TECHNICAL MEMORANDUM

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Assessment of ECMWF forecasts: widespread rainfall events during the Indian summer monsoon

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Abstract

The skill of dynamical forecasts of widespread rainfall events (WSREs) over central India is examined using high-resolution models from the European Centre for Medium Range Weather Forecasts (ECMWF). The WSREs entail interactions between the large-scale monsoon circulation and the convective systems which are embedded within the boreal summer Inter Tropical convergence zone (ITCZ). A diagnostic analysis of the ECMWF forecasts of WSREs during 2007 is performed. Several features of the observed rainfall distribution and large-scale organisation of convection during WSREs are found to be realistically captured by the ECMWF forecasts. The paper acknowledges a potential wider scope for diagnosing the influence of remote and regional forcings on the organisation of large-scale convection. The appraisal could be extended to break phases associated with the evolution of large-scale suppressed convection.

1. Introduction:

One of the complex and important issues of the Indian summer monsoon (ISM) for its agricultural and hydrological applications, is the accurate forecast of widespread rainfall events (WSREs), evolving from the boreal summer Inter Tropical convergence zone (ITCZ).

The study of large-scale rainfall fluctuation over India and its link to vorticity dynamics during the summer monsoons was initiated by Sikka and Gadgil (1978). The northward propagating moist convection (Sikka and Gadgil 1980) and westward propagation of weather disturbances (Sikka and Dixit, 1972, Krishanmurti and Bhalme 1976, Yasunari 1979), were found to be most prominent during the active spells of large-scale rainfall over India. The space-time clustering of the synoptic scale weather systems, modulated by the large-scale intra-seasonal variations of the circulation, was strongly attributed to the active phases of the monsoon (Goswami et al. 2003). The rainfall episodes during the active/break cycle of the ISM, also known as the mature phase of the monsoon and defined as the period from late June to early September, have been linked to sub-seasonal variations of the ISM (Singh et al. 1992, Krishnamurthy and Shukla 2000, Annamalai and Slingo 2001, Goswami 2005, Chattopadhyay et al. 2008, Krishnamurthy and Shukla 2008).

Several international programmes focus on understanding and predicting the large-scale tropical convection/rainfall. A recent report on ‘Continental Tropical Convergence Zone’ (available from India Meteorological Department (IMD), www.imdpune.gov.in/ctcz) highlights various aspects of large-scale convection over India such as convection organisation, boundary layer convergence and mid-tropospheric cyclonic vorticity. Rajeevan et al. (2008) have carried out an extensive analysis of the active and break spells of the ISM using a high resolution daily gridded rainfall data set over India (1951-2007). Moreover, numerous studies have either focused on the active and break cycle of the ISM (e.g. the comprehensive reviews by Goswami 2005 and Waliser 2006, Chattopadhyay et al. 2008, Krishnamurthy and Shukla 2008) or have had a special emphasis on better understanding and prediction of breaks or weak spells (e.g. Rodwell 1997, Krishnan et al. 2000, De and Mukhopadhyay 2002). Even though much has been said and investigated in the scientific literature on the ISM, there is very little mention of the crucial interactions between genesis, frequency, track or intensity, of the synoptic scale weather systems modulated by the Intra-seasonal Oscillations (ISO) (Goswami et al. 2003), and the occurrence of active spells with uniform distribution over central India. The aim of this paper is to gain a deeper understanding of the ability of models to predict these active spells over central India.

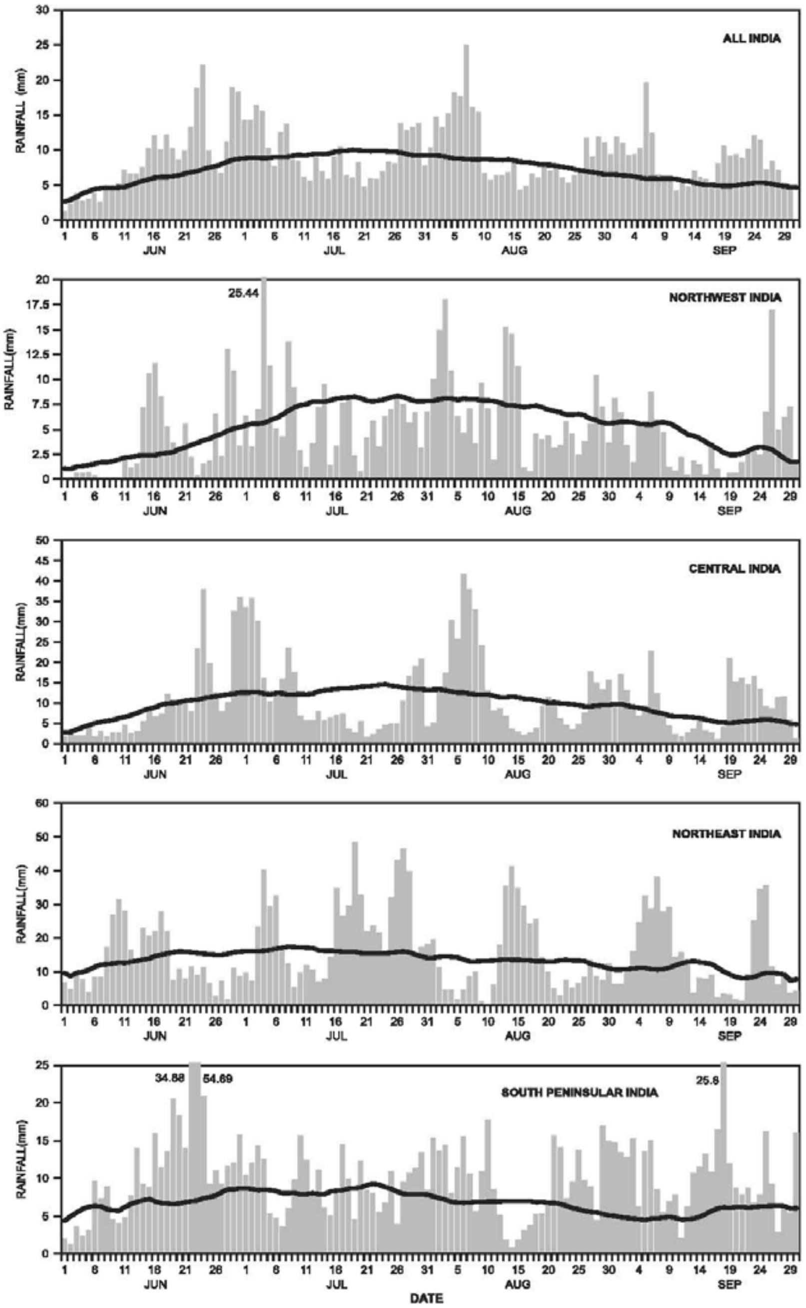

Figure 1: The daily mean rainfall (mm) averaged over the plains (vertical bars) and its long term normal (continuous line) for India as a whole and the four homogeneous regions during June-September 2007 (adopted from http://www.imdpune.gov.in/research/ncc/climatebulletin/monsoon_2007.pdf).

