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ORIGINAL ARTICLE

# Simulation of Indian summer monsoon intra-seasonal oscillations using WRF regional atmospheric model

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## Abstract

The present study examines the mean features of Indian summer monsoon and the boreal summer intra-seasonal oscillations (BSISO) as simulated by the Weather Research and Forecasting (WRF) regional atmospheric model. For this the WRF model at 30-km horizontal resolution is forced with NCEP-II reanalysis as the initial and boundary condition and integrated for a period of 8 years. The simulated results are compared with TRMM rainfall as well as with the reanalysis datasets of NCEP-II and ERA-Interim. Analysis reveals that the WRF model is able to reproduce the observed characteristics of large scale mean features and spatial variations of rainfall and winds at 850hPa and 200hPa. The northward propagating intra-seasonal oscillation (ISO) components over the monsoon trough and the equatorial Indian Ocean is reasonably simulated by the WRF model and shows some promise in understanding the regional characteristics of Indian summer monsoon and its ISO components. WRF model can act as suitable tool for predicting the ISO's over the Indian summer monsoon region. Further, the results presented here suggests that reanalysis with a realistic basic state and proper representation of northward moving ISO's is required to force a regional model. This study elucidate the WRF regional model has shown a reasonable representation of BSISO.

**Keywords**: Indian summer monsoon, Intra-seasonal oscillation, WRF model.

## 1. Introduction

Asian summer monsoon is the most vigorous weather system in the world, profoundly affecting most of the nations of South and Southeast Asia. Across the region, over 75% of the total annual rainfall occurs during the summer monsoon season. Nearly 60% of the planet's population relies on the soaking monsoon rains to support agricultural production, to provide adequate drinking water for humans and livestock and to generate hydroelectric power that drives agricultural and industrial production (Fein and Stephens, 1987). Indian summer monsoon has vigorous intra-seasonal oscillations in the form of ''active'' and ''break'' spells of monsoon rainfall within the summer monsoon season (Ramamurthy, 1969), associated with fluctuations in tropical convergence zone (TCZ) or zonally oriented belt of precipitation from its equatorial position to continental position (Yasunari, 1979; 1980; 1981; Sikka and Gadgil, 1980). The TCZ over the Indian monsoon region represents the ascending branch of the regional hadley circulation and has a bimodal structure in convection with two preferred locations of convection, one over the Indian continent and other over the equatorial Indian Ocean (Sikka and Gadgil, 1980).

The intra-seasonal oscillations (ISO's) of the Indian summer monsoon represent a broadband spectrum with periods between 10 and 90 days but have two preferred bands of periods (Krishnamurti and Bhalme, 1976; Krishnamurti and Ardunay, 1980; Yasunari, 1980), one between 10 and 20 days and the other between 30 and 60 days. The two oscillations such as northward propagation of the TCZ with a periodicity of 30–60 days and the westward propagation of synoptic scale convective systems that originates over the warm waters of Bay of Bengal (Gadgil, 2000), with a periodicity of 10–20 days contributes equally to the intra-seasonal active and break cycles of the monsoon rainfall. Active phase of monsoon is characterized by the clustering of the low pressure systems over the warm waters surrounded by


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the subcontinent. Relatively very few systems form during the break phase. The strength of monsoon activity has inverse (direct) relationship with slower 30–60 (faster 10–20) day mode (Kripalani *et al.*, 2004).

The prediction of Indian monsoon mean rainfall and the intra-seasonal variability of Indian summer monsoon are the uttermost important for Indian region. In the past there were many attempts to demonstrate the skill of the regional models embedded in a GCM to simulate the Indian summer monsoon climatology (Bhaskaran *et al.*, 1996; Jacob and Podzum, 1997; Vernekar and Ji, 1999; Lee and Suh, 2000; Dash *et al.*, 2006). All these studies reported that the regional models were able to produce an improvement in the spatial and temporal distribution of monsoon precipitation, which was attributed by the increased resolution of these models. Hence, we conducted an experiment with the WRF model at a horizontal resolution of 30-km over the South Asian domain. The prediction of active and break cycles of the monsoon rainfall is very crucial for agriculture planning, water management etc. Moreover, it also controls and limits the predictability of seasonal mean. Studies carried out for simulating monsoon features using WRF model (e.g. Ashrit and Mohandas, 2010; Srnivas *et al.*, 2012; Raju *et al.*, 2013) found that the WRF model able to capture mean monsoon circulation patterns and rainfall. Bhaskaran *et al.* (1998) studied ISO using a general circulation model (GCM) and a nested regional climate model (RCM) in the Indian summer monsoon. They suggested that the ISO's in the RCM was modulated by the driving GCM circulation via the lateral boundary forcing on the 30-50 daytime scale. Hence, a better representation of not only the monsoon climatology but also the intra-seasonal oscillations is very much required for a dynamical model to predict the monsoon accurately. The present study is therefore aimed at investigating the capability of a regional climate model, Weather Research Forecast (WRF) regional climate model in simulating the Indian summer mean monsoon circulation features, rainfall and intra-seasonal oscillations, when observed boundary conditions are provided.

## 2. Data, Model and Experimental Design

### 2.1 Data

TRMM (Tropical Rainfall Measuring Mission) rain rate at a spatial resolution of 0.25X0.25 degree grid boxes (~30X30 km) with a 3-hour resolution and precipitation and winds (at 850hPa and 200hPa) obtained from the reanalysis datasets namely 6-hourly NCEP–NCAR (National Centers for Environmental Prediction–National Center for Atmospheric Research) at a horizontal resolution of 2.5 X 2.5 degree (Kalnay *et al.*, 1996) and 6 hourly ERA-Interim at a spatial resolution of 1.5 X 1.5 degree (Simmons *et al.*, 2006) have been used for evaluating the performance of the model. The study utilised the observational dataset for the monsoon months (JJAS; June to September) of (2000-2007) eight years. Daily precipitation anomalies are calculated by removing the daily mean climatology (2000-2007) from the daily actual precipitation. These anomalies are then filtered using a Lanczos filter (Duchon, 1979), by retaining periodicities between 20 and 100 days to obtain intra-seasonal anomalies. These intra-seasonal anomalies are hereafter referred as “filtered anomalies”. In addition to this, the Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) at a spatial resolution of 0.25X0.25 degree gridded daily data (Yatagai *et al*., 2012) are used for the comparison of rainfall over Indian land region.

### 2.2 Description of the WRF model

The Advanced Research WRF (WRF-ARW) model version 3 is a fully compressible, Euler non-hydrostatic equations model from the NCAR Mesoscale and Microscale Meteorology division. Arakawa-C grid staggering is used for the horizontal discretization. Detailed description of WRF-ARW is available in Wang *et al.* (2008), and Skamarock *et al.* (2005). The microphysical sub grid scale processes are represented by the scheme described by Thompson *et al.* (2004) and the Betts Miller Janjic scheme (Betts, 1986; Betts and Miller, 1986; Janjic, 1996; 2000) is used to represent the cumulus parameterization. Mukhopadhyay *et al.* (2010) conducted sensitivity simulations by changing different convective parameterizations in order to represent the mean climatological precipitation. They found that the BMJ convective parameterization scheme is able to produce a reasonable mean monsoon pattern in the WRF model. Moreover, earlier study for comparing the performance of three different convection parameterization scheme in simulating contrasting monsoons (Ratnam and Krishna Kumar, 2005) reveal that the BMJ scheme has simulated less rainfall during the drought year of 1987 and the circulation features comparable with the observations. Hence, we selected BMJ convective parameterization scheme in our simulation. The Noah land surface model (Chen and Dudhia, 2001) and Yonsei University PBL parameterization scheme (Hong *et al.*, 2006; Hong and Dudhia, 2003) are used in these simulations. Rapid Radiative Transfer Model (RRTM, Mlawer *et al.*, 1997) is used for long wave radiation parameterization. The short wave radiation parameterization described by Dudhia (1989), is used


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to represent short wave radiation interactions in the atmosphere.

The model domain bounded by 40°-120°E and 20°S-40°N, covering South Asian monsoon regions have been selected for the present study. A horizontal resolution of 30 km and 28 sigma levels in vertical with model top at 10hPa is chosen so that the model can capture monsoon features embedded in the planetary-scale monsoon system. The initial conditions and large-scale lateral boundary conditions obtained from the NCEP-Department of Energy (DOE) (NCEP-DOE) Reanalysis II data (Kanamitsu *et al.,* 2002) is used to force the model. Observed Reynolds sea surface temperature (SST) weekly data with a spatial coverage of 1.0 degree latitude x 1.0 longitude global grid (180 x 360) are used in this simulation. The lateral boundary conditions (LBCs) are updated every six hours and SST updated at weekly in the model frame work. We simulate the model for 8-year period (2000-2007) with a time step of 180 seconds. Each WRF-ARW simulation was initialized from the 1st May and ran until 30th September for 8 year period.

