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Special Section:
The land-air coupling over Tibetan Plateau and its global climate effects

Key Points:
• Tropical cyclone (TC) Fani boosted the onset of the South China Sea (SCS) summer monsoon (SCSSM) in 2019
• Northward shift of the South Asian High resulting from TC Fani provided upper-tropospheric pumping to trigger early onset of the SCSSM
• Diabatic heating over the eastern Tibetan Plateau enhanced by atmospheric response to TC Fani to further advance the onset of the SCSSM

Abstract The late onset of the South China Sea (SCS) summer monsoon (SCSSM) has traditionally been attributed to El Niño events. However, the SCSSM built up around Pentad 26 in 2019, which was 10 days earlier than expected following the 2018/2019 El Niño event. The present study showed that the early onset of the SCSSM in 2019 could be ascribed to tropical cyclone (TC) Fani over the Bay of Bengal (BOB) from 27 April to 3 May 2019. Before the landfall in Pentad 24, the anomalous condensation heating released by the TC not only shifted the South Asian High (SAH) northward but also reinforced the upper-level barotropic trough to the west of the Tibetan Plateau (TP) at midlatitudes. This phenomenon facilitated the early establishment of monsoon convection by intensifying the upper-level pumping over the SCS. In addition, the TC carried abundant moisture to the eastern TP and the SCS when it landed in eastern India in Pentad 25 and strengthened the local rainfall in front of the deeper midlatitudinal trough in the upper troposphere over the TP, which in turn released more condensation heating to warm the tropospheric atmosphere. Afterwards, this warmer air advected downstream to the north of the SCS by the basic flow, resulting in the further northward shift of the SAH and the stronger monsoon onset convection over the SCS. Such an upsampling effect of the TC prevented the onset time of the 2019 SCSSM from being accurately forecasted by the ECMWF S2S model.

1. Introduction
The East Asian summer monsoon affects more than 20% of the world’s population and is one of the most pronounced members in the global monsoon system (Ding & Chan, 2005; Tao & Chen, 1987; Wang et al., 2012; Wang & Ding, 2008). The East Asian summer monsoon begins with the onset of the South China Sea (SCS) summer monsoon (SCSSM), which receives broad attention by meteorologists. After the SCS Monsoon Experiment (SCSMEX) in 1998 (Ding & Liu, 2001), extensive effort was devoted to exploring the onset features of the SCSSM. The climatological onset time of the SCSSM is Pentad 28 based on different monsoon onset criteria (Liu et al., 2015; Mao et al., 2004a; Wang et al., 2004). The onset of the SCSSM is accompanied by the “warm-in-north” and “cold-in-south” tropospheric temperature pattern surrounding the SCS, presenting the winter-to-summer seasonal transition of the meridional temperature gradient (MTG) in the middle-upper troposphere (Mao et al., 2004b; Webster et al., 1998; Zhang et al., 2004). Except for the flourishing of monsoon convection over the SCS, the onset of the SCSSM includes the intrusion of the South Asian High (SAH) into the upper troposphere over the SCS (Liu & Zhu, 2016), the eastward retreat of the western North Pacific subtropical high (WNPSH) in the middle-lower troposphere (Ding & Liu, 2001; He et al., 2017), and the generation of cross-equatorial flow south of Asia (Gao et al., 2012; Gao & Xue, 2006; Lin et al., 2017).

