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Predictability of Indian summer monsoon weather during active and break phases using a high resolution regional model

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[1] As the active and break phases of Indian monsoon are associated with different large scale background regimes, the predictability of monsoon weather is expected to be different during these phases. In the present study, an ensemble of 'identical twin' perturbation experiments are carried out using Weather Research Forecast model at 15 km resolution to demonstrate the predictability of weather during these phases. The initial conditions are taken from the 9 years (2001–2009) control simulations during periods of strong intra-seasonal oscillations events. The study revealed that the background estimates are different in these two contrasting regimes with more errors in the active phases confined mostly along the monsoon trough region. As a consequence, the predictability of active (break) period is found to be around 4 (10) days. Thus, the rapid (sluggish) error growth indicates that the monsoon weather such as lows are less (more) predictable during active (break) phases.
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1. Introduction

[2] Indian summer monsoon is an important component of global climate system and has vigorous intraseasonal oscillations (ISO) that manifest in the sub-seasonal active and break spells of monsoon rainfall. The Indian monsoon is characterized by convectively coupled monsoon ISO's that manifests in the form of active and breaks phases [*Goswami*, 2005] and the overall mean monsoon precipitation distribution significantly depends on the manifestation of ISO's in a season [*Waliser et al.*, 2003]. Monsoon synoptic systems namely lows and depressions account for most of monsoon rain during the June–September monsoon season [*Mooley and Shukla*, 1989]. It is established that during active and break phases the large scale organizations show contrasting behavior in terms of formation of the weather systems, large scale instability and most importantly the rainfall [*Yasunari*, 1981; *Murakami et al.*, 1986; *Goswami et al.*, 2003, *Krishnamurty and Ajaymohan*, 2010]. *Goswami et al.* [2003] showed that the large scale environments are significantly different in the two regimes with enhanced (decreased) frequency of occurrence of lows and depressions during the active (break) phases. In addition to that, the tracks of the synoptic systems are strongly clustered spatially along the monsoon trough during the active phases of monsoon. Reliable prediction of these events 5–7 days in advance is crucial for various sectors e. g. agricultural practices, water resource and disaster management. As the growth of the errors depends on the nature of the instability in the system which in turn depends on the background state, it is reasonable to assume that the growth of errors and hence weather predictability may be significantly different during active and break phases of monsoon. Inspite of rapid advancement of computing power and numerical model it has not been demonstrated how the error growth of a high resolution model behaves during two contrasting regimes within a monsoon season with two different large scale features. Hence, our aim in this paper is to demonstrate the non linear error growth associated with the weather scale in the backdrop of contrasting large scale instability regimes during active and break phases of monsoon and to study the weather predictability limit during these contrasting regimes.

[3] We believe that this study of predictability limit of weather during two different regimes of monsoon over Indian region can be a useful tool for operational forecasters to attach confidence to the forecasts during these contrasting windows. The paper is arranged with section 2 giving the model details, experimental design and methodology, followed by results and discussions in section 3 and conclusion in section 4.

2. Model Details, Experimental Design, and Methodology

[4] The model details and its experimental design are very much similar to an earlier study by *Mukhopadhyay et al.* [2010]. The non-hydrostatic, fully compressible with a terrain following sigma co-ordinate mesoscale model Weather Research Forecast (WRF) version 2.2 developed by National Center for Atmospheric Research (NCAR) has been used in the present study. The model is used with two nested domains with horizontal resolutions of 45 and 15 km (Figure S1 of the auxiliary material) and 31 sigma levels with model top at 10 hPa.[1] The model mother domain covers the large scale Indian monsoon region (59°–101° E; 2° S–37° N) with 100 grid points in the east-west and north-south direction. The nested domain focuses mainly on the Indian land mass (69°–91° E; 7°–27.5° N) with 160 grid points along the east-west and north-south. The model time steps are chosen to be 240 seconds. The physical parameterization schemes used in the model are the microphysics scheme of *Lin et al.* [1983], Monin-Obukhov [*Monin and Obukhov*, 1954] similarity

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scheme for surface layer, Yonsei university scheme for PBL, RRTM scheme for long wave [*Mlawer et al.*, 1997] and Dudhia [*Dudhia*, 1989] scheme for short wave in all the numerical experiments. The convective parameterization scheme of *Betts and Miller* [1986], but modified further by *Janjic* [1994]. Betts-Miller-Janjic (BMJ) is used in the simulation as it is found to produce a reasonable mean monsoon climatology in WRF [*Mukhopadhyay et al.*, 2010].