## 3. Results

To have a better monsoon simulation in the model, the model must have a better representation of the monsoon climatology at the first instance. Hence, the large scale features of monsoon as simulated by the model is compared with that of the observations as well as with the NCEP-II reanalysis (forcing field for the WRF model). Before investigating the model's ability in simulating monsoon intra-seasonal oscillations, a detailed discussion on the climatology and large scale features are provided in the following section.

### 3.1. Simulation of mean monsoon spatial rainfall and circulation features.

The important characteristics of the Indian summer monsoon is the circulation features such as the Findlater jet at 850hPa (Findlater, 1969), the easterly jet at 200hPa (Koteswaram, 1958). The seasonal mean characteristic of the flow pattern in the model is compared with corresponding fields from NCEP-II and ERA-Interim reanalysis (Fig 1). The reanalysis dataset show 850hPa wind maximum along northwest Indian Ocean over the latitudinal belt of 5°-15°N. ERA-Interim (Fig 1c) has stronger winds at 850hPa compared to NCEP-II (Fig 1a). The maximum strength of the mean westerly wind at 850hPa is well simulated by the WRF model, but with a slight overestimation in the wind speed (Fig 1e) compared to NCEP-II (Fig 1a) and underestimation when compared to ERA-Interim (Fig 1c). The figure shows that the cross equatorial flow at 850hPa in the Arabian Sea over the whole peninsular region, easterlies over Indo-Gangetic plains is well simulated. The upper level (200hPa) winds from NCEP-II reanalysis clearly show the tropical easterly jet stream with maximum winds along the equatorial region of southern tip of Indian peninsula. The presence of the Tibetan anticyclone can be noticed. The tropical easterly jet is well simulated. However, in the equatorial region, the maximum strength of mean wind at 200hPa is underestimated by the WRF model. The monthly variation of winds in the lower and upper troposphere also has a better representation in WRF model (figure not shown). When the monsoon is active, the lower level (850hPa) south-westerly winds get stronger over the Indian peninsula and eventually the precipitation becomes positive and while the monsoon is in the break phase the lower level (850hPa) south-westerly winds get weaker over the Indian peninsula and eventually the precipitation becomes negative. Therefore, circulation features are one of the most important components of monsoon simulation. The WRF model has shown a reasonable representation of large scale circulation.

Rainfall is an important parameter in many operational and research activities, ranging from weather forecasting to climate research. A comparison of JJAS rainfall climatology simulated by the WRF model with that of observed dataset of APHRODITE, and TRMM can be obtained from (Fig 2). The APHRODITE data are used for the better comparison of land region over the model domain. The APHRODITE data has a better representation of heavy rainfall over the Western Ghats, the foot hills of Himalayas and the monsoon trough region by the use of ground truth gauges network compared to TRMM data. The observed TRMM rainfall also show a maximum rainfall over west coastal regions near the Western Ghats, eastern Bay of Bengal and over eastern equatorial Indian Ocean. Analysis shows that the WRF model captures the general features of the JJAS seasonal climatology of rainfall over the Asian monsoon region (40°E-120°E, 20°S-40°N). A few deficiencies to note are the overestimation of rainfall over the equatorial Indian Ocean and the underestimation over the central India and foothills of Himalayas. The underestimation of precipitation over the core monsoon (Central India) region (Rajeevan *et al.,* 2010) is quantified by computing the mean and standard deviation in rainfall over the central Indian region (CI: averaged over the region bounded by 69°E-88°E and 18°N-28°N). There is discrepancy among the observations while estimating the mean (standard deviation) of rainfall over the CI region. When TRMM has shown mean monsoon (JJAS) CI rainfall of 7.89 mm/day with a standard deviation of 2.16 mm/day. The APHRODITE data show mean rainfall of 5.76 mm/day with a standard deviation of 1.93.


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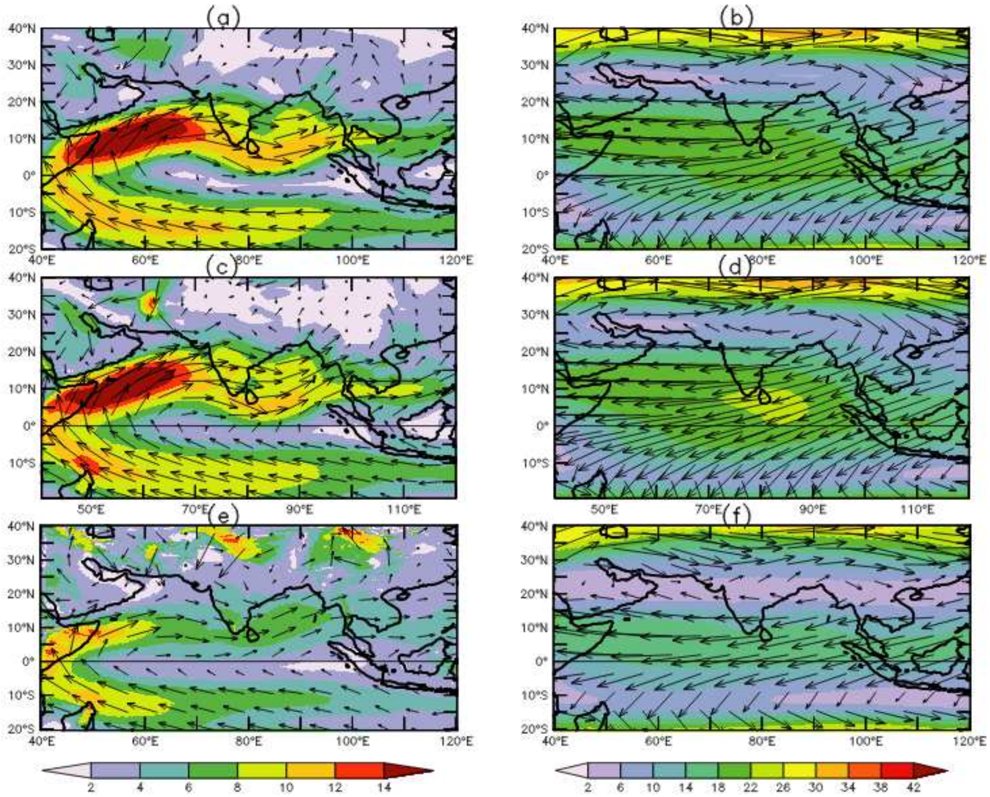


Fig 1: Climatology of monsoon circulation (JJAS). Horizontal winds at 850 (a, c and e) and 200 (b, d and f) hPa from NCEP (a and b), ERA-Interim (c and d) and WRF model (e and f) for the period (2000-2007).

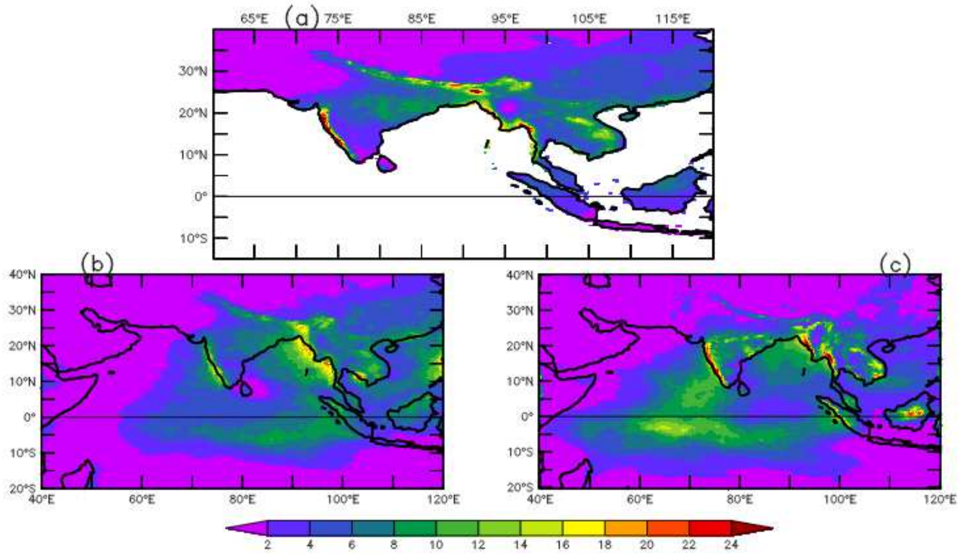


Fig 2: Summer monsoon (JJAS) rainfall (mm/day) climatology from a) APROHDITE b) TRMM, and c) WRF model for the period (2000-2007).