Many inspirational papers have investigated the large scale dynamics of organised convection and its association to active spells on sub-seasonal scales. They have also explored the predictability of the active/break cycles on a sub-seasonal scale using statistical and dynamical methods (Goswami and Xavier 2003, Waliser et al. 2003, Webster and Hoyos 2004, Krishnan and Sundaram 2005, Waliser et al. 2006, Xavier and Goswami 2007, Nanjundiah and Krishnamurti 2007). Even though the above studies show that forecasting phases of the ISOs may be possible, they fail to capture the variability of the spatial distribution of the ISM on a short to medium-range scale. Therefore, in this study ECMWF real-time forecasts of WSREs over central India during the mature phase of the summer monsoon are carefully analysed to assess the capability of the model to predict WSREs in the short to medium range lead times.

Figure 1 shows a time series of daily mean rainfall (Climate Diagnostic Bulletin of India, hereafter CDBI, 2007) averaged over all the continental IMD stations (Al) and over the stations of four homogenous regions (North-West, Central, North-East and South), for the period June-September 2007. The respective long term trend is superimposed on each daily time series. A noticeable number of concurrent spells of above normal rainfall over both AI domain and central India during the first week of each month July, August and September 2007 can be identified in Figure 1. CDBI (2007) describes the weather systems in the Bay of Bengal associated with these active spells. The present paper starts by looking at the evolution of active spells during the mature phase of the summer monsoon of 2007 in order to investigate the large-scale organisation of convection. The results of this exploration will be used to set up a framework for a qualitative assessment of the ECMWF medium-range forecast system.

The observational database and the models used for the medium-range forecasts are described in section 2. The methodology used in this study for identification of WSREs evolving from ITCZ is presented in section 3, while section 4 describes diagnostics of analysis and observations. Qualitative assessment of ECMWF real-time forecasts is summarised in section 5. Finally conclusions and future scope are discussed in section 6.

2. Observational dataset and models

High resolution gridded rainfall data, (Rajeevan et al. 2006, 2008) is used for identification of WSREs occurring during peak ISM periods of 1959-2007. The daily accumulated rainfall data, obtained from a dense network of about 2000 IMD stations, is made available on a 1°x1° regular latitude-longitude grid. The accumulation period in this case is 24 hours ending at 3 UTC. Further details of the interpolation of the daily rainfall data are available from Rajeevan et al. 2008. ECMWF analysed wind and outgoing long-wave radiation (OLR) data (Uppala et al. 2005) are interpolated to the same 1°x1° regular latitude-longitude grid. Examination of these parameters permits the diagnosis of the large-scale convection and dynamics of the WSREs for the mature phases of the ISM during the period 1959-2007. A five-day running mean is applied to the daily gridded rainfall data and ECMWF analyses to extract the large-scale signal and for each peak monsoon period (20 June to 14 September) 82 moving (17 independent) pentads are built. The 9-17, 42-50 and 69-77 pentadal running means represent the first weeks of July, August and September, respectively. The total number of pentads for the 49 mature phases of the ISM in the period 1958-2007 is 4018 and is referred to as TPMI. Here, AI (CI) represents a value of a parameter averaged over 70°-90°E and 10°-30°N, covering All India (74°-78°E and 20°-24°N, covering Central India).

ECMWF runs a suite of high resolution spectral Atmospheric General Circulation Models (AGCMs) with surface boundary fields available on a relatively coarse resolution Gaussian grid, and a high resolution coupled 'Ocean-Atmosphere' general circulation model (CGCM). The models are improved continuously; therefore vertical and horizontal resolutions, as well as parametrisations, vary over time. In this paper the Ensemble Prediction System (EPS) forecasts are used. The EPS comprises 50 perturbed forecasts and a control run. The initial conditions for the 50 perturbed forecasts are produced by adding/subtracting perturbations to the initial conditions of the control. Singular vectors are used to calculate the perturbations.

More information on the technique and the EPS description can be found in Buizza (2006). The horizontal and vertical resolution of the model was T399L62 which corresponds to a horizontal resolution of approximately 50km in the mid-latitudes, and 62 vertical levels.

The 82 pentadal running means are constructed for the forecast period t+0 to t+120 (5 day forecast or one-pentad lead time) and for the forecast range t+120 to t+240 (10 day forecast or two-pentad lead time). For example the first five days (20 to 24 June, inclusive) is used to construct the first 5-day running mean. Subsequently, the remaining 81 pentad are constructed by sliding the five day window over the mature phase of the summer monsoon. These one- and two-pentad lead time forecasts are referred to as EPS-1 and EPS-2, respectively.

3. Methodology

Following the work of Rajeevan et al. (2006 and 2008) and Chattopadhyay et al. (2008), who have characterised the evolution of wet and dry spells of the summer monsoon, the high resolution rainfall data, with an appropriate dynamical basis, is used to propose an objective criterion to capture WSREs over the CI domain. The dynamical characterisation of the WSREs provides insight into the evolution of the large-scale organisation of convection and the associated uniform distribution of rainfall. The criterion is first defined for the mature phase of the 2007 ISM and later applied and refined for the period 1959-2007 to capture the average characteristic of the WSREs. This criterion is then used to assess the ECMWF medium-range forecasts for the Indian peninsula.

The evolution of the large-scale convection associated with WSREs is analysed for the first weeks of each month July, August and September 2007. The smoothed daily rainfall series and its long term mean (9 mm; solid line) on the AI domain is presented in Figure 2a. A sequence of more than five days exceeding 9 mm identifies a set of WSREs. The above classification, in a standardised format, is similar to an ISO index (Chattopadhyay et al. 2008 and Rajeevan et al. 2008). However, in this study, a threshold value is preferred to validate the magnitude of spatial distribution of the rainfall over CI. The composite of rainfall (Fig. 2b) for the identified WSREs exhibits the uniform spatial distribution of enhanced rainfall, mostly exceeding 10 mm, over the CI domain associated with the organisation of synoptic-scale convective cells over the Indo-Pacific sector. It is, essentially, a classification of an active rain spell (Chattopadhyay et al. 2008). The Hovmoller diagrams (Fig. 3 a,b) describe the longitudinal (averaged over 15°-25°N) and latitudinal (averaged over 70°-90°E) variation of the mean OLR and anomalies of wind shear divergence. An attempt is made to illustrate the vertical variation of anomalous circulations resolving a large-scale baroclinic structure. The spatial distribution of the anomalous wind shear divergence indicates a clustering of synoptic scale convective systems which could serve as an appropriate dynamical indicator of large-scale circulation associated with the above WSREs. The latitudinal variation of the large-scale convection (Fig. 3a) shows clearly the meridional propagation of convective systems from oceanic regions to the sub-continent coinciding with the 2007 WSREs (Fig. 2b). Similarly, the longitudinal variation of the large-scale convection (Fig. 3b) exhibits West and North-westward propagation of convective systems from the West Pacific to the Indian sub-continent during the 2007 WSREs (Wang and Xu 1997, Sikka and Gadgil 1980, Krishnamurti et al. 1977). Thus, these WSREs evolving from the ITCZ are a unique classification of the active spells. The evolution of the meridionally and zonally propagating large-scale convection highlights an important issue of understanding the interaction between the above two modes during WSREs.