[5] The mother domain simulations are driven by the National Center for Environmental Prediction (NCEP)/NCAR reanalysis data at a resolution of 2.5° [*Kalnay et al.*, 1996]. The lower boundary conditions (LBCs) are updated every six hourly. RTG is a daily, high-resolution, real-time, global, sea surface temperature (SST) analysis [*Thiebaux et al.*, 2003] that has been developed at the NCEP/Marine Modeling and Analysis Branch (MMAB). The 6-hourly SSTs were obtained by linearly interpolating the daily SSTs of RTG and used as the slowly varying LBCs for the model. The model simulation spans from 1 May to 31 October for the years 2001 to 2009 and the simulations corresponding to JJAS are used as control integration in the present study allowing one month as a model spin-up time. One month spin-up period is sufficient for the dynamical equilibrium between the lateral forcings and the internal physical dynamics of the model [*Anthes et al.*, 1989]. The identification procedure of Active and Break phases are described below.

[6] Using 9-years (2001–2009) of daily JJAS precipitation data from the control integration, a daily climatological precipitation time series is constructed. Since the 9 year is not enough for a smooth climatological series hence we constructed a smooth climatological series by using the mean and retaining the first three harmonics in the original precipitation series. The dashed curve in the Figure S2a is the original climatological series where as the solid curve is the constructed smooth climatological precipitation series. Using the smoothed climatology, the daily anomalies in each year is computed. These anomalies are then standardized by normalizing them by their own standard deviation. The time series of standardized rainfall anomaly is shown in Figure S2b. The identifications of active and breaks are done between July and August with the view that June and September may not be suitable for inferring the phases as delayed onset or early withdrawal may lead to a misrepresentation of active and break phases. Significant amplification (reduction) of rainfall over central India is a characteristic feature of the active (break) phases. Based on 9 years of model simulated rainfall, it is found that the dominant rainfall variability is confined within the central region. Keeping this in background, we selected an area 73°–82° E; 18°–28° N, for crafting the criteria for identification of active and break phases. Actives (Breaks) phases are identified when the monsoon intraseasonal oscillation index (MISI) averaged over this region is more than 1.0 (less than −1) for consecutive 4 days.

[7] Based on these criteria, 13 active phases (includes 100 active days) and 14 break phases (127 break days) are identified during 2001–2009 (Table S1). After finding out the dates of active and break phases, 35 active days and 35 break days are chosen for identical twin perturbation experiments. These active and break days are chosen around the peak of the respective phases. The perturbation technique is similar to *Hohenegger et al.* [2006]; *Hohenegger and Schar* [2007] based on the random number generation with mean at zero. Perturbation is applied on three dimensional temperature field within a range of −1% to +1% of climatological standard deviation. The spatial distribution of climatological standard deviation (S.D.) of temperature and the area averaged vertical distribution are shown in Figures S3a and S3b. It is found that the spatial S.D. varies (Figure S3a) within 1.5 to 3.0 K and the vertical distribution (Figure S3b) lies within a range of 1.4 to 2.0 K. The magnitudes of perturbations are chosen to be ±0.025; ±0.05; ±0.075 and ±0.1. Each of the 35 active and break days are perturbed with these four sets of perturbing values making a total of 140 samples for each phases. The analyses of error growth are a composite of all these perturbation experiments of active and break days.

