Potential predictability and extended range prediction of Indian summer monsoon breaks

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[1] Extended range prediction (two to three weeks in advance) of Indian summer monsoon active (rainy) and break (dry) phases are of great importance for agricultural planning and water management. Using daily rainfall and circulation data for 23 years, a fundamental property of the monsoon intraseasonal oscillations (ISO's) is discovered and shown that the potential predictability limit (~20 days) of monsoon breaks is significantly higher than that for active conditions (~10 days). An empirical model for prediction of monsoon ISO's is then constructed and feasibility of useful prediction of monsoon breaks up to 18 days in advance is demonstrated. *INDEX TERMS:* 3314 Meteorology and Atmospheric Dynamics: Convective processes; 3364 Meteorology and Atmospheric Dynamics: Synoptic-scale meteorology; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology. **Citation:** Goswami, B. N., and P. K. Xavier, Potential predictability and extended range prediction of Indian summer monsoon breaks, *Geophys. Res. Lett.*, *30*(18), 1966, doi:10.1029/2003GL017810, 2003.

1. Introduction

[2] Indian summer monsoon season (June–September) is punctuated by periods of abundant rain ('active' or wet spells) and periods of scanty rain ('break' or dry spells) over the central India [*Rao*, 1976; *Ramamurthy*, 1969]. Frequent or prolonged breaks during the monsoon season can lead to drought conditions [*Goswami and Ajayamohan*, 2001]. Long breaks in critical growth periods of agricultural crops lead to substantially reduced yield [*Gadgil and Rao*, 2000]. Prediction of monsoon break two to three weeks in advance, therefore, assumes great importance for agricultural planning (sowing, harvesting etc) and water management but is currently unavailable. The active and break phases of the Indian summer monsoon are manifestations of northward propagating monsoon intra-seasonal oscillations (ISO) with characteristic time scales of 10–20 days and 30–60 days [*Sikka and Gadgil*, 1980; *Yasunari*, 1979; *Krishnamurti and Ardunay*, 1980; *Murakami et al.*, 1984; *Krishnamurthy and Shukla*, 2000]. Quasi-periodic nature of the monsoon ISO indicates certain potential predictability. However, a quantitative estimate of the potential predictability of monsoon ISO's has not been made. Here, we propose a method of estimating potential predictability of active and break conditions from daily rainfall and circulation observations for the recent 23 years. We discover that transition from a break to an active condition is much more chaotic than that from an active to a break, a fundamental property of monsoon ISO's. Feasibility of achieving this potential predictability is examined by developing an empirical model that demonstrates useful skill in predicting the monsoon breaks up to 18 days in advance, while the skill in predicting the active conditions is limited to less than 10 days in advance.

2. Data and Methods

[3] The intra-seasonal component of precipitation is extracted from Climate Prediction Center Merged Analysis of Precipitation (CMAP) [*Xie and Arkin*, 1996] data for 23 years (1979–2001). The pentad CMAP data is linearly interpolated to daily values and is found to represent the observed ISO in rainfall over India well. However, the day-to-day fluctuation of observed rainfall over India is not well represented by the interpolated CMAP data. As our objective is to estimate predictability of the intra-seasonal component, a 10–90 day bandpass Lanczos filter is applied to daily anomalies defined as departures from the annual cycle (sum of annual mean and first three harmonics). The choice of the filter was to retain all important intra-seasonal variability including the 10–20 day mode. We define an index of ISO by filtered precipitation anomaly averaged over the box 70°–90°E, 15°–25°N representing the monsoon trough. The ISO index is created for 1 June–30 September (122 days) for each year of the 23-year period and normalized by its own standard deviation (2.35 mm day^{-1}). A sample of the index for a five year period is shown in Figure 1. Normalized index values $>+1(<-1)$ represent active (break) conditions. Daily rain-gauge data [*Singh et al.*, 1992] analyzed into regular grid boxes over the Indian continent for 10 years (1980–1989) have also been used to make estimate of predictability of active and break conditions. The daily bandpassed surface pressure anomalies from NCEP/NCAR reanalysis [*Kalnay et al.*, 1996] have been used as one of the predictors along with CMAP in the model development.