The interannual variability in the onset of SCSSM has large effects on the summer rainfall over East Asia, which has been attributed to the impact of underlying conditions. For instance, the El Niño Southern Oscillation (ENSO) can directly modulate the onset time of the SCSSM by changing the large-scale Walker circulation (Ju & Slingo, 1995; Xie et al., 1998), WNPSH, and SAH (Liu et al., 2016; Zhou & Chan, 2007) or indirectly by altering the monsoon circulation over the SCS via sea surface temperature anomalies (SSTA) in the tropical Indian Ocean and western Pacific (Hu et al., 2014; Huang et al., 2006; Yuan et al., 2008). The SCSSM generally tends to exhibit earlier (later) onset following a La Niña (El Niño) event in the previous season, and this correspondence became especially significant after 1994 (Liu et al., 2016). The sensible heat anomalies over the Tibetan Plateau (TP) (Wu & Zhang, 1998) and Indochinese Peninsula (Zhang & Qian, 2002) and the midlatitudinal land surface temperature patterns over East Asia...
(Liu et al., 2009) can also alter the onset time of the SCSSM via air-land interactions. On intraseasonal timescale, the Madden-Julian Oscillation (MJO) and its northward propagation (Li et al., 2019; Lin et al., 2016; Straub et al., 2006) and the quasi-biweekly (i.e., 10–20 day) oscillation (Keshavamurty, 1972; Wang et al., 2016) can modulate the year-to-year onset time of the SCSSM. On synoptic timescale, both case study and statistical analysis suggest that the tropical cyclones (TCs) over the SCS and western Pacific are able to affect the onset process of the SCSSM (Huangfu et al., 2017; Kajikawa & Wang, 2012; Kubota et al., 2017; Mao & Wu, 2008). In addition, the fronts at midlatitude and high-latitude and wave trains also show their influences on the onset of the SCSSM (Ding et al., 2018; Huangfu et al., 2018; Tong et al., 2009). Consistent with the traditional understanding, the onset of the SCSSM based on different criteria was later or equal to Pentad 28 following the warm SSTA in the equatorial eastern Pacific from 2015 to 2017; however, this relationship was broken in 2018 and 2019 (Figure 1). Although a La Niña event occurred in the 2017/2018 winter, the SCSSM in 2018 built up extremely late in Pentad 31. This phenomenon has been ascribed to the joint influence of the MJO in the tropics and the upper-tropospheric Rossby wave train at midlatitude and high-latitude over Eurasia due to the strongest positive tri-pole pattern of North Atlantic SSTA since 1981 (Liu & Zhu, 2019). In 2019, an unexpected early onset of the SCSSM again occurred in Pentad 26 after the 2018/2019 El Niño event in the previous winter (Figure 1). These variations imply that there is great uncertainty in the seasonal forecast of the onset time of the SCSSM solely based on the ENSO events. Thus, the present study aims to investigate the physical processes responsible for the early onset of the SCSSM in 2019, and explore new predictors of the onset time of the SCSSM. The remainder of this paper is organized as follows. Section 2 introduces the data sets and the numerical models. The onset features of the SCSSM in 2019 are shown in section 3. Section 4 investigates the causes of the early onset of the SCSSM. The conclusions and discussion are given in section 5.

2. Data Sets and Methods

2.1. Data Description

The onset features of the SCSSM in 2019 were depicted by the daily JRA-55 reanalysis data set developed by the Japan Meteorological Agency (Harada et al., 2016; Kobayashi et al., 2015). The horizontal resolution of the JRA-55 reanalysis data set is 1.25°×1.25° with 37 standard isobaric surfaces from 1000 to 1 hPa. The variables included the three-dimensional winds, geopotential height, air temperature on isobaric levels, and precipitation at the surface. Convection was also represented by the 2.5°×2.5° daily outgoing
longwave radiation (OLR) without interpolation, which was provided by NOAA. The best tracks of TCs during 1981–2018 were provided by the Joint Typhoon Warning Center (JTWC) of the Naval Oceanography Portal, whereas the typhoon tracks in 2019 were obtained from the Regional and Mesoscale Meteorology Branch (RAMMB) of NOAA. We calculated the diabatic heating following Luo and Yanai (1983), and its vertical integration from land surface to 100 hPa was defined as the atmospheric heat source in the troposphere. The pentad values were the mean values in every 5 days, such as 1–5 January, 6–10 January, ..., and so forth. We always obtained 73 pentads per year in which Pentad 12 covered 25 February to 1 March whether or not there was a leap year. During the onset of the SCSSM in 2019, Pentad 24, 25, 26, and 27 started on 26 April, 1 May, 6 May, and 11 May, respectively. For addressing the anomalies in 2019, the climatological values during 1981–2010 were subtracted from the original records. The anomalies did not depend on the selection of the climatology (figure not shown). The two-tailed student t test was used to show the statistical significance of the anomalies. In observation, the statistically significant differences of mean state in every 5 days from 26 April to 15 May between the case in 2019 and the climatology represented the remarkable anomalies in each pentad.

