

## Role of west Asian surface pressure in summer monsoon onset over central India

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# Environmental Research Letters



## LETTER

# Role of west Asian surface pressure in summer monsoon onset over central India

### OPEN ACCESS

#### RECEIVED

22 October 2016

#### REVISED

31 May 2017

#### ACCEPTED FOR PUBLICATION

2 June 2017

#### PUBLISHED

27 June 2017

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**Keywords:** monsoon onset, moisture flux, atmospheric stability, surface pressure, CMIP5 models

Supplementary material for this article is available [online](#)

## Abstract

Using rain-gauge measurements and reanalysis data sets for 1948–2015, we propose a mechanism that controls the interannual variation of summer monsoon onset over central India. In May, about a month before the onset, the low level jet over the Arabian Sea is about 40% stronger and about 2.5 degrees northward during years of early onset as compared to years of late onset. A stronger and northward shifted low level jet carries about 50% more moisture in early onset years, which increases low level moist static energy over central India in the pre-monsoon season. The increase in low level moist static energy decreases the stability of the atmosphere and makes it conducive for convection.

The strength and position of the low level jet are determined by surface pressure gradient between western Asia and the west-equatorial Indian Ocean. Thus, an anomalous surface pressure low over western Asia in the pre-monsoon season increases this gradient and strengthens the jet. Moreover, a stronger low level jet increases the meridional shear of zonal wind and supports the formation of an onset vortex in a stronger baroclinic atmosphere. These developments are favourable for an early onset of the monsoon over the central Indian region. Our study postulates a new physical mechanism for the interannual variation of onset over central India, the core of the Indian monsoon region and relevant to Indian agriculture, and could be tested for real-time prediction.

## 1. Introduction

The summer monsoon onset over Kerala (MOK), an Indian state on the south-west coast, heralds the rainy season over India and has received large attention in past few decades [1–6]. MOK is a continuation of the progress of onset isochrones toward south Asia, that starts over the South China Sea in mid-May [7]. After reaching Kerala, the onset isochrones progress from south-east toward north-west and cover north-west parts of India by mid-July. This progress is controlled by a feedback between atmospheric shallow convection and land-surface processes, and the time taken by the onset isochrones to cover the entire country shows substantial interannual variations [8]. Previous studies [9] show that the date of MOK is correlated well with that over the Indo-China peninsula and western Pacific Ocean, but the relationship with onset

over central India is not that apparent. Moreover, the dates of MOK are not correlated well with the Indian summer monsoon rainfall (ISMR). An onset date which is more representative of the Indian monsoon region is better correlated with ISMR [10]. It is, therefore, pertaining to study the interannual variations of summer monsoon onset over central India (MOCI), the region over which the seasonal mean rainfall shows higher coherence to ISMR. Several authors have documented different facets of rainfall characteristics of this region including active-break cycles, the dominant intraseasonal mode of the Indian summer monsoon [11, 12].

Climatologically, MOCI occurs in mid-June, about two weeks after MOK [7], and is often preceded by an onset vortex over the Arabian Sea [13]. The low level jet over the Arabian Sea [14], crucial to the development of onset vortex, is sensitive

to surface pressure gradient over western Asia and the Arabian Sea, as well as to latent heating due to convection over the Bay of Bengal [1, 15, 16]. We explore the connection between MOCI and surface pressure gradient over western Asia, which persists much in advance to the beginning of convective activities over the Bay of Bengal in May. Many previous studies [17–20] have identified the importance of surface heating over western Asia in the context of Indian summer monsoon. The role of this heating in creating surface pressure anomalies is well understood. Studies [21, 22] have shown that pre-monsoon surface pressure anomalies over north and north-west India are negatively correlated to ISMR. In this work, we propose a physical mechanism relating surface pressure gradient over western Asia and onset over central India.

This paper is organised as follows. Section 2 describes data sets and the method used for defining onset. In section 3 we detail results of our study. Section 4 contains discussions and summaries pertaining to this study.

## 2. Data sets and the definition of onset

We use the daily precipitation data set obtained from rain-gauge observations by India Meteorological Department (IMD), with  $1^\circ \times 1^\circ$  spatial resolution [23]. The atmospheric parameters are taken from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis product [24]. This daily data set has  $2.5^\circ \times 2.5^\circ$  resolution in longitude-latitude. We also use sea surface temperature from Hadley Centre analysis [25]. We have taken a common period of all these data sets, 1948 through 2015, for this study.

