On understanding the role of South Asian High on the Onset and Withdrawal of the Indian Monsoon

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Research Article

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Abstract

The Indian monsoon is always considered to be a large-scale process that has a profound impact on the agriculture and economic conditions of India. The present study addresses the role of South Asian High (SAH) and subtropical westerly jet (STJ) on the onset and withdrawal of Indian monsoon. For this purpose, we have utilized the output of the Regional Climate Model (RegCM v4.6) and reanalysis ERA5 pressure level data for 24 years (1982–2005) of study. We begin our analysis with the evaluation of Tibetan Plateau (TP) heating and its connection with different atmospheric factors during the seasonal transition of monsoon is perused. We have further tried to decipher the link between SAH and inter-annual variability of monsoon. Our analysis shows the efficiency of the model in simulating inter-annual variability of monsoon onset and withdrawal features. The days of onset and withdrawal simulated by the model have a similar mid-latitude connection as that obtained from the reanalysis data. The vertical structure of the Hadley cell and the horizontal position of SAH have been produced realistically during the transition of the monsoon. We found that the change in meridional position of STJ has a significant impact on phase-shifting of arrival and departure of monsoon. This repositioning of STJ in a meridional direction is strongly correlated to the upper-level high developed over the eastern periphery of the western pacific which is an important component of monsoon flow over the Bay of Bengal. Thus the zonal position of SAH is observed to have direct implications on the onset and withdrawal dates of India.

1. Introduction

The Indian monsoon is mostly considered as a synoptic-scale process that was initially thought to be driven by land-sea thermal contrast due to pre-monsoonal heating over Indian landmass. The classical conception of sea-breeze and associated convection was proved to be inappropriate and it was replaced by the notion of strong tropospheric temperature gradient in the atmosphere that makes conditions favorable for deep convection (Flohn 1957; Schneider and Lindzen 1976; Yanai et al. 1992). Studies have shown that the large sensible heating over Tibetan Plateau (TP) tends to develop a strong meridional temperature gradient and baroclinicity that alters the general circulation of the atmosphere. Various studies have categorized the thermal variability over TP into three segments, the eastern plateau region, the central part, and the western plateau also known as the Iranian plateau (Wu and Zhang 1998; Wang et al. 2008; Xie and Wang 2019). These have analyzed the individual and combined influences of TP segments on the convective structure of the atmosphere over the South Asian region. In such studies, the eastern part consists of the northern Bay of Bengal (BoB) and Indochina peninsula that affects precipitation over China and Western Pacific regions. The convective anomalies in this part are significantly high during the boreal summer due to the onset of the BoB monsoon. The onset process aligns with the notable presence of an anticyclone in the upper troposphere that tends to move westwards and establishes over the southern flank of TP during the summer monsoon months of India. This upper level high is known as the South Asian High (SAH) (Liu et al. 2013; Wei et al. 2017). SAH begins to appear over the South China Sea during the late spring and moves northwestward in subsequent months (Reiter and Gao, 1982; Chen et al., 1991). During boreal summer it is stabilized over southern Asia and TP and oscillates in the southeast-northwest directions (Mason and Anderson 1963; Krishnamuti and Bhalme 1976).

Similarly, the western regions are dominated by Subtropical Jets (STJ) which developed over the descending branch of Hadley cell as the result of Coriolis force, thus the regions where it appears becomes a high-pressure zone that tends to inhibit convection. STJ is considered to modulate the genesis and intensification of western disturbance and Tibetan Plateau Vortices (TPV) in areas where seasonal precipitation is not dominantly high (Li et al., 2011; Li et al., 2017). Hunt et al. (2018) have shown that latitudinal shift in STJ has a strong relationship with Western Disturbances (WD) and TPV during boreal spring and winter. Thus there are huge chances of their interference on the timing of onset and withdrawal of summer monsoon over India. The thermodynamic conditions over western TP are strongly connected to its topography, convective disturbance in the eastern parts, and temperature anomalies in the western parts (Abe et al. 2013; Ge et al. 2017; Wang et al. 2019). Different studies have tried to analyze the variability in position and intensity of STJ and its linkage with other atmospheric factors (Ramaswamy 1961; Ding and Wing 2005; Hong et al. 2011). Sato (2009) showed that the thermal and dynamical effects of the Tibetan Plateau (TP) have a profound influence on the meridional position of STJ.

The importance of SAH for Asian monsoon has been realized in recent decades and several studies have tried to understand its influence on monsoon conditions over the western Pacific and China. E.g. Zhang et al. (2002) revealed the bimodal displacement of SAH between TP and Iran which influences regional and global precipitation distribution of Asia. SAH acts as a bridge between the Indian Summer Monsoon (ISM) and East Asia Summer Monsoon (EASM) (Wei et al. 2015). Studies have shown that the years having the stronger ISM rainfall correspond to the westward shift of SAH due to positive diabatic heating rate over TP and Indian monsoon region (Wei et al. 2015; Wei et al. 2017). Thus, SAH is largely considered to be influenced by the Indian monsoon but very few studies have focused on the two-way relationship between monsoon and SAH. The present study attempts to fill this gap by analyzing the seasonal variability of SAH and its relationship with the meridional displacement of STJ on the inter-annual time scale. We also evaluate the combined effect of SAH and STJ on the arrival and reversal of the Indian monsoon. We presume that the shifting of SAH towards the northwest can dominate the surface divergence caused by the descending branch of the Hadley cell which can promote the early development of monsoon over India. The correlation and composite analysis are performed by extracting the dates of onset and withdrawal and observing the location of the westerly jet and its phase relationship with SAH are obtained. The study is organized as follows, Sect. 2 describes the details of datasets being used, and Sect. 3 demonstrates the results from the model and reanalysis data. We have concluded the study in Sect. 4.

2. Data And Methodology

2.1 Model and Data used

For the present analysis, we have used the output of the Regional Climate Model (RegCM v4.6) which is obtained for 24 years (1982–2005) of our study over the CORDEX South Asian domain. The description of the experiment setup and parameterizations used is given in few recent papers (Kumar et al. 2019; Agrawal et al. 2020). The model data is obtained at 25 Km horizontal resolution on daily basis. For comparison of our results, we have used the reanalysis ERA5 dataset obtained at different pressure levels for the same spatiotemporal resolution as that of the model. The analysis is performed by analyzing the capability of the model in evaluating the climatological features of monsoon transition, variations in the SAH, and the position of STJ. We further extracted the dates of monsoon onset and withdrawal to comprehend the causes of their phase shifting. We have finally tried to establish a relationship between STJ, SAH, and ISM on the inter-annual time scale.

2.2 Methodology for the selection of Onset and Withdrawal dates

The onset of the Indian monsoon is accompanied by several changes in tropospheric circulation, temperature, and precipitation over India and its adjoining regions. It is marked as the beginning of 4 month-long rainy season in India and different methodologies have tried to evaluate this (Fasullo and Webster 2003; Pai and Rajeevan 2009; Wang et al. 2009; Carvalho et al. 2016; Ordonez et al. 2016). These studies have tried to determine the date of Monsoon Onset over Kerala (MOK) by analyzing the rainfall, humidity, Outgoing Longwave Radiation (OLR), and winds over the Kerala region. The exact dates of monsoon onset and withdrawal are released by the Indian Meteorological Department IMD every year and it has been seen that Pai and Rajeevan (2009) have the potential to improve the forecasting skill of MOK (Chevturi et al. 2019). It has been further realized that most of the parameters used for evaluation of onset and withdrawal dates are subjective and can provide a bogus measure to monsoon when used operationally (Soman et al. 1993; Taniguchi and Koike 2006; Joseph et al. 2015). Xavier et al. (2007) showed that reversal in meridional temperature gradient near the surface and upper troposphere establishes necessary baroclinic structure over India for monsoon. The difference in upper tropospheric temperature (averaged between 600 hPa and 200 hPa) between a northern (40°:100°E, 5°:35°N) and a southern box (40°:100°E, 15°S:5°N) turned out to be a reliable estimate for monsoon onset. The onset is defined at the date where TT reverses its sign showing the low pressure over the Indian landmass. This criterion is thought to be convenient by most of the modeling studies as the temperature is well simulated in present state–of–the–art climate models. The present study utilizes the same criteria provided by Xavier et al. (2007) to evaluate the dates of monsoon onset and withdrawal and to understand its link with other atmospheric factors.