2.2. Definition of the Onset Time of the SCSSM

Two methods were used to identify the onset time of the SCSSM. One method was the Asian summer monsoon onset criteria (ASMOC) (Liu et al., 2015). The criteria included (1) the 500–200-hPa-averaged MTG over the SCS (5°–20°N, 110°–120°E) changes from negative to positive and remains positive, (2) the wind direction at 10-m is greater than 100°, and (3) the rainfall intensity is greater than 5 mm day \(^{-1}\). The onset time of the SCSSM was defined as the first pentad when the above conditions were simultaneously satisfied and remained for the next 10 days (i.e., 2 pentads). As suggested by Liu et al. (2015), the ASMOC-based onset time of the SCSSM was significantly positively correlated with the times defined by other methods. The other method was an objective definition proposed by Wang et al. (2004) and Kajikawa and Wang (2012). In this method, the onset time of the SCSSM was the first pentad after 25 April that satisfied the following conditions: (1) in the onset pentad, the 850-hPa zonal wind over the domain (5°–15°N, 110°–120°E) \(U_{\text{SCS}}\) is greater than 0; (2) the \(U_{\text{SCS}}\) must be positive in at least three of the four subsequent pentads (including the onset pentad), and the cumulative four-pentad mean \(U_{\text{SCS}}\) is greater than 1.0 m s \(^{-1}\). In 2019, the onset time of the SCSSM was Pentad 26 according to the ASMOC, but the onset time was Pentad 25 according to the \(U_{\text{SCS}}\) method, indicating a robust earlier than normal onset of the SCSSM (Figures 2a and 2b). The onset time defined by the daily record consists with the pentad results (figure not shown).

2.3. Subseasonal-to-Seasonal (S2S) Numerical Prediction Model

The present study checked the performance of the real-time S2S prediction released by the European Center for Medium-Range Weather Forecasts (ECMWF) on the onset of the SCSSM in 2019. The differences between the successful and unsuccessful predicting members could identify the primary causes of the early onset of the SCSSM. This production has an ensemble identifier code of CY45R1 in the ECMWF (see details in https://confluence.ecmwf.int/display/S2S/ECMWF+Model+Description+CY45R1). It is a global ensemble system that simulates initial uncertainties using singular vectors and an ensemble of the data assimilation and model uncertainties due to physical parameterizations using a stochastic scheme. This model runs twice a week (Monday and Thursday at 00Z) and outputs 51 predicting members up to day 46. The daily outputs were transformed to the pentad mean results for convenient comparison with observations.

3. Onset Features of the SCSSM in 2019

The early onset of the SCSSM in 2019 featured a positive MTG, westerly wind at 850 hPa, and a seasonal change in the wind direction at 10 m in Pentad 25, followed by precipitation greater than 5.0 mm day \(^{-1}\) in Pentad 26 over the SCS (Figures 2a and 2b). Before Pentad 24, the middle-upper-tropospheric air temperature became warmer-than-normal in the tropics surrounding the SCS (red and blue lines in Figure 2c) as a thermal response to the El Niño event (Domeisen et al., 2019; Miyakoda et al., 2003; Trenberth & Smith, 2006). The intensity of the warm anomaly, which was represented by the difference between value in 2019 and climatology, was comparable between the southern (red lines in Figure 2c) and northern SCS (blue lines in Figure 2c). This suggested that the MTG in 2019 (black solid line in Figure 2c) was close to its climate mean status (black dashed line in Figure 2c). Although the warm anomaly of tropospheric air temperature...
tended to weaken over the southern SCS, it rapidly increased over the northern SCS and advanced the negative-to-positive transition of the MTG over the SCS in Pentad 25 (Figure 2c). The spatial distribution of the thermal and convection field and atmospheric circulation associated with the early onset of the

