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Key Points:
- We identify geographic regions of critical behavior as tipping elements
- We use critical fluctuations in air temperature as a precursor of monsoon timing
- We improve the time scale of monsoon onset and withdrawal forecasting

Supporting Information:
- Supporting Information S1

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Tipping elements of the Indian monsoon: Prediction of onset and withdrawal

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Abstract Forecasting the onset and withdrawal of the Indian summer monsoon is crucial for the life and prosperity of more than one billion inhabitants of the Indian subcontinent. However, accurate prediction of monsoon timing remains a challenge, despite numerous efforts. Here we present a method for prediction of monsoon timing based on a critical transition precursor. We identify geographic regions—tipping elements of the monsoon—and use them as observation locations for predicting onset and withdrawal dates. Unlike most predictability methods, our approach does not rely on precipitation analysis but on air temperature and relative humidity, which are well represented both in models and observations. The proposed method allows to predict onset 2 weeks earlier and withdrawal dates 1.5 months earlier than existing methods. In addition, it enables to correctly forecast monsoon duration for some anomalous years, often associated with El Niño–Southern Oscillation.

1. Introduction

The prediction of the Indian summer monsoon (hereafter monsoon) timing is a vital question for the Indian subcontinent and significantly affects agricultural planning and the gross domestic product of the country, which is determined as up to 22% by agriculture [*Subash and Gangwar*, 2014]. A slight deviation of the monsoon timing manifested as delay (or early arrival) may lead to drastic droughts (floods) causing damages to infrastructure and losses of crops and livelihoods of the population. The onset of monsoon takes place abruptly and its predictability for more than 2 weeks in advance, as well as early predictability of withdrawal, remains an important concern.

Various prediction attempts for monsoon onset and withdrawal dates (OD and WD) have been made for different time scales from short (up to 4 days) and medium (4–10 days) range forecasts using Numerical Prediction Models (Indian Meteorological Department (IMD), 2015, http://www.imd.gov.in, hereinafter referred to as IMD, available online, 2015; National Center for Medium Range Forecasts, 2015, http://www.ncmrwf.gov.in/) to extended (10–30 days) and long-range forecasts (subseasonal, 30+ days) [*Alessandri et al.*, 2014; IMD, available online, 2015]. Forecasting methods have so far been mostly based on statistical model approaches, which include averaged values of zonal asymmetric temperature anomaly [*Prasad*, 2005], sea surface temperature, mean sea level pressure [*Goswami et al.*, 2006 ; IMD, available online, 2015], tropospheric moisture buildup over areas south of the Indian peninsula [*Taniguchi and Koike*, 2006], vertically integrated moisture budget (hydrologic onset and withdrawal index) [*Fasullo and Webster*, 2003], moist static energy [*Rajagopalan and Molnar*, 2014], outgoing longwave radiation (OLR), and wind fields [*Wang et al.*, 2009].

The Indian Meteorological Department (IMD, available online, 2015) provides a forecast of monsoon OD for Kerala 21 days in advance with an accuracy ±4 days with 10% deviation. However, there are certain difficulties in the existing forecasting methods, in particular, of "bogus" (false) monsoon onsets mostly related to nonmonsoonal atmospheric circulation systems [*Flatau et al.*, 2001]. In addition, the methodology used for forecasting of WD, which determines the length of the monsoon season, has certain issues and limitations, in particular, predicting a WD earlier than 1 September or forecasting of late WD (IMD, available online, 2015). These limitations require the improvements of the prediction skills for monsoon onset and withdrawal dates.

In this study, we propose a novel method for forecasting monsoon onset and withdrawal by identifying tipping elements of the monsoon. The notion of a *tipping element* in Earth system was introduced by *Lenton et al.* [2008]. According to the definition, a tipping element is a component of the Earth system that may pass a tipping point—a critical threshold at which a small perturbation can qualitatively change the state of the Earth system [*Lenton et al.*, 2008]. The global monsoon system has been argued to be one of the tipping elements of the Earth. The Indian monsoon is a part of the global monsoon system, one of the main characteristics of which is its onset—an annual event which happens abruptly and its timing varies on the interannual time scale.

Prior to monsoon onset, climatic variables exhibit signs of critical behavior. In particular, humidity and temperature cross a critical threshold at the onset of monsoon [*Schewe et al.*, 2012]. Hence, the forecasting of the Indian summer monsoon onset is connected with the problem of critical transition identification. The predictability of criticality in spatial dynamics poses challenges in climate systems [*Kéfi et al.*, 2014]. It is especially challenging when the process model does not yet exist. In our study, we make a step into this direction by proposing how to detect tipping elements—origins of the critical conditions—in the spatiotemporal organization of a critical transition. We show that during the premonsoon the origins of critical conditions occur in two specific regions of the Indian subcontinent. We demonstrate that the existence of criticality in both of these regions together provides physical conditions for the monsoon arrival in the central part of the Indian subcontinent. Therefore, we coin these geographic regions as tipping elements of the monsoon.