3. Results And Discussion

In the present study, we have tried to assess the capability of the model in simulating and understanding the basic features of monsoon transition and its relationship with SAH. The analysis is being performed by evaluating the climatological and inter-annual variability of monsoon onset and withdrawal. We further intend to investigate the shifting in onset and withdrawal dates and its link with STJ and SAH.

3.1. Climatological conditions of monsoon transition and associated circulation

Figure1 shows the climatological changes in TT gradient between northern and southern boxes following Xavier et al., (2007). We observe a sudden change in the sign of TT gradient between May and June that corresponds to the shift of the low-pressure belt over India (Fig. 2). The TT gradient becomes positive due to the solar insolation prior to the monsoon and it remains positive throughout the monsoon period due to the diabatic heating of clouds and cloud-radiative effects that amplifies the monsoon flow. The strongest values appear between July and August when the monsoon is observed to be at its peak. Thereafter we obtain significant weakening in meridional thermal contrast that changes its sign again during the withdrawal of monsoon when the seasonal heating is shifted southwards. The off-equatorial heating in subtropical zones over India incites cross-equatorial flow as per the circulation pattern shown by Gill (1980). Thus the reversal of thermal structure affects the direction of winds throughout the troposphere and a strong wind shear between the lower and upper troposphere is also formed. We have shown the difference in zonal winds at the upper (200 hPa) and lower (850 hPa) troposphere in Fig. 1.1 for the same mean monsoon period. The changes in wind shear reveal the presence of a persistent southwesterly jet near the lower troposphere. The intensity of this jet determines the strength of the monsoon and it is intensified the most during the July-August months. It weakens in subsequent months and is diminished as the withdrawal of monsoon appears to set about. The model has shown efficiency in capturing these features realistically. The reversal of TT gradient has always been associated to the growth of diabatic heating over Indian landmass due to monsoon convection. The steep turnaround of TT gradient is observed to causes a significant shift in surface pressure too. Figure 2 shows the seasonal evolution in Mean Sea Level Pressure (MSLP) anomalies (in hPa) averaged between a northern box (50^0 E-100^0 E; 20^0 N-35^0 N). The MSLP values are observed to face a steep decline in the pre-monsoon period, the values drop by ~ 10 hPa during the strongest monsoon months of July and August. The values appear to increase gradually after the monsoon season. Thus, the changes in TT gradient are expected to be contributed mainly by the north tropical belt (> 20^0 N) including the TP and Iran-Afghanistan regions.

The transitions of temperature and wind shear during the Indian monsoon are strongly influenced by the seasonal heating of TP. The climatological variability of sensible heating averaged over 30^0 N – 45^0 N of TP is shown in Fig. 3 from the model and reanalysis datasets. The heating appears to intensify during the pre-monsoon season and lasts up to the departure of monsoon in both the datasets. The earlier warming of eastern TP is associated with the diabatic heating due to monsoon onset in the Bay of Bengal that typically appears in May whereas delayed warming in the western parts is closely linked with the subsidence over Iran-Afghanistan regions due to their diabatic cooling in the spring season (Yanai et al. 1992). The large heating of TP is known to induce a Rossby wave response that is characterized by low-level cyclonic ascent over the southeastern plateau and anti-cyclonic descent over northwestern parts including the Pakistan-Iran-Afghanistan regions. The resultant upper-level divergence over the southeastern plateau is known to control seasonal precipitation over India and its neighborhood. Since the eastern part is strongly influenced by SAH during the pre-monsoon season, it becomes necessary to understand its zonal shift and associated influence on western TP during the monsoon season. For this reason, we have considered the South Asian High Index (SAHI) which is defined as the standardized series for 200 hPa geopotential height averaged between (20°–27.5°N, 85°–115°E) and (27.5°–35°N, 50°–80°E) that provides a useful estimate of SE-NW shift of SAH (Wei et al., 2015). The horizontal extent of SAH covers north Africa and western Pacific regions and it provides a useful estimate of divergence and temperature variability in the upper atmosphere (Wei et al. 2017). The seasonal variability of SAHI from the model and reanalysis datasets is shown in Fig. 4. A positive SAHI represents an eastward shift of SAH whereas the negative values indicate a westward shift. Figure 4 shows that SAHI starts to migrate to the westward parts of the plateau during the summer monsoon months and remains therein during the peak monsoon period of July-August. The westward shift of SAH is linked to multiple atmospheric oscillations, circulation of western pacific, Bay of Bengal, and northwestern regions. The zonal shift of SAH stimulates moisture convergence and convective development over India. The SAH is located in the west during the monsoon season as appears to shift eastward in the subsequent months as the flow of the monsoon weakens following the withdrawal.

The seasonal variability of the sun affects the meridional position of Hadley cell (HC) too. During the boreal summer, the descending branch of HC approaches the subtropics and gets reflected eastward due to the rotation of the earth. This effect produces a subtropical jet that surrounds India and its neighboring regions throughout the year. Figure 4 shows the climatological variability in the latitudinal shift of the STJ axis averaged between 70^0E-90^0E longitude belt. The jet seems to cover India throughout the year except during the monsoon. The STJ moves northwards as the upper level high over TP intensifies and moves westwards (Fig. 3). During this period there exists ascending motion over TP and eastern India whereas notable subsidence is observed over northwestern regions including Pakistan-Afghanistan. The low-level divergence and upper-level convergence form the upper-level Rossby wave due to the presence of upper level high over TP. The appearance of this wave is seen as a Gill response to tropical heating by various studies and it has the potential to affect the position of STJ. On the eastern side, the SAH induces tropical westerlies (easterlies) in its northern (southern) flank and the change in its position affects the axis of the two jets locally. As the SAH progresses westward, there is a northward shift in the jet axis too. The latitudinal shift of the jet axis allows tropical convection to form over India during summers. The jet appears to move southwards as the monsoon flow weakens and SAH shifts eastwards.

3.2 Interannual Variability

3.2.1 Assessment of Onset and Withdrawal dates

The transition of monsoon accompanies large thermodynamical changes over India. To study these changes we tried to obtain the dates of monsoon arrival and withdrawal as per the criteria mentioned in Sect. 2.2. The time series showing the inter-annual variability in onset and withdrawal dates in Julian days are shown in Fig. 5. Dates extracted using the model data appear to be similar to the inter-annual dates provided using the ERA5 reanalysis data fields during the onset of the monsoon. The mean monsoon onset date over 24 years of the study is obtained to be 22 May with a standard deviation of 9 days from the model whereas the reanalysis data provides 23 May as the mean onset date with a standard deviation of 9.5 days. Thus the model has shown efficiency in simulating the arrival of the Indian monsoon on the inter-annual time scale. The differences are evident when considering its departure in Fig. 5 which shows inconsistent dates of monsoon withdrawal from the model and reanalysis data. The length of the Indian monsoon is influenced by various atmospheric and oceanic responses which have significantly affected the withdrawal dates of the monsoon in the model. Here the mean withdrawal dates are estimated to be 5 October with a standard deviation of 11 days from the model output. The reanalysis data shows the mean monsoon departure on 14 October with a standard deviation of 9.3 days. Moreover, the onset of monsoon has a downward trend in both the datasets which shows the tendency of early monsoon onset in later decades. The withdrawal of summer monsoon on the other hand has no specific trend in the reanalysis data whereas it is significantly downward in the model data. Thus the model has produced realistic timing of onset but the discrepancies still exist while considering the timing of withdrawal.