The date of MOK is defined as the first day of the monsoon season (after 15 May) when the daily rainrate over  $74^\circ\text{--}78^\circ\text{ E}$ ,  $8^\circ\text{--}12^\circ\text{ N}$  exceeds  $4\text{ mm day}^{-1}$  and remains above this value for at least three consecutive days, provided that zonal wind averaged over  $55^\circ\text{--}75^\circ\text{ E}$ ,  $5^\circ\text{--}12.5^\circ\text{ N}$ , and vertically integrated from surface to 600 hPa, exceeds  $3\text{ m s}^{-1}$  and stays above this value for at least ten days from the date of onset. The criterion used to define onset from daily rainrate is similar to that used in [26, 5]. Moreover, the criterion for lower and middle tropospheric winds in defining onset has been used in several previous studies [6, 27–29]. The use of a combined rain and wind criteria for determination of onset date minimises the possibility of capturing pre-onset heavy rainfall as bogus onset. Although the threshold for vertically integrated wind is lower than the mean zonal wind at 850 hPa over the Arabian Sea, this criterion holds good for most of the years and takes into account the fact that the strength of westerlies over the Arabian Sea decreases with height and persists long after a real onset (online supplementary figure S1 available at [stacks.iop.org/ERL/12/074002/mmedia](http://stacks.iop.org/ERL/12/074002/mmedia))).

The correlation between MOK dates during 1971–2007 obtained from our method to that in [5] is 0.87.

With this, the date of MOCI is defined as the first day of the monsoon season when, after MOK, daily rainrate over central India ( $76^\circ\text{--}86^\circ\text{ E}$ ,  $16^\circ\text{--}26^\circ\text{ N}$ ) exceeds  $4\text{ mm day}^{-1}$  and stays above this threshold for at least three consecutive days. In this definition, we take advantage of the fact that monsoon onset isochrones move from south to north and thus onset over central India is later than that over Kerala. Lower tropospheric winds turn anticlockwise over central India in response to the monsoon trough. These winds are weak compared to those over Arabian Sea. Thus, we chose to use only precipitation threshold to define MOCI. The regions used for onset definitions are marked in figure 1(a).

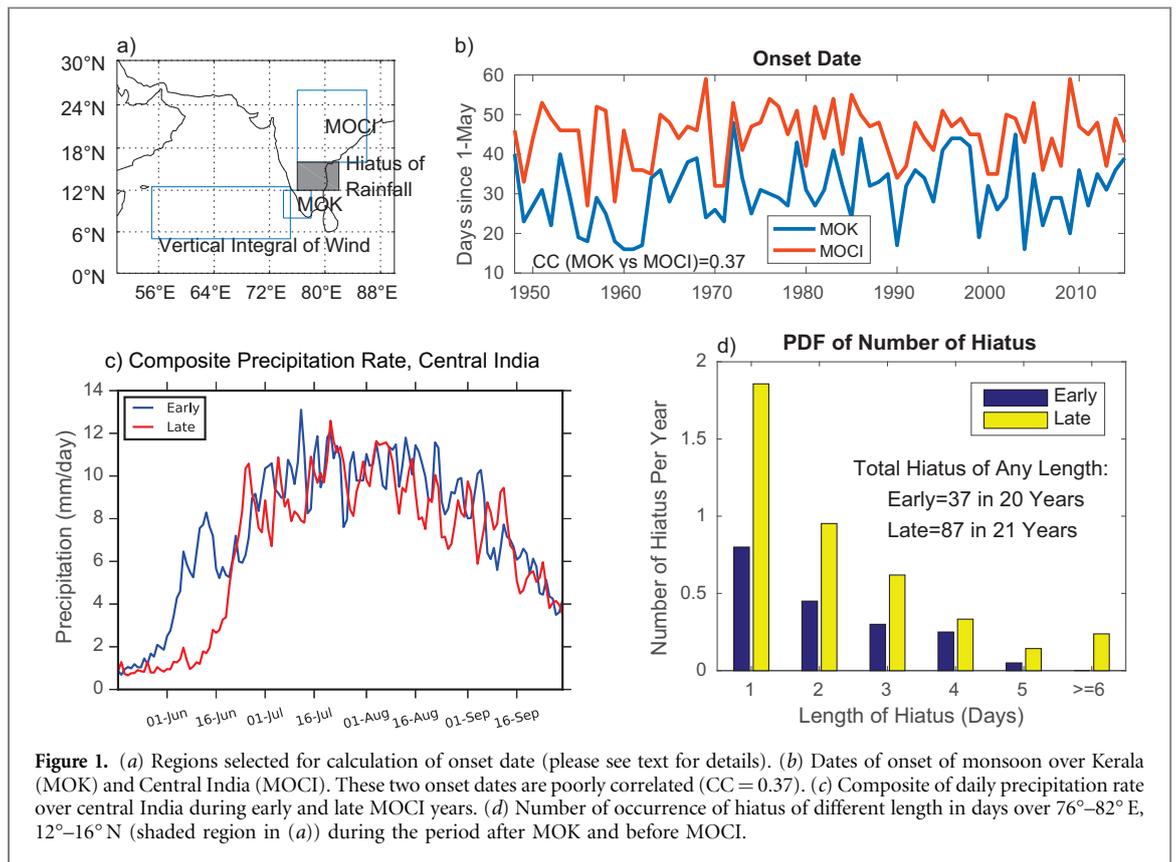
We also use simulated surface pressure and precipitation data sets from eight models which participated in the Coupled Model Intercomparison Project (CMIP%) listed in supplementary table 1. The ensemble *r1i1p1* of the historical period is used here. The data is monthly mean from 1861 through 2005. We have not detrended the data set since previous studies suggest a weak trend in Indian summer monsoon precipitation, as simulated by the CMIP5 models in the historical period [30].