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However, the data covers only land points. The reanalysis products, NCEP-II (ERA-Interim) show low values of rainfall with mean 5.85 (6.72) mm/day and standard deviation 2.29 (1.21) compared to the TRMM. The WRF model has simulated mean rainfall of 5.77 mm/day with a standard deviation of 1.65 mm/day over the region; comparable with NCEP-II reanalysis and APHRODITE ground truth data, but significantly lower than the TRMM observation. Although the models capture the spatial structure of variability, the amplitude of the variability is considerably underestimated, when compared to TRMM observation. Individual months of climatological pattern of rainfall simulated by the model are compared well with TRMM observation (figure not shown). However, an overestimation of rainfall over Arabian Sea is seen in all months in the WRF simulated rainfall. Rainfall over the core monsoon region is underestimated in the WRF model compared to observations; the possible reason is evident from the simulated wind climatology at 850hPa as shown in (Figs 1a, c, e). Since the WRF simulated winds are weaker during the monsoon season which brings the lesser moisture to the core monsoon region and eventually results in deficient rainfall over the core monsoon region. If we consider the core monsoon region especially the CI, the rainfall is deficient due to two reasons, (1) the northward extent of the cross equatorial flow is to the south of CI region (Fig 1e), (2) WRF simulates more rainfall over the Arabian sea (Fig 2c) which dries out the winds reaching the core monsoon region.

Further, the ability of the model to simulate extreme dry and wet years have been assessed by comparing the WRF model simulations and observations for two extreme dry monsoon year of 2002 and wet year of 2007 period. The model has simulated a mean rainfall over the CI region of 10.42 mm/day for the dry monsoon year (2002) while the observed TRMM (APHRODITE) data showed mean rainfall of 7.71 (6.36) mm/day. However, during the wet year of 2007, the model produce a rainfall of 8.78 mm/day while the observations were 7.90 (6.01) mm/day. Assessment of the day to day variation of rainfall for the years show that the WRF model failed to capture break monsoon period during July 2002. The WRF model underestimates the June rainfall, over estimates in July and August. Model simulated rainfall variability is close to observations only during the month of September. Unlike the dry monsoon year, the daily rainfall variations are reasonably well simulated by the model during the wet monsoon year of 2007 (Fig 3b). The model has shown a correlation of 0.17 (0.17) with the observed TRMM (APHRODITE) in simulating the day to day variation of monsoon rainfall of the dry year (2002), while the variations of Central Indian rainfall for the wet year (2007) is well simulated with a correlation of 0.38 (0.49) with TRMM (APHRODITE) data.

## 3.2. Simulation of Boreal Summer Intra-Seasonal Oscillations (BSISO) characteristics

The skill of the atmospheric model in simulating the mean summer monsoon climate and BSISO variance can be assessed from the (Fig 2 and 4). The rainfall maxima over the west coast of India and over the monsoon trough region are realistically simulated in WRF model (Fig 2), indicating that the northward propagation of the monsoon convection has a good representation in the model. To obtain detailed understanding of the boreal summer intra-seasonal oscillations (BSISO). A 20-100 day band pass filter, which covers the broad band spectrum of the intra-seasonal oscillations, is applied to the observed and model simulated precipitation anomalies. Composite seasonal mean intra-seasonal variance of the filtered precipitation anomalies (Fig 4) identifies two zones of maximum precipitation variance, the primary zone of maximum precipitation variance is over the eastern equatorial Indian Ocean and the secondary zone of precipitation maximum stay over the two locations, one over the west coast of India and the other over the northern bay of Bengal. These rainfall characteristics are reasonably captured by the model. Enhanced intra-seasonal variance of precipitation anomalies is seen in the most of the Indian monsoon domain, large variance is simulated mainly over western Indian Ocean. Our diagnostics show that the basic state in precipitation, the zonal and meridional extent in easterly vertical shear and the magnitude of simulated intra-seasonal variability in precipitation (Figs 1, 2, and 4) as well as the BSISO properties remain close to observations (TRMM and NCEP-II/ERA-Interim reanalysis).

In order to understand the propagation characteristics of BSISO, filtered precipitation anomalies are regressed at different time lags with respect to a reference time series averaged over the regional heat sources (monsoon trough and equatorial Indian Ocean region). The reference time series is computed based on the area averaged filtered precipitation anomalies over a box in the monsoon trough region (18°–25°N, 70°–95°E) and a box in the Equatorial Indian Ocean (10°S–5°N, 70°–110°E) for the boreal summer season from 1 June to 30 September. Lag-lead regression analysis have been


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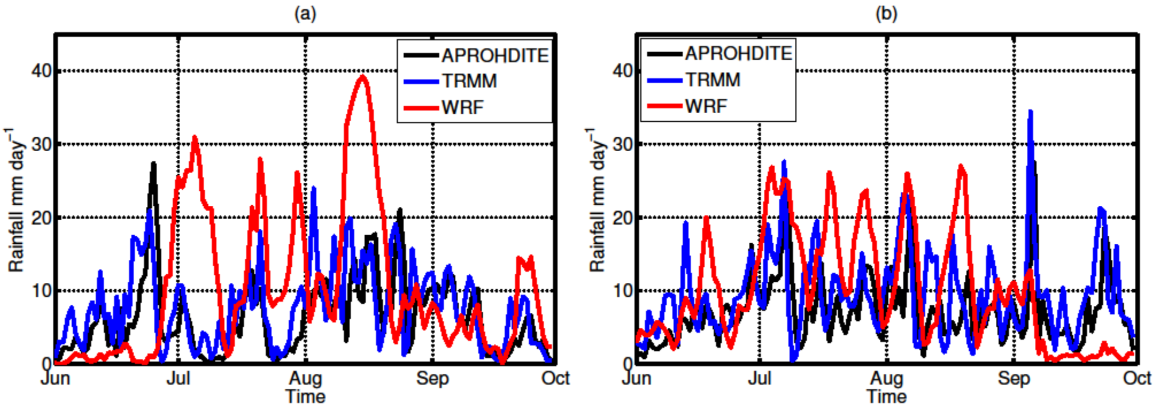


Fig 3: Daily rainfall time series averaged over central India (18°-25°N, 75°-90°E) from observations and model for two extreme monsoon years of (a) dry year (2002) and (b) wet year (2007).

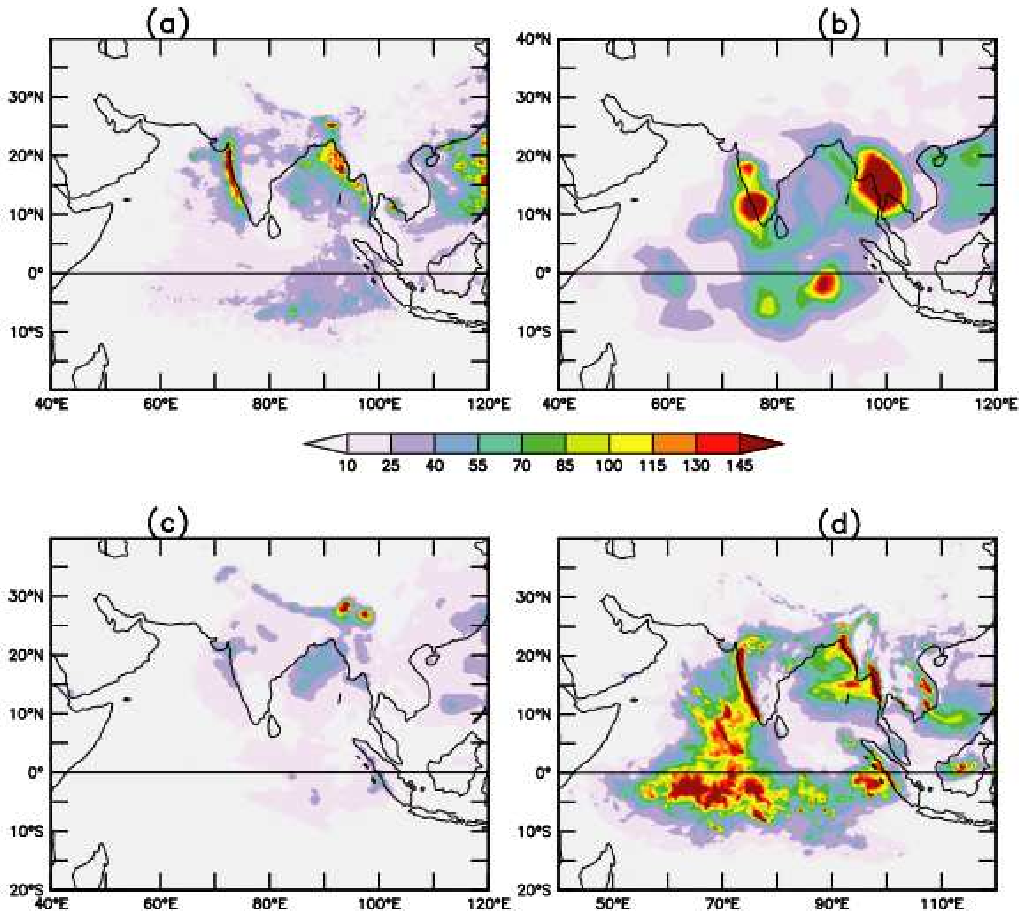


Fig 4: JJAS composite mean variance of 20–100 day filtered precipitation anomalies ($mm^2/day^2$) from a) TRMM, b) NCEP, c) ERA-Interim and d) WRF model.


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performed between the filtered rainfall anomalies and the time series to understand how well the model simulates the influence of the heat sources on the northward propagation characteristics of BSISO (Figs 5, 6, 7 and 8).