Figure 2. Temporal evolution of meteorological elements over the SCS during the onset of the SCSSM in 2019 (solid and dashed lines are for 2019 and the climatological situation, respectively). (a) Precipitation (red lines, mm day$^{-1}$), MTG (blue lines, 10$^{-7}$ K m$^{-1}$) and 10-m wind direction (black lines, degree) in the ASMOC over the region (5°–20°N, 110°–120°E). The precipitation 5.0 and 10-m wind direction 100° are drawn for convenient plotting. (b) 850-hPa zonal wind (m s$^{-1}$) over the domain (5°–15°N, 110°–120°E). (c) 500–200 hPa averaged air temperature over the northern (blue lines) and southern (red lines) SCS, while their differences (northern minus southern) are indicated by the black lines. The elements in 2019 and the climatology are drawn by solid and dashed lines, respectively.
SCSSM in 2019 are shown in the following section. The negative (positive) anomalies of the OLR indicate the enhanced (suppressed) convection.

3.1. Thermal and Convection Fields

In Pentad 24, a significant warming center of the middle-upper-tropospheric air temperature emerged over the TP, along with a relatively weak warming belt over the southern SCS and south of 10°N over South Asia (Figure 3a). The ridge line in the upper troposphere shifted toward the warming center, indicating that the SAH was clearly located northward of its climate mean position over the northern Indian Ocean. In the meantime, the ridge line remained south of its climate mean position over the SCS, where monsoon convection was evidently suppressed (Figures 3a and 4a). As the warming center over the TP expanded southeastward to the north of the SCS in Pentad 25, the SAH moved northward of its climate mean position over the SCS, where monsoon convection started to develop (Figures 3b and 4b). In Pentad 26, when the SCSSM built up, monsoon convection remarkably deepened over the SCS, along with the further northward shift of the SAH and the strengthened warming to the north of the SCS (Figures 3c and 4c). These anomalies of monsoon convection and the thermal field remained in Pentad 27, although their intensity was attenuated (Figures 3d and 4d).

Two additional negative OLR anomalies were pronounced outside the SCS during the onset of the SCSSM in 2019. One anomaly occurred over the BOB in Pentad 24 (Figure 4a), and the other was over the northern TP in Pentad 25 and 26 (Figures 4b and 4c). Over the BOB, the significant deeper convection, which was represented by the negative OLR anomaly, settled to south of 10°N in Pentad 24 and moved northward to the east coast of India afterwards (Figure 4a). Although the deeper convection became statistically insignificant over
the northern BOB in Pentad 25, a remarkable negative OLR anomaly emerged over the northern TP with complex terrains (Figure 4b). The anomalous in situ precipitation observations confirmed that the negative OLR anomaly over land consisted with the strengthened rainfall over the TP (figure not shown). In Pentad 26, enhanced convection disappeared over the BOB but remained over the northeastern TP (Figure 4c). When these two convection anomalies disappeared in Pentad 27, the anomalous monsoon convection remained but weakened over the SCS (Figure 4d).

3.2. Atmospheric Circulation

The anomalies of the thermal and convection field accompanied with anomalous circulation during the onset of the SCSSM in 2019. In Pentad 24, a striking anticyclonic anomaly existed in the upper troposphere over the southern TP, along with two anomalous cyclones to the west of the TP and over the SCS (Figure 5a). Upper-level divergence anomalies took place over the northern TP, the southern BOB and the Maritime Continent, where the local tropospheric circulation increasingly ascended (Figures 5a and 5d). In the lower troposphere, cyclonic anomalies formed over the southern BOB and the Maritime Continent, where more abundant water vapor was converged (Figure 5g). At this moment, less moisture was transported to the SCS (Figure 5g).