3. Estimate of Potential Predictability

[4] From Figure 1 we note that an active (break) phase normally evolve into a break (an active) phase after a period of 15–20 days. However, the rate of transition, the magnitude of the next minimum (or maximum) and the timing of achieving the minimum (maximum) of the next phase varies from event to event. Predictability of the phases (active or break) depends on the degree of regularity of transition from one phase to the other. During the 23-year period, there are 66 peaks and 63 troughs of the index that satisfy active and break criteria respectively. The peaks or troughs which fall in the neighborhood of the transition from one year to another are not included in the analysis, since those might sometimes falsely represent phases of the ISO due to

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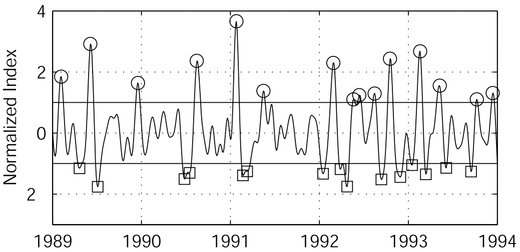

Figure 1. An index of summer monsoon intra-seasonal variability. Time series of 10–90 day filtered precipitation anomalies averaged over the monsoon trough during 1 June–30 September for five years (1989–1994), normalized by its standard deviation (2.35 mm day^{-1}). Active (break) monsoon condition correspond to the index >+1 (<−1).

filtering. Starting from the peaks (or troughs) as the initial time, the evolution may be noted for the next 30 days. Spread in evolution from peaks toward troughs (or from troughs toward peaks) among the ensemble members during the next 30 days, as measured by the variance, may be considered as 'growth of errors'. The thin dashed line in Figure 2a shows growth of spread in evolution as a function of days from troughs, representing divergence of transitions from breaks to active conditions. It may be noted that the initial spread was 0.11 standard unit (SU). The thin solid line in the figure represents spread of transitions from active to break conditions (namely from peaks to troughs of the index). The initial spread among the peaks is 0.52 SU, significantly higher than that among the troughs. The rate of growth of the spread is nearly twice as fast in the case of transitions from troughs to peaks (break to active) compared to that from peaks to troughs (active to break) in their growth phases. Thus, transitions from break to active are intrinsically more chaotic than those from active to break. The limit on predictability is reached when the spread in evolutions become as large as the 'signal'. The signal is the amplitude of the ISO, defined as the variance of the filtered time series over a period comparable to the period of the ISO (taken as 50 days). The thick dashed (thick solid) line in Figure 2a is the mean (averaged over all 66 or 63 events) signal starting from troughs (peaks). As expected, the signals starting from either troughs or peaks are close to each other. The spread becomes larger than the signal in 8 days (20 days) for transitions from break to active (active to break). Thus, monsoon breaks are inherently more predictable than active conditions. The ensemble mean of all evolutions for both transitions (Figure 2b) shows that a transition from an active (break) phase does go over to a break (active) phase. However, the two transitions become indistinguishable from each other after about 25 days. Together, these results indicate that useful prediction of monsoon breaks could possibly be made up to about 20 days in advance while those for active conditions is likely to be limited to a lead time of about 10 days.

[5] The Indian summer monsoon ISO has large spatial scale and the associated circulation and precipitation are convectively coupled [*Goswami and Ajayamohan*, 2001; *Goswami et al.*, 2003]. If the difference in growth of errors for the two transitions is a fundamental property of the Indian summer monsoon ISO's, it should also be evident in other related parameters. To investigate this, the growth of spread in transitions from active to break and from break to active over the eastern equatorial Indian Ocean is examined where precipitation fluctuates out of phase with that over the monsoon trough on intra-seasonal time scales [*Goswami and Ajayamohan*, 2001; *Goswami et al.*, 2003]. A 10–90 day filtered CMAP time series averaged over 80°–100°E, 5°S–5°N is constructed and active (break) over this region is defined by normalized (by its own s.d., 3.95 mm day^{-1}) anomaly >+1 (<−1). The growth of spread in evolution during transition from active to break and from break to active in this region (Figure 2c) is also very similar to those over the monsoon trough region (Figure 2a). Similar to the result over the monsoon trough region, the limit on predictability for transitions from break to active is limited to about 7 days while that for active to break is about 20 days.