Observed pattern of northward propagation of ISO's, associated with the influence of monsoon trough (Fig 5a, regressed with monsoon trough precipitation index) and the equatorial Indian Ocean (Fig 5b, regressed with equatorial Indian Ocean precipitation Index) are shown in (Fig 5) (using TRMM rainfall), similarly for reanalysis (Fig 6) (NCEP-II rainfall) and (Fig 7) (using ERA-Interim rainfall) are shown. In general, these lag–regression plots show the coherent poleward propagation of filtered precipitation anomalies in intra-seasonal time scales. The northward propagation characteristics simulated by WRF model (Fig 8) corresponds well with the northward propagation seen in observed TRMM precipitation (Fig 5). Sperber and Annamalai, (2008) noted that ECHAM family of coupled models outperforms other coupled models in capturing the boreal summer intra-seasonal variability (BSISO).

Though, WRF has shown some improvement compared to NCEP-II reanalysis, WRF model downscaled simulation do not agree very well with the observed characteristics of ISO as seen from the TRMM observational analysis (Fig 9a and 10a) due to the constraints imposed by the boundary conditions (NCEP-II reanalysis), nevertheless the northward moving anomalies are faster (Fig 9d and 10d) along the latitudes 10°-20°N when regressed with the area averaged index over the longitudes 70°–95°E (monsoon trough region) and over 70°–110°E (equatorial region) respectively, which suggested that the northward moving anomalies (propagation) are improved well in the WRF simulation compared to the NCEP-II reanalysis (Fig 9b and 10b) and also it is clear from the figure that the northward component over the monsoon trough region has significantly improved in the WRF downscaled simulation (Fig 9d and 10d). The WRF downscaled simulation did not capture the observed ISO pattern (or) the northward propagating anomalies as observed by TRMM observation due to additional limitations posed by the boundary condition. Since the WRF model is forced by NCEP-II reanalysis at the lateral boundary condition (LBC), we may not expect a very good ISO simulation. An improved reanalysis lateral boundary condition may provide a better ISO simulation using WRF over the Indian region. The ERA-Interim reanalysis shows some promising results (Fig 9c and 10c), when compared with the ISO of TRMM (Fig 9a and 10a). Due to time and computational constraints we could not repeat the entire experiment with the ERA-Interim LBC: we can expect a better ISO and northward propagation in the WRF model with the ERA-Interim LBC.

## 4. Discussion and Conclusions

The WRF regional model with 30 km resolution driven by NCEP-II reanalysis is used to simulate the summer monsoon regional climate and its associated rainfall intra-seasonal oscillations (ISO's) over India for an 8-year period from 2000 to 2007. The model performance is evaluated for climatological mean simulation as well as for ISO signals by comparing with TRMM and global reanalyses (NCEP-II and ERA Interim).

The WRF regional atmospheric model forced with NCEP-II reanalysis is found to capture reasonably the Indian summer mean monsoon circulation features, rainfall and intra-seasonal oscillations. Our study suggests that the WRF model has a reasonable representation of daily mean rainfall during wet monsoon years compared to dry monsoon years. A 20-100 day band pass filter, which covers the broad band spectrum of the intra-seasonal oscillations, is applied to obtain boreal summer intra-seasonal oscillations (BSISO). Analysis reveals that the northward propagation of ISO's associated with the influence of monsoon trough and the equatorial Indian Ocean, obtained by regressing the precipitation with monsoon trough precipitation index and equatorial Indian Ocean precipitation Index, are reasonably simulated by the WRF model. The results presented here suggest that the regional model forced by reanalysis data with a realistic basic state and a proper representation of the equatorial ISO component are the basic ingredients for the regional model to capture a reasonable representation of the BSISO. The northward propagation characteristics seen in TRMM observation corresponds reasonably with the WRF simulated northward propagation. Though, WRF model simulation agrees with observed characteristics of ISO in TRMM, the WRF model has limitations with the simulation of northward propagation due to the reason; it is forced by NCEP-II reanalysis at the lateral boundary condition (LBC). Modelling studies (e.g. Palmer and Anderson, 1994; Brankovic and Palmer, 1997; Bhaskaran *et al.*, 1998; Raju *et al.*, 2013) suggested that the mean monsoon rainfall is sensitive to initial conditions; thus our study also corroborates that the accurate representation of initial conditions are necessary for reliable ISO simulation with a regional model.

## Acknowledgements

NCEP-II Reanalysis data is provided by the NOAA/OAR/ESRL PSD, Boulder, CO, USA, from their website at http://www.esrl.noaa.gov/psd/and


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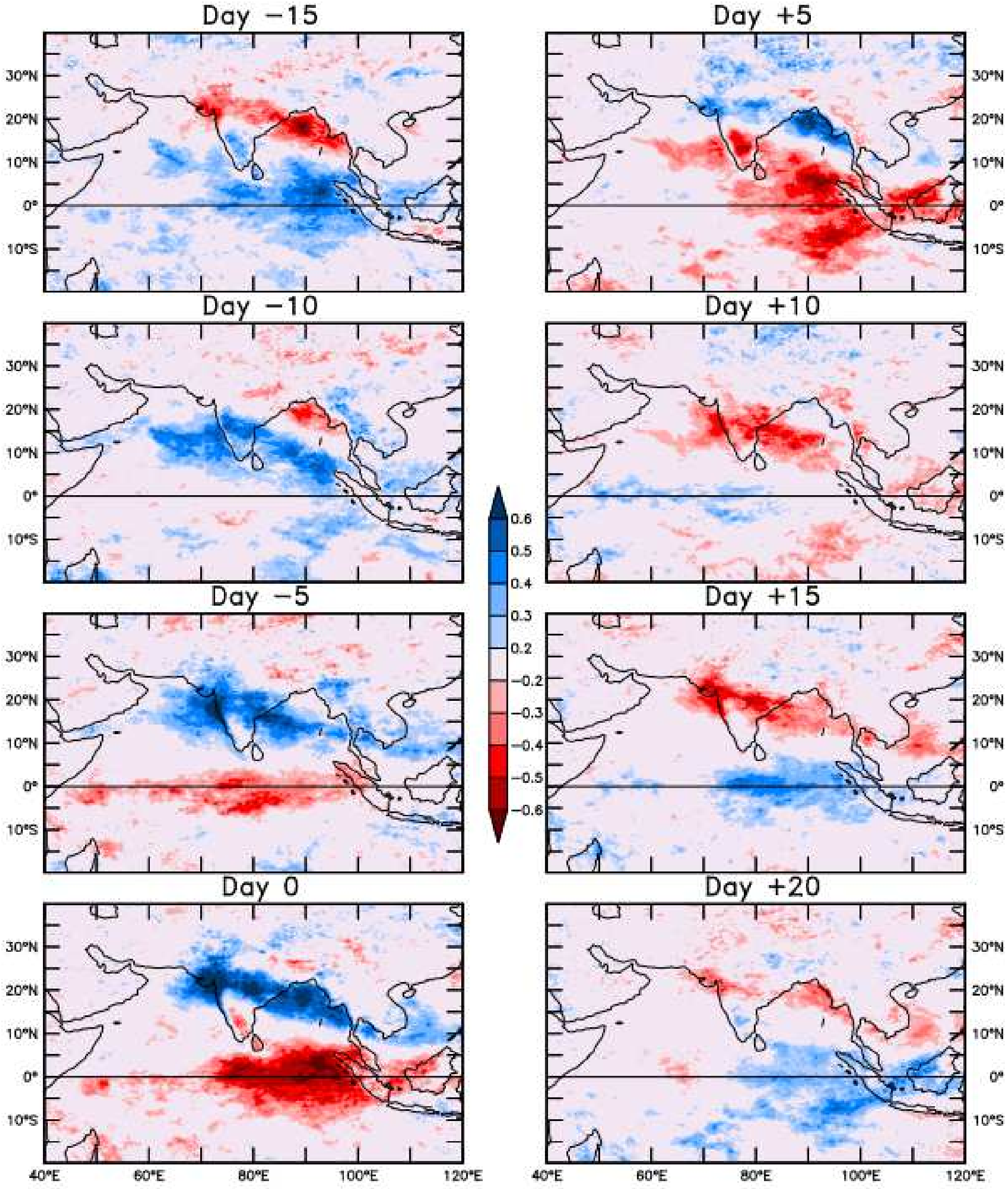


Fig 5a: Spatial regression coefficient of filtered precipitation anomalies (mm day$^{-1}$) based on monsoon trough index from TRMM during the (2000-2007) period.


