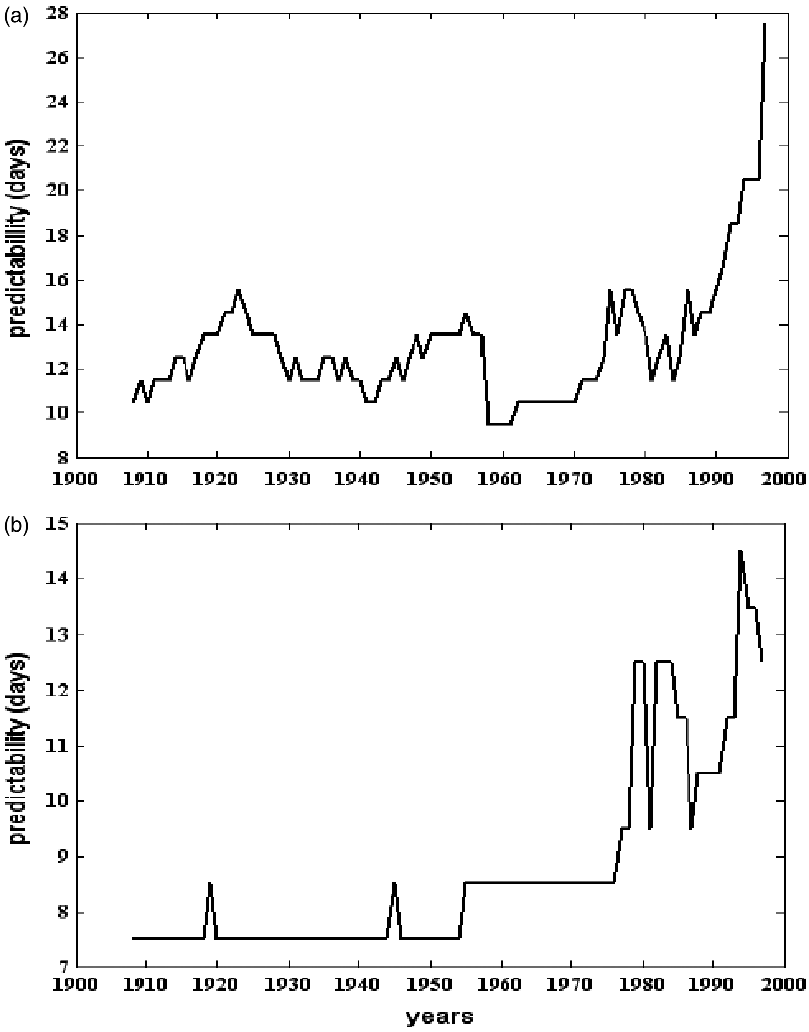

Figure 1. Change in potential predictability of rainfall ISO through a 15-year sliding window. (a) Potential predictability for evolution from active to break, (b) potential predictability for evolution from break to active.

minimum value by 3 to 5 days and later grows in amplitude, whereas for evolutions from breaks to active the error starts to grow within 1–2 days. This may be because of the delay the convective anomalies take to die out and the break phase to set in during active-to-break transitions and the fast development of convection during break-to-active transitions. This may introduce certain asymmetry in the evolution from active-to-break and break-to-active phases.

The magnitude of initial errors, i.e. variance among peak active/break conditions, decreases steadily over the years (Figure 3(b)). It means that there is lesser event-to-event variability in the magnitude of ISO peak phases. Thus, monsoon ISOs seem to have become increasingly more regular in recent years, leading to the increased predictability. Defining the growth rate of error as the difference between saturation error and initial error divided by the number of days for reaching saturation, it was found that the error growth shows a decreasing trend after the 1970s (Figure 3(c)). If the initial error was the sole controlling factor behind the increased predictability, a steady increasing trend in predictability would be expected. Since this is not the case, it can be said that in addition to the influence of the decreasing initial error there may be some other factors contributing to the increasing predictability, particularly after the 1970s.