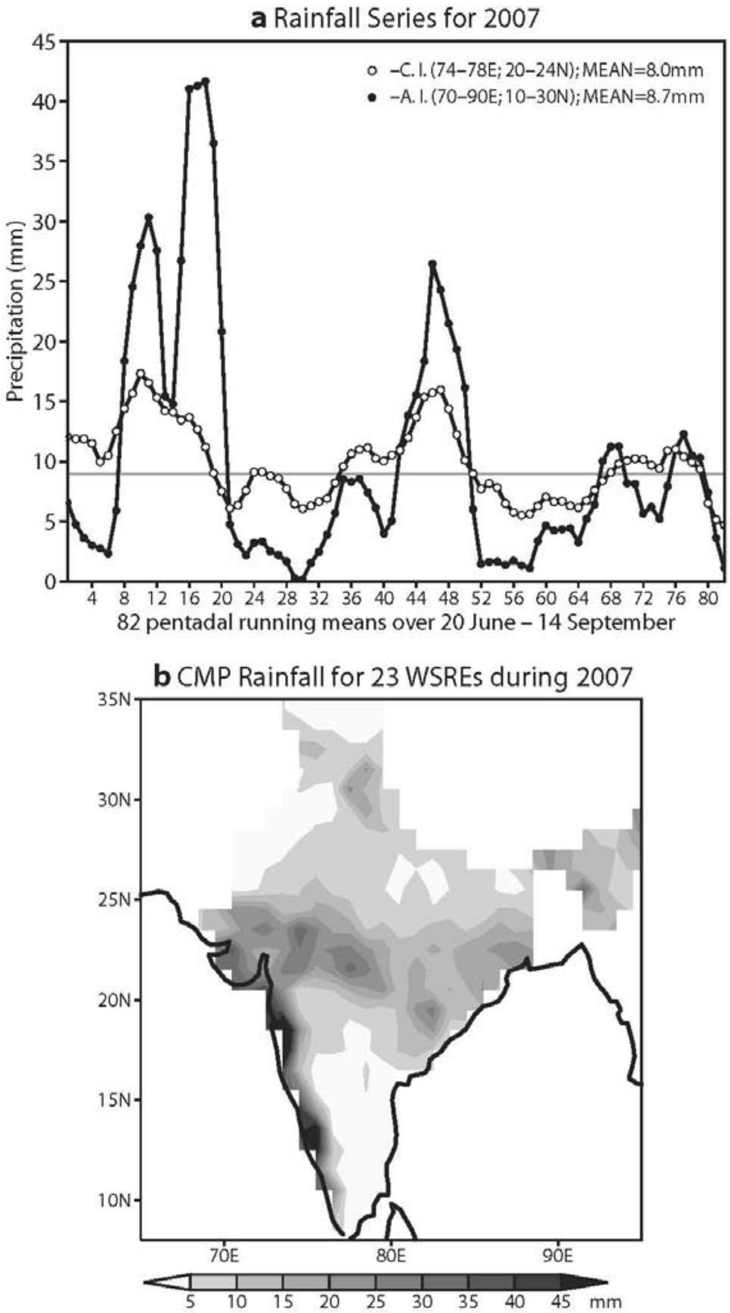

Figure 2a: IMD Rainfall Series for 82 pentadal running means during 20 June - 14 September 2007, averaged over (70°-90°E, 10°-30°N) box covering All India (AI) and (74°-78°E, 20°-24°N) box covering central India (CI). The rainfall series for CI is denoted by open circles and that of AI by closed circles. The 82 pentad are marked on x-axis, while the y-axis represents the rainfall in mm. The line is drawn at 9 mm to show the points in both the series AI and CI exceeding 9 mm (the threshold value, as described in the text) for the clear identification of WSREs. 2 b: The spatial distribution of (IMD) Rainfall (mm, grey shaded) for the composite of 23 WSREs during 2007.