The situation changed in Pentad 25, when the upper-level divergence, middle-tropospheric ascent, and convergence of tropospheric water vapor strengthened together over the northern BOB (Figures 5b, 5e, and 5h). In the upper troposphere, the anomalous trough deepened to the west of the TP, along with the enhancement of the anticyclonic anomaly over the southern TP (Figure 5b). On the one hand, the upper-tropospheric divergence and the 500-hPa ascending motion strengthened over the northern TP downstream of the deeper trough at midlatitudes (Figures 5b and 5e). The water vapor over the BOB was transported...
poleward by the anomalous southerly wind and converged over the northeastern TP to strengthen in situ convection measurements (Figures 4b and 5h). On the other hand, the anomalous anticyclone over the southern TP expanded eastwards toward the northern SCS, leading to the anomalous northerly wind in the upper troposphere over the SCS (Figure 5b). It resulted in the intrusion of high potential vorticity from high latitudes to the SCS, which facilitated an upper-level pumping effect and ascending motion over the SCS (Figure 5e), as proposed by Liu and Zhu (2016). These conditions also corresponded to the southeastward extension of warmer air, giving rise to the summer pattern of the MTG over the SCS (Figures 2c and 3b). As required by the thermal wind relationship, the vertical easterly shear strengthened over the SCS to develop upper-level easterly and low-level westerly winds. Thus, low-level westerly winds increased dramatically over the southern SCS, consistent with the onset time of the SCSSM defined by USCS (Figures 2b and 5h). This change increased water vapor transport from the BOB with convergence over the SCS to start the monsoon onset convection (Figures 4b and 5h).

In Pentad 26, a positive feedback formed between monsoonal circulation and precipitation to augment the anomalies of convection and circulation over the SCS. The feedback included the southwestward extension of the anomalous anticyclone in the upper troposphere, the strengthened middle-tropospheric ascending motion and the increased abundance of water vapor over the SCS (Figures 5c, 5f, and 5i). The monsoon convection flourished over the SCS in the meantime (Figure 4c). The anomalies of the lower-tropospheric circulation resembled the anomalous vertically integrated water vapor flux during the onset of the SCSSM in 2019 (figure not shown). It is noteworthy that anomalous anticyclone persisted in the middle-lower troposphere of the western North Pacific (WNP) during the onset of the SCSSM in 2019, suggesting the enhancement of the WNPSH after the El Niño event, as their common relationship (Figures 5d and 5e; 5g and 5i). However, the anomalous northward shift of the SAH contradicts its relationship with the El Niño event, in which the SAH in May would move southwards if the warm SSTA persisted in the equatorial eastern Pacific (Liu et al.,

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**Figure 5.** Three-dimensional structure of the anomalous circulation from Pentad 24 to 26 in 2019. (a–c) are the anomalies of 200-hPa divergence (shading, $10^{-6}$ s$^{-1}$) and winds (vectors, m s$^{-1}$). (d–f) are the anomalous vertical velocity (shading, $10^{-2}$ pa s$^{-1}$) and flows at 500 hPa (vectors, m s$^{-1}$). (g–i) are the anomalies of vertically integrated water vapor flux from surface to 300 hPa ($10^2$ kg m$^{-1}$ s$^{-1}$) and its divergence ($10^{-5}$ kg m$^{-2}$ s$^{-1}$). Black contours denote the 1500-m topography. The vectors exceeding the 95% confidence level are plotted, while the stipple indicates the values exceeding the 95% confidence level.
The middle-upper-tropospheric warming center surrounding the TP directly promoted the onset of the SCSSM by advancing the seasonal transition of the MTG over the SCS and shifting the SAH northward. The onset of the SCSSM thus was not postponed in 2019, as expected.

4. Attribution of the Early Onset of the SCSSM in 2019

The remarkable deeper convection over the BOB before the onset of the SCSSM was ascribed to the TC Fani. As shown in Figure 6a, TC Fani originated as a tropical storm near 5°N over the southern BOB on 27 April and gradually developed and moved northwestward to 10°N on 29 April, corresponding to the strong tropical convection in Pentad 24. The TC then grew into a typhoon on 30 April and shifted northward toward the Odisha state of India on 3 May. Fani was the strongest TC to make landfall over this region in the last 20 years, and it induced heavy rainfall near the east coast of the Indian peninsula in Pentad 25. Afterwards, the TC and its resultant convection rapidly attenuated in Pentad 26. The daily evolution of the ASMOC and USCS (figure not shown) indicated that the early onset of the SCSSM in 2019 started with the winter-to-summer seasonal reverse of the MTG in the middle-upper troposphere when the TC Fani generated over the southern BOB. It was followed by the establishment of the low-level westerly wind over the SCS as the TC landfall. The monsoon onset convection finally formed over the SCS after the TC fading away. Here, we will examine how the TC Fani boosting the onset of the SCSSM in 2019.