We use the tipping elements of the monsoon as optimal observation locations or reference points (RPs). Based on the analysis of time series of near-surface air temperature (T) and relative humidity (rh), we create a long-range (>30 days) forecasting scheme for monsoon onset and withdrawal dates, which overcomes previously identified forecasting difficulties, such as the bogus onset of 2002 and abnormally late withdrawal in 2008. Our approach exhibits two major differences to existing methods: (i) Unlike most predictability methods, we do not rely on the analysis of precipitation time series, which are often poorly measured and modeled [*Fasullo and Webster*, 2003]. Instead, we use near-surface air temperature (T) and relative humidity (rh), which are well represented in both measurements and models and show clear indicators of the upcoming monsoon onset [*Soman and Krishna Kumar*, 1993]. (ii) Our approach allows to adjust the prediction scheme for abnormal years, often associated with El Niño–Southern Oscillation.

2. Climatic Setting, Data, and Methods

2.1. Climatic Setting

The monsoon is driven by several factors, including temperature and pressure gradients between land and ocean, latent heat release during the monsoon season [*Choudhury and Krishnan*, 2011], associated migration of the Intertropical Convergence Zone (ITCZ) [*Saha and Saha*, 1980; *Gadgil*, 1998], and the high elevation of Himalayan mountain peaks resulting in orographic shielding [*Boos and Kuang*, 2010], which establish an area of deep convection over the Indian subcontinent (Figures 1a and 1b).

The monsoon is characterized by a sudden onset associated with an abrupt and large-scale shift of the regional circulation pattern over the Indian peninsula [*Gadgil*, 1998; *Stolbova et al.*, 2014]. In particular, a few days before monsoon onset outgoing longwave radiation (OLR) shows deep convection over the Bay of Bengal and Arabian Sea, relative humidity increases abruptly in the vertical direction before the onset of monsoon [*Soman and Krishna Kumar*, 1993], and vertically integrated zonal moisture transport increases [*Fasullo and Webster*, 2003; *Holloway and Neelin*, 2009]. A withdrawal of monsoon occurs gradually and is caused by a southward movement of the ITCZ, resulting in an anticyclonic flow over northern and central India, a displacement of the moist marine air with dry continental air and, leading to a deceleration of the low-level westerly flow, followed by a reduction of rainfall over the Indian subcontinent (Figures 1c–1f).

2.2. Data

We use daily values of near-surface air temperature (T) (at 1000 hPa), relative humidity (rh) (at 1000 hPa), and wind fields at 700 hPa from two reanalysis gridded daily data sets: ERA40, provided by the European Center for Medium-Range Weather Forecasts (ECMWF) [*Uppala et al.*, 2005] for the period 1958–2001, and NCEP/NCAR, provided by the National Center for Environmental Prediction and the National Center for Atmospheric Research [*Kalnay et al.*, 1996] for the period 1951–2015. The spatial resolution of both data sets is 2.5°. We have extracted data for the monsoon region (62.5–97.5°E, 5.0–40.0°N; see Figure 1),