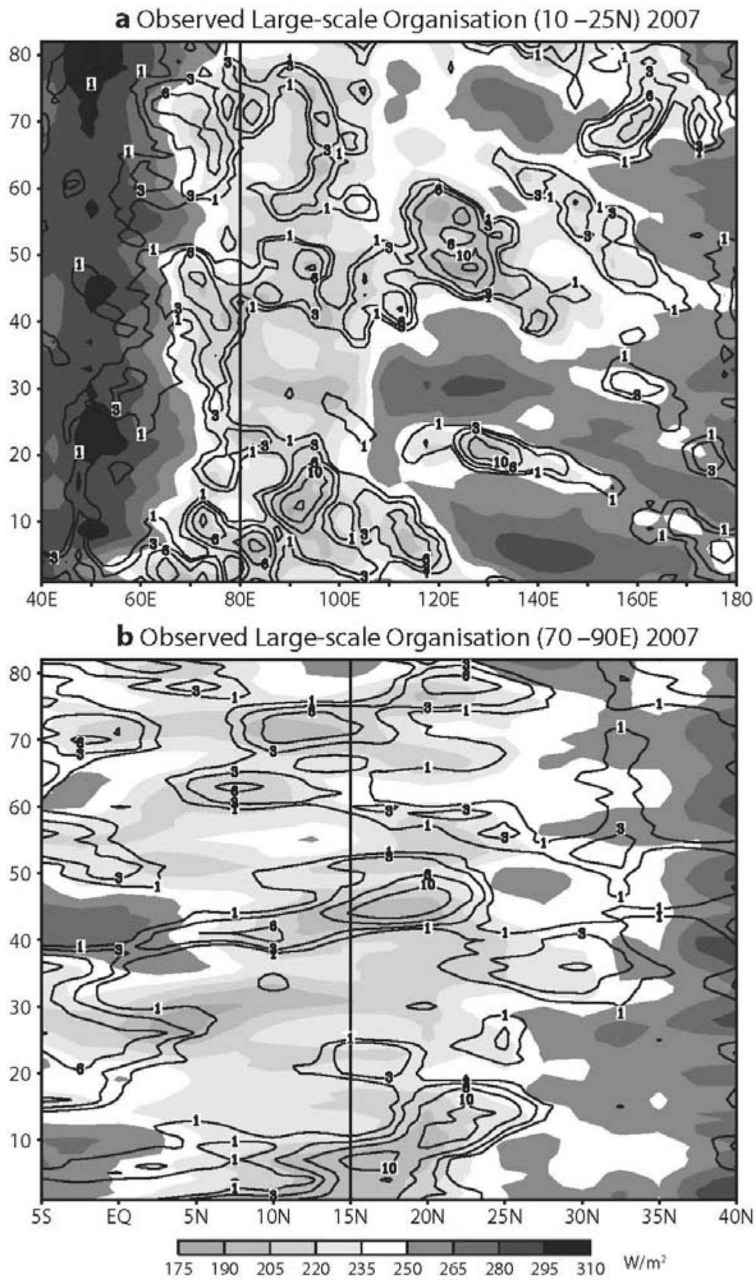

Figure 3a: The time-longitude cross-section of OLR (W/m^2) and anomalies of wind shear divergence $10^{-6}s^{-1}$, contours) averaged over (10°-25°N). Deep convection is characterised by low cloud-top temperatures and small OLR values (light grey shading): while high OLR values indicate scarcity of absence of cloud cover (dark grey shading). The x-axis shows the variation in longitudes while the y-axis is marked for 82 pentad. b) As in a) but for time-latitude section averaged over (70°-90°E).

The above analysis is extended to the period 1959-2007. The mean rainfall distribution computed from TPMI is shown in Figure 4 and clearly shows intense rainfall over the Indian West coast and in the North East regions, with only moderate rainfall over East-Central India. This is a prominent feature of the seasonal mean rainfall distribution (Fig. 3, Rajeevan et al. 2006).

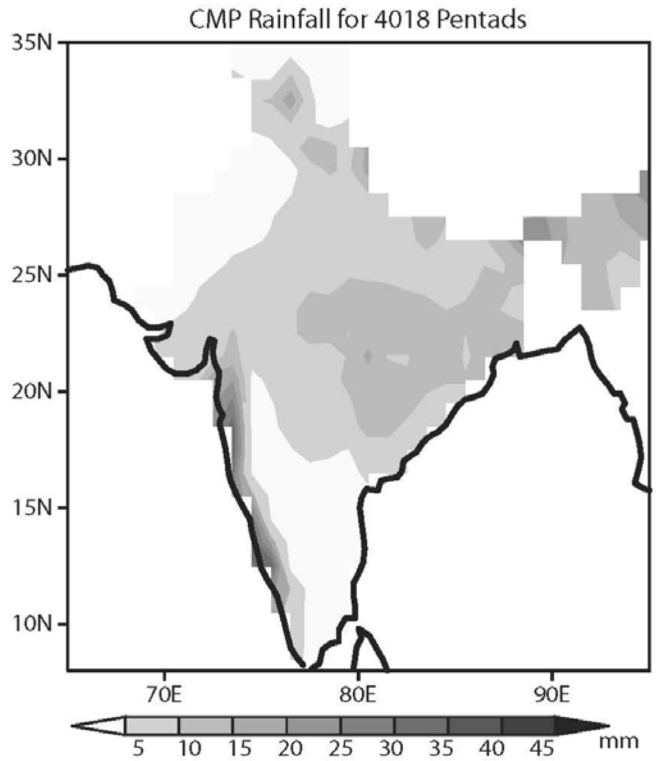

Figure 4: Rainfall (mm, shaded) distribution over India for the composite of all the 4018 pentads during the mature phases of (1959-2007) ISMs.

The same criterion of five consecutive days exceeding the 9mm threshold for the AI rainfall was applied to all the 4018 pentad. Active rainfall events were identified in only 47% of cases. In these cases, the rainfall distribution was not widespread over CI but stretched over the West-coast and North-Eastern regions (not shown). Therefore, averaged rainfall over AI is inadequate for an accurate identification of WSREs over the central Indian region, away from both West and East coasts. An additional criterion over CI was explored for an accurate identification of WSREs by looking at the correlation between anomalous wind shear divergence, averaged over CI, and spatial rainfall (Fig. 5). This correlation has a maximum (exceeding 0.5), at the 99% significance level (not shown), over the central region of the sub-continent away from the coasts. The box over CI, which is 22° N of that of Webster and Hoyos (2004), covers the semi-arid regions of west Madhya Pradesh (M.P.)[1], where the total seasonal rainfall is 75 cm less than its eastern and western counterparts where the seasonal rainfall exceeds 100 cm (www.imd.gov.in/section/climate/jun-sep-rainfall.htm). Therefore, intense rainfall events over this region of West M.P. are crucial in identifying uniformly distributed WSREs. It is also evident from Figure 2a that precipitation over both AI and CI regions consistently exceeds their respective long term mean during WSREs. Thus the following objective criterion is proposed for the identification of WSRE: **The five days running mean rainfall over CI and AI exceeds 9 mm.**

[1] The Indian author Milind Mujumdar (MM) graduated from ‘KHANDWA’, a city located in south-west (M.P.).

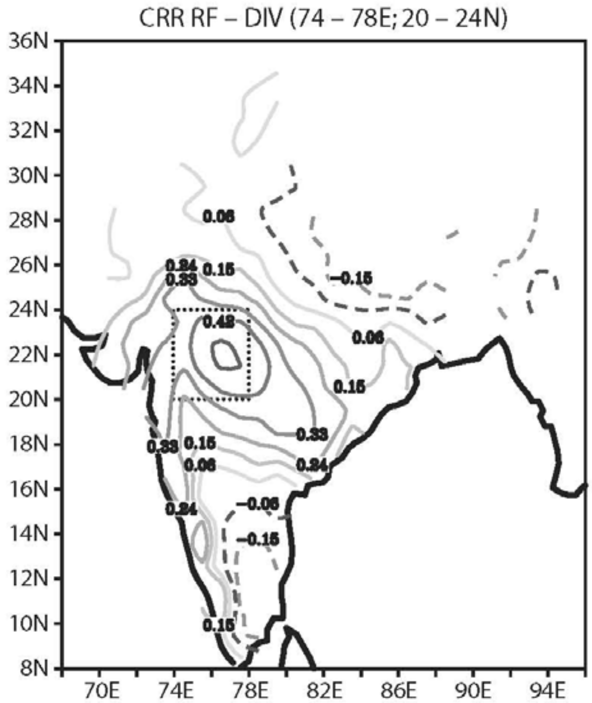

Figure 5: The spatial distribution of correlation (contours) between anomalies of wind shear divergence, averaged over a box (74°-78°E, 20°-24°N, denoted by the dotted line) of CI, and the gridded Indian rainfall data for the mature phases of summer monsoon during 1959 to 2007.