4.1. Observed Results

TC Fani produced great diabatic heating to change the atmospheric circulation and thermal structure during the onset of the SCSSM in 2019. In Pentad 24 before its landfall, large diabatic heating anomalies were released with a deep anomalous cyclone below 200 hPa and an anticyclone above 200 hPa, consistent with the enhanced tropical convection over the southern BOB (Figures 4a and 7a). As a Gill response to the tropical diabatic heating (Gill, 1980), an upper-level anticyclonic anomaly came out over the TP to the northwest of the diabatic heating center to shift the SAH northward over the BOB (Figures 7a, 7d, and 4a). In the upper troposphere, the easterly wind accelerated over India and the Arabian Sea, along with the stronger westerly wind over the TP (Figures 7a and 7d). Meanwhile, the TC-released diabatic heating could strengthen the upper-level barotropic trough to the west of the TP by stimulating a transient meridional wave train in the extra-tropics (Figure 7d). This upper-level trough facilitated the ascending motion over...
Considering the coincidence between the anomalous warm core and the SAH anomaly (Wu et al., 2015), a warming center got developed in the middle-upper troposphere near the TP (Figure 3a).

When TC Fani landed on the east coast of the Indian peninsula in Pentad 25, the center of the diabatic heating anomaly moved northward to the northern BOB (Figure 7b). In this stage, the most prominent changes of diabatic heating and circulation occurred over the TP. Over the TP, when the anomalous southerly wind on the east of the TC in the lower troposphere brought more abundant water vapor onto the TP, the local rainfall became heavier in conjunction with the anomalous ascending motion in front of the deeper upper-level trough (Figures 5e and 5h). The increased diabatic heating was thus released to strengthen the baroclinic anticyclone in the upper troposphere over the TP (Figure 7e), which maintained the

**Figure 7.** Pressure–longitudinal cross section of anomalous diabatic heating (shading, K day\(^{-1}\), values exceeding the 95% confidence level are stippled), relative vorticity (contours, 10\(^{-5}\) s\(^{-1}\)), and zonal circulation (vectors, m s\(^{-1}\)) averaged over (left column) 5°–20°N and (right column) 30°–50°N from Pentad 24 to 26 in 2019 ([a, d] Pentad 24, [b, e] Pentad 25, [c, f] Pentad 26). Vectors exceeding the 95% confidence level are plotted. Gray shading is used for the topography.
anomalous northward shift of the SAH (Figures 3b and 5b). When this anomalous anticyclone extended and moved downstream with the strengthened upper-level westerly wind, the warmer tropospheric air extended eastward to the north of the SCS (Figures 3b and 7e). As a result, the winter-to-summer transition of the MTG occurred over the SCS in Pentad 25, corresponding to the timing of the seasonal transition of the USCS (Figures 2a and 2b). The thermal and circulation anomalies favored the establishment of monsoon onset convection over the SCS in this stage.

The SCSSM did not fully establish until the monsoon convection prevailed over the SCS in Pentad 26. TC Fani faded away in this pentad, manifesting as a positive OLR anomaly and anomalous diabatic cooling over the BOB (Figures 4c and 7c). The anomalies of diabatic heating and atmospheric circulation obviously attenuated over the TP without the presence of TC Fani (Figure 7f). In contrast, diabatic heating released by the monsoon onset convection over the SCS maintained the monsoonal circulation, including vertical easterly shear, strong ascending motion, and a baroclinic structure with an upper-level anticyclone and low-level cyclone over the SCS (Figure 7c). The positive feedback sustained monsoon onset convection and circulation over the SCS.

4.2. ECMWF S2S Prediction

For validating the observed influences of TC Fani on the early onset of the SCSSM in 2019, we have checked whether such atmospheric internal disturbance could be adequately predicted by the ECMWF S2S model.