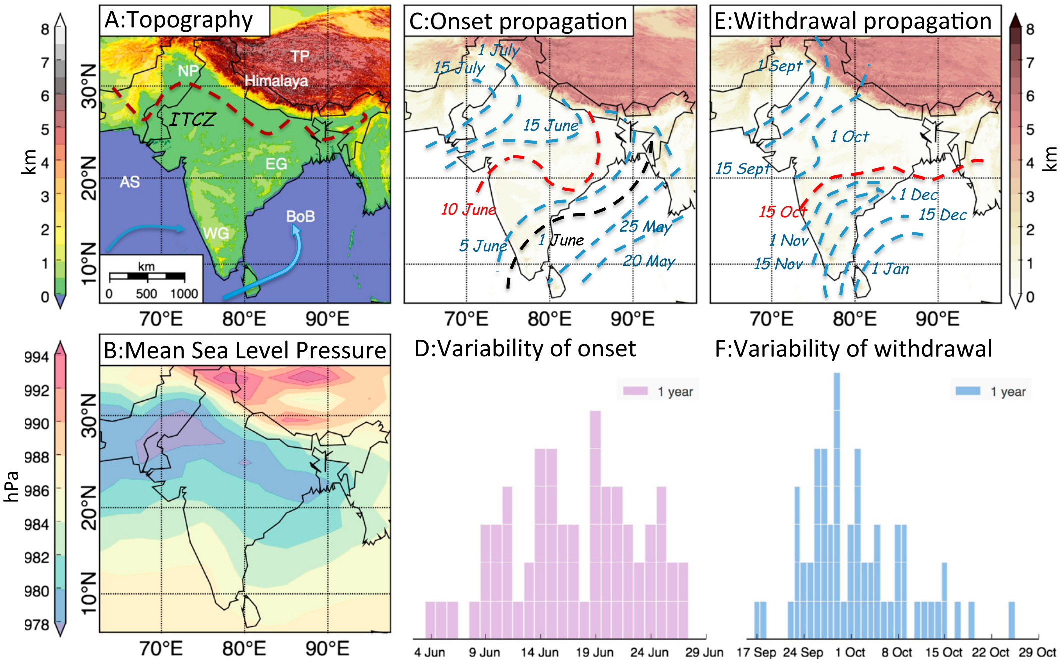

Figure 1. (a) Topography of the Indian subcontinent with key features of the Indian Summer monsoon: Himalaya, Tibetan Plateau (TP), North Pakistan (NP), Eastern Ghats (EG), Western Ghats (WG), Arabian Sea (AS), Bay of Bengal (BoB), Intertropical Convergence Zone (ITCZ) [topography data used - etopo1]. Blue arrows indicate near–sea level wind direction; (b) Composites of mean sea level pressure (June–September, 1951–2014 based on NCEP/NCAR data); (c and e) Schematic representation of the long-term average propagation (since 1951, based on IMD (available online, 2015)) of the advance and withdrawal of monsoon over the Indian subcontinent (northern limit of monsoon). Dashed black line shows averaged monsoon onset for the Kerala region forecasted by IMD and dashed red line for the Eastern Ghats (the region of main interest in this study); (d and f) histograms of onset and withdrawal dates for the Eastern Ghats region (1951–2014).

which results in $15 \times 15 = 225$ gridded points. OD and WD of monsoon are taken from *Singh and Ranade* [2010] and the IMD (IMD, available online, 2015). ENSO years were classified based on the Oceanic Nino Index (http://ggweather.com/enso/oni.htm).

2.3. Methods

We propose a novel approach for predictability of monsoon OD and WD, which consists of three main steps: (i) We identify tipping elements of the monsoon using a precursor of critical transitions that indicates the proximity of the system to a critical threshold—the phenomenon of prebifurcation growth of fluctuations [*Surovyatkina et al.*, 2005]. The tipping element is a geographic region, which shows the maximal growth of the variance of fluctuations (σ^2) prior to the monsoon onset. (ii) We choose the tipping elements of the monsoon as optimal observation locations or reference points (RPs) for targeted observations, and by analyzing time series within these RPs, we establish a causal relationship between them and derive an indicator of monsoon onset and withdrawal. (iii) We introduce a prediction scheme for onset and withdrawal dates, based on trends of T and rh in the RPs.

1. *Identification of RPs*. We calculate σ^2 of T and rh for each grid point for a window length of $w = 7$ days prior to the OD (see supporting information for the details). Our result uncovers that the Eastern Ghats and the North Pakistan regions (marked by pink and blue boxes) experience the highest growth of σ^2 of T while approaching the critical transition to monsoon onset (see Figure 2). An analysis of σ^2 of rh while approaching the OD shows similar results (see Figure S1). We define these regions as the tipping elements of the monsoon (see supporting information, section S5, Figure S2 for details) and choose them as optimal observation locations or reference points (RPs) for comparative analysis aiming to predict monsoon onset and withdrawal (see Figure S3 for details).
2. *Identification of the OD and WD with a time series analysis for the RPs*. We analyze the time series of T and rh in the RPs. We find that there is an important relation between the two tipping elements of the monsoon: the Eastern Ghats (EG) and North Pakistan (NP). The intersection of the average time series in the RPs for

