Early Indian Summer Monsoon Onset Driven by Low Soil Moisture in the Iranian Desert

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Abstract Advancing the leading time for onset prediction of the Indian summer monsoon (ISM) onset is an imperative task; however, it has remained a challenging subject. In particular, the land-atmosphere coupling associated with monsoon onset prediction is poorly understood. Here we attempt to investigate the land factor as the ISM onset precursor through studying the internal mechanism of atmospheric heating, which is distinguished by monsoon onset. The low (high) soil moisture in the Iranian desert during March and April advances (delays) ISM onset by enhancing (disturbing) the vertical easterly wind shear. In addition, midtropospheric heating is affected by soil moisture in the Iranian desert. By investigating the internal atmospheric heating process and suggesting the relationship between low soil moisture and ISM onset, these findings clarify the monsoon onset mechanism in terms of the vertical atmospheric profile and land-atmosphere interaction, which eventually extend the lead time for the onset prediction.

1. Introduction

As the time at which the Indian summer monsoon (ISM) starts can directly affect agriculture, the economy, and society in general, it is important to understand the onset of the summer monsoon (Moon & Ha, 2017; Ueda et al., 2015; Webster et al., 1998; Zhang et al., 2014). The social impact of not only the monsoon but also the start date is severe, especially in populated regions (Moon & Ha, 2017; Turner & Annamalai, 2012; Webster et al., 1998; Zhang et al., 2014). Note that the relationship between the monsoon rainfall rate and early monsoon onset is not linear (Figure 1b). Even if the mean monsoon intensity is typical, early or late onset of the summer monsoon can dramatically disrupt human activity (Dhar et al., 2002; Mao & Wu, 2007). Because predicting and understanding the onset of the ISM has long been of great interest, many previous studies have proposed definitions of ISM onset from various viewpoints. Abrupt changes in rainfall (Webster et al., 1998; Zhang et al., 2004), the horizontal wind direction (Lu & Chan, 1999; Wang & Fan, 1999; Wang et al., 2001; Webster & Yang, 1992), the structure of the atmosphere (MAO et al., 2004), the tropospheric temperature gradient (Xavier et al., 2007), and zonal moisture transport (Fasullo & Webster, 2003) are used as key indices to determine the onset date in specific years. Furthermore, a unified Asian summer monsoon onset has also been suggested (Li & Zhang, 2009; Wang & LinHo, 2002).

To predict the future climate accurately and plan for climate change, the precursor of monsoon onset should also be understood. The climatological onset of Asian summer monsoon starts in the Bay of Bengal owing to cyclonic circulation driven by the sensible and latent heat fluxes (Figure 1a). The onset is propagated to India by strengthening of the Somali jet and heating of the Tibetan Plateau (TP; Figure 1a; Moon & Ha, 2017; Wang & LinHo, 2002; Webster, 1992; Zhang et al., 2004). Furthermore, ISM onset is negatively correlated with the El Niño–Southern Oscillation and Pacific Decadal Oscillation (Chevuturi et al., 2018; Goswami & Xavier, 2005; Watanabe & Yamazaki, 2014). La Niña induces an early ISM onset by strengthening the meridional tropospheric temperature over the South Asian monsoon region (Goswami & Xavier, 2005). The stationary wave train associated with a negative Pacific Decadal Oscillation generates a warm anomaly and intensifies the land-sea thermal contrast, resulting in an early ISM (Watanabe & Yamazaki, 2014). The effect of Eurasian snow cover reduces the midtropospheric heating over the TP and the meridional temperature gradient (Blanford, 1884; Verneker et al., 1995). Using the surface moist static energy over the Indian subcontinent and the Niño4 index, the predictive skill of ISM onset is improved (Rajagopalan & Molnar, 2014). In light of the geographic concept, the air temperature and relative humidity over the Northern Pakistan and the Eastern Ghats have suggested the critical behavior which has good prediction than existing...
methods (Stolbova et al., 2016). However, the impact of soil moisture on ISM onset has received much less attention until recently. Soil moisture is a crucial component of the climate system and indicates the land surface hydrology (Douville et al., 2001; Entekhabi et al., 1996; Maxwell et al., 2007). Soil moisture conditions can last long enough to modify the atmospheric circulation over seasonal to interannual time scales (Douville et al., 2001; Entekhabi et al., 1996; Shukla & Mintz, 1982). Through an evaporation feedback mechanism, the soil moisture can affect the intercontinental hydrological cycle (Douville et al., 2001; Serafini, 1990).