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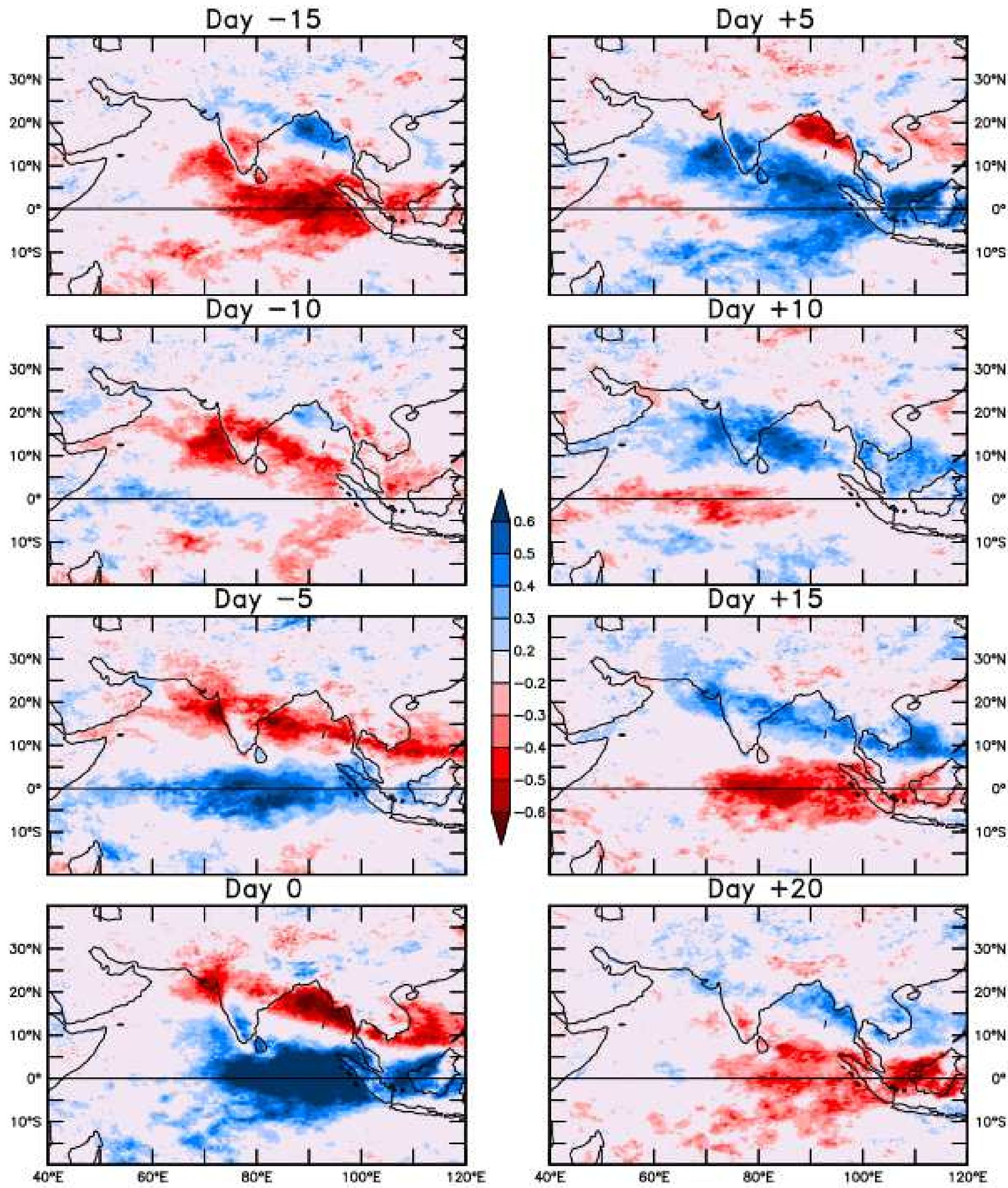


Fig 5b: Spatial regression coefficient of filtered precipitation anomalies (mm day$^{-1}$) based on Equatorial Indian Ocean index from TRMM during the (2000-2007) period.


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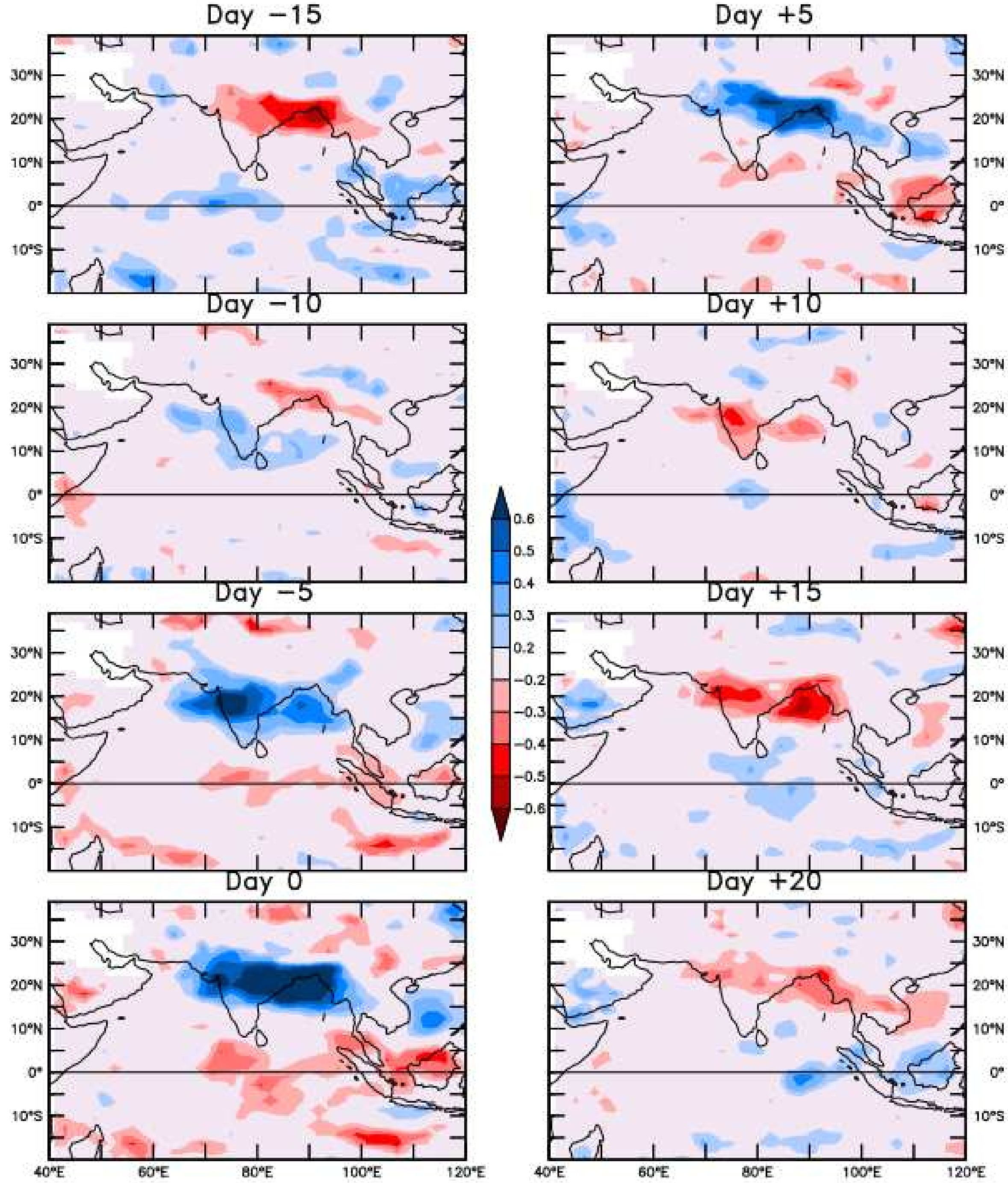


Fig 6a: Spatial regression coefficient of filtered precipitation anomalies (mm $day^{-1}$) based on monsoon trough index from NCEP during the (2000-2007) period.