3.2. Variability in active-to-break and break-to-active evolutions

The mode of evolution is another determining factor of potential predictability. A slower evolving event is considered to have higher potential predictability than a faster evolving event. Active-to-break and break-to-active evolutions are governed by two different processes. While the break-to-active transition is brought out by the fast-growing convective instabilities, the active–to-break transition occurs through subsidence brought out by the descending branch of the monsoon Hadley cell. For understanding the changes in evolution characteristics of the two ISO phases, the mean evolution times from active peak to break peak and vice versa were computed in each of the 15-year windows. The mean period of evolution from active phase to break phase is about 15 days, showing a slight decrease to 13 days after the mid-seventies. While the mean period of evolution from a break phase to an active phase shows a steady value of about 15 days until the mid-seventies, it increases to 21 days in recent times (Figure 4). This indicates that until the seventies the monsoon ISO's were more sinusoidal, while becoming less sinusoidal in recent years. The recent increase in mean period is associated with a reduction in number of faster (period <10 days) evolutions and increase in number of slower evolutions

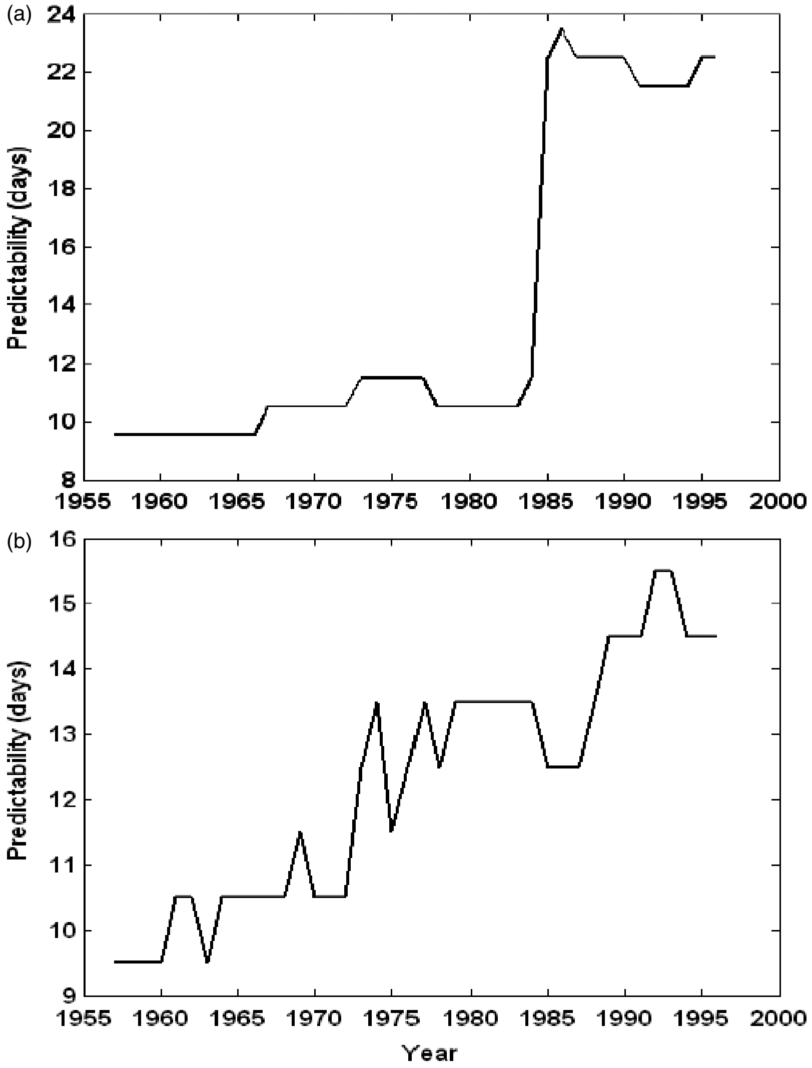

Figure 2. Change in potential predictability of 850 hPa vorticity ISO through a 15-year sliding window. (a) Potential predictability for evolution from active to break, (b) potential predictability for evolution from break to active.

(period >20 days). Along with the reduced initial errors, this slower rate of evolution would also favour an increase in potential predictability of the active phases.