We further determined the correlation between the transition dates of the monsoon and the SAHI in Table 1. The correlations were obtained from the reanalysis ERA5 and the RegCM v4.6 datasets. Our analysis shows that the onset and withdrawal phase of monsoon are significantly correlated with the SAHI in both datasets. The westward (eastward) position of SAH is observed to be favorable for the early-onset (withdrawal) of the monsoon. It is worth noting that the onset and withdrawal dates of monsoon are extracted from the deep tropospheric temperature gradient between the northern and southern hemisphere boxes. Therefore, the variability of monsoon transition is expected to be linked strongly to TT changes in the northern box. We have quantified the correlation between the TT gradient of the northern box and SAHI during the May-June-July-August-September-October (MJJASO) months for 24 years of our study. The CC between SAHI and TT gradient is observed to be very strong (~ -0.8) from both datasets. The CC value exceeds − 0.98 when the climatological MJJASO months were considered. Since the evolution of SAHI has been associated to western Pacific and the monsoon circulation of BoB in previous studies, the possible drivers of large TT gradient can be associated with the released diabatic heating of Indian monsoon convection and western Pacific influences. This suggests that the SAHI can either be seen as a cause or an effect of the large TT change during the monsoon transition.

Table 1
Correlation between SAHI and the dates of monsoon onset and withdrawal

SAHI	RegCM v4.6	ERA5
Onset	0.42	0.47
Withdrawal	-0.32	-0.39

3.2.4 Hadley Cell and associated convection

The relationship between SAHI and monsoon transition is expected to be understood by looking at the outflow characteristics of HC that is developed over the tropical Indian landmass region. Therefore, we quantified the position of HC averaged between the longitude range of 75^0E – 95^0E and associated vertical motion during the earlier and delayed monsoon periods. All the values are displayed on the day of mean onset and withdrawal from both the datasets. Generally, the HC is formed when the seasonal position of the sun and diabatic heating of the atmosphere produces near equator ascent that transports the air poleward at higher altitudes. Air at these latitudes faces significant descent and it starts moving equatorward in the lower troposphere. Figures 6 and 7 show meridional components of velocity and corresponding ascent/descent to depict the position of HC during earlier and late periods of monsoon transition. We observe that during the years of early-onset the HC is located as per its theoretical description on the mean monsoon onset day. The tropical heat source seems to be located around 10^0N which causes significant ascent and produces poleward air aloft. The heat sink and associated descent are observed in the sub-tropical latitude range of 30^0N– 40^0N from where we observe equatorward winds. The years of delayed onset show reversed condition of HC, here we observe weakened ascent and descent at tropical and subtropical latitude positions which have failed to produce the expected circulation pattern. The positions of heat source and sink are exchanged during this period which results in equatorward winds aloft and the absence of characteristic Hadley circulation. A similar situation is observed during the withdrawal. The early withdrawal shows distorted HC on the mean withdrawal date, whereas the late withdrawal shows that the presence of HC is appropriate as per its description in both the datasets.

3.2.3 South Asian High and the position of the subtropical jet

We now investigate the location of the westerly STJ axis during the early and delayed phases of monsoon from both the datasets in Fig. 8. We observed that earlier (delayed) onset accounts for the northward (southward) shift of STJ during the day of monsoon onset. The regions occupied by STJ face subsidence due to the proximity of descending limb of HC. The existence of STJ over India restricts the flow of monsoon and inhibits the development of low-pressure systems therein. The earlier withdrawal of monsoon occurs as the STJ begins to shift southward in India and prevents it from receiving further precipitation by reinforcing cooler and drier air from the mid-latitude regions. During the delayed withdrawal it remained close to the northward flank of TP that continued the seasonal flow of monsoon on the mean day of monsoon withdrawal in both the datasets. We have now quantified the composite value of SAHI from the observed and model dataset. We found that during the years of early-onset the SAH index remains slightly negative whereas the delayed onset accounts for positive values of SAHI. Similarly for withdrawal SAHI appears to be stronger in the model data and has positive (negative) values during early (late) withdrawal of monsoon. This shows that the northwestward position of SAH is favorable for the Indian monsoon. A similar result of the westward shift of Tibetan high during the onset of the Indian monsoon is also reported in Saini et al. (2011). The westward position of SAH is thought to be affected by the diabatic heating of the Indian monsoon to its northwestern parts. Similarly, the strength of SAHI helps determine the condition of ISMR by blocking the moisture in the Indian subcontinent. The zonal shift in SAH should significantly affect the easterly and westerly jets over southern and northern flanks of the Himalaya respectively whose positions are known to affect the direction of winds and precipitation rate throughout the monsoon season (Li et al. 2019; Cen et al. 2020).

The relationship of SAH and westerly STJ is investigated in Fig. 9. It shows the scatter plot and correlation coefficient (CC) between the two time series for the May-June-July-August-September-October months for 24 years of study. The scatter diagram of the two quantities is highly clustered and has a negative correlation of -0.7 and – 0.6 from the observed and model datasets respectively. This shows that whenever SAHI becomes negative, the latitude of the STJ axis is meridionally elevated and vice versa. This happens as the upper-level anticyclone reinforces the westerlies in the north and has the potential to shift the axis of the midlatitude jet. We should observe a similarly strong relationship of SAH with easterly jet too but we have not tried to assess this in the present study. To check the significance of this result we have further obtained the composite location of STJ during different phases of SAH for the boreal summer months in Fig. 10. It shows that STJ occupies major parts of northern India when the position of SAH is located eastward. As SAH begins to move westward, STJ appears to shift northwards. It is stabilized at the northern flank of TP when SAH appears to localize in the northwestern regions as in the case of the Indian monsoon. Thus our hypothesis that SAH controls the position of STJ gets confirmed as we analyzed Fig. 10. We have seen that zonal shift in SAH has a strong relationship with the transition of monsoon. The phase-shifting in the timing of onset and withdrawal can be predicted accurately in advance if the strength of SAH is known.

4. Conclusion

The onset and withdrawal of the Indian monsoon are critical for harvesting, hydro-power plants, and management of water resources. The commencement of the summer monsoon brings moisture-laden winds from the southwestern coast that moves northwestward and covers major parts of India for a few weeks whereas its departure begins when the cooler and drier winds start to prevail thereby sweeping the convective activity over India. The position of surface low and upper-level high generated in the vicinity of TP plays a pivotal role in the establishment and progression of monsoon winds. The present study tries to analyze the variability in upper level high and its relationship with STJ which affects the onset and withdrawal of the Indian monsoon. We performed our study with the help of RegCMv 4.6 and reanalysis ERA5 datasets. The model has shown efficiency in capturing large-scale features of onset and withdrawal throughout the study. The statistical measures of inter-annual variability of monsoon onset are coherent with the observations. There exist certain differences in the withdrawal dates but the model has captured the underlying characteristics realistically. We observe that the relationship between SAH and STJ is well simulated by the model. The analysis shows a negative correlation between SAH and STJ. We found that STJ shifts northward as the SAH moves westwards and vice versa. The zonal displacement of SAH affects the onset and withdrawal of the Indian monsoon as well. The delay of onset and early withdrawal appears when the position of SAH is located to the east. Due to which STJ begins to cover northern parts of India which hinders the development of convective activity over therein. Similarly, the years of earlier onset and delayed withdrawal have shown the westward position of SAH which has shifted the position of STJ northward away from the Indian subcontinent. We obtained a similar pattern in both our datasets. Thus, the model has realistically captured the interannual variability of onset and withdrawal features of monsoon including the position of STJ and SAH. Our analysis suggests that more studies on SAH can be used as a major predictor of monsoon transition over India and the studies on SAH need to be further encouraged to gain further insights into the Indian monsoon and its teleconnection.