3. Results and Discussions

[8] It is well established that during the active and break conditions of Indian summer monsoon (ISM), the large scale flow shows contrasting behaviour in terms of formation of the weather systems, large scale instability and most importantly the rainfall [*Yasunari*, 1981; *Murakami et al.*, 1986; *Goswami et al.*, 2003]. In view of this, we have decided to first see whether the model control run shows the large scale contrasting features in the atmosphere during the active and break phases. The composite relative vorticity pattern at 850 hPa for the active and that for the break phases are shown in Figures 1a and 1b. The low level vorticity maxima centered around the head Bay of Bengal and its extension along the monsoon trough (over the central India) during the active phase composites (Figure 1a), are clearly absent in the break composites (Figure 1b), signifying a weak lower level vorticity. A difference between active and break composites of wind anomalies and corresponding relative vorticity are shown in Figure 1c. It may be inferred that the increases (decreases) in the vorticity along the monsoon trough during the active (break) phases may lead to enhanced (decreased) cyclogenesis and could be the reasons behind the higher (lower) frequency of occurrence of weather disturbances. This finding is in good agreement with the *Goswami et al.* [2003] based on the observations. Another metric that differentiates the large scale instability regime is the moist static energy (MSE). The composite MSE for active and break phases are shown in Figures S4a and S4b and the difference between them are shown in Figure S4c. During the active phases (Figure S4a), the monsoon trough region and most of the central Indian region is under the influence of a high MSE which indicates a large scale convective instability regime. On the contrary the break composites (Figure S4b) hardly show any instability over the land region. The high MSE region is only present over some parts of east central Bay of Bengal. The difference of active and break (Figure S4c) actually reflects the large scale high instability regime during active periods as compared to that in break phases. As the rainfall variability depends on the above two parameters (i.e. lower level instability and vorticity), we believe that the inherent differences in the large scale could be reflected through the root mean square error (RMSE) of rainfall for the active and break phases. Therefore the RMSE of rainfall with respect to model daily climatology are also computed. The RMSE of rain for active phases (Figure 1d) is found to be mostly along the monsoon trough region and over the west coast of India. However the RMSE is found to