Figure 8. Real-time predicted MTG index over the SCS in 2019 in the ECMWF S2S production. (a) Predicted MTG index starting on different dates. Solid and dashed lines are for the ensemble successful and unsuccessful predictions, respectively. (b) Predicted MTG index starting on 22 and 25 April 2019. Black, blue, and green lines with hollow circles represent the ensemble total, successful, and unsuccessful ensemble predictions, respectively. Light gray lines denote the prediction members. The observed MTG index is presented by the solid red line.
The MTG index was used to show the onset process because the upper-tropospheric anomalies were most striking during the onset of the SCSSM in 2019. As shown in Figure 8a, the ensemble prediction by the ECMWF model cannot correctly predict the onset of the SCSSM until 22 April 2019. After the formation

![Figure 9](image_url)

**Figure 9.** Differences in (left column) Pentads 24 and (right column) 25 between the successful and unsuccessful categories of the ECMWF S2S predictions starting on 22 and 25 April 2019. (a, b) Precipitation (shading, mm day\(^{-1}\), values exceeding the 95% confidence level are stippled) and 500–200-hPa averaged air temperature (contours, K, values exceeding the 95% confidence level are plotted). (c–f) Pressure-latitudinal cross section of diabatic heating (contours, K day\(^{-1}\)), geopotential height (shading, gpm, values exceeding the 95% confidence level are stippled), and meridional circulation (vectors, reference scale is at the bottom) averaged along (c, d) 80°–90°E and (e, f) 110°–120°E. Bold maroon lines in (a, b) represent the 1500-m topography, while gray shading in (c–f) represents the topography.
of the TC, the predictions starting on 25 April, 29 April, and 2 May became closer to the observations. Because the dispersion of the 102 members was largest in the predictions starting on 22 and 25 April, we divided these members into successful and unsuccessful categories (Figure 8b). Comparing with observations, the members with the predicted MTG greater than $2.0 \times 10^{-7}$ Km$^{-1}$ in Pentad 25 and maintaining positive in Pentad 26 were classified to the successful category. Whereas the members in the unsuccessful category featured the predicted MTG less than $-2.0 \times 10^{-7}$ K m$^{-1}$ in Pentad 25 and keeping negative in Pentad 26. We obtained 16 most successful and 15 most unsuccessful members, respectively. In the successful category, the ensemble TC track resembled the observation (Figure 6b). But no ensemble TC track was seen in the unsuccessful category, in which the minimum SLP was anchored over the southern slope of the TP (Figure 6c). This result implies that the model needs to obtain accurate TC information to correctly predict the onset of the SCSSM in 2019.

The two initial dates were both in Pentad 23, when the mean initial status in the successful category resembled that in the unsuccessful category (Figure 8b). Thus, we can compare the differences in Pentads 24 and 25 between the two categories to identify the causes of the correct prediction. Compared with the unsuccessful category, the heavy rainfall in Pentad 24 induced more diabatic heating over the southern BOB, consistent with the TC generation in the successful category (Figures 9a and 9b). The upper-level anticyclonic anomaly and a warmer troposphere occurred to the northwest of the rainfall center (Figures 9a and 9c). Meanwhile, the rainfall, diabatic heating, and circulation anomalies were weak over the SCS (Figure 9e). In Pentad 25, when the TC moved northward, strong rainfall and diabatic heating settled near the east coast of the Indian peninsula, along with the development of diabatic heating over the TP with its center in the

Figure 10. Schematic diagram of the boosting effect of the TC Fani on the onset of the SCSSM in 2019. Elements on the surface surrounded by the dashed lines are in the upper troposphere. See the details in the text.
middle troposphere (Figures 9b and 9d). The upper-level anticyclone and warming center enhanced over the TP and expanded onto the SCS to enhance the tropospheric ascending and monsoon onset convection over the SCS, corresponding to the early onset of the SCSSM (Figure 9f). The real-time S2S prediction by the ECMWF model suggested that the useful forecast efficiency of the SCSSM onset is limited to less than 2 weeks when TC Fani played an important role in 2019.

5. Conclusions and Discussion

5.1. Conclusions

The onset time of the SCSSM in 2019 was Pentad 26, which was much earlier than normal after a persistent El Niño event. This phenomenon disrupted the traditional relationship between ENSO and the onset time of the SCSSM. In the present study, we ascribed the early onset of the SCSSM in 2019 to the TC Fani over the BOB based on observation analysis and S2S numerical predictions. The major conclusions are sketched in Figure 10.

