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Southerly Moisture Surges over the South China Sea in Early-Summer Season: Multiscale Variations and Impacts on Rainfall

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Abstract: Southerly moisture surges over the central South China Sea (SCS) are characterized by the strengthening of low-level southerlies that transport moisture northward from the Pacific or Indian Oceans to South China. These surge events typically occur for days in the early-summer season (from April to June) and can lead to heavy rains in South China. This study categorizes surge events into three types of flow patterns and examines their multiscale variations and impacts on rainfall. The first type occurs mainly in April, with the southeasterlies enhanced by a deepening trough in South China and the western Pacific subtropical high established over the SCS. The second type of surge events mostly appears in June, featuring the prevailing southwesterlies of summer monsoon from the Indian Ocean during the active phases of intraseasonal oscillations. Most surge events exhibit semi-diurnal variations with morning and afternoon peaks of northward moisture fluxes. Specifically, the first type features a dominant afternoon peak, while the second type shows a dominant early-morning peak, which is induced by thermal contrast between the Indochina Peninsula and the SCS. In general, the surge events enhance moisture convergence and increase rainfall downstream in South China, but they show some regional differences. The second type strengthens moisture convergence and rainfall in coastal regions with a morning peak. In contrast, the first type enhances inland rainfall with a morning peak, while moisture divergence dominates coastal regions. The third type of surge events denotes transitional conditions between the first two types, in terms of atmospheric circulations, diurnal cycles, and rainfall patterns. These results highlight a diversity of regional moisture surges and related rainfall ranging from diurnal to sub-seasonal scales.

Key words: southerly moisture surges; diurnal variations; synoptic disturbances; rainfall; South China Sea

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1 INTRODUCTION

The climate and weather over the South China Sea (SCS) exhibit obvious variations at a wide range of time scales. On the seasonal scale, the atmospheric circulation has an evident change from the winter pattern to the summer pattern in the early summer (April–June) (Lau and Yang 1997; Wu et al. 1998; Wang et al. 2004). On shorter time scales, the weather of SCS is affected by the intraseasonal oscillations (ISOs) that last for several weeks, including Madden-Julian oscillation (MJO) and quasi-biweekly oscillation (QBWO) (Wang and Chen 2017; Wang et al. 2018; Chen et al. 2019; Li et al. 2020). The multi-day synoptic disturbances, such as the

western Pacific subtropical high (WPSH), mid-latitude westerly disturbances, monsoon trough, and tropical waves are also crucial for the weather of SCS (Wu et al. 2015; Chen et al. 2017; Huangfu et al. 2017a, 2017b, 2018). The low-level winds also show evident diurnal variations over the SCS, and they can transport moisture downstream and affect the weather there (Aves and Johnson 2008; Chen et al. 2016; Du and Chen 2018, 2019; Zhang et al. 2024). These variations are expressed as a response to the active ocean-atmosphere-land interactions over the SCS at a wide range of time scales.

Moisture transport is one of the key processes in these multiscale variations. The SCS is characterized by the confluence of two major moisture flows in the tropics, i.e., the southeasterly flow from the western Pacific and the southwesterly flow from the Bay of Bengal and Indian Ocean (Zhou and Yu 2005; Li et al. 2011, 2013; Chu et al. 2017; Peng et al. 2022). These zonal flows turn into southerly flows over the SCS, providing a key supply of moisture for extratropics, particularly the East Asian monsoon region (Li et al. 2021). The moist southerlies can be particularly strong for days or a few weeks, which are regarded as southerly moisture surges (Zhang 2002; Liu et al. 2022). These moisture surges undergo pronounced multiscale variations over the SCS. On the

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seasonal scale, the moist southeasterlies from the western Pacific are dominant in spring, while the moist southwesterlies from the Indian Ocean prevail after the onset of the SCS summer monsoon (Joseph et al. 1994; Wang and Chen 2012; Chen et al. 2022). On synoptic scale, these moist flows may exhibit as the atmospheric rivers, cross-equatorial flow, and low-level jets (LLJs) that induce strong northward fluxes of moisture in the central and northern SCS for several days (Lu and Hao 2017; Hu et al. 2018; Kamae et al. 2019; Pan and Lu 2020). The LLJs and local forcing, such as sea-land breeze, can also lead to diurnal variations of moisture transport (Du and Chen 2019; Fujinami et al. 2022; Liu et al. 2023). Therefore, the multiscale variations of moisture fluxes over the SCS need to be distinguished into different types at various time scales.