This study focuses mainly on the vertical structure of atmospheric change before and after the ISM onset. Because the dynamics have little effect on the vertical integration of the values, it is difficult to study the mechanism and the interactions between levels. Therefore, the vertical profile should be emphasized for understanding the dynamics as well as physics. Here we asked (1) how the features and internal processes of the monsoon differ with altitude before and after onset and (2) whether there are any distinguishing land precursors of ISM onset. Our approach sheds light on advancing the prediction time of ISM onset associated with the land-atmosphere interaction.

2. Data and Method

The primary data are daily means from the European Centre for Medium-range Weather Forecasts Interim reanalysis products (Dee et al., 2011), including the winds, air temperature, and specific humidity, with a horizontal resolution of 2.5° × 2.5° and 27 standard isobars from 1,000 to 100 hPa. The pentad precipitation data were extracted from the Global Precipitation Climatology Project version 2.2 recorded by the World Climate Research Program (Adler et al., 2003). To unify the time scale, the daily data are converted to
five-day mean pentad data. Monthly soil moisture data from the NOAA Climate Prediction Center (Higgins et al., 2000) are used. The climatology of each element is defined by its average from 1979 to 2016.

To confirm the effects of the thermodynamic characteristics, the apparent heat source $Q_1$ and apparent moisture sink $Q_2$, which were introduced by Yanai et al. (1973), are used:

$$Q_1 = \frac{\partial s}{\partial t} + \nabla s \mathbf{V} + \frac{\partial \omega_c}{\partial p} = Q_R + L(c-e) - \frac{\partial \theta w}{\partial p}$$  \hspace{1cm} (1)

$$Q_2 = -L \left( \frac{\partial q}{\partial t} + \nabla q \mathbf{V} + \frac{\partial q \omega_c}{\partial p} \right) = L(c-e) + L \frac{\partial q \omega_c}{\partial p}$$  \hspace{1cm} (2)

where the overbar indicates the 15-day running mean for each year and the prime indicates the departure from the 15-day running mean. Further, $s = C_p T + g z$ is the dry static energy, which consists of the sensible heat and potential energy; $Q_1$ is the heating rate induced by radiation; $Q_2$ is a contributing heat source in the upper troposphere (600–200 hPa). $Q_1$ and $Q_2$ are abruptly strengthened in the entire atmospheric column when the ISM begins and show maxima at 600–200 and 800–600 hPa, respectively (Figures 1a and 2b). If $Q_1$ and $Q_2$ have similar values, most of the heating is due to condensation (Yanai & Tomita, 1998). $Q_1$ is determined mainly by $Q_2$ in the lower troposphere, but the radiational heating $Q_2$ is a contributing heat source in the upper troposphere (600–200 hPa). Note that the radiative–convective effect appears during monsoon onset. $Q_1$ at intermediate altitude and $Q_2$

3. Results

3.1. Internal Process of ISM Onset in Terms of Thermodynamics

We investigate the influence of ISM onset on the atmospheric heating structure. The apparent heat source $Q_1$ and moisture sink $Q_2$ represent the hydrological cycle and drive the land-sea thermal contrast. For example, $Q_1$ heating over the TP is a key Indian onset mechanism involving the thermal contrast (Luo & Yanai, 1984; Yanai et al., 1973; Yanai & Tomita, 1998). Because it is difficult to unravel the interactive mechanism between altitudes in the vertically integrated $Q_1$ and $Q_2$, we emphasize the vertical structure of the atmosphere to examine the dynamic-oriented and vertical structure-based internal mechanism of the monsoon (Yanai & Tomita, 1998). We consider the year-to-year onset date over the Indian domain and define the onset date as pentad 0 (Figures 1b and 2). The time evolution patterns are valid at the 95% confidence level dependent on the individual year cases. The onset date based on the monsoon rainfall range, which we used in this study, is highly correlated (＞0.62) with others (Table S1) that emphasize the dynamic effects (Wang & Fan, 1999; Xavier et al., 2007).

$Q_1$ and $Q_2$ are abruptly strengthened in the entire atmospheric column when the ISM begins and show maxima at 600–200 and 800–600 hPa, respectively (Figures 2a and 2b). If $Q_1$ and $Q_2$ have similar values, most of the heating is due to condensation (Yanai & Tomita, 1998). $Q_1$ is determined mainly by $Q_2$ in the lower troposphere, but the radiational heating $Q_2$ is a contributing heat source in the upper troposphere (600–200 hPa). Note that the radiative–convective effect appears during monsoon onset. $Q_1$ at intermediate altitude and $Q_2$
at lower and higher altitude combine to form a large heat source in the vertically entire level over the SA. High clouds caused by convection and latent heat release at the ISM start date are represented by the shift in $Q_r$ from the surface to the upper troposphere (Figure 2c). As the Indian monsoon occurs in the tropics, the impact of the eddy flux on the atmospheric heating is minimal (Figure 2d).