3.3. *Role of internal dynamics and boundary forcing*

The predictability of ISOs is determined by the internal atmospheric dynamics and the intraseasonal sea-surface temperature (SST) variability. Internal dynamics includes the variability arising due to the atmospheric response to errors in specifying initial conditions for a given boundary forcing. Besides this, the intraseasonal fluctuations in SST also give rise to some internal variability. Such a boundary-forced external component of variability represents the predictable component of ISO. But, it is not feasible to separate out the influences of variations in boundary forcing and internal atmospheric dynamics in intraseasonal time-scales. The convective heating responses to SST fluctuations produce wind responses which feed back to the ocean to give rise to SST fluctuations. Such atmosphere–ocean coupled processes influence the monsoon ISO (Sengupta *et al.*, 2001; Fu *et al.*, 2007). Thus, ocean–atmosphere coupling and land–atmosphere interaction play a major role in determining the strength and propagation of the monsoon ISO. Any change in the large-scale dynamics of the tropical atmosphere or its response characteristics to convective heating or changes in atmosphere–ocean coupling will affect the variability and predictability of ISOs. An increasing trend has been observed in the Indian Ocean SST, and the increase is more prominent after the mid-eighties. The increase in SST favours increased air–sea coupling. Also, the increased SST may influence the oscillations of the regional monsoon Hadley circulation. Both these changes have a potential for affecting the intrinsic predictability of the monsoon ISOs. While the growth rate of errors from break to active phase is governed by the fast-growing convective instability, the growth of errors in the transition from active to break is mainly governed by the low-frequency 30–60-day oscillations of the regional Hadley cell (Goswami and Shukla, 1984). The increase in predictability of breaks after the mid-eighties in conjunction with the SST increase in recent decades implies that the increased air–sea coupling might have crossed a threshold of influence such that the boundary-induced variability is well above the chaotic variability due to nonlinear internal dynamics. However, it remains a conjecture at this point as we do not have enough direct evidence to link them.