## 3. Results

### 3.1. The early and late onset years

During our study period (1948–2015), the dates of MOCI span from 27 May to 28 June; the mean is 14 June, which is close to that declared by IMD. Its interannual standard deviation is about 7 days, very close to the interannual standard deviation of dates of MOK [3]. Figure 1(b) shows the interannual variations of MOK and MOCI. These two time-series are poorly correlated (correlation coefficient = 0.37). Dates of MOK show an increasing trend of about 0.9 days per decade, which is significant at about 93% level (using a *t*-test). This is consistent with a previous study reporting a delay in onset over Arabian Sea after 1977/78 [31]. On the other hand, dates of MOCI show weak (0.24 days per decade) and non-significant (42% level) increasing trend. The 68 year correlation coefficient between MOCI (MOK) and ISMR is  $-0.38$  ( $-0.21$ ), suggesting MOCI would be more relevant to the seasonal mean rainfall as compared to MOK.

From here, an early onset year is defined when the date of MOCI is on or before the 25th percentile (10 June) of its interannual distribution (figure S2). Similarly, a late onset year is defined when the date of MOCI is on or later than the 75th percentile (18 June) of this distribution. During our study period, there are 20 early onset years and 21 late onset years (supplementary table 2). In figure 1(c), we show the composite daily time series of rainfall over central



India for the early and late onset years. Irrespective of early or late onset, separated by about two weeks, daily rainrate increases sharply during onset. However, after the onset and up to the end of the monsoon season daily rainrate of late and early onset years are comparable. This shows that an early or late onset does not necessarily indicate the intensity of rainfall during the subsequent period of the season, and the underlying mechanisms could be different. This result is consistent with previous modelling studies illustrating that the prevailing atmospheric dynamics controls monsoon intensity after the onset phase [32, 26].