In 2019, TC Fani was generated over the southern BOB on 25 April and moved northward toward land on the east coast of the Indian Peninsula on 3 May (TC symbol in Figure 10). In Pentad 24, when the TC settled over the BOB, its convection released diabatic heating to produce an anticyclonic anomaly over South Asia and an anomalous cyclone to the west of the TP in the upper troposphere (“C” and “A” in Figure 10). The former contributed to the northward shift of the SAH, while the latter corresponded to a deeper upper-level trough upstream of the TP, which enhanced the ascending motion over the TP (red arrow over the TP in Figure 10). During landfall of the TC, the lower-tropospheric southerly wind to east of the TC transported abundant water vapor onto the TP in Pentad 25 (blue arrow directing to the TP in Figure 10). Moist air converged over the northern TP with complex terrain to increase the local rainfall in front of the deeper upper-level trough (rainfall symbol over the TP in Figure 10). Diabatic heating thus increased over the TP, leading to a further northward shift of the SAH and a warmer troposphere to the north of the SCS (purple shading in Figure 10). On the one hand, the northward shift of the SAH

![Figure 11. Tracks of TC over the BOB prior to the onset of the SCSSM during 1981–2018. (a) and (b) represents the early and late onset years, respectively. The tropical depression, tropical storm, and typhoon phases are plotted in green, yellow, and red, respectively. The black and white dots denote the center locations of TC at 12Z and 00Z UTC, respectively.](https://example.com/figure11.jpg)
provided an upper-level pumping environment over the SCS (light orange shading and red arrow over the SCS in Figure 10). On the other hand, the warmer air in the middle-upper troposphere to the north of the SCS assisted with the winter-to-summer transition of the MTG over the SCS. As required by the thermal wind relationship, the upper-level easterly and low-level westerly winds accelerated over the SCS. More moisture was transported by the stronger low-level westerly wind from the BOB to converge over the SCS, where the monsoon convection flourished (blue arrow and rainfall symbol over the SCS in Figure 10). Positive feedback then established between convection and atmospheric circulation to maintain the summer monsoon even after the TC fading away.

The present study sheds new light on the remote influences of a TC over the BOB on the onset of the SCSSM by altering the atmospheric heat source over the TP. In the ECMWF S2S model, the forecasted effectiveness of the onset time of the SCSSM is limited to approximately 1 week. The model could not correctly forecast the early onset of the SCSSM in 2019 until the information of TC Fani was included after Pentad 23. Compared with the unsuccessful predictions, the successful ones showed a boosting effect of the TC on the onset of the SCSSM, as indicated by the observations. Therefore, the strong synoptic perturbation is able to disturb the seasonal transition of the SCSSM via the upscaling process and break the traditional robust relationship between onset time of the SCSSM and ENSO event.

5.2. Discussion

The TC over the BOB might provide a new precursor to the onset time of the SCSSM on a subseasonal timescale. We further investigated the correspondence between the BOB TCs in pre-monsoon season and the onset time of the SCSSM during 1981–2019. TCs appeared over the BOB in 5 out of the 11 early onset years (<Pentad 28), whereas in 13 out of 19 of the late onset years (>Pentad 28), TCs was observed over the BOB. In the early onset years, most TCs generate over the tropical BOB and move along a “C-sharp” track to land on the northeastern India and Indochinese peninsula (Figures 6a and 11a); 60% of these TCs develop and land as typhoons (i.e., 1982, 1994, and 2019). While in the late onset years, the 13 TCs over the BOB do not share some common features of either intensity or track (Figure 11b). Only four of them grow into landfall typhoons over the northern Indochinese peninsula (i.e., 2004, 2006, 2008, and 2017). It suggests that landfall intensity of the TC over the BOB may be important for its boosting effect on the onset of the SCSSM. In addition, more TCs are observed over the BOB in the late onset years. This is probably because both the BOB TC frequency and the late onset of the SCSSM rely on the underlying conditions in these years, such as the warmer Indo-Pacific warm pool. It implicates the complexity in upscaling effect of the BOB TCs on the onset of the SCSSM. Since the sample size of the TC boosting the onset of the SCSSM is limited, more future works are required to identify the constraints whether a TC over the BOB is able to advance the onset of the SCSSM by taking the influences of the external forcing into account.

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