Using the above criterion, 1164 cases out of all the 4018 pentadal running means were classified as WSREs. For most if these WSREs, the minimum rainfall over the CI region exceeds 6mm (near its mean). The standard deviation of rainfall for AI is 3 mm, while it is about twice as much for CI. Moreover, the precipitation over CI during these WSREs is greater than 9 mm, as seen during 2007 (Fig. 2a). Five consecutive events with precipitation above 9mm were identified in most of the cases. Moreover, of those cases where only AI exceeds the threshold value of 9 mm, 18% do not represent accurately the WSREs, as discussed above. For all those cases not identified as WSREs, i.e. those with precipitation amounts smaller than 9mm for both the AI and CI domains, a large number (45%) are in phase with the near-equatorial Indian Ocean convection and show large-scale deficiency of rainfall over India. For those cases where the precipitation amount for CI alone exceeds the 9mm threshold, about 8% are characterised by a relatively weaker rainfall distribution over the western and eastern part of India, which indicates a dominant influence of regional factors as opposed to that of large-scale ITCZ over the Indo-Pacific sector. These cases could be related to the transition phases of large-scale wet-spells over the Indian sub-continent (Chattopadhyay et. al. 2008). It is clear from the above analysis that the proposed objective criterion, which includes both CI and AI, is needed for an accurate identification of WSREs.

4. Analysis and observation diagnostics

Figure 6 depicts the spatial distribution of rainfall for the WSREs composite (29%). The rainfall over large areas of the CI domain exceeds 15mm which is 6-8 mm higher than that of the composite of 47% of cases when exclusively AI rainfall satisfies the proposed criterion (not shown). Although the frequency of occurrence of these WSREs is relatively small during mature phases of the ISM, their contribution to the seasonal distribution of rainfall is important.

Composites of OLR and circulation anomalies for each of the WSREs in the 49 mature phases of the ISM were computed. Figure 7 shows the spatial distribution of differences between the composites of the WSREs and of the composites obtained from TPMI for OLR (light and dark grey shaded), anomalous wind-shear (grey shaded stream lines) and its divergence (contours).

The large-scale enhanced convection with the associated strong wind divergence anomalies over the Eastern Arabian Sea, the Bay of Bengal, the South China Sea and extending further East over the Indo-Pacific sector, is a characteristic of the rainfall in most of the CI domain. Moreover, the difference of wind-shear anomalies highlights the mid-latitude wave structure extending over West-Asia to the Far East (Fig. 7). This wave structure is important as anomalous Westerlies modulate the Tibetan anticyclone and have linkages with the large-scale organisation of convection. A more detailed investigation of how anomalous Westerlies influence the evolution of WSREs is subject of a separate study.

The large-scale organisation of convection, typical of the WSREs and significant at the 99% level over the Indo-Pacific sector (not shown), can be identified by looking at the equatorial flow pattern over the Indo-Pacific sector dominated by a strong northerly component and the sub-tropical anticyclonic large-scale flow pattern in the Southern-hemispheric regions complementing its equatorial and Northern hemispheric off-equatorial counterparts over the Indo-Pacific sector. This analysis also provides an opportunity to diagnose the nature of meridionally and zonally propagating large-scale convection modes.

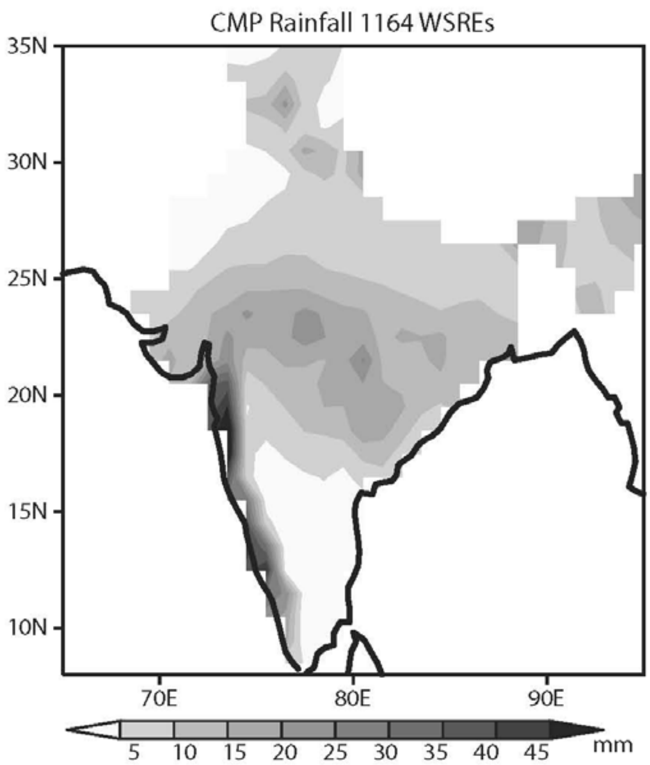

Figure 6: As in Figure 4 but for the composite of 1164 (29%) selected WSREs over central region of the sub-continent.

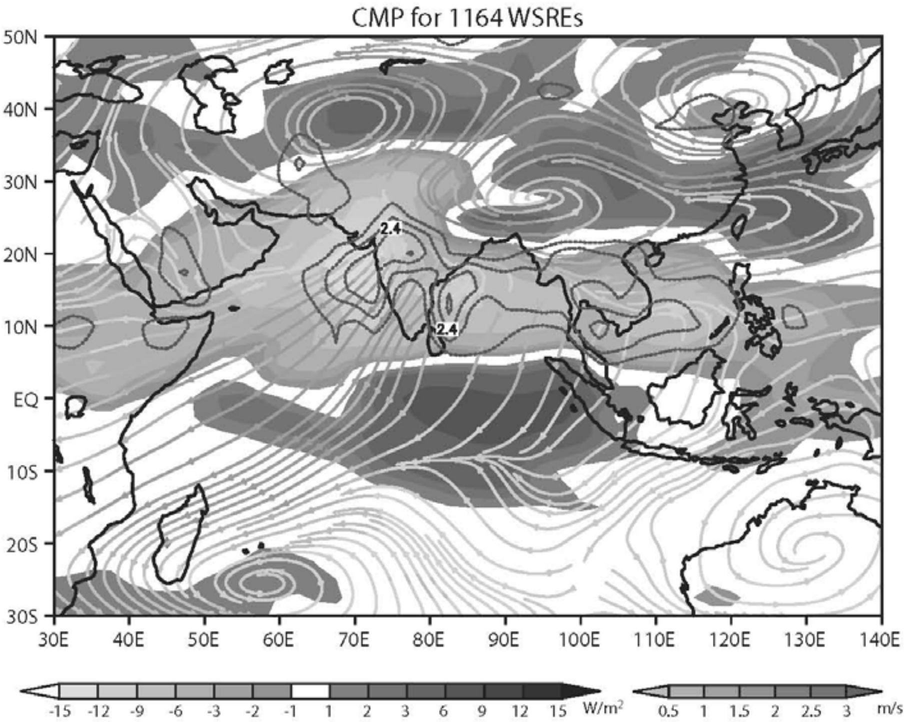

Figure 7: The differences for OLR (W/m^2) and anomalous wind shear (streamlines), between the composites of (1164) selected WSREs and (4018) total pentad. The light (dark) grey shading indicates relatively strong (weak) convection, grey shades superimposed on the streamlines are magnitudes (m/s) of the wind shear. The contours are the difference of anomalous wind shear divergence ($10^{-6}s^{-1}$).