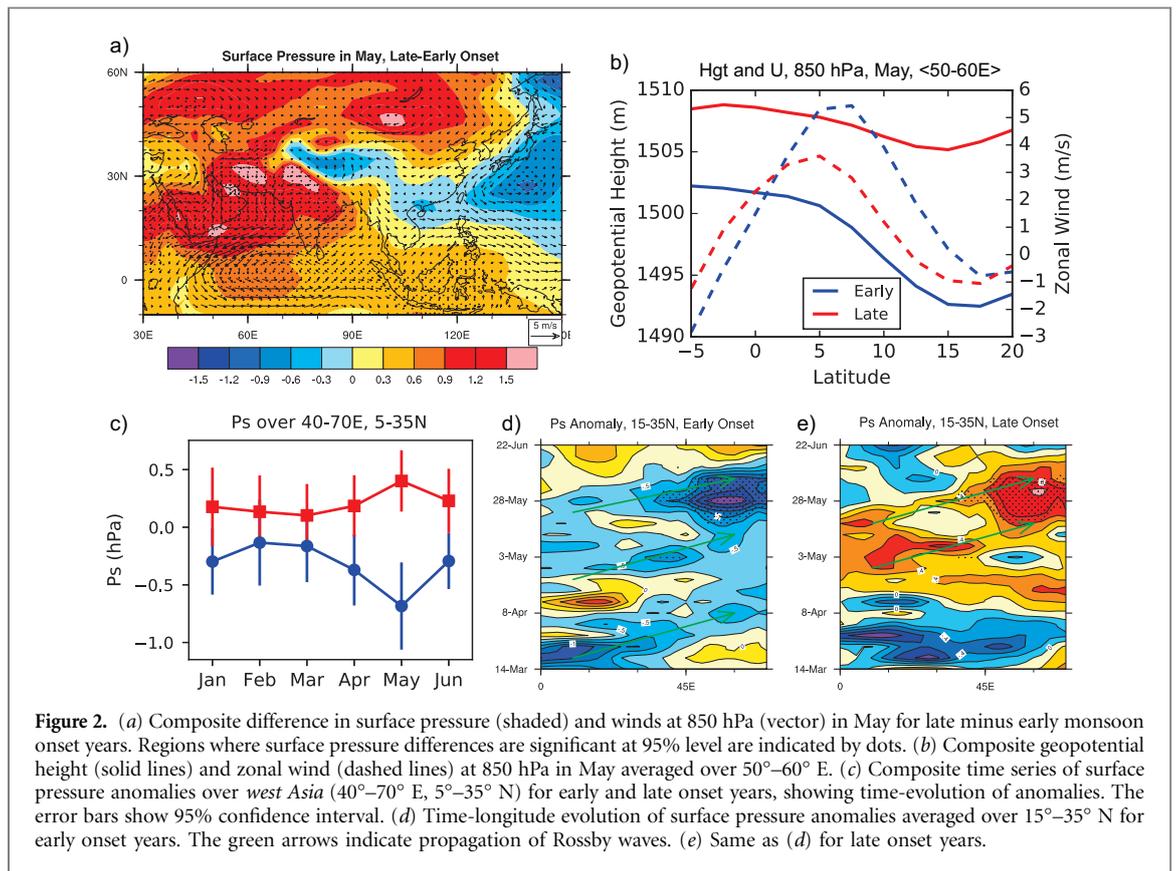
After MOK and before the monsoon onset isochrones cover the entire Indian monsoon region, several spells of no rain are observed. The length and frequency of such hiatus of rain spells determine the meridional speed of progress of onset isochrones and the interannual variation of MOCI. In figure 1(d), we show the frequency distribution of spells of hiatus which occurred after MOK but before MOCI over the region confined between south India and central India (shaded in figure 1(a)). The total number of hiatus is more than double during a late MOCI as compared to an early MOCI. Figure 1(d) shows that during late MOCI years, probability of hiatus of all duration (one day through to more than six days) is higher as compared to early MOCI. The hiatus in monsoon progression has been shown to be related to dry air intrusion from north-west of India [33], which inhibits the convective activities over the Indian monsoon region during the onset phase. This westerly intrusion of dry air has been related to pressure

anomalies over western Asia [34]. We explore these connections in the following section.

### 3.2. Relation to pre-onset conditions

Figure 2(a) shows, the composite difference of surface pressure ( $p_s$ ) in May between late and early onset years. A large region over western India, the northern Arabian Sea, and western Asia experiences increased  $p_s$  in late onset years when compared to early onset years in May, about a month before onset. This difference exceeds 1 hPa over a large domain. Overlaid on figure 2(a) is the composite vector wind difference at 850 hPa. These 850 hPa winds, consistent with the  $p_s$  and 850 hPa geopotential height gradients, are anomalously anticlockwise over the Arabian Sea and southern parts of India in late onset years as compared to early onset years. It should be noted that the strongest differences in winds are near the coast of Somalia ( $50^{\circ}$ – $70^{\circ}$  E and  $0^{\circ}$ – $15^{\circ}$  N).

Since the spatial distribution of  $p_s$  climatology in northern summer indicates prevailing surface heat-low over western Asia as compared to the equatorial Indian Ocean (not shown), the increased  $p_s$  in late onset years suggests a reduction of the meridional pressure gradient in the lower troposphere. Such change is reflected in the 850 hPa geopotential height, averaged between  $50^{\circ}$ – $60^{\circ}$  E (figure 2(b)). An increased (decreased) meridional gradient in the 850 hPa geopotential height gives rise to stronger (weaker) zonal winds with the axis of the low level jet (LLJ) shifted northward (southward) in early (late) onset years. Moreover, these decreased zonal winds at



around 5° N reduce the meridional shear of zonal winds in the late onset years, which is unfavourable for the formation of onset vortex during the early phase of monsoon [13]. Note that, during June–September, the 850 hPa zonal winds over the Arabian Sea are strongest near 65° E (figure S3). However, before the onset (in May) the cross-equatorial winds are strongest near the coast of Somalia. Additionally, figure 2(b) indicates a weaker meridional gradient of 850 hPa zonal winds in late onset years and the low level jet is nearly 40% weaker and shifted southward by approximately 3 degrees as compared to early onset years.