[6] The robustness of the estimates made from CMAP daily interpolated data is tested by creating an ISO index from 10–90 day filtered daily raingauge data averaged over the monsoon trough region for 10 years (1980–1989).The spread in transitions from active to break and from break to active conditions are again estimated from the index normalized by its own standard deviation. The spread in

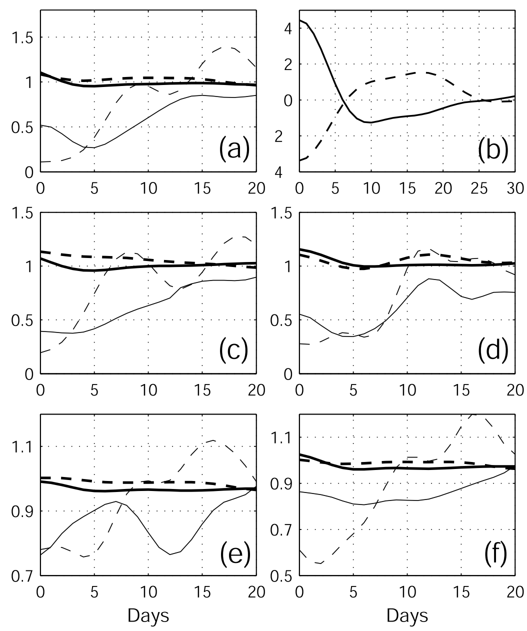

Figure 2. (a)The thick dashed (solid) line is the monsoon ISO 'signal' starting from troughs (peaks) of the index (Figure 1). The thin dashed (solid) line is the variance (or spread) of ensemble members as a function days from the initial date corresponding to all troughs (peaks) of the index representing transitions from break to active (active to break). (b) Mean of all the ensemble members of normalized precipitation as a function of days from the initial date for transition from break to active (dashed) and from active to break (solid). (c) same as (a) but for a precipitation index averaged over the eastern equatorial Indian Ocean (80°–100°E, 5°S–5°N). (d) same as (a) but for evolution of filtered gridded gauge daily rainfall anomalies averaged over the monsoon trough region. (e) same as (a) but for evolution of zonal wind at 850 hPa averaged over 80°–95°E, 12°–18°N. (f) same as (a) but for relative vorticity at 850 hPa averaged over the monsoon trough.

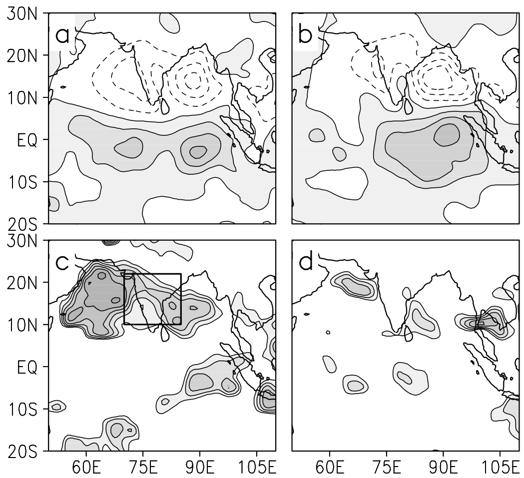

Figure 3. (a) Mean of an ensemble (57 in number) of 18-day predictions (mm day^{-1}) of breaks and (b) mean of corresponding verifications (mm day^{-1}). Contours start with a value of −6 with an interval of 2. Initial conditions correspond to days when the index is greater than 1.5 during the six summers of the test period (1996–2001). (c) Correlations between 18-day predictions of breaks and corresponding verifications. (d) Same as (c) but for predictions of active conditions. Only positive correlations greater than 0.3 and significant at 95% confidence level using a student t-test are plotted. Contour interval is 0.1.