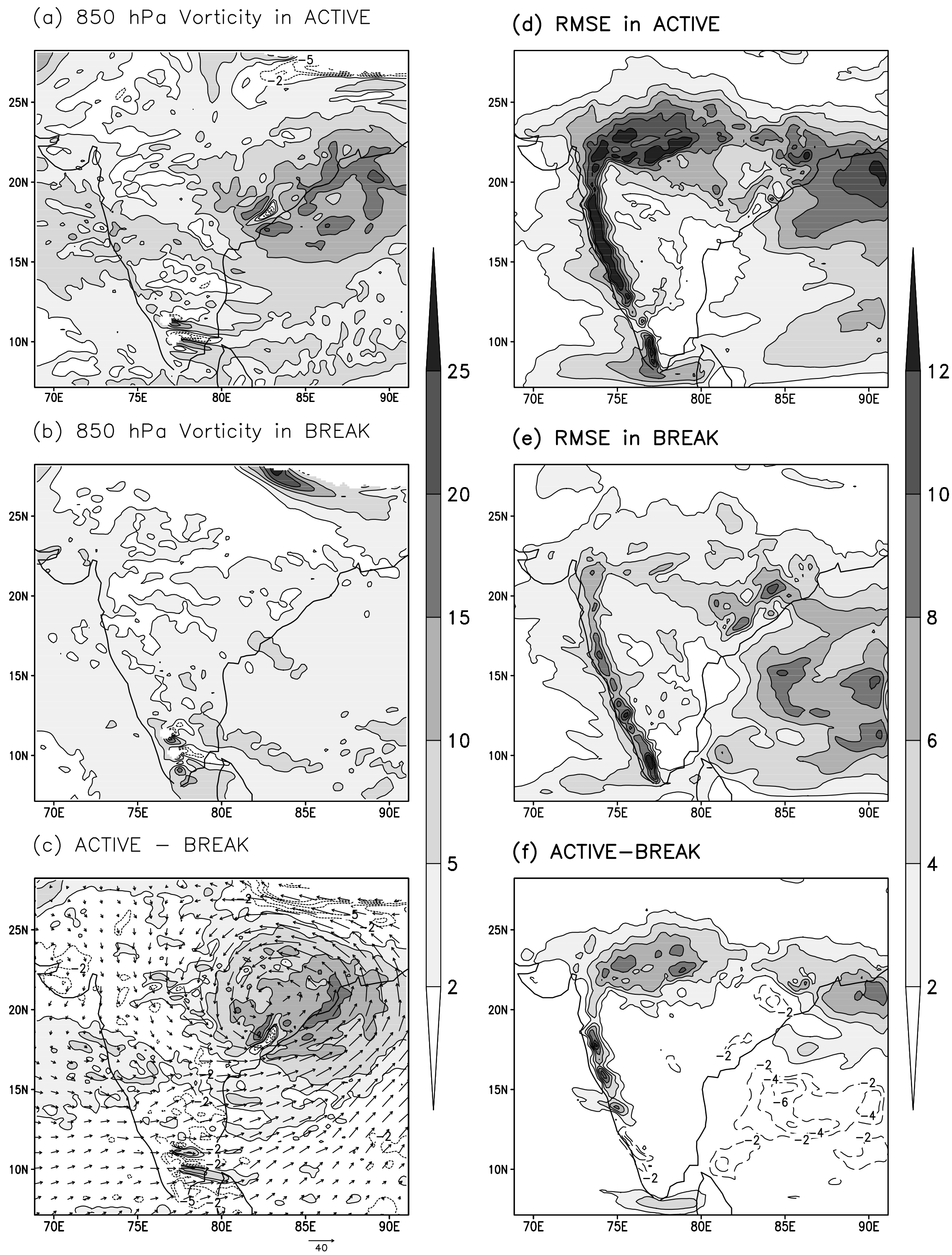

Figure 1. Composites of 850 hPa vorticity during (a) Active (MISI > +1); (b) Break (MISI < −1) and (c) Active minus Break during 2001–2009. (c) The Active minus Break composites wind anomalies (m/s) at 850 hPa. The region of positive vorticity is shaded only. (d–f) Similar to Figures 1a–1c but for the Root Mean Square Error (RMSE) of precipitation.

be significantly reduced over the monsoon trough and west coast region during the break composites (Figure 1e). The difference of RMSE between active and break composites (Figure 1f) clearly show that the error dominates the monsoon trough and west coast region influenced by the active phases. These analyses are able to bring out that the model control run reasonably captures the contrasting large scale environment with higher (lesser) horizontal shear and moist static energy during the active (break) phases of monsoon regimes.

[9] In the perturbation experiments, signal is defined as the variance within a sliding window of width (2L+1) in the control integration where L is taken as 30 days to encompass a complete ISO event. Noise implies the mean squared