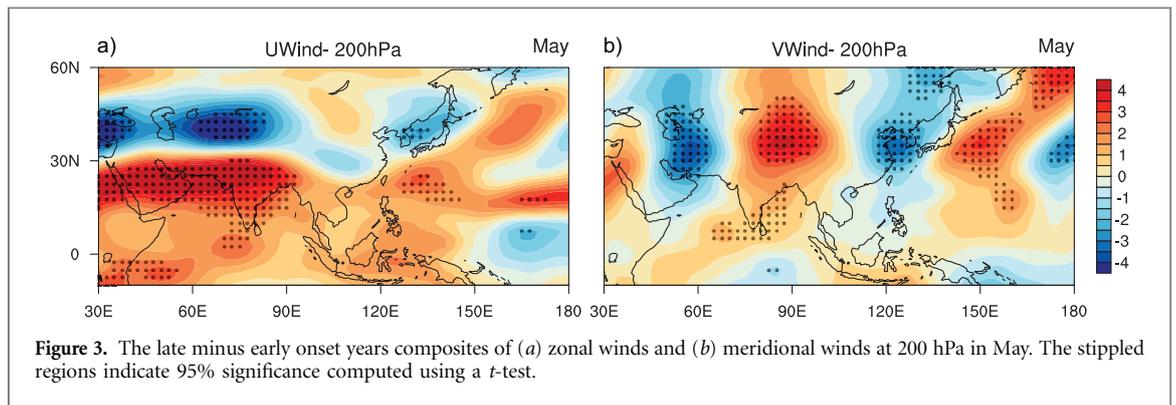
Next, we compute composites of  $p_s$  anomaly averaged over 5°–35° N, 40°–70° E, henceforth referred as *west Asia*, for the late and early onset years (figure 2(c)). The  $p_s$  anomaly starts evolving at least three months before the mean onset date (mid-June) for early or late onset year. Further, the magnitude of  $p_s$  anomalies in May associated with early onset years ( $\sim -0.7 \pm 0.3$  hPa) is higher as compared to the late onset years ( $\sim +0.3 \pm 0.2$  hPa). A regression analysis between onset dates and surface pressure for March, April and May suggests that this signature of the interannual variation of onset is present in surface pressure anomaly of March, which becomes stronger in subsequent months (figure S4). Hence, the time-persistent surface pressure anomaly over the northern Arabian Sea and western Asia in the pre-monsoon season can be considered as a precursor for early and late MOCI.

The geopotential height differences between late and early onset years over *west Asia*, seen in figure 2(b),

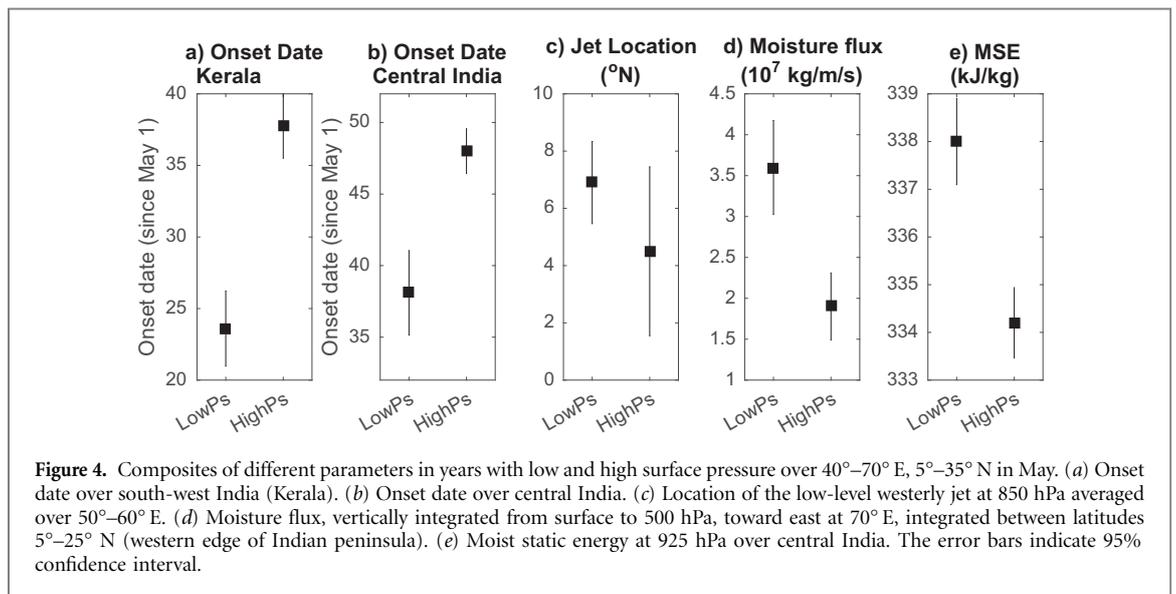
extend up to 350 hPa (figure S5); that is deeper than a heat low which is normally confined to the lower troposphere. It has been shown [20] that the evolution of pressure over this region is controlled not by surface heating alone but also by orographic and dynamical factors. Surface pressure anomaly acts as an integrated indicator of all these influences.