The evolution of the WSREs is examined by extending the composite analysis to a few days prior and after its occurrence. The composites of OLR differences and wind shear divergence anomalies, for each of the 15 days before and after the occurrence of WSREs, are prepared. This lead-lag analysis is centred on the 15th day, when the WSREs occur. The Hovmoller diagrams (Fig. 8a-c) show the baroclinic structure of meridionally and zonally propagating large-scale convection. The northward propagation of anomalously enhanced convection and the anomalous strong divergence (overlaid), averaged over 70° -90°E, can be seen clearly through their latitudinal variation (Fig. 8a) for the 15 days of lag and lead. This northward propagation has a close resemblance to that shown by Sikka and Gadgil (1980). The minima of the OLR anomalies and maxima for the divergence anomalies are close to the day of occurrence of WSREs. After the occurrence of WSREs this large-scale convection weakens rapidly, characterising the different propagation speeds of moist and dry modes. The convection and circulation anomalies over the equatorial oceanic region have opposite phase to those of the continental WSREs. The negative anomalies over the sub-tropical regions of India prevail for about one week prior to the occurrence of WSREs.

Figure 8b exhibits the longitudinal variation of the differences of OLR and anomalous wind shear divergence, averaged over the equatorial region (5°S-5°N), for 15-day lag and lead time. The eastward propagating enhanced convection and the divergence anomalies (overlaid) depict the baroclinic structure of eastward propagating moist Kelvin Waves over the equatorial Indo Pacific sector more than one week prior to WSREs. This eastward propagation agrees closely with that displayed by Vitart (2004) and Wheeler and Kiladis (1999). This contrasts with the eastward propagating dry convection and weaker divergence anomalies within one week's time of the occurrence of WSREs (Fig. 8b). The prolonged enhanced convection characterised by the strong anomalous wind shear divergence is seen East of 150°E, which may be influential in modulating the occurrence of WSREs.

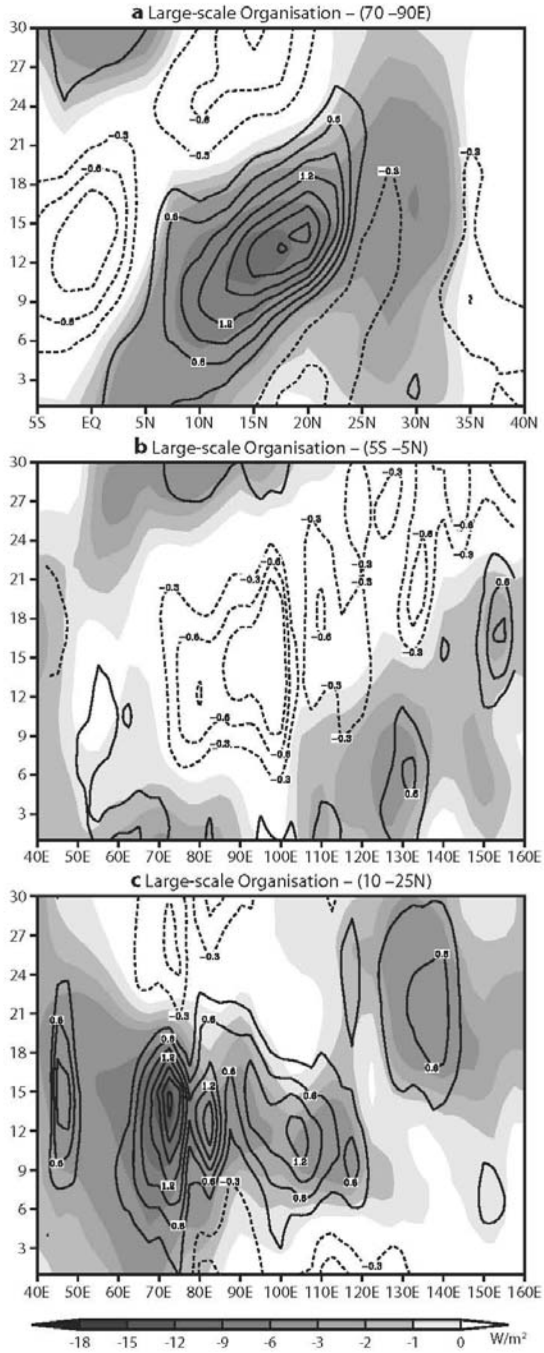

Figure 8a: The time-latitude cross section of the composite of differences for OLR (W/m^2) and anomalies of shear divergence ($10^{-6}s^{-1}$), averaged over (70°-90°E). The y-axis represents the time scale, 15 days before and after the occurrence of WSRE. The day of occurrence of WSRE is centred on 15th day. b) As in a) but for time-longitude cross, averaged over (5°S-5°N). c) As in b) but for averaged over (10°-25°N). The grey shading indicates relatively enhanced convection and contours are the difference of anomalous wind shear divergence ($10^{-6}s^{-1}$).

The Westward propagation of enhanced convection and the anomalous stronger divergence (overlaid) on the synoptic time-scale prior to the occurrence of WSREs, is the prominent feature seen over the off-equatorial region (15°-25°N) in the longitude-time cross-section (Fig. 8c). This Westward propagation of convection has been attributed to the propagation of the reminants of the deep convective systems in the West Pacific (Krishnamurti et al. 1977 and Wang and Xu 1997). The stronger, but relatively slower, eastward propagation of the anomalous equatorial convection and wind shear divergence are seen more than one week prior to the occurrence of WSREs. The dissipation of the convection and divergence occurs less than one week after WSREs, while the dry convection and weaker circulation over 110°-130°E evolves about 10 days prior to WSREs, which could be associated to the meridionally dispersive wave pattern. This prominent a priori signal was detected in the cases under investigation by examining a longitude-time cross-section of convection and circulation over the domain 5°-15°N and a latitude-time cross-section over the area 110°-130°E (not shown). Thus, WSREs identified in this study are closely associated with the systematic intensification of meridionally and zonally propagating convective systems, exceeding the synoptic time-scale, embedded into large-scale organised circulation. The "interaction" of these meridionally and zonally propagating modes can be better diagnosed while analysing the ECMWF forecasts of WSREs. It is also worth testing whether this systematic organisation of large-scale convection provides a basis for the prediction of WSREs.

5. Forecast diagnostics

The diagnostic analysis is now extended to ECMWF medium range forecasts for the mature phase of the 2007 ISM. The forecast pentadal running means, relative to day 1 to day 5 (EPS-1) and day 5 to day 10 lead time (EPS-2), have been constructed in a similar fashion to those of the analysed fields and WSREs have been defined using the same double criterion whereby both AI and CI rainfall has to exceed simultaneously the 9mm threshold.