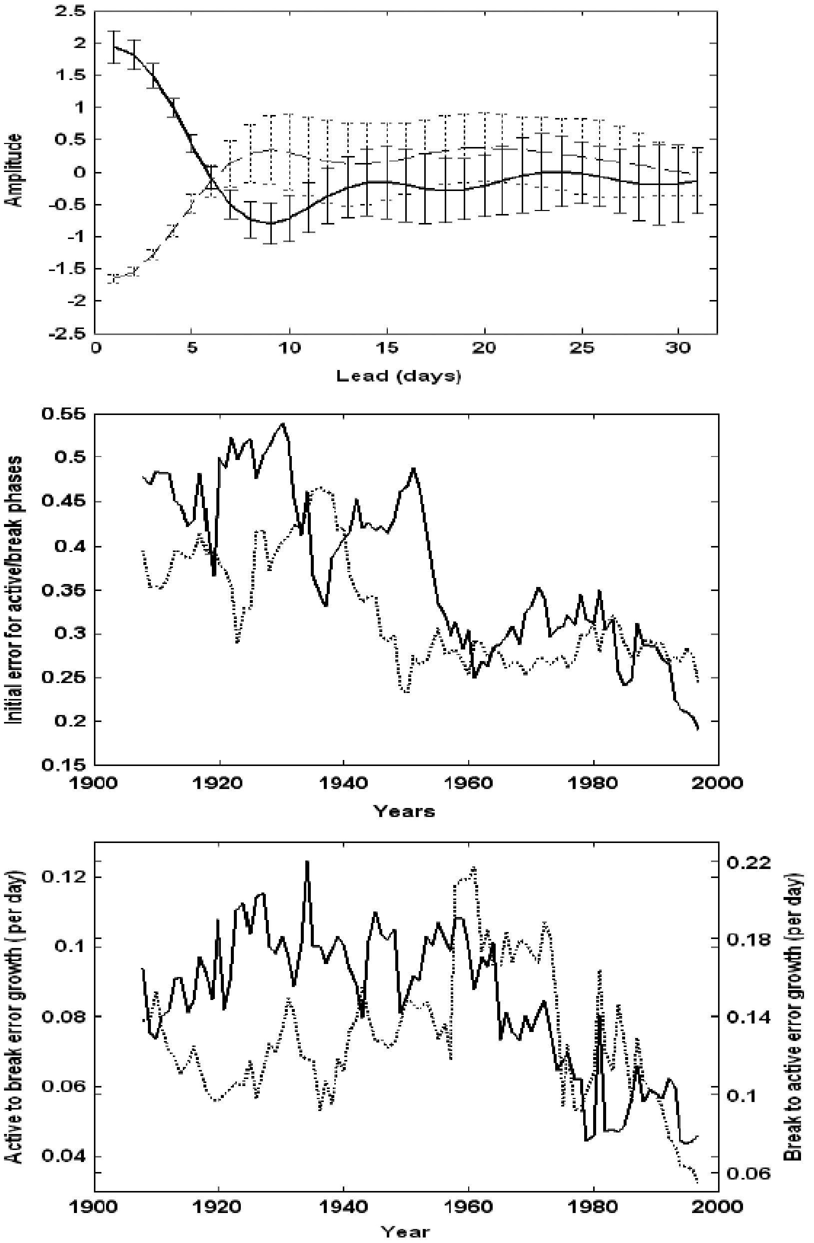

Figure 3. (a) Mean and variance among different ISO events during a 15-year period corresponding to different lead days starting from peak active (solid) and peak break (dashed) conditions. The curve shows the evolution of mean states and the error bars give variance among different ISO events corresponding to each lead day. (b) Initial divergence of active and break phases among different ISO events in a 15-year sliding window. Initial error for active phases (dotted line) and break phases (solid line). (c) Estimates of error growth, in a 15-year sliding window. Growth rate of error for evolution from active to break (dotted) and break to active (solid).

3.4. *Phase-locked component of ISO*

Even though the ISOs exhibit large interannual variability, phase locking of the ISO phases to the annual cycle has been reported over the different monsoon regions. Phase locking refers to the regularity of occurrence of an event at the same time every year. The phase-locked component of ISO is termed the climatological ISO (CISO). In a recent study using rainfall data over the ISM domain, it has been found that the CISO component has gained significance over recent decades. The ratio of CISO to the total ISO variance for the post-1979 (1979–2004) period has been found to be larger than that during the pre-1975 (1951–1975) period (Suhas and Goswami, 2008), following the climate regime shift of 1976–1977. As CISO represents the phase-locked predictable component of ISO, an increased significance of CISO denotes a higher potential predictability of the ISO phases. Thus, increased predictability of monsoon ISO's during recent years is consistent with the increased significance of CISO during the same period.

4. Synoptic–ISO-scale interactions

Lorenz (1969), based on turbulent flow dynamics, postulated that a multi-scale flow (as in the atmosphere) could have an intrinsic finite limit on predictability. The nature of error growth is scale-dependent, showing faster growth and saturation in smaller scales and upscale cascading of these small-scale errors. Over the years, using turbulence closure models, the nature of error propagation and its scale dependence has been addressed by many researchers (Leith and Kraichnan, 1972; Tribbia and Baumhefner, 2004). The

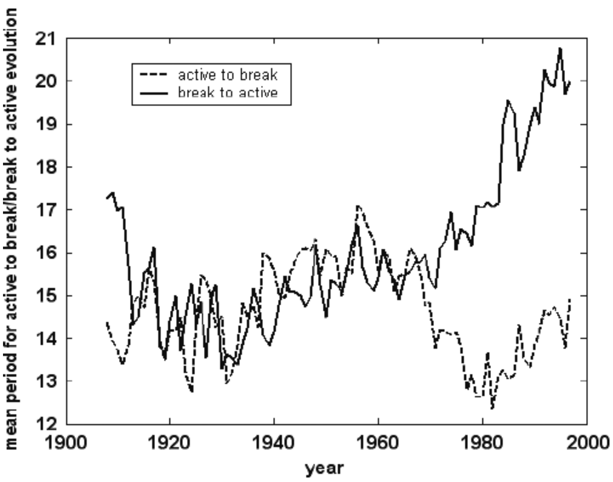

Figure 4. Mean period of evolution from peak active to peak break phase (dotted line) and that for evolution from peak break to peak active phase (solid line), calculated over each 15-year sliding window.

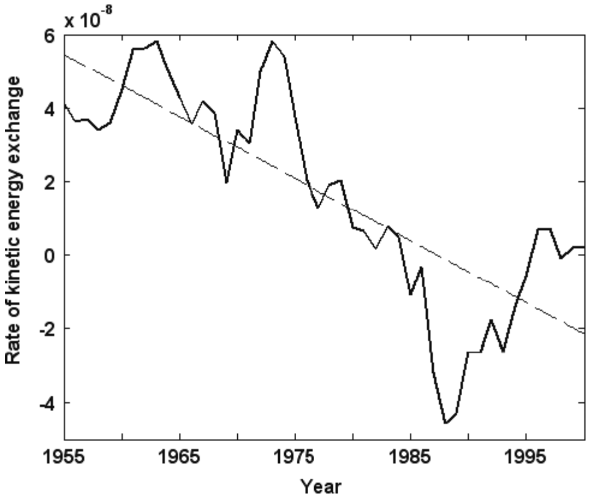

Figure 5. Rate of kinetic energy exchange (15-year running mean) between ISO and synoptic scale. Positive values indicate the ISO gains kinetic energy from the synoptic scale.