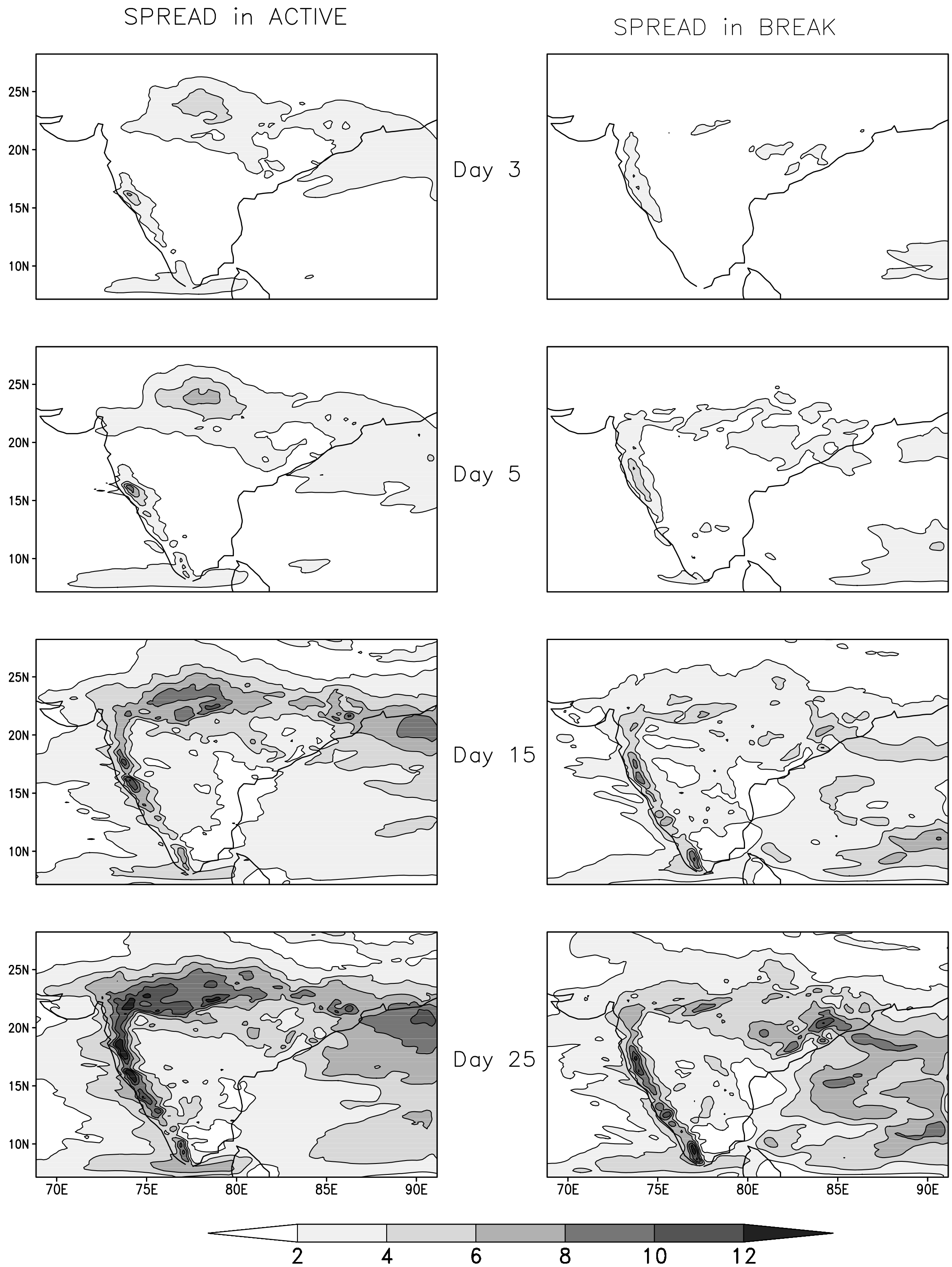

Figure 2. Composites Spatial pattern of Spread of precipitation after 3rd, 5th, 15th and 25th Days of forecast for Active and Break phases during 2001–2009.

difference between the perturbed and the control case [*Waliser et al.*, 2003; *Krishnan and Sundaram*, 2005]. The composite spatial pattern of Signal and Noise after 3, 5, 15 and 25 days of forecast for Active and Break Phases are shown in Figure S5. During the active phases the noise is seen to grow rapidly and within 3 day of integration, it exceeds the signal. In the forecast of subsequent days, noise is seen to spread across the domain with the maximum lying along the monsoon trough and over west coast region. The noise in the forecast of break phase composite (right panel of Figure S5) grows much slowly and becomes equivalent to the amplitude of the signal by ~15 days. Since the model simulations show a reasonable skill in capturing the contrasting features associated with the active and break phases