5. Declarations

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The authors have received no funding for this research.

Author's contribution

The first author has performed the analysis and framed the results, the corresponding author has supervised the work.

Conflict of interest

The authors report no conflict of interest.

Availability of data and material

Data used in this analysis can be shared if required by reviewers and editors.

Code availability

We can share the MATLAB codes used for the analysis.

Ethics approval

All applicable international, national, and/or institutional guidelines were followed.

Consent to participate

All the participants provide their consent for participation in this study.

Consent for publication

All the authors give their consent for publication of the manuscript.

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Figures

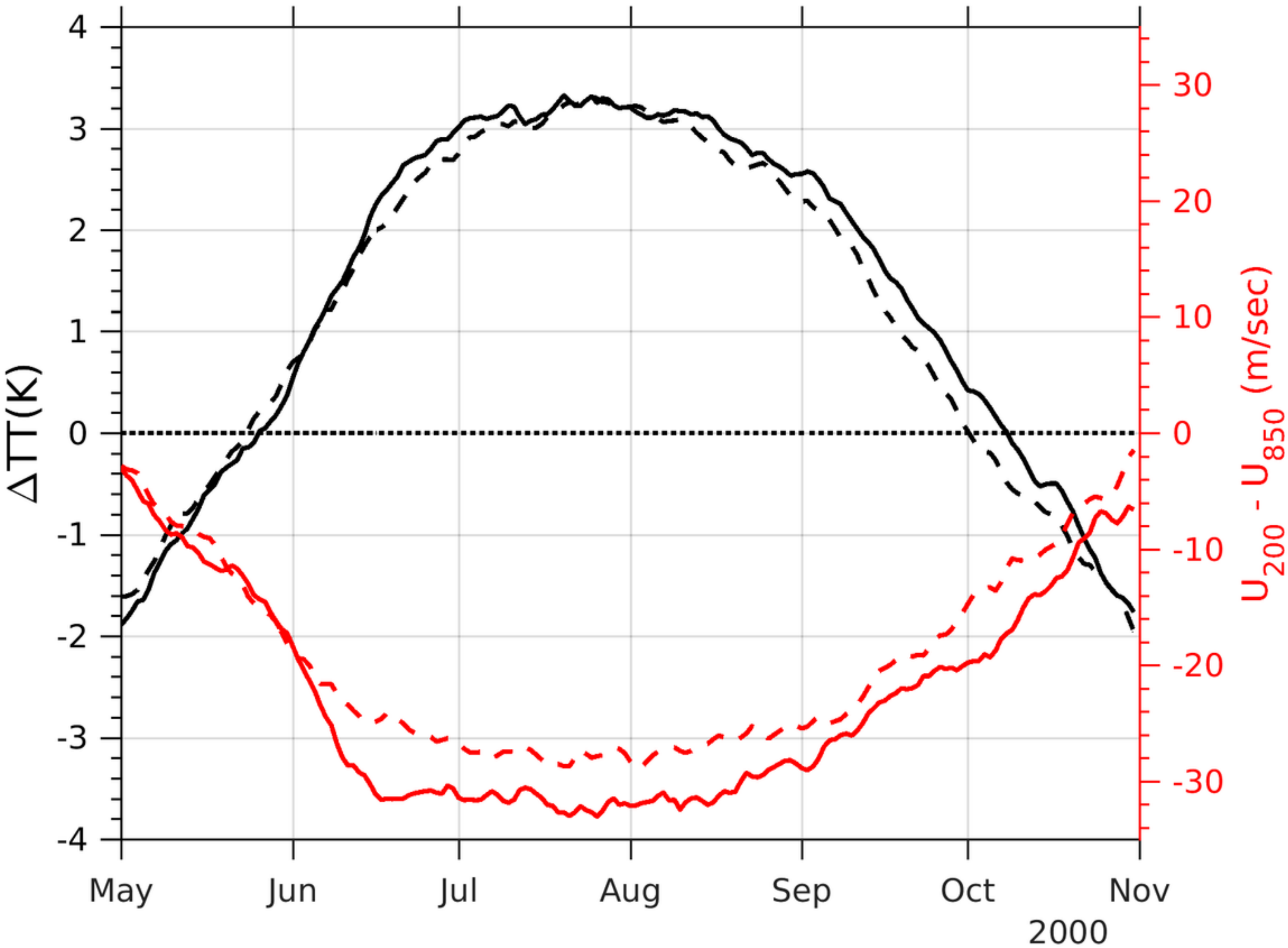

Figure 1

TT gradient and vertical wind shear from the model and ERA5 data, solid lines represent the reanalysis whereas dashed lines correspond to the model simulation.

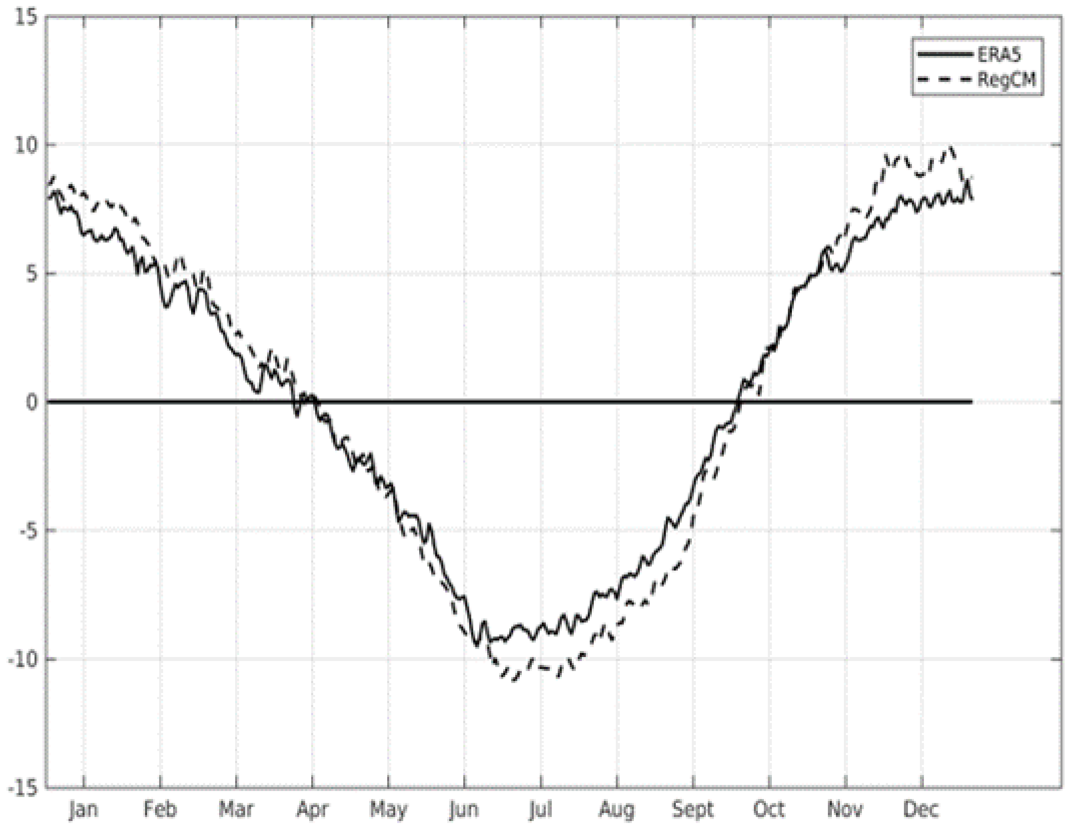

Figure 2

Seasonal distribution of MSLP anomalies (in hPa) averaged between 500 E-1000 E; 200 N – 350 N from the reanalysis ERA5 and model data.