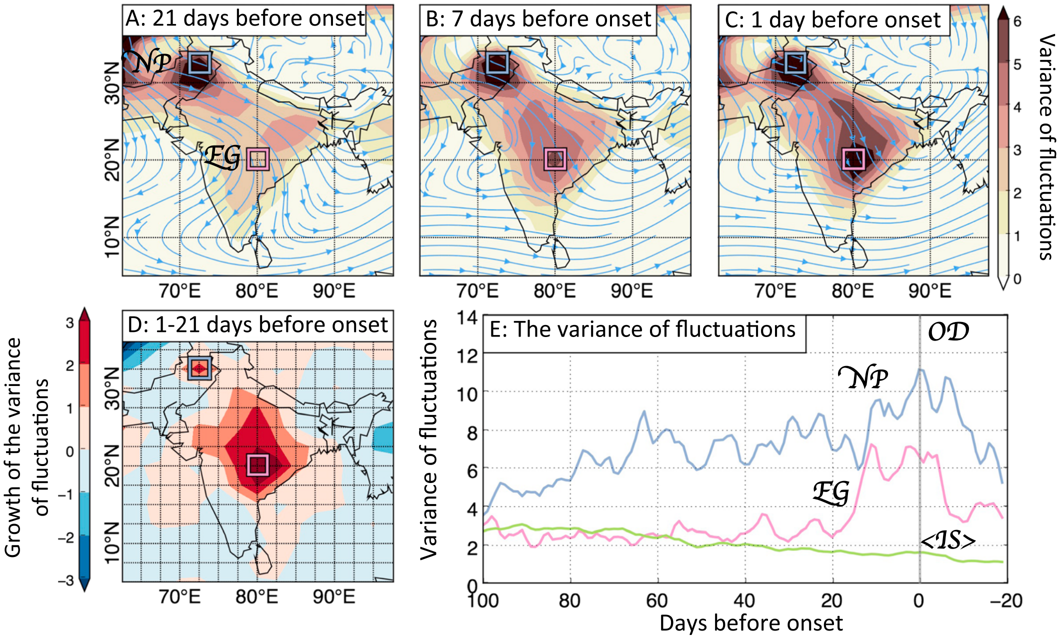

Figure 2. Premonsoon growth of the variance of fluctuations (σ^2) of the weekly mean values of near-surface air temperature (T) (a) 21 days, (b) 7 days, and (c) 1 day before the monsoon onset at the Eastern Ghats: (d = c − a) Composites are for the period 1958–2001 and were calculated from the ERA40 reanalysis data set, 700 hPa winds are indicated by the blue lines. Two boxes refer to RPs: North Pakistan, NP (blue) and Eastern Ghats, EG (pink). (e) Growth of the variance of fluctuations in NP (blue), EG (pink), and averaged over the Indian subcontinent (< IS >) at approaching onset date of the monsoon (OD).

the period from 1951 to 2014 takes place twice. At both times, it coincides with the mean values of the OD and WD as determined by the IMD within the EG with a standard deviation of ±5 days (see Figure 3). We observe that yearly variations in the intersection also occur within a few days of monsoon onset at the EG (see supporting information). This allows us to equalize temperatures in the tipping elements of the monsoon and derive a prediction scheme for forecasting the OD and WD of monsoon in the EG.

3. *Prediction schemes for the OD and WD of monsoon*. We develop a prediction scheme for forecasting the OD and WD with reanalysis data for the period from 1951 to 2015. As a training period, we use 14 years of data prior to the year when a prediction is made. We refer to Figure S5 for the sensitivity analysis of the prediction scheme to the length of the training period. We illustrate the performance of this prediction scheme for OD and WD with a case study for 2012 (see Figure 3 and Table S1).

Our first step is to make a qualitative prediction of the OD. We perform a linear time series trend estimation for the two RPs and compare these with trends of the mean time series of the training period. The slopes of the trends for the RPs provide an estimation of an early, normal, or late monsoon arrival: greater than average trend in NP of T will lead to an earlier than usual OD, and vice versa. Trends of rh in the RPs in comparison with the average trends for the training period add up to the predictability of the OD: higher than average values of rh lead to a late OD, and vice versa. In addition, the tendency of expected early (late) intersection of the time series of rh from the RPs usually leads to an earlier (later) than normal OD.

The analysis of the mean time series from the RPs shows that the OD coincides with the date when T in EG and in NP become equal (see Figure 3). Therefore, for the forecasting of OD, we need to predict when T for EG will abruptly decrease and meet T for NP. However, during the premonsoon period T for EG is in a nonlinear saturation mode (when T reaches maximum on 145 day of year (DOY)) and it is a challenge to predict how close the system is to a critical threshold and when an abrupt transition will occur. At the same time period, T in NP gradually increases and can be approximated by a linear trend. Hence, using the linear trend we can predict when T in NP will reach a certain value, which for EG is a critical threshold for the onset of the monsoon. The value of the critical threshold might be estimated using the average critical threshold from the training period (see supporting information).