The time-longitudinal variation of  $p_s$  anomalies averaged over 15°–35° N are shown in figures 2(d) and (e) for early and late onset years respectively. The  $p_s$  anomalies propagate from west to east during years of early and late onset. These anomalies, however, get intensified over western Asia. The speed of propagation of these anomalies is about  $3 \text{ m s}^{-1}$ , a typical phase speed of atmospheric Rossby waves at these latitudes. Thus, existence and eastward propagation of such  $p_s$  anomalies (which are also related to geopotential field anomalies up to 350 hPa level) are likely to be associated with midlatitude westerly winds. This is consistent with the previous study showing the impact of mid-level anomalous high over western Asia on the break phase of the Indian summer monsoon [34]. This also explains the higher number of hiatus events noted during years of late onset as compared to early onset (figure 1(d)).

Do horizontal winds of the upper troposphere carry signals of early or late onset in pre-monsoon season? The upper tropospheric westerly jet of northern summer [35] jumps from the south of the Tibetan Plateau to its north during the onset of the monsoon over the South China Sea and south Asia [36, 37]. In



**Figure 3.** The late minus early onset years composites of (a) zonal winds and (b) meridional winds at 200 hPa in May. The stippled regions indicate 95% significance computed using a *t*-test.



**Figure 4.** Composites of different parameters in years with low and high surface pressure over  $40^{\circ}$ – $70^{\circ}$  E,  $5^{\circ}$ – $35^{\circ}$  N in May. (a) Onset date over south-west India (Kerala). (b) Onset date over central India. (c) Location of the low-level westerly jet at 850 hPa averaged over  $50^{\circ}$ – $60^{\circ}$  E. (d) Moisture flux, vertically integrated from surface to 500 hPa, toward east at  $70^{\circ}$  E, integrated between latitudes  $5^{\circ}$ – $25^{\circ}$  N (western edge of Indian peninsula). (e) Moist static energy at 925 hPa over central India. The error bars indicate 95% confidence interval.

figure 3(a) we show the composite difference of 200 hPa zonal winds in May between late and early onset years. The most prominent difference is seen west of  $90^{\circ}$  E where the upper level westerly jet is shifted southward by about 20 degrees in late onset years as compared to early onset years, a month before the onset. These differences are significant at 95% level over most of these regions of large change in winds. The composite difference of 200 hPa meridional winds in May between late and early onset years (figure 3(b)) shows the change in the phase of Rossby waves, with anomalous southerly over Indian monsoon region and northerly west of it in late onset years. A similar change in phase of pre-monsoon upper-tropospheric Rossby waves has been related to a weak Indian summer monsoon [38]. Thus, it can be inferred that significant differences exist in both the near-surface and upper tropospheric conditions during the pre-monsoon months of early and late onset years.

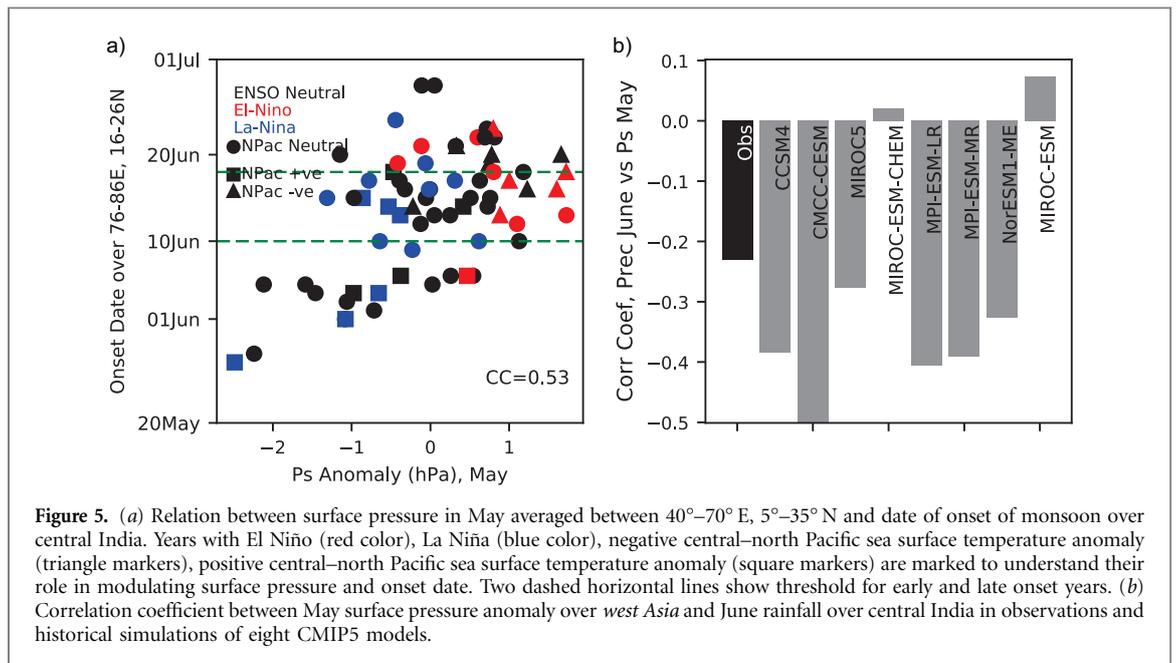
### 3.3. The mechanism of interannual variation of onset