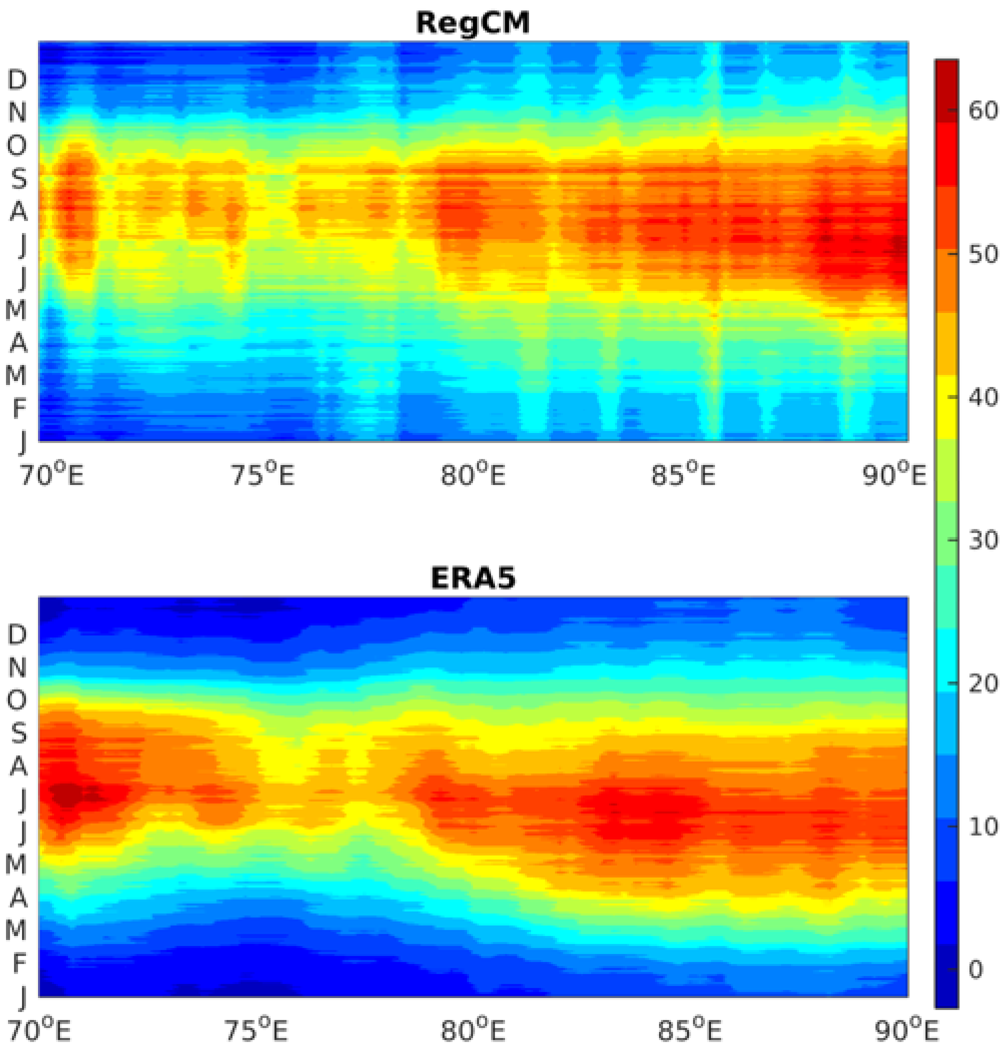

Figure 3

Climatological changes in Sensible Heating (in W/m2) averaged over 300 N-450 N of the TP region from the model and the ERA5 data

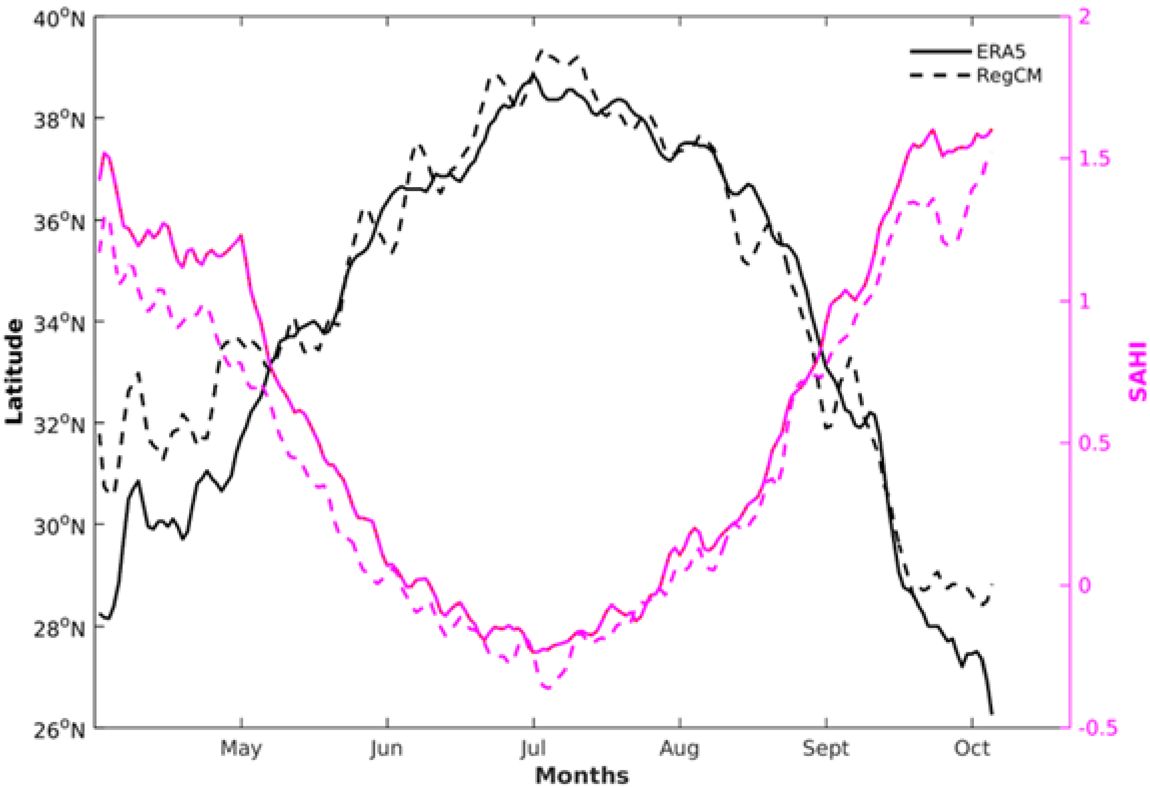

Figure 4

Seasonal variability of SAHI and STJ axis obtained from the RegCM and reanalysis ERA5 datasets