The criterion is applied to every member of the ensemble for each pentadal running mean. The proportion of members which satisfies the criterion defines the probability of the event to happen. The forecast WSREs in the EPS-1 system are identified with a higher probability than those in the EPS-2. These forecast WSREs are then validated against those of the observed WSREs. The spatial distribution of rainfall over CI in each correctly forecast case of WSREs exhibits a close agreement with observations.

In order to assess the performance of the ensemble forecast, contingency tables (Jolliffe and Stephenson, 2003, Casati et al, 2008) are constructed for each probability class. Table 1 shows an example of a generic contingency table where HIT denotes a complete match between forecast and observed, FALSE ALARM indicates a forecast but not observed event, MISS refers to an observed event that was not forecast and CORRECT NEGATIVE is the correct forecast of a not occurring event. Two readily computed scores are the HIT rate, which is HIT/(HIT+MISS), and FALSE ALARM RATE, which is FALSE ALARM/(FALSE ALARM + CORRECT NEGATIVE). The EPS-1 forecast captured almost all of the 23 observed WSREs during the first weeks of July, August and September 2007 for probabilities less than 70%, while the FALSE ALARM rate equals the HIT rate for higher probabilities.

The diagnostic analysis of forecast WSREs is discussed here for EPS-2. The double criterion is satisfied in 30% of the ECMWF ensemble forecasts, which corresponds to 43 forecast WSRE events. Of these events, 11 are in close agreement with the observed WSREs for the same period in time. As the occurrence of a WSRE is a relatively rare event, the low probability class of EPS-2 is selected as a compromise between skillful forecast and the rarity of the event. Higher probability thresholds do not contain useful information in the medium range.

Table 1: Generic contingency table

Quantitative Assessment	Observed yes	Observed no
Forecast yes	HIT	FALSE ALARM
Forecast no	MISS	CORRECT NEGATIVE

Figure 9 shows the spatial distribution of rainfall composite of these 11 forecast and observed WSREs during the first weeks of July and August 2007. It is encouraging to note that the spatial distribution of the composite of forecasted rainfall pattern (Fig. 9) over the Indian subcontinent matches well with the observed composite (Fig. 2b). In particular, the magnitude of the simulated rainfall over the CI domain is captured realistically. The composite of OLR and wind shear divergence (not shown) exhibits good agreement with the characteristics of the observed large-scale convection over the Indo-Pacific sector (Fig. 7). Figure 10 (a and b) shows the time evolution of longitudinal (averaged over 10°-25°N) and latitudinal (averaged over 70°-90°E) cross sections of mean OLR and anomalies of wind shear divergence for the 11 cases. The zonal (westward of 80°E) and meridional (northward of 15°N) propagation of the large-scale convection and wind shear divergence (overlaid) agrees reasonably well with that of observed propagation (Fig. 3a and 3b). Interestingly, the propagation of a cluster of convective systems during the first week of September is not captured by the EPS-2. The unrealistic simulation of the secondary ITCZ over South of the equatorial Indian Ocean and the longitudinal distribution of the spurious wind shear divergence and convection in EPS-2 constitutes a limit to the forecast skill of WSREs. However, the overall agreement of the zonal and meridional propagation of coherent large-scale convection, during the first weeks of July and August 2007, confirms the influence of ITCZ on the evolution of the 11 cases of forecast and observed WSREs.

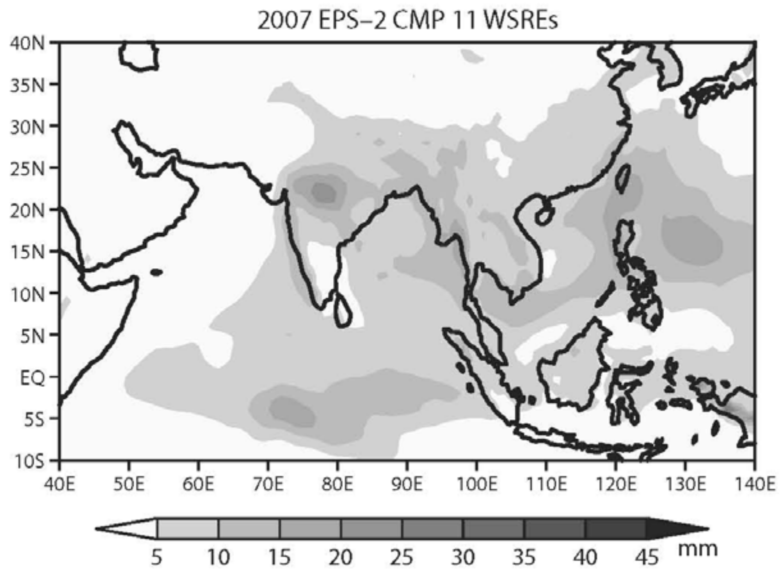

Figure 9: As in Figure 2b but for the composite of 11 cases where observed and forecast WSREs match. Forecast WSREs are relative to the day 5 to day 10 lead time (two-pentad lead time).