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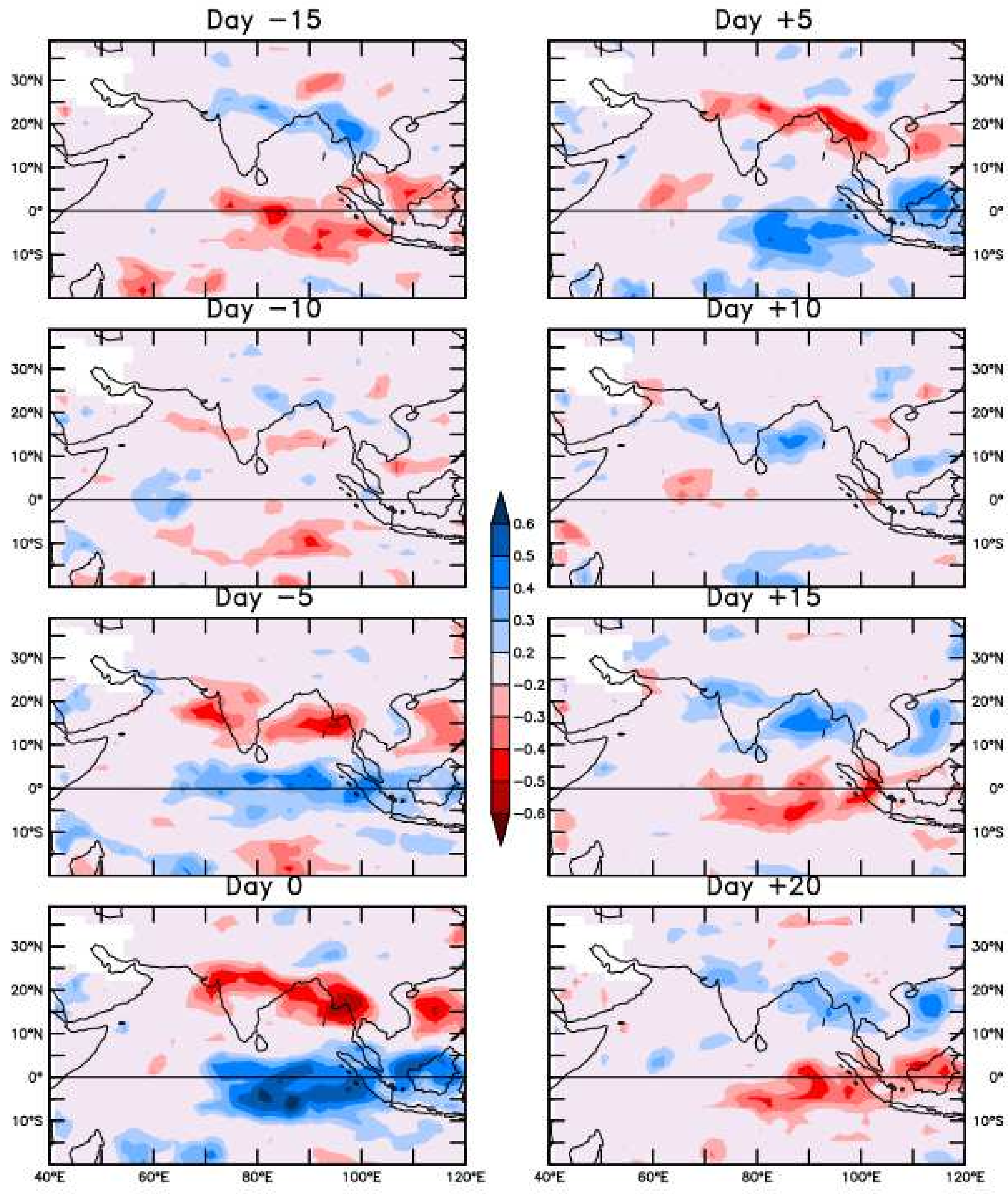


Fig 6b: Spatial regression coefficient of filtered precipitation anomalies (mm day$^{-1}$) based on Equatorial Indian Ocean index from NCEP during the (2000-2007) period.


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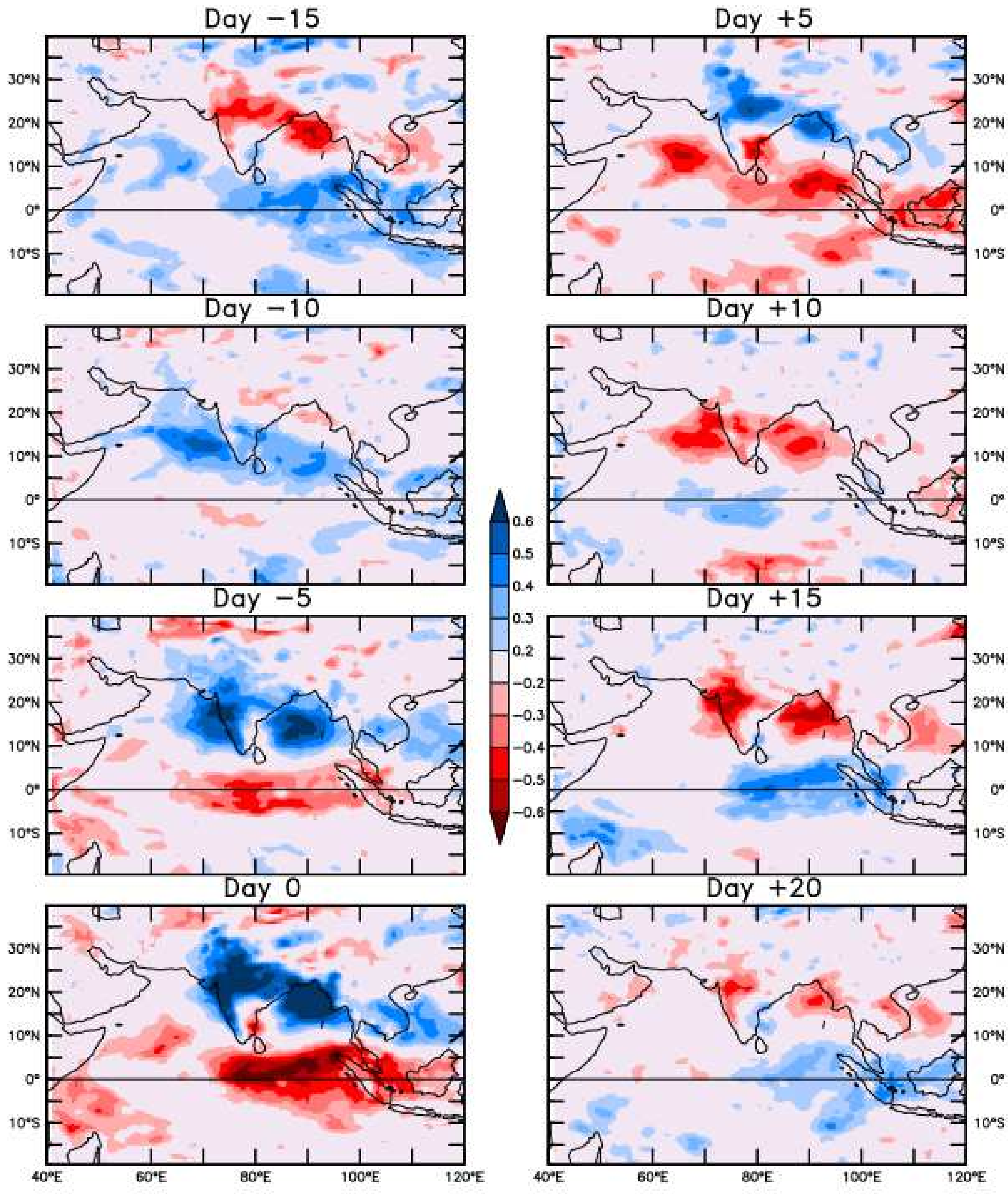


Fig 7a: Spatial regression coefficient of filtered precipitation anomalies (mm day$^{-1}$) based on monsoon trough index from ERA-Interim during the (2000-2007) period.


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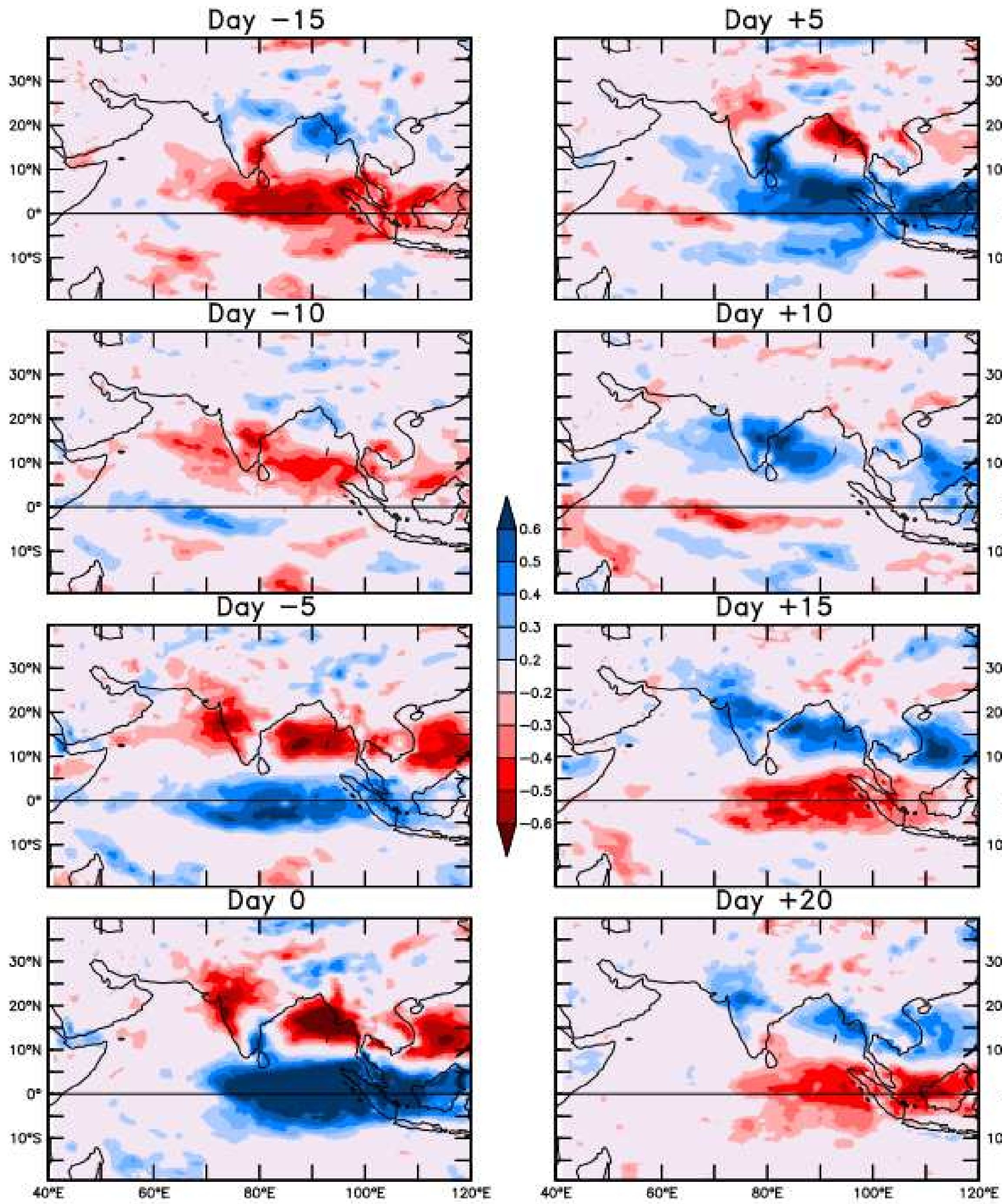