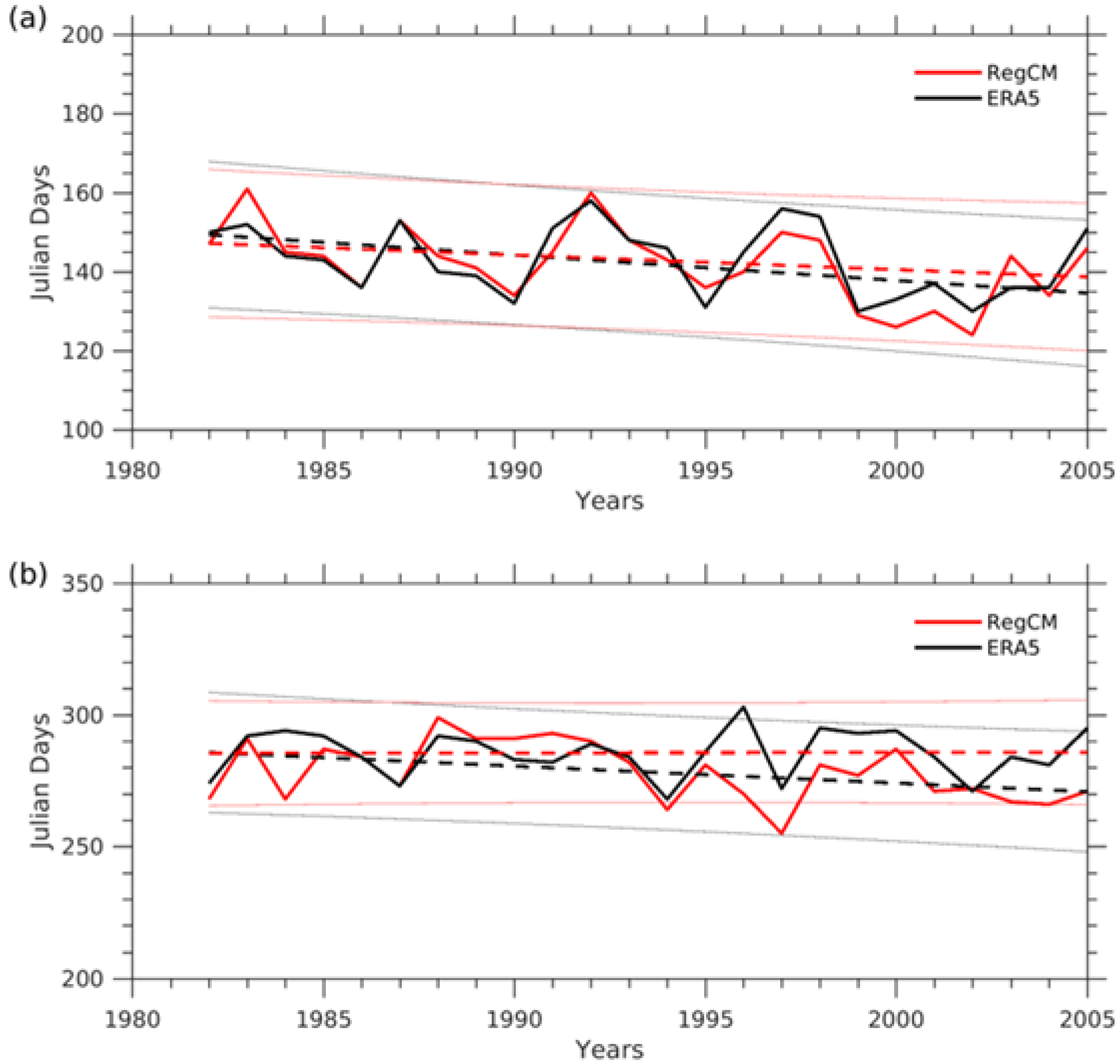

Figure 5

Inter-annual variability of monsoon (a) onset and (b) withdrawal from the reanalysis ERA5 and the model data. The trend is depicted through thick dashed lines and dotted thin lines represent a 95% prediction level.