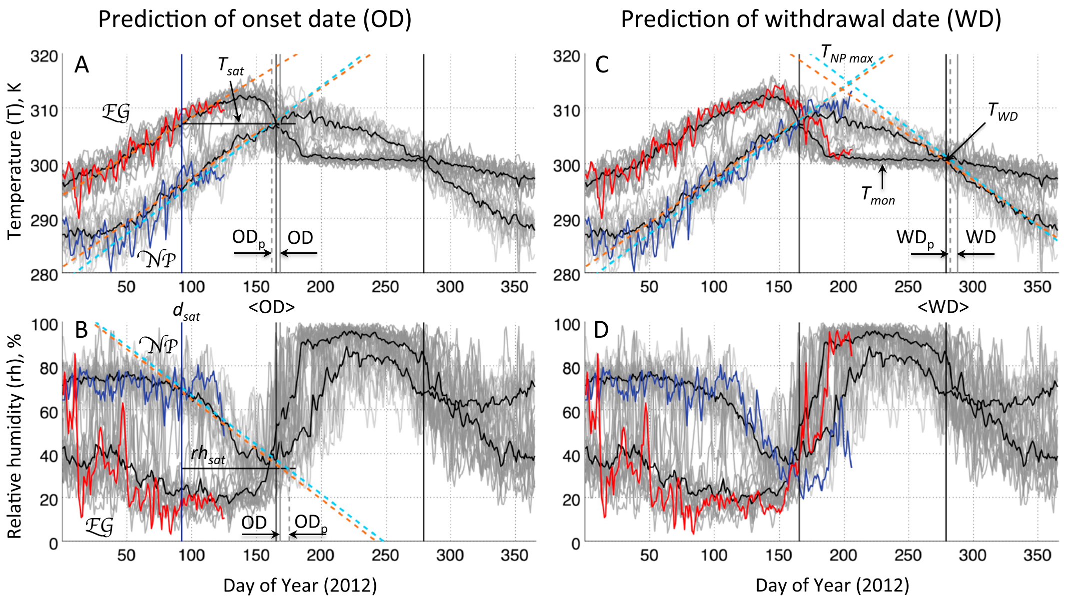

Figure 3. Prediction of onset date (OD) and withdrawal date (WD): case study 2012. (a, b) Prediction of the onset date (OD); (c, d) withdrawal date (WD) of monsoon in the EG. Air temperature at 1000 hPa (Figures 1a and 1c); relative humidity at 1000 hPa (Figures 1b and 1d). Time series from reference points (NCEP/NCAR data): previous 14 year mean (black) and 2012 values for NP (blue) and the EG (red). Grey lines show time series from the NP and EG for the training period of previous 14 years. Saturation temperature T_{sat} (Figure 1a) and saturation humidity rh_{sat} (Figure 1b) are marked by horizontal black solid lines ($T_{sat} = T_{onset}$, T_{onset} and rh_{sat} calculated as intersection of mean time series for the training period from the EG and NP) and day of the saturation (d_{sat}) (when temperature in the EG in 2012 reaches T_{sat})—with dark blue. Orange lines indicate trends to the mean time series in the NP and EG for the training period, light blue—trends for 2012. Black solid lines indicate mean values of the OD (< OD >) and WD (< WD >) for the training period. Dotted grey lines correspond to the predicted onset (OD_p) and withdrawal dates (WD_p), while solid grey lines—to actual onset and withdrawal dates for 2012.

We forecast the OD by identifying the time when the linear trend of T in NP reaches T_{sat}, which is characterized by monsoon onset temperature in the EG from the training period (see Table S1 in the supporting information). When T in NP highly fluctuates during a year and causes difficulties to correctly determine the trend, the trend from the training period can be used for OD forecasting.

An additional way of estimating the OD of monsoon is using variations of the relative humidity (rh) in the NP region. We estimate the OD by identifying the time when the linear trend of the rh in North Pakistan reaches rh_{sat}, which is determined by the intersection of rh from the EG and NP (see Figure 3b and Table S1 in the supporting information).

The prediction scheme of the WD is based on the symmetry of T changes in NP during the year. Knowing the T in EG from the training period, the trend of NP in the premonsoon period, and the maximum T in NP, we can estimate the trend of the T decrease in the NP region. The WD is then estimated as the intersection of the projected T decrease in NP and the T in the EG during the monsoon season (see Figure 3c). Variations of rh are too high for WD prediction and the intersection of the rh time series usually takes place 1 month later than the actual WD (see Figure 3d). Thus, we do not attempt to predict the WD based on rh. (Sensitivity of the proposed prediction scheme to the choice of geographic area of the tipping elements is discussed in the supporting information.)