Fig 7b: Spatial regression coefficient of filtered precipitation anomalies (mm day$^{-1}$) based on Equatorial Indian Ocean index from ERA-Interim during the (2000-2007) period.


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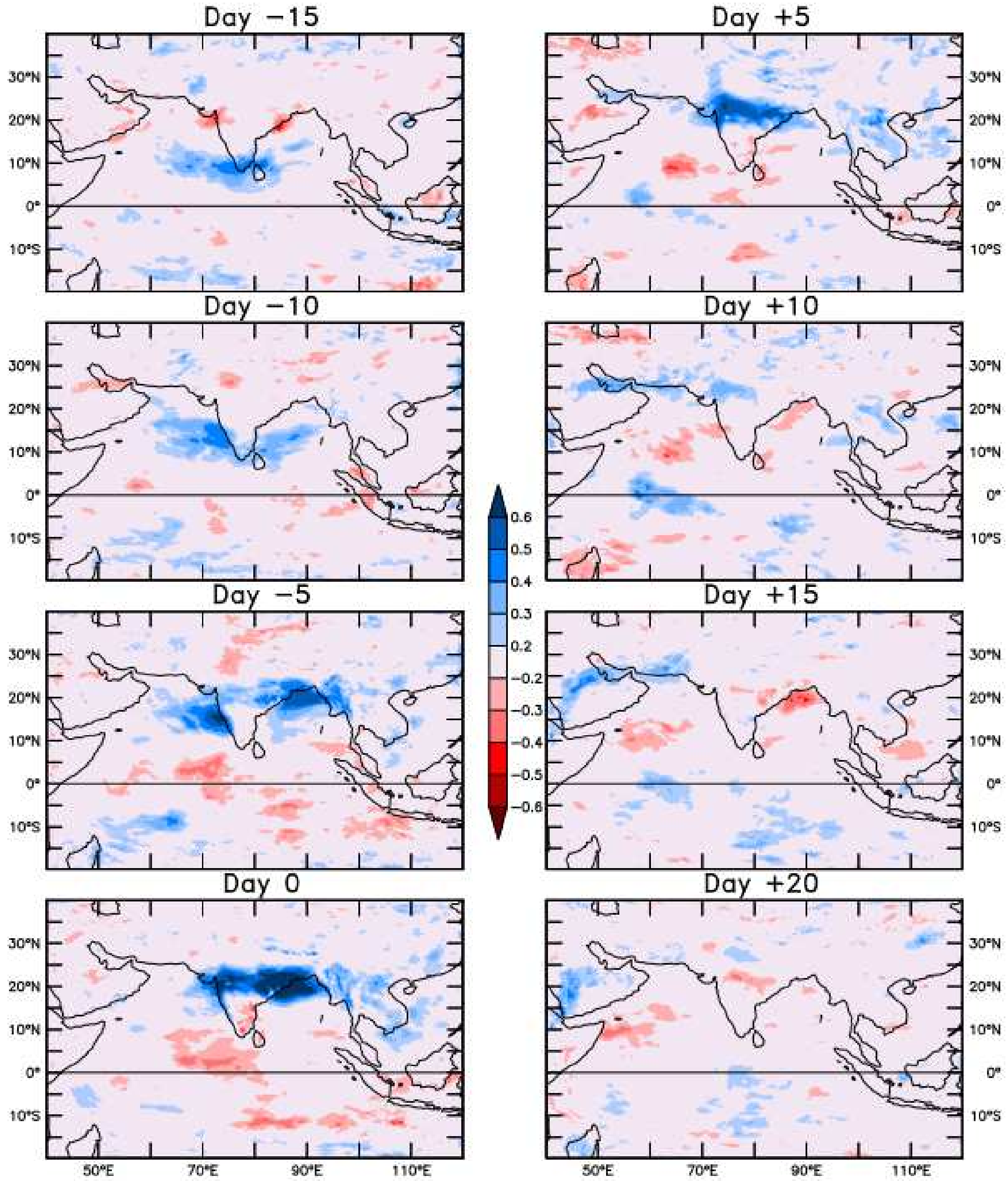


Fig 8a: Spatial regression coefficient of filtered precipitation anomalies (mm day$^{-1}$) based on monsoon trough index from WRF simulations during the (2000-2007) period.


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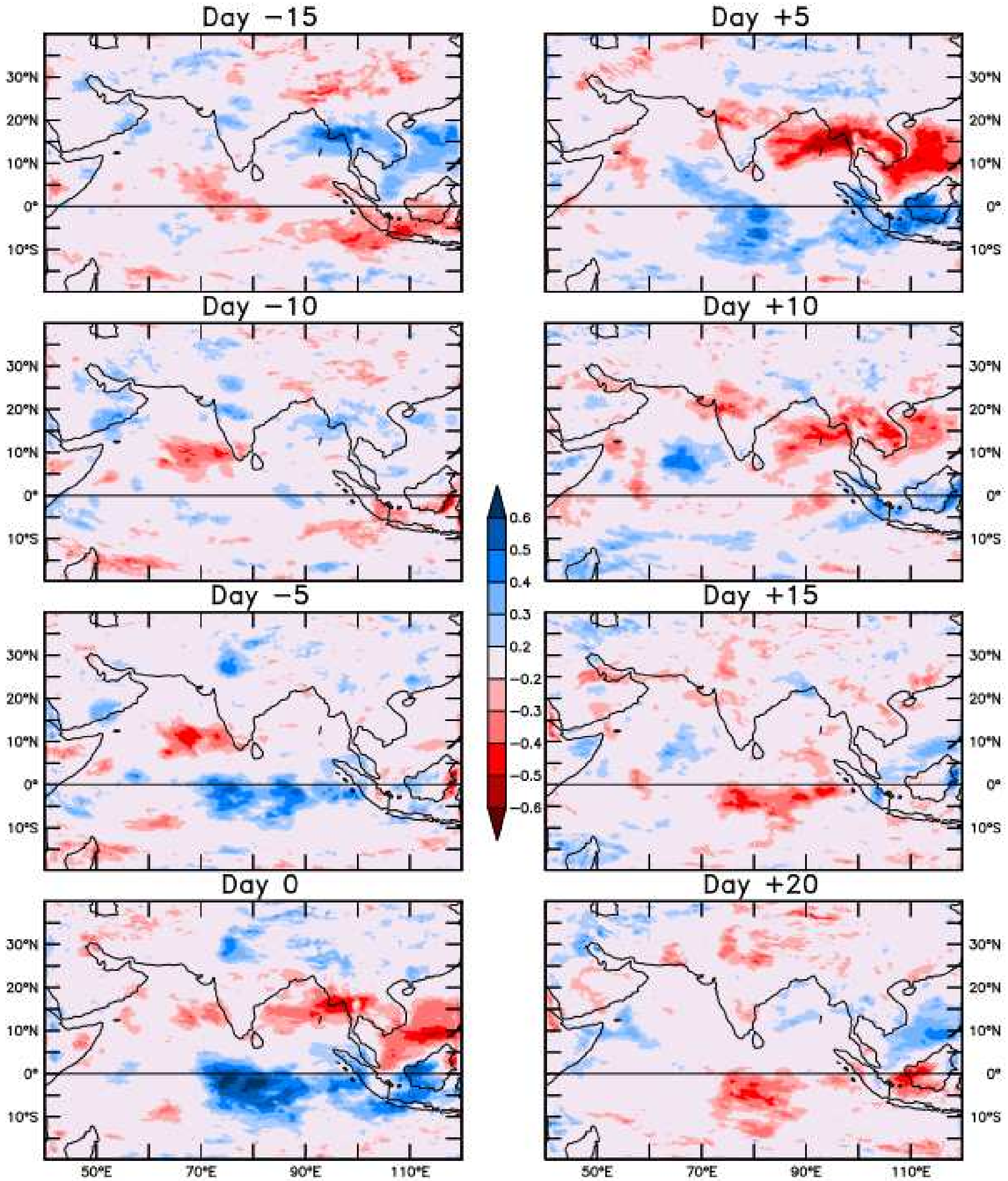


Fig 8b: Spatial regression coefficient of filtered precipitation anomalies (mm day$^{-1}$) based on Equatorial Indian Ocean index from WRF simulations during the (2000-2007) period.