cascade rate or growth of errors in any scale is dependent on the eddy turnover time and is determined by the slope of the energy spectrum. This suggests that the ISO predictability would be closely linked to the error energy cascading from the synoptic scales and the interaction between these scales. In a recent study it was found that the increase in high-frequency events (Goswami *et al.*, 2006) was causing increased cascading of errors to the synoptic scale, lowering the monsoon weather predictability (Mani *et al.*, 2009). The observed increase in ISO predictability in the present study implies the ineffectual influence of the synoptic-scale errors on the ISO scale. Tribbia and Baumhefner (2004) present an alternative view to the classical inverse cascade theory – that the error is introduced to the synoptic scales via the inverse cascade mechanism, and once the errors are in the synoptic scale the errors organize within the synoptic structures, drawing energy from the large-scale background flow, and exhibiting slower exponential growth rate. In regard of this view the energy exchange and interactions between the synoptic and ISO scales need to be examined. The importance is further underscored by the two-way influences of the ISOs and synoptic-scale depressions. The wet and dry spells in rainfall over central India during active (break) conditions result from spatial and temporal clustering of lows and depressions by modulation of the large-scale circulation by the monsoon ISO. And the lows and depressions in turn facilitate the enhancement of the ISO activity. Rajeevan *et al.* (2000) showed that the frequency of occurrence of depressions and storms shows a decreasing trend since the 1970s, while the total number of low pressure systems (LPS) shows an increasing trend. In a recent study, Krishnamurty and Ajayamohan (2008) examined the variability of the LPS in detail and found that this apparent discrepancy is due to a strong increase in the number of lows, the weaker category of LPS. In recent years, the increasing Indian Ocean (IO) and Bay of Bengal SST might be favouring the formation of LPS, but the associated changes in circulation patterns may be hindering the growth of these systems to depressions and storms (Rajeevan *et al.*, 2000). This might have two-fold implications on ISO predictability. The reduction in number of strong events would reduce the efficiency of clustering of LPSs along the monsoon trough. Support for this notion can be found in the decreasing growth rate of error in recent years (Figure 3(c)). Hence a longer period may be necessary for a wet spell to be realized from the organization of these weak LPSs. As seen in Figure 4, the evolution from dry to wet spell does take a longer period after the mid-seventies. The longer period of evolution may enhance the potential predictability of the wet spells. The restricted growth of LPS implies a weakened influence of the synoptic-scale errors on the larger scales. This might explain the observed increase in ISO predictability even in the backdrop of reduced weather predictability. To validate this argument we estimated the nonlinear kinetic energy transfer between the ISO and synoptic scales.

4.1. *Nonlinear kinetic energy exchanges in the frequency domain*

The growth or decay of kinetic energy of a disturbance can be estimated from the daily wind data (Saltsman, 1957). The calculation of rate of kinetic energy involves three important processes. Firstly: the transfer of kinetic energy to the scale of frequency n from pairs of other frequencies m and p. It is restricted by a trigonometric selection rule, i.e. $n = m + p$ or $n = |m - p|$ for an exchange. Hence it is also known as triad interaction. Secondly: the gain of kinetic energy of a given 'frequency n' through interaction with the time mean. Lastly: the growth of kinetic energy in a given frequency by conversion from eddy available potential energy of the same scale.

A simpler method of estimation of nonlinear energy transfer by the cross-spectral method was proposed by Hayashi (1980), applicable in both wave number and frequency domain. The interaction between synoptic and Madden–Julian time-scale of surface and boundary-layer fluxes of moisture was analysed over different tropical oceanic basins in the frequency domain by Krishnamurti *et al.* (2003). In the present study, using June–September zonal and meridional wind at 850 hPa over the domain 60°E–110°E, 5°S–27.5°N from 1948 to 2007 (NCEP-NCAR reanalysis: Kalnay *et al.*, 1996), the kinetic energy exchange between synoptic scale (2–9 days) and ISO (10–122 days) was estimated using the Hayashi (1980) method, for each season, and a 15-year running mean was applied to bring