3. Results and Discussion

3.1. Tipping Elements of the Monsoon

Tipping elements of the Indian monsoon is an appealing climate concept from two different perspectives. First, it highlights the interaction of two phenomena—a local weather phenomenon (differential heating between the sea and land during the monsoon), which results in the occurrence of the EG tipping element due to the collision of two branches of monsoon (Arabian Sea and Bay of Bengal), and a global phenomenon (based on the shift of the ITCZ), which causes the occurrence of the NP tipping element as northernmost

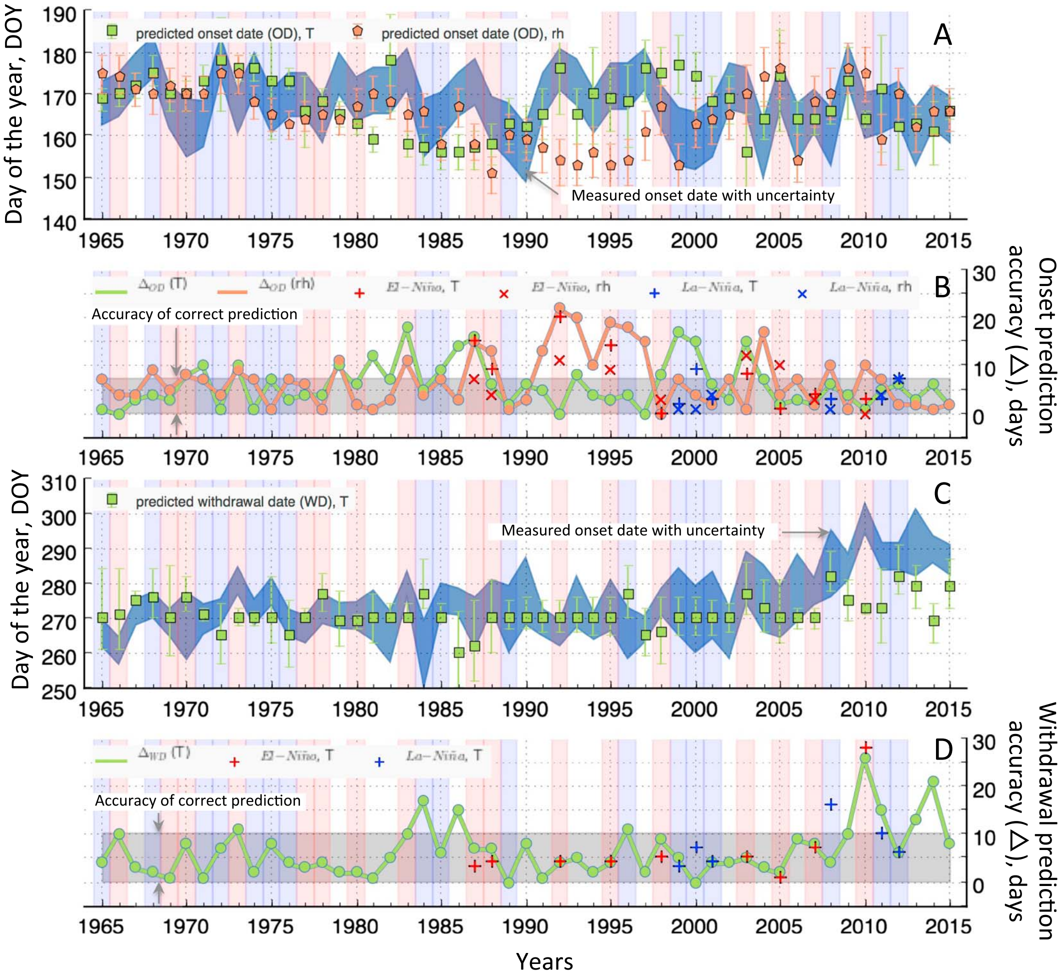

Figure 4. Monsoon OD and WD prediction based on T (green) and rh (orange) and measured (dark blue) (a) OD and (c) WD (NCEP/NCAR data). Red and light blue shading indicates positive ENSO (El Niño) and negative ENSO (La Niña) years. Also shown is the difference (Δ) between the real onset or withdrawal and predicted dates in days ($\Delta_{OD(T)}$: prediction based on temperature, $\Delta_{OD(rh)}$: on relative humidity). (b) Grey shading indicates range of 7 days, within the prediction is considered accurate (absolute value of the difference between the real onset date in a given year and the predicted onset date). (d) The accuracy of prediction of the WD has a range of 10 days (grey shadow). Plus (T) and cross (rh) markers show improved prediction based on the training period of 14 years only from preceding positive (red) and negative (blue) ENSO years (Figures 4b and 4d). We observe a significantly improved prediction for La Niña years.