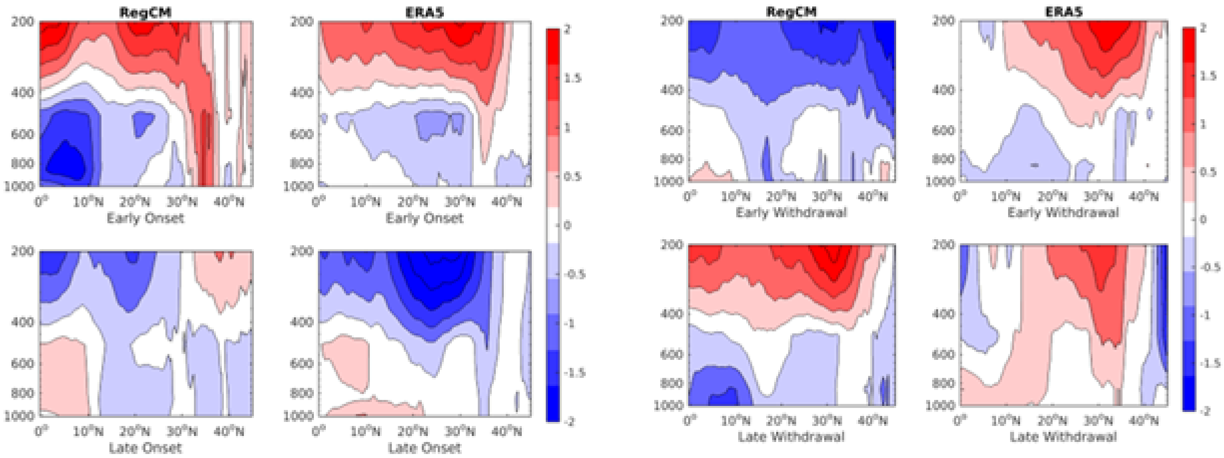

Figure 6

Meridional winds during the period of early and late withdrawal

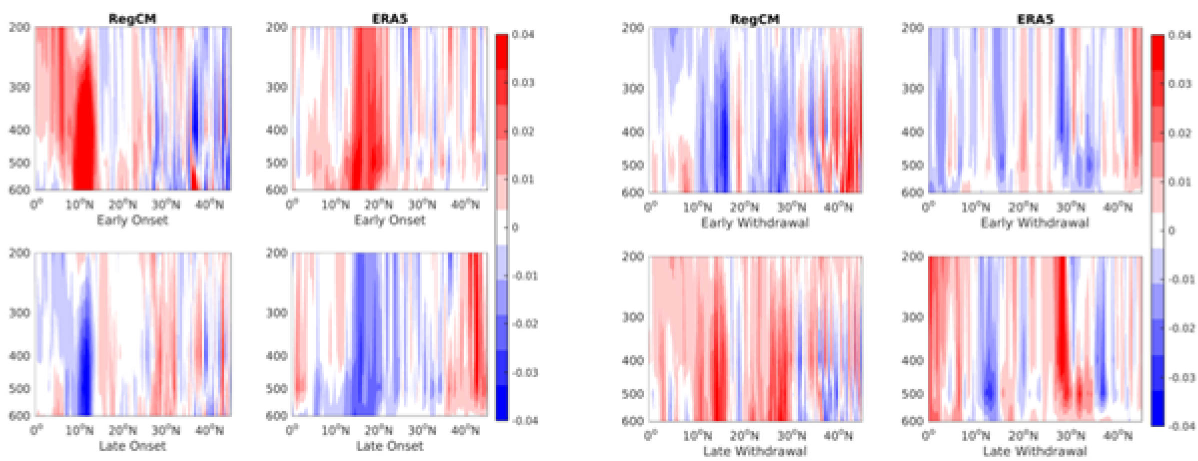

Figure 7

Vertical velocity during the period of early and late withdrawal

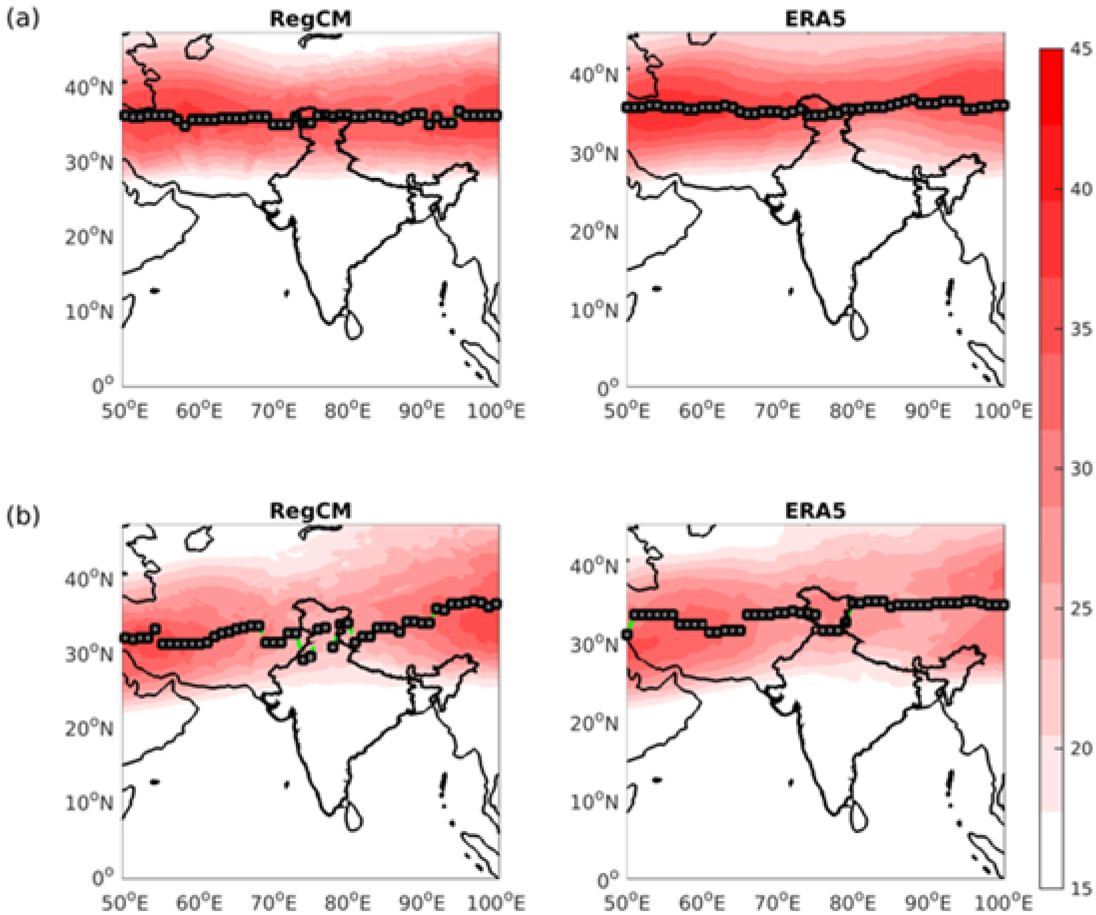

Figure 8

Position of STJ axis during (a) early and (b) delay onset. Shaded regions represent the zonal winds (in m/sec) and boxed lines represent the axis of the STJ. (Figure 8.1 in the manuscript.) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

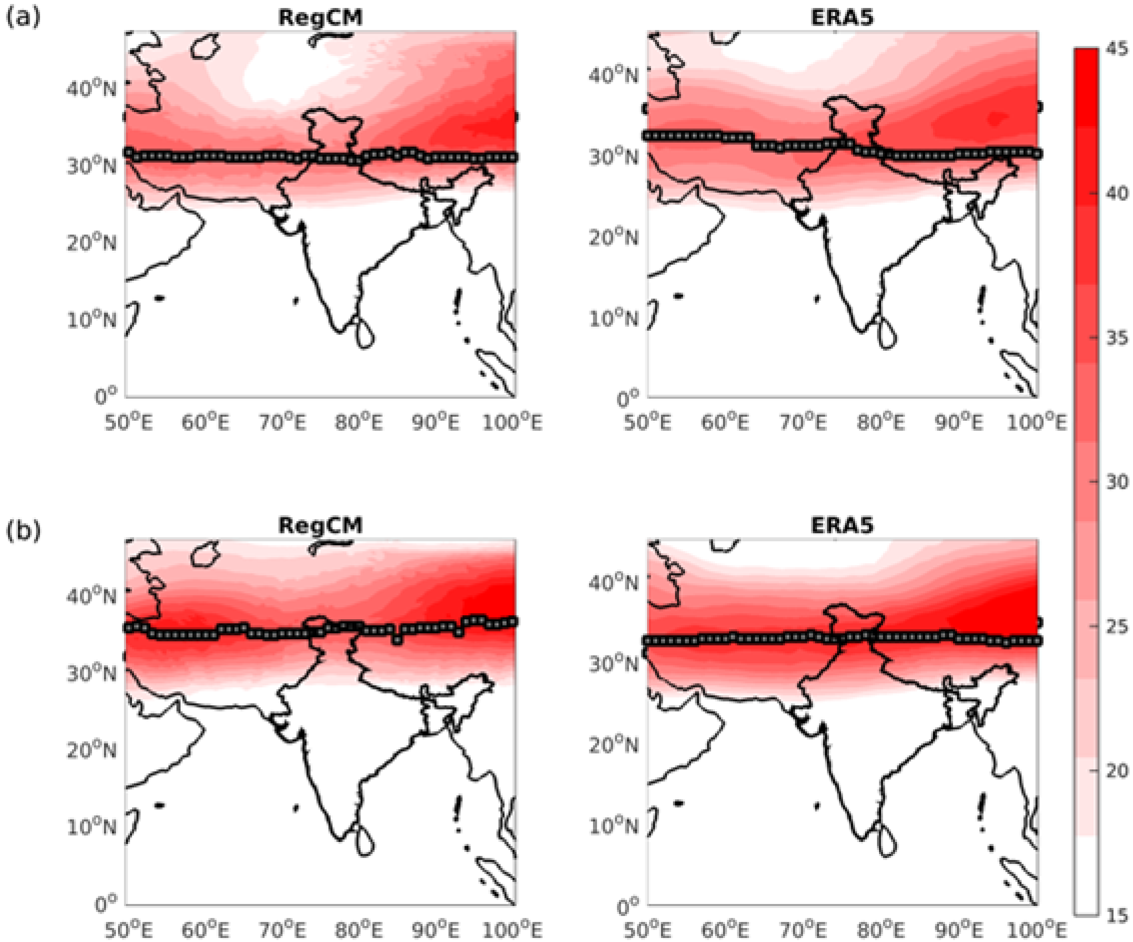

Figure 9

Position of STJ axis during (a) early and (b) delay withdrawal. Zonal winds are demonstrated using shaded regions (in m/sec), the boxed lines represent the STJ axis. (Figure 8.2 in the manuscript.) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