Figure 2a also shows the ISM onset propagation from Kerala to the northern part of India with the time evolution of the heat source (Moon & Ha, 2017; Wang & LinHo, 2002; Zhang et al., 2004). At pentad 0, monsoon onset over the Kerala region occurs, resulting in atmosphere heating by the combined effects of increased rainfall and radiational heating by cumulus clouds. After the onset in Kerala, additional strong heating occurs owing to northward propagation of rainbands. As a result of the vertical interaction between the heat sources, such as the moisture sink, radiation, and eddy flux effect, the atmospheric structure is transformed and becomes unstable. Although the ISM is part of the Asian summer monsoon, individual subregional Asian monsoons have distinct vertical structures in response to monsoon onset (Figure S1). The main differences from the ISM are the eddy flux effect over the East Asian domain and the strong $Q_2$ in the entire column over the western North Pacific region. Where the dominant roles of the terms involving $Q_1$ vary depending on geographical features, it is necessary to understand vertical interaction among the factors that make up the heat source.

Not only the atmospheric vertical interaction but also the surface boundary condition can drive the change of atmospheric structure and influence one another at the local, regional, and global scales (Entekhabi et al., 1996; Maxwell et al., 2007). The energy balance partitioning is strongly impacted by soil moisture and is essential to the atmospheric boundary (Asharaf et al., 2012; Jones & Brunsell, 2009). Note that the soil moisture memory, that is a key aspect of land-atmosphere interaction, is much longer than the atmospheric memory (Seneviratne et al., 2006). The soil moisture could be a chief precursor of monsoon onset on subseasonal to seasonal time scales (Koster et al., 2002; Seneviratne et al., 2006). The dots in Figure 2 show the significant level from the regression of individual terms constituting atmospheric heating against the MA soil moisture of the Iranian desert, which is defined in next chapter. It indicates that high (low) soil moisture corresponds to the weak (strong) $Q_2$ from the surface to the upper troposphere before the onset. Our hypothesis is that the soil moisture plays a role as not only a controlling factor of atmospheric heating but also a precursor of ISM onset to expand the long-range prediction skill of ISM onset.

Figure 2. Vertical profile of atmospheric heating 12 pentads before and after ISM onset. Climatological vertical structure of (a) apparent heat source $Q_1$, (b) apparent moisture sink $Q_2$, (c) radiational heating $Q_r$, and (d) moisture eddy flux from 1979 to 2016. The unit is 100 J kg$^{-1}$ day$^{-1}$. For each year, the onset date is defined as pentad 0, and dates before and after the onset date are given as negative and positive pentads, respectively. The green (blue) dot denotes positively (negatively) statistical significance at the 90% confidence levels by regression of each term against the MA soil moisture over the Iranian desert.
3.2. Role of Soil Moisture as a Precursor of ISM Onset

The soil moisture content determines how the surface radiation energy is divided into the latent heat of evapotranspiration and the sensible heat flux into the atmosphere (Ruoostenoja et al., 2018). Such soil moisture effects could endure sufficiently long to modify the atmospheric circulation and the evaporation feedback mechanism (Douville et al., 2001; Shukla & Mintz, 1982). Figure 3a shows the climatological March-April (MA) soil moisture during the period from 1979 to 2016. Indian monsoon region has averaged 136.3 mm soil moisture, whereas most of the Arabian Peninsula and the Iranian domain is arid with below 100 mm soil moisture. To improve our ability to predict ISM onset and determine any ISM onset precursors, we analyzed the composite differences in soil moisture between the early and late ISM onset years during the MA period (Figure 3b). Our results show that the notably low soil moisture appears in the Iranian desert and the region to the north of India (hereafter referred to as the Iranian desert region (IDR)). The IDR is mostly composed of salt deserts by the nature stream salinity, wind-borne salinity, and seawater intrusion (Qadir et al., 2008). Since the evaporation rate of soil falls with the increase in salt concentration, the selected Iranian region is sensitive to the soil moisture amount (Gran et al., 2011). Although the Iranian desert has lower soil moisture owing to geological effects, the standard deviation of the soil moisture in the IDR is 19.26 mm (Figure 3a), which is larger than those in the Indian domain (16.49 mm) during the MA period. To verify the sensitivity to soil moisture in the selected domain, the GLDAS Noah model (Rodell et al., 2004) data set and other ISM onset definitions (Wang et al., 2001; Wang & LinHo, 2002; Xavier et al., 2007) were compared to obtain a reasonable result (Figure S2). The dynamically based onset definitions clearly show how the soil moisture is lower in early onset years than delayed onset years. When the soil moisture of the Iranian desert is low, the upward latent heat is decreased significantly and maintained until June. At the same time, the humidity, which is highly correlated (>0.6) with soil moisture, gets dry up to 800 hPa and the air temperature increase at the lower level as a result of land-atmosphere interaction. The time series of soil moisture in the IDR shows interannual variation, but relatively low (high) soil moisture appears in most early (late) onset years (Figure 3c).