geographical boundary of the monsoon. Second, it sheds light on the mechanism underlying drastic change (abrupt monsoon onset), in the form of establishment of the monsoon through the collision of the cyclonic circulation located at the center of the EG with an anticyclone centered in the NP at the onset of monsoon (partly controlled by trapping mechanisms exerted by the Himalayan topography, see Figure S3). This atmospheric feature causes an abrupt onset of the monsoon over large parts of the Indian subcontinent north of the EG and ultimately results in the disruption of the Intertropical Convergence Zone (Figure S3 in the supporting information). Therefore, these two regions become connected exactly at the monsoon OD in the EG. The situation is mimicked during the WD, with the main difference that the ITCZ moves southward and not northward. We use this observation of the regional connection in response to monsoon onset and exploit it for a forecasting scheme. Our time series analysis shows that intersection of near-surface air temperatures and relative humidity takes place twice: at the onset and withdrawal of the monsoon over the EG.

3.2. Performance of the Prediction Schemes

The performance of the proposed prediction scheme is shown in Figure 4. The described prediction in this subsection is made for all years in the period 1965–2015 and all years were treated equally. The prediction is regarded successful if the time difference between predicted and real OD is less than a week—≤ 7 days (note that condition for the successful prediction does not mean the accuracy of the prediction of ±7 days; this difference is unique for each year and cannot exceed 7 days) and ≤10 days for WD (issues regarding the variability and correlations are discussed in Sec 3.3). The proposed scheme based on *T* results in 73% of successful predictions of the OD on day 125 of year (DOY) (5 May) with accuracy of ±4 days (based on rh in 67%). Predictability of the OD using rh is lower than using *T* (67% versus 73%) mostly because of the high variability of rh and the associated difficulties in approximating a linear trend. Still, in some cases, the OD prediction based on rh may be useful, if the prediction based on *T* fails. The IMD earliest published forecast for the monsoon onset date over Kerala (southwest coast of India) is on May 15-th, which is two weeks earlier than the averaged onset date for Kerala, June 1-st. Our approach allows to forecast the arrival of monsoon in the Eastern Ghats (central India) on May 5-th, which is 35 days in advance of the averaged onset for the Eastern Ghats, June 10-st. The main advantage of our method is that it not only allows long-range forecasting of the full monsoon arrival onto the Indian subcontinent but also enables us to estimate the exact onset date, while the IMD long-range forecasting only give a qualitative forecast of early, normal, or late monsoon arrival. We would like to highlight that our approach outperforms existing approaches not in the accuracy of the prediction (which cannot be better than ±4 days due to the uncertainty of the onset date estimation, see supporting information), but in the ability to forecast 2 weeks earlier than the IMD method.

The prediction scheme for WD succeeds in 84% of years on 205 DOY (July 25) with ±5.6 days accuracy. Our approach allows to predict WD from the Eastern Ghats 72 days in advance (averaged withdrawal date from this region is October 10th), while the IMD does not provide a long range forecast for WD and only declares it post factum (http://www.imd.gov.in).

3.3. Anomalous Years

Although, our prediction scheme works for most of the years, the proposed approach has certain limitations. They are associated with difficulties in estimating the trend of *T* and rh for some years. We refer to a year as anomalous when the proposed approach has difficulties to predict OD and WD. We identified three main reasons for the increased uncertainty in the forecasting of monsoon timing during these years.

First, increased uncertainty might be caused by difficulties in the correct determination of the real OD and WD in the EG [*Wang et al.*, 2009, *Meehl et al.*, 2009, *Pai et al.*, 2009]. Second, increased uncertainty occur because of the difficulties in the trend estimation in NP because of high fluctuations of *T* and rh possibly due to intensification of the Western Disturbances in NP [*Cannon et al.*, 2014] and—as a result—an increase in winter and premonsoon rains, caused by positive phases of North Atlantic Oscillation (NAO) and El Niño–Southern Oscillation [*Syed et al.*, 2012]. In particular, we observe an increased uncertainty in the forecasting of the OD based on rh for the years 1990–1993 and based on *T* for the years 1998–2000 (Figure 4), which might be associated with two regime shifts in the fog frequency during the premonsoon in the 1990s and from 1998 to 2006 [*Syed et al.*, 2012; *Cannon et al.*, 2014]. Third, forecasting of monsoon timing meets certain difficulties because of the intricate relationship between the monsoon and ENSO systems. It has been shown that positive ENSO years cause local anomalies in the spatial distribution of the atmospheric pressure, temperature, and wind during the premonsoon [*Byshev et al.*, 2012; *Ludescher et al.*, 2014; *Hlinka et al.*, 2014] and thereby affect estimation of trends.