transitions (Figure 2d) are quite similar to those obtained from CMAP data (Figure 2a). The difference in transition from active to break and from break to active in zonal winds averaged over 80°–95°E and 12°–18°N (north Bay of Bengal) and relative vorticity averaged over the monsoon trough region were examined using active and break dates defined by the precipitation index and are shown in shown in Figures 2e and 2f respectively. The difference in transition of the circulation parameters is very similar to that for precipitation. The differences in variances for the two transitions in Figures 2a, 2c, 2d, 2e and 2f at lead times between 10 and 20 days are found to be significant at 90% level using a F-statisic. Hence, the difference in growth of spread in evolution for transitions from break to active compared to that from active to break is a fundamental property of monsoon intra-seasonal variability and the limit of potential predictability of monsoon breaks is much higher than that for active conditions. It may also be noted that both CMAP and raingauge data show initial spread amongst the peaks (active conditions) to be much larger than those amongst the trougs (breaks).

4. Empirical Extended Range Prediction

[7] To explore whether this potential predictability of the monsoon breaks is achievable, we construct an empirical model for predicting different phases of monsoon intra-seasonal variability. An empirical orthogonal function (EOF) analysis of the 10–90 day filtered precipitation (CMAP) during the summer monsoon season (1 June–30 September) is carried out and the first four EOF's explaining more than 40% of variability are used to construct the model with the corresponding principal components (PC's) as predictants. In addition to the first four PC's of precipitation, we also use first two PC's of filtered surface pressure from NCEP/NCAR reanalysis, as predictors. The first four PC's of precipitation are then predicted by a linear multiple regression model similar to the one developed by *Lo and Hendon* [2000] for predicting Madden-Julian Oscillations [*Madden and Julian*, 1994]. The prediction scheme we employ is of the form,

$$PC(t+\tau) = \sum_{i=1}^{N} \beta_i(\tau) PC_i(t) \qquad (1)$$

where, $PC(t + \tau)$ are PC's of rainfall predicted at a lead time τ, $PC_i(t)$ are the predictor PC's at the initial time t, N is the number of different predictors used for prediction (six in the present model) and β_i are the multiple linear regression coefficients at different lags determined by least square estimation. The model is developed on 17 monsoon seasons (1979–1995) and tested on independent data for the next six years (1996–2001). The predicted precipitation is constructed using

$$P(x,y,t+\tau) = \sum_{i=1}^{4} PC_i^p(t+\tau) E_i^p(x,y) \qquad (2)$$

where $E_i(x, y)$, i = 1 to 4, are the first four EOF's. The predicted anomalies are compared with full filtered anomalies. As we are using only four EOF's for prediction, the predicted anomalies are generally weaker in amplitude than corresponding observations. It is found that the systematic bias of the predictions can be corrected by multiplying the predicted anomalies everywhere by a constant factor proportional to the ratio between the total variance and that explained by the first four EOF's. Taking

Table 1. Correlation Between Predictions and Observations Over Monsoon Trough Region (70°–85°E, 10°–22°N)

Lead time	Prediction of break	Prediction of active
15 days	0.65[a]	0.38[b]
18 days	0.56[a]	0.43[b]

[a]significant at 99% level.
[b]significant at 95% level.