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ERA-Interim data obtained from the website (http://data-portal.ecmwf.int/data/d/interim_daily/). The TRMM data is obtained from NASA, USA (http://mirador.gsfc.nasa.gov/collections/TRMM 3B42 daily-06.htm). We also thank to Dr. Suvarchal K. Cheedela for scientific discussion. We thank to two anonymous reviewers comments who greatly improved content of this manuscript.

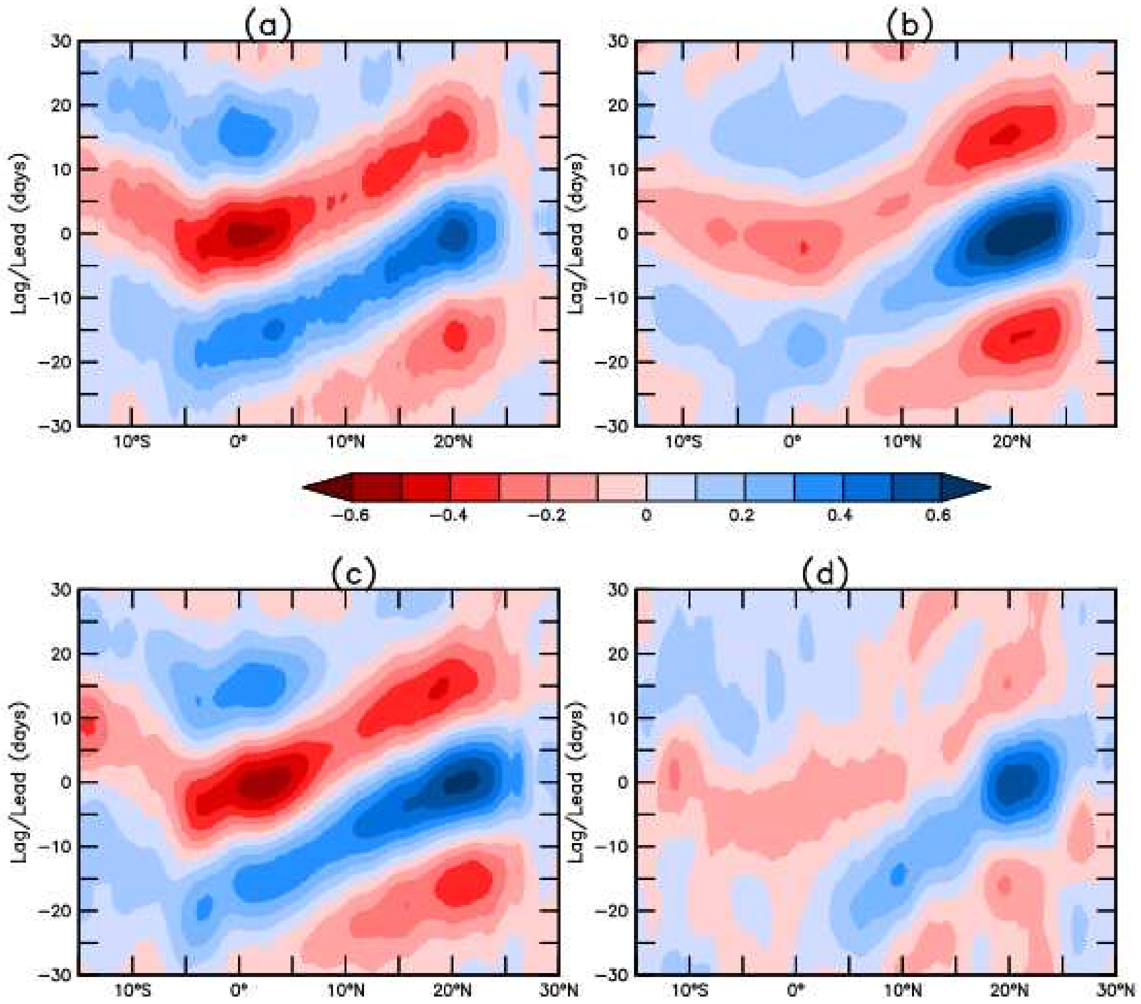


Fig 9: Filtered anomalies of precipitation (mm day$^{-1}$) regressed with monsoon trough region index, area averaged over 18°N-25°N, 70°E–95°E from (a) TRMM, (b) NCEP, (c) ERA-interim, (d) WRF as a function of latitude and time lag during the 2000-2007 period.


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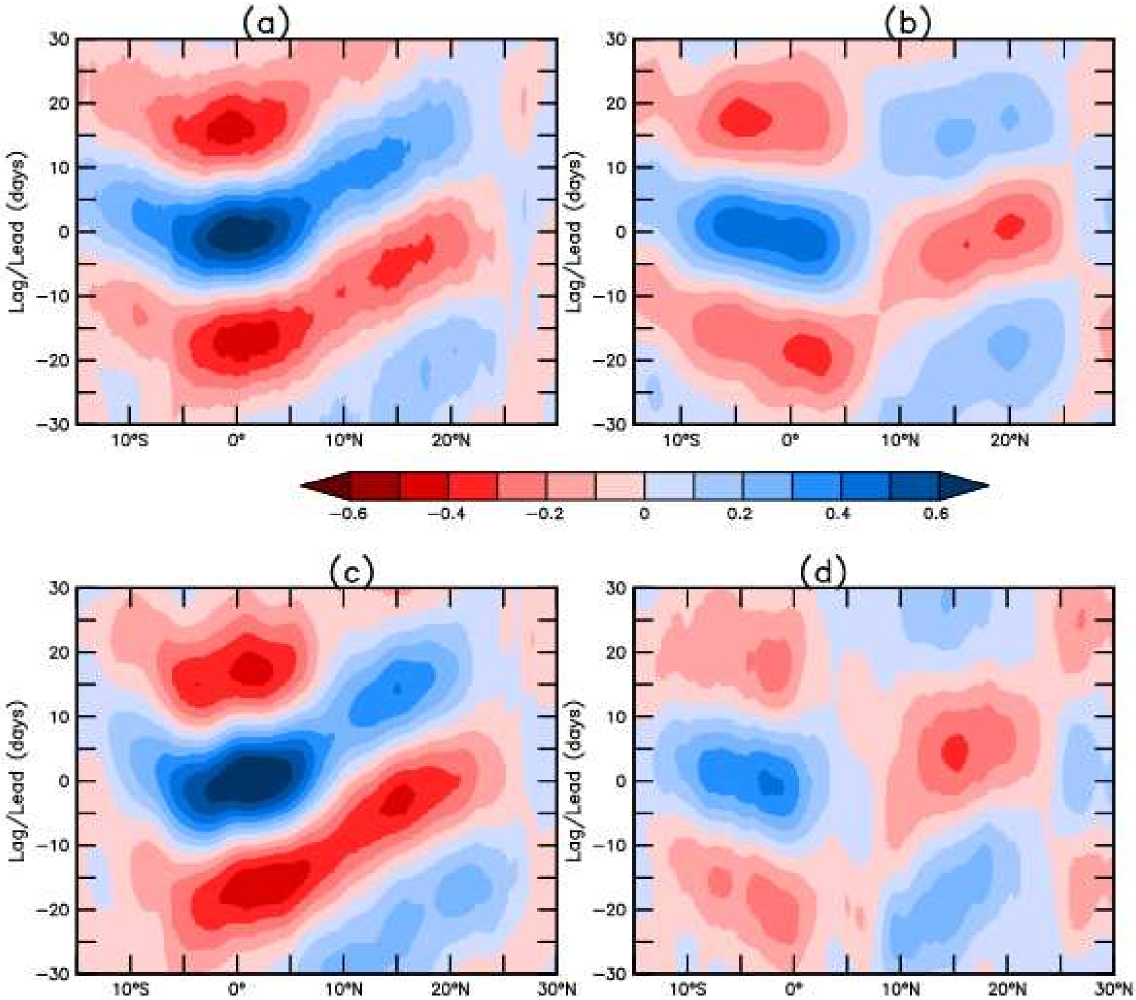


Fig 10: Filtered anomalies of precipitation (mm day$^{-1}$) regressed with Equatorial Indian Ocean index, area averaged over, 10°S–5°N, 70°E–110°E from (a) TRMM, (b) NCEP, (c) ERA-interim and (d) WRF as a function of latitude and time lag during the (2000-2007) period.

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