Two thirds of the anomalous years are ENSO years. ENSO affects predictability of the OD: while negative ENSO years do not change the accuracy of prediction in comparison to ENSO neutral years, positive ENSO years decrease the accuracy of prediction with respect to neutral ENSO years by 13%, from 76% to 59% for the prediction scheme based on *T* (similar for rh). In particular, inaccurate prediction based on *T* is made for the following years: 1973, 1983, 1987, and 2003 (positive ENSO years); 1971, 1985, 1999, and 2000 (negative ENSO years); and1979, 1981, and 1986 (neutral ENSO years). For the prediction of the WD, anomalous years are 1973 and 2010 (positive ENSO years); 1984, 1996, and 2011 (negative ENSO years); and 1986, 2013, and 2014 (neutral ENSO years). For these anomalous years a more thorough analysis is required, as *T* and rh in NP and EG do not exhibit typical behavior.

We can improve the prediction quality by taking into account the ENSO state during the training period. The extension of the prediction scheme to ENSO years is made by the following additions: instead of the 14 years prior to a prediction during an El Niño year, the training period is taken from the 14 prior El Niño years. This takes into account the trend behavior during El Niño years. Our prediction scheme based on the training period of 14 years with a separate analysis of positive, negative, and neutral ENSO years increases the forecast accuracy of WD up to 89% for positive ENSO (9 years) and does not change the accuracy for negative ENSO years (see Figure 4c). Forecast of the OD during the positive ENSO years do not improve the accuracy of prediction, possibly due to the high fluctuations in NP causing problems with the trend estimation. In contrast, forecast for negative ENSO years considerably improves the prediction of the OD, resulting in 83% of accurate predictions within 7 days (out of 6 years) based on *T* and accurate predictions within 7 days for all years (out of 6 years) based on rh (see Figure 4b).

In addition, there are some difficulties in estimating the WD for the period 2010–2014 (see Figures 4c and 4d) while prediction of the 2015 withdrawal date was successful. Data of determined postfactum withdrawal dates in EG (which we call real withdrawal dates and compare our results with) show an increase in the last decade (IMD, available online, 2015). That is, the length of the monsoon is increasing. This observation might be caused by difficulties in the determination of the WD during these years, since *T* variations were more erratic. Alternatively, the change in WD may be related to a change in the monsoon state. Since our analysis is mostly based on the estimation of the WD using a training period (in the wider sense the state of the system), it seems that during the last several years the state of the system has changed. As a result, information only from the training period based on observation of the previous years is not sufficient for an accurate prediction of the WD in the last pentade. If we exclude the period 2010–2014 from the prediction of the WD, we obtain an improved forecasting prediction skill up to 93%. Above mentioned issues, however, do not affect the accuracy of prediction of the OD during the last pentade, which remains high (5 out 5 accurate predictions based on *T*, and 4 out 5 - based on rh) (Figures 4a and 4b).

4. Conclusion

We have proposed a novel approach for Indian monsoon onset and withdrawal prediction based on a critical transition precursor—the prebifurcation growth of fluctuations. We have revealed two geographic regions (North Pakistan and the Eastern Ghats) of critical behavior that exhibit the largest growth of the variance of fluctuations prior to the onset of the monsoon. We call these regions tipping elements of the monsoon and treat them as coupled reference points to predict the onset and withdrawal dates of the monsoon based on time series analysis of near-surface air temperature and relative humidity.

Based on this approach, we have developed a prediction scheme for long-range (more than 30 days in advance) forecasting of onset and withdrawal dates of the monsoon. The proposed scheme allows to predict onset dates 2 weeks earlier than existing forecasting methods, and in 73% of the considered years gives an accurate prediction with a range of 7 days. Also, our approach allows to predict the withdrawal date 1.5 month earlier than existing forecasting methods, and for 84% of the considered years it results in an accurate prediction within 10 days difference from the real withdrawal date. In addition, the proposed approach allows to include information about the ENSO events in the forecasting scheme and notably improves the forecasting of monsoon timing during La Niña years.

Because North Pakistan and the Eastern Ghats are regions of critical behavior when the monsoon season approaches, we propose to improve observational data in these regions, especially in Pakistan, where the number of stations is quite low.

Our approach can be used for identifying tipping elements in spatially organized systems undergoing a critical or abrupt transition and using them for prediction of spatiotemporal abrupt transitions.

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Erratum

In the originally published version of this article errors in parameter sensitivity test have been detected. The following have since been corrected and this version may be considered the authoritative version of record.

Additional statistical analysis to exclude model system bias in the prediction skill and parameter identification (revised figures S5 and S6 in section 10, and a new section 11 with the title ″Limitation of our approach and parallels to existing methods“ in the Supporting Information).

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