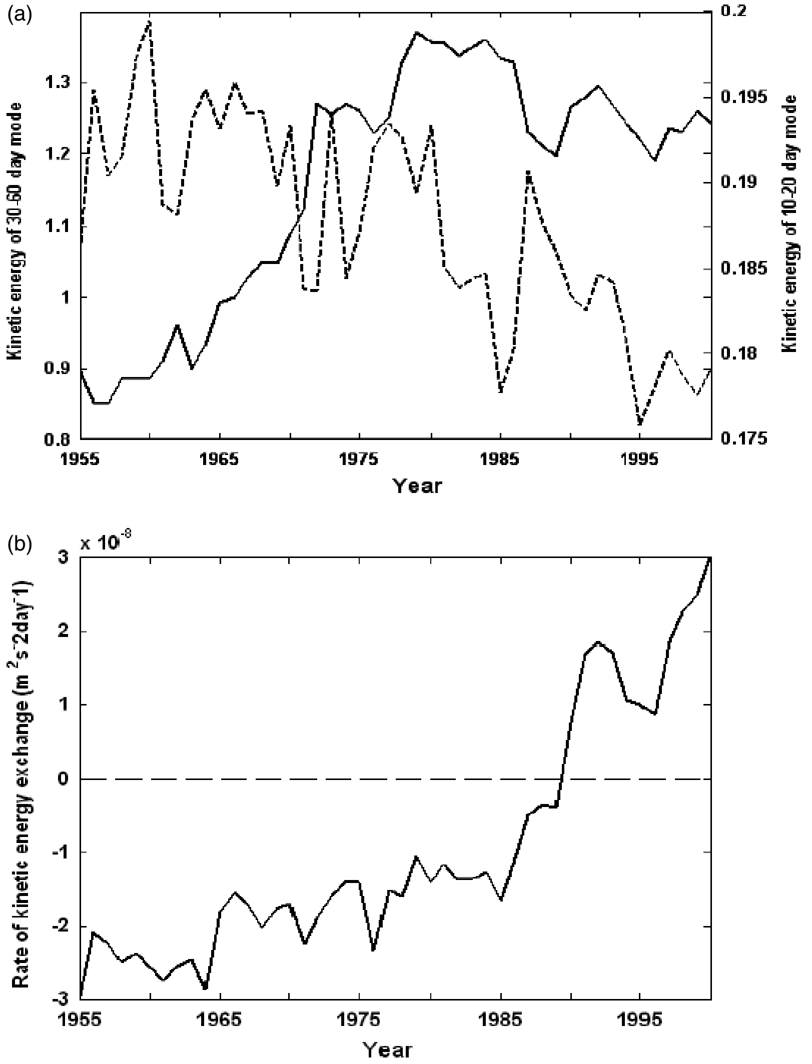

Figure 6. (a) Fifteen-year running mean of kinetic energy of 30–60-day mode (solid line) and 10–20-day mode (dashed line). (b) Fifteen-year running mean of the rate of kinetic energy exchange between 30–60-day and 10–20-day modes. Positive values of the rate of kinetic energy exchange indicate that the 30–60-day mode gains energy from the 10–20-day mode.

out the interdecadal changes (Figure 5). It is found that until 1980 the exchange was positive, i.e. ISO was drawing energy from the synoptic scales; after the eighties the exchange is predominantly negative, implying a downscale transfer of kinetic energy (from ISO to synoptic). Since the error energy spectrum is directly related to the total kinetic energy spectrum, these results support our earlier argument of inefficient error cascading from synoptic to ISO scale. In other words, even though cascading of error from energetic high-frequency extreme events to the synoptic scale has made them less predictable in recent years, the ISOs remain isolated, as errors from the synoptic scales are not flowing to the ISO scale.

The 30–60-day variability governed by the north–south excursions of the ITCZ represents the more predictable component of ISV, whereas the 10–20-day variability being closer to the high-frequency weather scale represents the more chaotic part of ISV. A closer examination of the kinetic energy (KE) of these two modes shows that the 30–60-day mode is becoming more energetic, while the 10–20-day mode is losing energy (Figure 6(a)). Further examination of the nature of kinetic energy exchange between these two modes reveals a change in character of KE exchange after the mid-eighties (Figure 6(b)). After the mid-eighties, considerable amount of kinetic energy flows from the 10–20 to the 30–60-day mode. The dominance of the more periodic 30–60-day mode may have contributed to the enhanced predictability of ISM ISO.