Having illustrated a relationship between the date of onset of monsoon over central India that occurs in June, and surface pressure over *west Asia* in May, we focus our analysis on the mechanism that relates them. Firstly, similar to what has been done for onset dates,

we categorise years between 1948–2015 based on  $p_s$  anomalies in May averaged over *west Asia*. A year when this anomaly is lower than the 25th percentile (higher than the 75th percentile) is categorised as *LowPs* (*HighPs*) year. There are 18 *LowPs* and 17 *HighPs* years in this time period. In our subsequent analysis, composites are performed for these *LowPs* and *HighPs* years. The mean difference in  $p_s$  for these two clusters is 2.3 hPa. Categorising the years in terms of  $p_s$  over *west Asia* (as the independent variable) and compositing other parameters including onset date (as the dependent variable) could help in understanding the mechanism and developing models for monsoon onset prediction in future studies.

In figures 4(a) and (b) we show the mean MOK and MOCI for the *LowPs* and *HighPs* years. The error bars on the mean indicate the 95% confidence band, calculated using a *t*-test. These figures show that the onset dates are significantly different, by about 10 (14) days for MOCI (MOK) for *LowPs* and *HighPs* years. This is, in fact, derived from and consistent with figure 2(a).

We further investigate the changes in circulation, moisture flux, and moist static energy of the atmosphere arising on account of these difference in  $p_s$  over *west Asia* during pre-monsoon season. We



calculate the location of the axis of LLJ after averaging zonal wind at 850 hPa along 50°–60° E, and then locating the latitude of its maximum intensity over the Arabian Sea (within 5° S to 20° N). This is done for every year separately and composites are obtained for the *LowPs* and *HighPs* years. Figure 4(c) shows that for years with *HighPs* anomaly, the location of the LLJ is shifted south by about 2.5 degrees compared to the years with *LowPs* anomaly, although the spreads of these two ensembles show some overlap. This is also consistent with figure 2(b). In *LowPs* years, the low level westerlies are stronger (as also evident from figure 2(b)), in addition to a northward shift of the LLJ axis. Most of these differences in zonal winds for *LowPs* and *HighPs* years are found between surface to 500 hPa pressure level (figure S6(a)). These differences are much weaker when composited based on El Niño and La Niña (figure S6(b)).

The composites of moisture flux, vertically integrated from surface to 500 hPa at 70° E (eastward positive) and integrated from 5° N to 25° N, during *LowPs* and *HighPs* years are shown in figure 4(d). A strong and northward shifted low level jet in *LowPs* anomaly years brings more moisture toward Indian monsoon region in May. In fact, mean eastward moisture flux at this longitude is about 1.5 times in *LowPs* years as compared to *HighPs* years.

In figure 4(e) we show the composites of moist static energy (MSE) at 925 hPa over central India in May during *LowPs* and *HighPs* years. MSE is defined as

$$MSE = C_p T + gz + L_v q \quad (1)$$

where  $T$ ,  $q$  and  $z$  are temperature, specific humidity and geopotential height, respectively;  $C_p$ ,  $L_v$  and  $g$  are specific heat at constant pressure for air, latent heat of vaporisation for water and acceleration due to gravity,

respectively. Note that, an increased eastward moisture flux crossing 70° E results in an increase in the lower level MSE (of the order 4 kJ kg<sup>-1</sup>) over central India, without much change in upper level MSE (figure S7). This enhancement in MSE in the lower troposphere destabilises the atmosphere and makes it conducive for convection [26, 39, 40]. It then leads to early onset during *LowPs* years as compared to late onset during *HighPs* years.