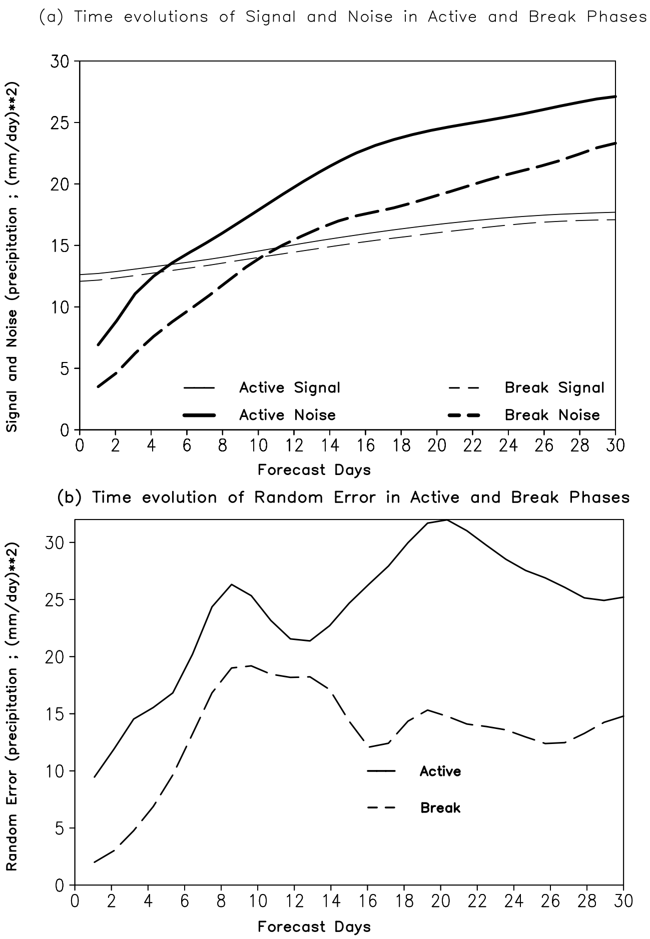

Figure 3. (a) Time evolution of Signal (lighter) and Noise (darker) for the Active (solid) and Break (dashed) phases of rainfall [$(mm/day)^2$]. (b) Variance of random errors of precipitations for Active (solid) and Break (dashed) phases. The horizontal average has done in both the cases over 70°–90°E and 10°–25°N.

(Figures 1 and S4), we further investigate the predictability issue during these two regimes. As a measure, we use the ensemble spread as a metric where a large spread would denote a poor predictability and vice versa. The spread is defined as the standard deviation of a variable and is expressed as follows [*Walser and Schär*, 2004; *Hohenegger et al.*, 2006]

$$S = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(\phi_i - \overline{\phi})^2}$$

where N= No. of Ensemble member, $\overline{\varphi}$ = Ensemble mean of variable. Following the above, the spread in precipitation for 3, 5, 15 and 25 days of forecast are shown in Figure 2. The spread in active composites is found to be significantly higher than that of break. The spread encompasses most of the monsoon region by 15 days during active whereas the spread is substantially less over the central Indian region during breaks.

[10] After identifying the contrasting results in error growths (Figure S5) and spreads (Figure 2) for active and break phases, we investigate further the source of error. In order to answer why the break phases is able to show lower error growth compared to the active phases, we analyzed the random components of total error in the precipitation since the systematic component does not vary significantly with time. The random error is defined as the deviation from the time mean at each day for a fixed forecast time [*De and Chakraborty*, 2004] and computed as follows

$$U_{er} = U_{cntl} - U_{pert}$$

$$U_{raer} = U_{er} - \langle U_{er} \rangle$$

Where U_{er} is the total error (between control and perturbed field). U_{raer} is the random error component. $\langle\ \rangle$ represents the average over the lead forecast hours. The variance of random error of active phases is found (Figure S6) to increase at a much faster rate as compared to that of break and the random error component of break for 15 days forecast is found to be comparable with that of 5 days forecast of active phases. Also, random error component during active phases are found to generate from the region of strong convection over the head Bay of Bengal and then found to cascade fast in the other region of the domain. This fast cascade of random error from convective scale to larger scale actually is responsible in limiting the otherwise predictable large scale.

[11] To estimate the predictability of these two contrasting monsoonal regimes, the area averaged (70°–90°E and 8°–25°N) signal and noise (mean squared error) are plotted in Figure 3a. It is clearly seen that noise during the active phase crosses the signal by about 4 days and that of break crosses the signal by 10–12 days. Time evolution of area averaged random error (Figure 3b) also indicates a similar sharp growth rate during active and slower growth rate during break. Thus from the above analyses, it may be concluded that the predictability of weather during the active phase is much less (~4 days) compared to that during break (~10 days).

4. Conclusions

[12] The objective of this study is to estimate the weather predictability limit of active and break phases of south west monsoon over India using a high resolution WRF. The study brings out that the non linear error growth rates are significantly different during active or break phases. The spatial pattern of noise during active phases is seen to be significantly high from the initial forecast lead time itself and confined within the monsoon trough and along the Western Ghats mountainous regions. The noise of break composites after 15 day forecast is found to be equivalent to that of active phases with just 3 day forecast lead. The variance of random error component echo a similar feature that the error growth during the active phases is high in amplitude and spread faster over the large scale as compared to that of break phases. The predictability limit for the active and break phases are found to be around 4 and 10 days respectively over the Indian region. The higher predictability during break is consistent with much lower horizontal shear of zonal wind and much lesser moist static energy during this phase as compared to active phase. This analysis for the first time brings out the weather predictability of monsoon phases using a high resolution regional WRF model. These results will be

useful to the forecaster in issuing and evaluating monsoon forecasts over India.

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