To investigate the critical role of soil moisture in driving the ISM, we apply regression analysis using the soil moisture in the IDR (black box in Figure 3b) from pentads 27 to 30 (Figure 4). The strong westerly Somali jet at lower level is a key process that transports moisture to India, inducing vertical shear with the upper level easterly wind (Webster, 1992; Wang & Fan, 1999). The lower level westerly flow emerges from the Coriolis force following up on the cross-equatorial component of the monsoon Hadley circulation. Result from the thermal wind balance of the temperature gradient between the warm troposphere over the TP and relatively cool troposphere over the Indian Ocean, the upper level easterly wind over the Indian Ocean arises (Chevuturi et al., 2018). However, high (low) MA soil moisture in the IDR is associated with weakened (enhanced) lower tropospheric westerly wind flow in May due to the decreasing (increasing) zonal gradient of moisture over the Arabian Sea (Figures 4a–4d). Additionally, the vertical easterly wind shear is inhibited (strengthened) because the upper tropospheric easterly wind is disturbed (encouraged) by the effect of soil moisture in the Iranian desert. As a result of high (low) soil moisture in the IDR, the meridional moisture advection flow at 925 hPa over the Arabian Sea decelerates (accelerates) because of the lower (higher) meridional thermal gradient (Figures 4e and 4f). Consequently, the $Q_1$ value at 500 hPa decreases (increases) over the south Asian monsoon region, leading to dry (wet) conditions over the Indian domain. This result indicates that in spite of the low soil moisture existed, the relation is significant; low MA Iranian soil moisture—early IND onset and high MA Iranian soil moisture—delayed IND onset.

Here we carried out 21 model ensemble performance of historical Coupled Model Intercomparison Project phase 5 for verifying the role of soil moisture onto the ISM onset date (Table S2). Similar to the reanalysis data, the Coupled Model Intercomparison Project phase 5 ensemble projection suggests that the weakened easterly wind shear over the Arabian Sea is affected by high soil moisture over the IDR. Moreover, as diminishing the moisture-burdened cross-equatorial flow, the ISM onset is retarded by the background condition (Figure S3).

In other words, dry soil reduces evapotranspiration and ultimately enhances the latent heat flux, resulting in high air temperature. Note that the large meridional temperature gradient is favorable for ISM onset (Chung & Ramanathan, 2007; Jin & Wang, 2017; Roxy, 2017). As the meridional temperature gradient between the Indian Ocean and the Iranian domain continuously increases from spring, the favorable early ISM onset
Figure 3. Relationship between MA soil moisture and ISM onset date. (a) Climatological MA soil moisture (shading, unit: mm) and the standard deviation (cross symbol) from 1979 to 2016. The blue (red) cross symbol denotes 40-mm (60-mm) standard deviation for MA soil moisture, respectively. (b) Composite difference in soil moisture (unit: mm) between early-onset years (1990, 1999, 2000, 2001, 2006, 2013) and late-onset years (1979, 1982, 1983, 1992, 2012) during MA. The green dot indicates statistical significance at the 95% confidence levels (Student’s t test). (c) Time series of MA soil moisture (unit: mm) in the Iranian desert region (55°E–85°E, 25°N–40°N, black box). The blue (red) dots indicate early (late) ISM onset years based on one standard deviation. MA: March and April.
conditions are prompted by atmospheric circulation, strengthening of the lower level cross-equatorial flow, and upper level easterly wind (Figure 5). When the ISM onset is investigated in the context of the Iranian desert soil moisture amount, this study suggests the low soil moisture years conduct to 1.3 pentads earlier ISM onset date than the wet soil moisture years. This result shows that low MA soil moisture can be a precursor for ISM onset and we can understand the land-atmosphere interaction.