5. Conclusions and discussion

Using an empirical tool for estimating potential predictability of active/break spells developed by Goswami and Xavier (2003), the present study has addressed the changes in predictability of active/break spells over the past hundred years. Based on 104-year long rainfall data the first time estimates of predictability changes of ISM ISO are presented. The main findings are that the potential predictability of active as well as break spells shows a rapid increasing trend over the last 20–30 years. The predictability of active phases has increased from a stable value of 7–8 days to 14 days in the recent period. Similarly, the predictability of break phases also shows a marked increase from about 14 days in the period prior to the 1970s to about 26 days in recent times. Generally an active (break) phase goes over to a break (active) phase within about 15–20 days. These results indicate that useful predictions of monsoon breaks could possibly be made up to three weeks in advance while those for active conditions may be made up to 14 days in advance. Similar results of extended potential predictability were also obtained for vorticity at 850 hPa, underscoring the robustness of the results. The possible influences of the large-scale environment on such potential predictability changes and the factors causing such increase in potential predictability have been investigated.

The limit on predictability arises from the event-to-event variability of ISO (signal) as well as differences in evolution of the ISO from the same phase in different events (error). From the analysis it is seen that the ISO signal has not undergone significant change over the years. Therefore, the increased predictability limit during recent decades may be the product of decreased variability in the evolutionary character of the ISO. From the analysis of initial errors corresponding to the peak active or break phases, it is found that the phases are becoming more regular, reflecting the increasing similarity amongst events. The decreased variability of initial phases and the changes in evolution characteristics from break to active and active to break may have brought about the rapid increase in potential predictability since the 1970s.

The tropical atmosphere has been affected by the influence of global warming and the associated increase in tropical SSTs. The influence has been felt in almost all scales of atmospheric variability. The increased tropical SSTs and the recent increase in ISO predictability support the notion of increased atmosphere–ocean coupling in intraseasonal time-scales. It can be investigated using coupled model simulations and presents scope for further research. The increasing IO SST has a greater influence on break predictability by modulating the regional Hadley circulation. An unprecedented increase in IO SSTs has been observed after the mid-eighties. The rapid increase in break predictability is also in conjunction with this SST increase. The increased air–sea coupling in recent times might have reached such a threshold such that the boundary-forced predictability outweighs the less predictable component arising from internal dynamics.

The observed increase in phase locking of the ISO pulse to the annual cycle has been reported, as evidenced from increased CISO amplitude in recent years (Suhas and Goswami, 2008). This is consistent with the diminished energy of the aperiodic 10–20-day mode compared to the 30–60-day mode. The increased significance of CISO over ISO variability in itself presents the picture of regularity in ISO events and more potential predictability.

The increasing ISO predictability in spite of the decreasing weather predictability presented an apparent puzzle. While the increasing frequency and amplitude of extreme events due to global warming was causing decreasing weather predictability through cascading of errors from small scales, for some reason the errors from synoptic scales were not propagating to ISO scales. A nonlinear kinetic energy exchange in the frequency domain brings out the changes in the nature of energy transfer between these scales. Through computations using triad interactions it was found that during recent decades the energy transfer is downscale, i.e. from ISO to synoptic scale, whereas, prior to the 1980s, ISO was drawing energy from the synoptic scale. This downscale cascading of kinetic energy does not favour the synoptic-scale errors cascading to the ISO scale. The reduction in the number of lows developing to depression or storm stage during recent years over the monsoon trough region also points to the fact that the recent changes in the large-scale environment may not be favouring upscale transfer of energy. In the absence of strong LPSs, a wet spell may be realized through the organization of only the weaker events and may take a longer time. This would lead to an increase in the period of evolution from break to active and may give rise to increased potential predictability of wet spells. It was also found that the 30–60-day mode was gaining energy while the 10–20-day mode was losing energy, and their energy exchange pattern has also undergone a phase reversal. The energized 30–60-day mode may have also favoured the increase in potential predictability. The observed increase in ISO potential predictability implies a longer range for skilful predictions, which may be realizable through focused efforts using improved coupled models. Effective predictions of active/break spells 15–25 days ahead would provide impetus to mitigate the devastating effects of droughts and floods.

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