A scatter plot between the  $p_s$  anomaly over *west Asia* and MOCI is shown in figure 5(a). The linear correlation coefficient between these quantities (0.53) is much higher compared to that of MOCI with sea surface temperature anomalies over Niño 3.4 region (0.21) or central–north Pacific Ocean (–0.33) (figure S8). This figure also suggests that while negative  $p_s$  anomaly in May almost always ensures an early MOCI, onset dates for positive  $p_s$  anomalies have larger interannual variations. Moreover, while El Niño years tend to be associated with positive  $p_s$  anomaly, the opposite is true for La Niña years. Similarly, positive (negative) central–north Pacific Ocean (150°–210° E, 20°–40° N) sea surface temperature anomalies are clustered along negative (positive)  $p_s$  anomaly. Note that, conventionally a positive central–north Pacific sea surface temperature anomaly is associated with a negative Pacific Decadal Oscillation (PDO) index [41]. Thus, the mechanism proposed in this study offers a plausible explanation for the existing teleconnection between Indian monsoon rainfall and ENSO (and PDO), that is through changes in surface pressure over western Asia due to large-scale changes in circulation during ENSO or PDO years. This figure also suggests that the relationship between  $p_s$  anomaly over *west Asia* and date of onset over central India is stronger (weaker) during negative (positive) PDO years. Similar asymmetry in teleconnection between ENSO and rainfall over eastern Australia during different

phases of PDO due to the zonal shift of Walker circulation was reported in a previous study [42]. In summary, a combination of ENSO and PDO, when manifested in terms of surface pressure anomaly over the northern Arabian Sea and western Asia can affect the onset of monsoon over central India.

To show that this observed relationship between pre-monsoon surface conditions over *west Asia* and onset over central India is captured by numerical models, we refer to a recent work [43] that uses a global general circulation model. This study shows that surface soil moisture over regions west of India is crucial in determining the seasonal cycle of monsoon, especially in its early phase. We have further investigated the relationship between surface pressure over west Asia and monsoon onset over central India using simulations of eight CMIP5 models. Instead of calculating the date of onset, we have taken the mean rainfall in June over central India as representative of the onset date in these models. This avoids defining different onset criteria in these models depending on their simulated intensity of daily rainfall. In observations, the correlation coefficient between June mean rainfall and onset date over central India is  $-0.57$ . We correlate the rainfall over central India in June with surface pressure in May over *west Asia* for the historical period (1861–2005). The correlation values are shown in figure 5(b). Note that, six out of the eight models show negative correlations (similar to that observed), indicating a decrease in June rainfall over central India with an increase in May surface pressure over west Asia, which is consistent with the results reported in our study based on observational datasets.

#### 4. Summary and discussions

This study presents a mechanism that controls the interannual variation of summer monsoon onset over central India: a region with spatial coherence in seasonal mean rainfall and which has been the focus of numerous previous works [11, 12, 44–46]. Our study also provides an objective definition of monsoon onset over central India, similar to previous studies defining onset over south and east Asia [4, 6, 26]. The mean onset date over central India is 14 June with an interannual standard deviation of about 7 days. We find that pre-monsoon surface pressure anomaly over western Asia and Arabian Sea controls monsoon onset over central India by modulating lower tropospheric circulation. A lower than normal surface pressure over western Asia strengthens the equator-to-pole surface pressure (and lower tropospheric geopotential height) gradient. This results in stronger zonal winds over Arabian Sea, with the axis of the low level jet shifted northward in May. The enhanced westerlies bring more moisture toward Indian monsoon region and increase the moist static energy in the lower

troposphere, causing the development of vertical instability in the atmosphere required for initiation of convection [26, 39]. A stronger low-level jet over the southern Arabian Sea also increases the meridional shear of zonal wind and thus favours the formation of an onset vortex [13] before the onset of monsoon over central India. Thus, a negative surface pressure anomaly over western Asia acts as a precursor to an early onset over central India.

This study, for the first time, provides a mechanism that explains the interannual variation of summer monsoon onset over central India. Thus, this mechanism could be tested to model the progress of onset isochrones from south-east to north-west India. Finally, given the fact that the western Asian surface pressure anomaly is a persistent phenomenon that can be traced back up to March, results presented in this study can be used to develop a real-time prediction system for the onset of monsoon over central India, which can be instrumental in planning for the water and agriculture resources.

#### Acknowledgments

This work is supported by the Ministry of Earth Sciences (MoES), Government of India under the National Monsoon Mission project. Authors acknowledge the rainfall data provided by the India Meteorological Department, and the reanalysis data sets obtained from NCEP/EMC website. Authors greatly acknowledge useful comments by two anonymous reviewers.

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