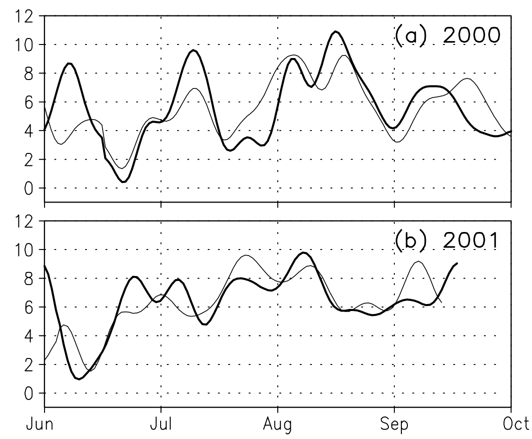

Figure 4. Time series of 18-day predictions (thin line) and observations (thick line) of the rainfall (mm day^{-1}) averaged over the monsoon trough region for June to September of (a) year 2000 and (b) year 2001.

the days when the normalized rainfall index is above 1.5, an ensemble of 57 predictions of monsoon breaks are made up to lead time of 20 days. Good correspondence between the mean of all 18-day predictions (Figure 3a) and the mean of corresponding verifications (Figure 3b) indicate skill of the 18-day predictions. Similarly, an ensemble of 53 predictions of monsoon active conditions are made starting from days when the precipitation index is less than −1.5 during the test period. The mean of predictions and verifications are found to start deviating significantly after about 9 days of lead time (not shown). The correlations between 18-day predictions of breaks (starting from active conditions) and verifications (Figure 3c) show large and significant correlations over the monsoon trough together with even larger correlations over north Arabian Sea and eastern equatorial Indian Ocean. Similar correlations between 18-day prediction of active conditions and corresponding verifications are rather poor almost everywhere (Figure 3d). Prediction of precipitation anomaly averaged over the box shown in Figure 3c (representing central Indian monsoon region) summarized in Table 1, shows that monsoon breaks could be predicted with useful skill up to 18 days in advance. However, neither 15-day nor 18-day predictions of active conditions have useful skill. In fact, the active conditions are difficult to predict even 10 days in advance (not shown). Predictions made from a variety of other initial conditions corresponding to different phases of the ISO cycle were examined and found that the predictions made from around the peaks of ISO index have the maximum skill.

[8] Figure 4 compares 18-day predictions of evolution of rainfall averaged over the box shown in Figure 3c (seasonal mean + intraseasonal anomaly) with corresponding observations during the summer seasons of 2000 and 2001. Reasonably good correspondence between the two indicates useful skill of the 18-day predictions of evolution of rainfall. It may be noted that largest errors come from prediction of the peaks (active conditions).

5. Conclusions and Discussions

[9] A fundamental difference in transitions from active to break and from break to active monsoon conditions is discovered and potential predictability limit for breaks (active conditions) is estimated to be approximately 20 (10) days. The feasibility of achieving the limit on potential predictability of monsoon breaks is investigated by constructing an empirical model. The simple model constructed in this study is used on hindcast mode and demonstrate useful skill of prediction of monsoon breaks 18 days in advance. When used on real time, the present model may yield slightly lower skill. However there is scope for improving this preliminary attempt and we speculate that the potential limit of 20 days for predicting monsoon breaks may be achieved.

[10] What is responsible for the fundamental difference in divergence of trajectories from break to active as compared to that from active to break? It may be recalled that the monsoon synoptic activity (lows and depressions) is clustered in space and time [*Goswami et al.*, 2003] through modulation of large scale circulation by the ISO's. As a result of this clustering of synoptic activity, the transition from break to active phase of monsoon ISO occurs through growth of gregarious convective activity and their organization while the transition from active to break represents the decay phase of organized convection, with far fewer growing convective elements. The growth of errors in the transition from break to active is, therefore, governed by fast growing convective instability while the growth of errors in the transitions from active to break is governed by the low frequency 30–60 day oscillations of the monsoon Hadley circulation [*Goswami and Shukla*, 1984].

[11] The significance of our findings is that they are not limited only to the Indian summer monsoon ISO's but represents a fundamental property of tropical intra-seasonal variability in general. For example, they are applicable to the eastward propagating Madden-Julian Oscillations [*Waliser et al.*, 2003] in its convectively coupled regime over the Indian Ocean and western Pacific. While extended range prediction of convectively active conditions may remain to be difficult, our work provides conceptual and modeling support to a claim that dry spells are predictable up to three weeks in advance.

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