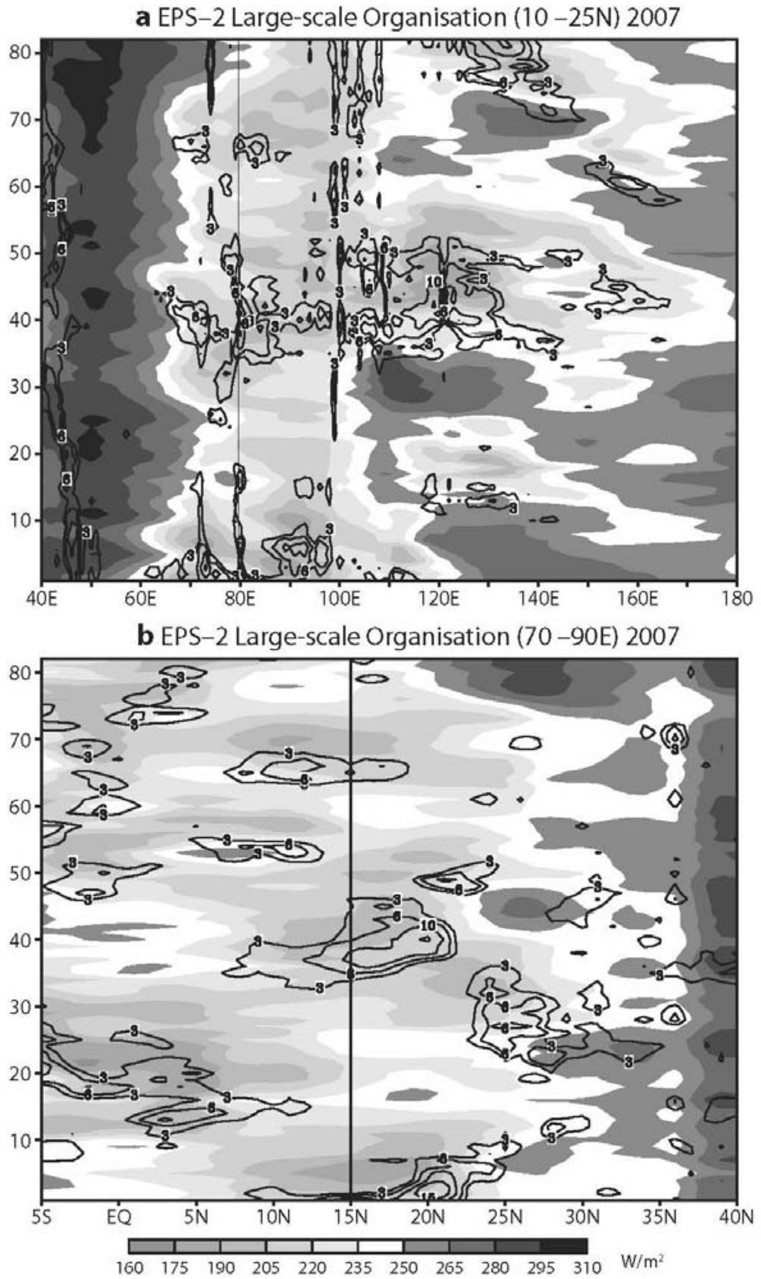

Figure 10: As in figure 3 but for the 11 cases where observed and forecast WSREs match. Forecast WSREs are relative to the day 5 to day 10 lead time.

6. Concluding remarks and future scope

Accurate forecasts of widespread rainfall events (WSREs) during the mature phase (July and August) of the Indian summer monsoon are vital for the Indian agriculture and hydrology sector. The paper focuses on understanding the mechanisms behind WSREs by looking at a criterion that both characterises them and includes elements of the large scale organised convection during the Indian summer monsoon. The criterion is first applied to the observed rainfall and the analysed fields that act as indicators of the large scale patterns, and then to the ECMWF Ensemble Prediction System forecasts with up to ten days lead time.

The objective criterion proposed in the paper requires that the rainfall exceed a threshold of 9mm simultaneously in two areas: All India, which includes the whole Indian peninsula, and Central India, defined as 74°-78°E and 20°-24°N.

To begin with, the 5-day running means of the observed rainfall for 49 mature phases of the Indian monsoon were investigated together with the 5-day running means of OLR and wind shear divergence analysed fields to assess whether the proposed criterion is actually defining the WSREs. The criterion was then applied to the forecasts.

The application of the criterion on the observed rainfall produced 1164 WSRes, which corresponds to 29% of the total 5-day running means for the 49 years. They were associated to the baroclinic structure which transforms the large-scale convection, described in terms of wind shear divergence, over the Indo-Pacific sector.

The same criterion applied to the Ensemble Prediction System showed that skilful forecasts of WSREs can be identified with a higher probability in the EPS-1 system and with a lower probability for EPS-2. This limit is the result of a compromise between the rarity of the event (the rainfall in both areas satisfies the criterion simultaneously) and the skill of the forecasting system. The agreement between forecast and observed events was obtained in 11 cases for the 10-day lead-time forecasts. In these cases the rainfall pattern clearly indicated a predominance of rainfall above the threshold over Central India. Moreover, the interaction with the large scale convection was shown to mimic that found for the analysed fields. Furthermore, the forecast diagnostics provides an opportunity to analyse the intense active phase of the ISO. The clustering of convective cells, as a product of the interaction between meridional (ISO scale) and zonal (synoptic scale) propagation embedded within large-scale convection, could be an important factor for extended range prediction of WSREs.

The present study indicates the existence of a dynamical linkage between meridionally and zonally propagating modes, and the organised convection typical of the WSREs. Figure 11 presents a schematic of

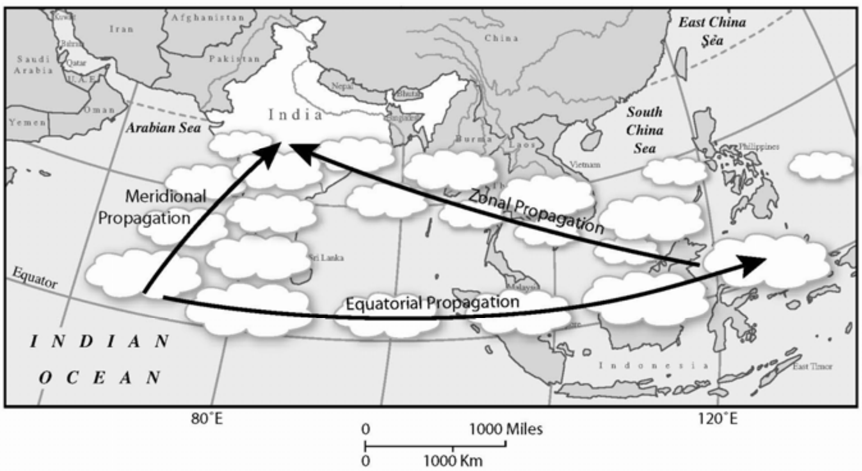

Figure 11: Schematic describing the dynamical linkage between meridionally and zonally propagating modes, modulating the large-scale organisation embedded in the boreal summer ITCZ, during the occurrence of WSREs.

this interaction by showing how the meridionally (ISO scales) and zonally (synoptic scales) propagating modes affect the large scale convection, resulting from a clustering of convective cells, associated with the WSREs. The meridional propagation of convection, on the 10-20 days time scale, over the South-Asian monsoon region could be attributed to the weakening of the meridional circulation as a result of the strong South-westerly monsoon flow. The eastward equatorial propagation over the Indo-Pacific sector resembles the moist Kelvin waves associated with the MJOs. The fast westward propagation of convection from the West-Pacific warm pool region to the South-Asian summer monsoon region, within one week's time, could be attributed to the mixed-Rossby gravity waves (Fig. 8c).

Another interesting outcome of the assessment of the predictive skills (one- to two-pentad lead time) of the ECMWF Ensemble Prediction System over India is the acknowledgement of a potential wider scope for diagnosing the influence of remote and regional forcings on the organisation of large-scale convection. The appraisal can be extended to break phases associated with the evolution of large-scale suppressed convection (Krishnan et al. 2000). In a separate study, simulation experiments have been initiated, using ECMWF relaxation technique, to diagnose the influence of mid-latitude wave disturbances on the evolution of WSREs.

Future studies of extended range monsoon prediction should focus on the Variable Resolution Ensemble Prediction System (VarEPS: Buizza et al. 2007, Vitart et al. 2008, Vitart and Molteni 2008) introduced recently at ECMWF. VarEPS is complemented with a 20 year hindcast which will be helpful for diagnosing the large-scale organisation during the mature phase of the summer monsoon on an extended forecast period by carrying out the composite analysis a few days prior to and after its occurrence, similar to that of the observed analysis (Fig. 8a-c). Finally this study could be extended to monthly and seasonal scales to understand the 30 to 60 days variability.

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