**Figure 4.** Effect of March-April (MA) soil moisture on the atmospheric field in May. Regressed spatial distribution from pentads 27 to 30 of (a–d) 850-hPa zonal wind (shading, m/s) and 200-hPa wind (vector, m/s) and (e–h) 925-hPa meridional moisture advection (shading, s⁻¹) and 500-hPa apparent heat source (contours, 200 J kg⁻¹ day⁻¹ interval) onto the MA soil moisture in the Iranian desert. The green dots (wind vectors) in (a–d) indicate statistical significance for the 850-hPa zonal wind (200-hPa wind) at 95% confidence level. The green (red) dots in (e–h) represent statistical significance for the meridional moisture advection (Q1) at the 95% confidence level.
4. Summary and Discussion

This study has investigated the precursor of ISM onset, which could affect the modifying atmospheric vertical structure and advance the prediction time. Being associated with the atmospheric profile, the heat source is composed with distinct portion by moisture sink, radiative force, and eddy flux effect according to the altitude. The dominant factor is the mean vertical advection of moisture, which is described mainly by $Q_2$ and induces instability. We also have suggested that the strength and vertical expansion are different in each Asian subregional monsoon domain (Figure S1). Not only the apparent moisture sink but also the radiative–convective effect and mean-eddy interaction can be used to try to understand the inertial process of rainfall generation and the heating mechanism. As a factor, which makes the change of atmospheric heating, this study explores the delayed hydrological effect in terms of soil moisture. The soil moisture in the IDR has prolonged memory evokes the early ISM onset by modulating the vertical wind shear through the land–atmosphere coupling. Under these favorable conditions to make a monsoon rainfall, the ISM onset is earlier than usual.

Although the soil moisture is a key variable for better understanding of the future hydrology, ecophysiology, and agriculture, it has not been robustly understood to date owing to a lack of in situ data (Dorigo et al., 2012; Ruosteenoja et al., 2018; Seneviratne et al., 2010). Improvements in the available satellite-based surface soil moisture data and a state-of-the-art land-ocean-atmosphere coupled model may greatly increase our knowledge of the present and future climate in terms of soil moisture. Under global warming, desertification, a slow process that transforms dry regions into arid regions and results in more frequent natural disasters, increases in some parts of the global domain. Individual domains face different levels of desertification risk (Seneviratne et al., 2010). If desertification in the IDR increases and exceeds a threshold of desertification risk, the relationship between ISM onset and the soil moisture in the IDR might change dramatically. Besides soil moisture, increasing amounts of dust and black carbon aerosols can lead the tropospheric heating and affect the land-atmosphere warming (Lau et al., 2010; Ramana et al., 2004; Roxy, 2017; Roxy et al., 2015; Wu et al., 2012). The linkage between the soil moisture and other possible factors associated with the ISM monsoon onset is left for future study. For instance, the TP heating has the highest lag correlation coefficient that is 0.42 when the Iranian soil moisture leads the TP heating by one month. By maximizing the advantage of the long memory of soil moisture, the effects of El Niño–Southern Oscillation and Pacific Decadal Oscillation on monsoon could be sustained also. It is a novelty of our work in the fact that it emphasizes the role of soil moisture in the IDR to affect the monsoon onset, while most of the previous studies

Figure 5. Schematic diagram showing the Indian summer monsoon (ISM) onset depending on the March-April (MA) Iranian soil moisture. Shading is the ISM pentad onset date, and the red (blue) cross symbol is dry (wt) Iranian desert. The onset date for (a) seven low soil moisture years (1985, 1989, 1994, 1999, 2000, 2001, and 2002) and (b) eight high soil moisture year (1979, 1982, 1983, 1996, 2007, 2013, 2015, and 2016) is selected based on 0.75 standard deviation of the CPC soil moisture over the Iranian desert. The black contour indicates the ISM domain. ① The MA dry (wt) soil moisture over the Iranian desert region, which modulates ② less (more) latent heat release and more (less) sensible heat flux. This can generate ③ the relatively warm (cool) air temperature. Due to the enhanced (reduced) the air-sea thermal contrast by the warm (cool) Iranian land from spring, ④ the lower level cross-equatorial flow and the upper level easterly wind are strengthened (weakened). This results in ⑤ the advanced (delayed) ISM onset.
focused on the monsoon rainfall-induced by the desertification of soil. By dealing with the delayed hydrological effect on monsoon, our results will certainly expect to expand the leading time of ISM onset prediction. Furthermore, it can utilize as an element to access the projection skill of models in the concept of the land-atmosphere interaction, which has been far less studied.

**Author Contributions**

S.M. and K.-J.H. designed the study, performed the analysis, and wrote the manuscript.

**Competing Interests**

The authors declare no competing financial interests.

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