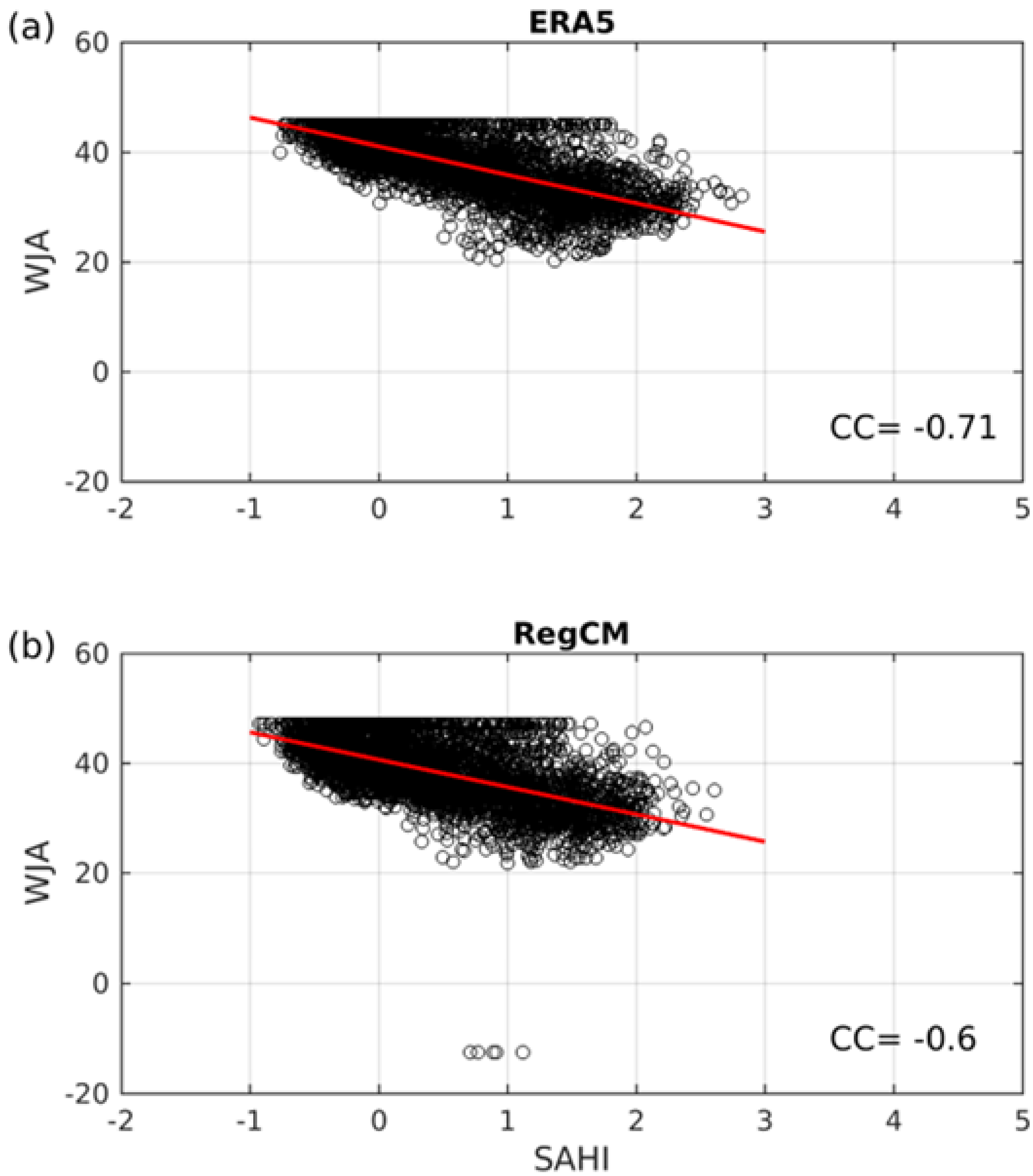

Figure 10

Scatter Diagram showing the relationship between SAHI and meridional position of STJ as per the (a) reanalysis (b) model data

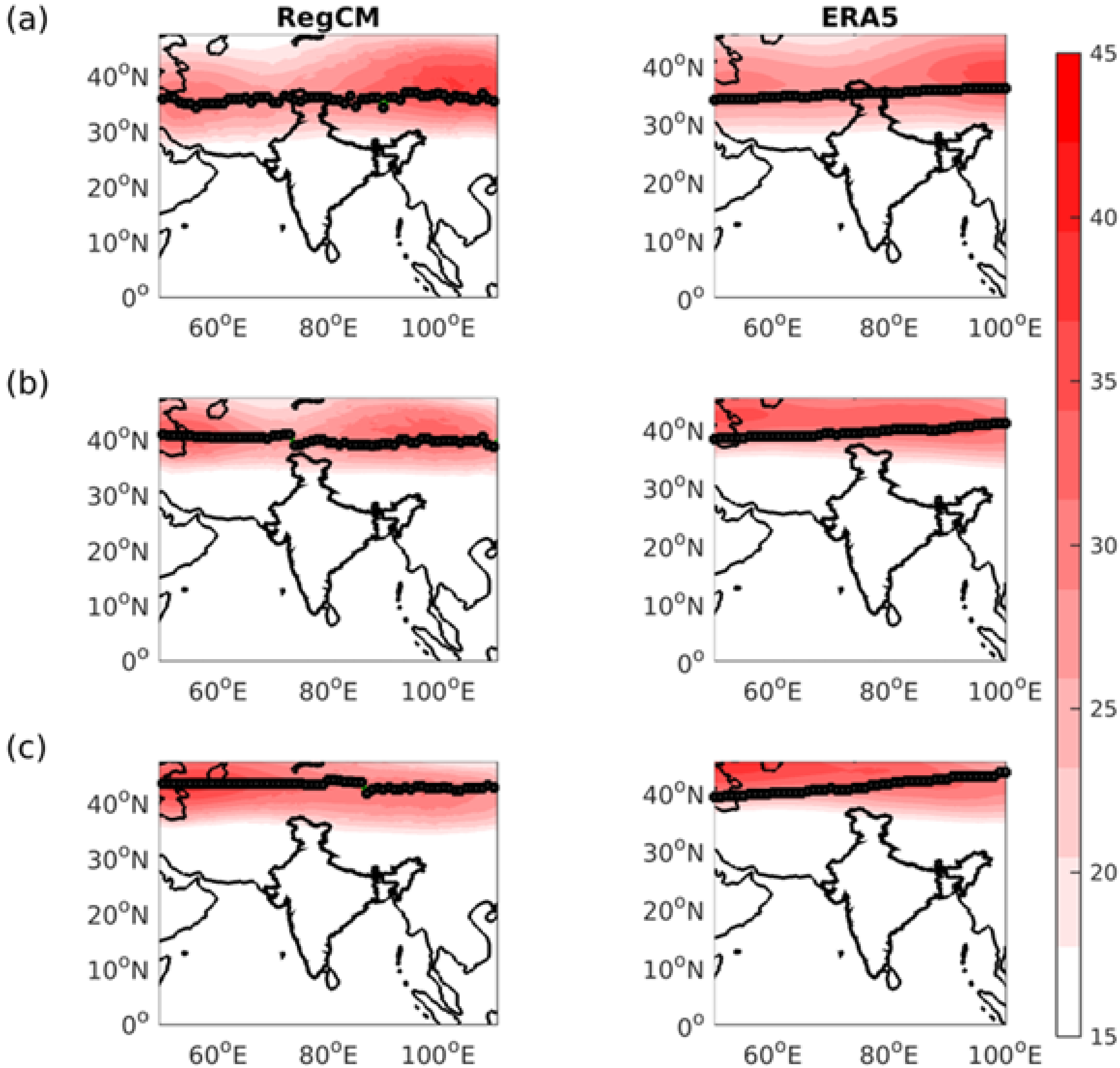

Figure 11

Position of STJ during different phases of SAH (a) SAHI>0 (b) SAHI = 0 (c) SAHI<0 as per the model and reanalysis dataset. Shadings represent the zonal winds (in m/sec). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.