A key issue in studying these variations is to clarify their relationship with the variations of atmospheric circulation. On the seasonal scale, the transition of winter monsoon to summer monsoon over the SCS remarkably changes the moisture pattern, including the source and transport pathways (Shaw and Chao 1994). On the subseasonal scale, the wind patterns associated with ISOs are shifted from southeasterlies to southwesterlies over the SCS that regulate the moisture transport between different ocean basins (Weickmann and Berry 2009; Li et al. 2018; Hu et al. 2020). In specific, the second and third phases of MJO help to enhance the southwesterly moisture transport over the SCS (Jia et al. 2011; Ordonez et al. 2013; Chen et al. 2015). On the synoptic scale, the WPSH, tropical cyclones, cross-equatorial flow, and monsoon troughs in low latitudes, as well as westerly systems in middle latitudes, are crucial for the moisture transport over the SCS (Sun and Wang 2015; Chu et al. 2020; Li et al. 2021). Recent studies further show the impacts of synoptic-scale weather systems, such as tropical waves, on moisture transport (Huangfu et al. 2022; Chen et al. 2023; Hu et al. 2023). On the diurnal time scale, recent studies also note that land-sea thermal contrast can strengthen the southerly wind at night and then regulate the diurnal variation of moisture transport (Fujinami et al. 2022; Liu et al. 2022). Moreover, there are some synoptic-scale moisture surges that occur over East Asia, which are linked not only to intraseasonal oscillations but also to diurnal variations (Liu et al. 2022, 2024). Therefore, the study of synoptic moisture surges, particularly their diversity, plays a key role in connecting atmospheric forcings at long- and short-time scales.

The impacts of southerly moisture from the SCS on weather over East Asia, especially heavy rain events, have been widely studied (Simmonds et al. 1999; Li 1999; Du and Chen 2018, 2019; Sun et al. 2019). When the moisture transport exhibits as surge events, their impacts are more critical. On the subseasonal scale, the southerly moisture fluxes from the SCS will be significantly facilitated after the onset of the southwesterly monsoon, and the rainfall over the downstream area will also be enhanced (Li et al.

2016; Chen and Luo 2018; Matsumoto et al. 2020). On the synoptic scale, the occurrence of tropical disturbances and LLJs over the SCS strengthens the moisture transport and increases rainfall (Hu et al. 2022; Du et al. 2020b, 2022). The downstream rainfall also shows evident diurnal variation with the maximum at night or in the early morning (Ohsawa et al. 2001; Hirose and Nakamura 2005; Chen 2020; Chen et al. 2009, 2013). As indicated, the impacts of moisture transport affected by different systems on downstream rainfall have diverse features. It is better to establish the relationship between moisture transport and downstream rainfall by categorizing the differences in moisture transport. For example, the moisture transport caused by mid-latitude westerlies is related to the northern rainfalls, while those by tropical disturbances are related to the southern rainfalls (Sun and Wang 2015; Chu et al. 2020). The moisture flux induced by synoptic-scale systems such as LLJs, low-level vortexes, and shear lines can cause local enhancement of moisture convergence and rainfall (Chen et al. 2011; Huang et al. 2018; Du and Chen 2018, 2019; Luo et al. 2020). The diurnal variations of rainfall are closely related to local forcings such as terrain uplift, land-sea breeze, and cold pool (Du et al. 2020b; Fujinami et al. 2022). Clarifying the different types of moisture flux and their different effects can help understand the formation of downstream rainfall better.

Previous studies have noticed obvious multiscale variations of moisture transport over the SCS. Our study aims to figure out how the synoptic-scale moisture surge events over the SCS are related to the atmospheric forcings at longer and shorter time scales, and whether these relationships are different in diverse patterns of moisture surges. To address this issue, we identify and categorize different types of moisture surges over the SCS, explore how they are affected by longer time scale atmospheric circulation and regional diurnal forcing, and their different effects on rainfall. The rest of this paper is organized as follows. Section 2 introduces the data used in this study and the method for identifying and classifying the southerly moisture surges. Section 3 shows the climatology of southerly moisture surges. Section 4 compares the relevant atmospheric conditions in different types of southerly moisture surges. Section 5 analyzes the impact of the southerly moisture surges on the downstream rainfalls. Section 6 is the summary and discussion.

2 DATA AND METHODS

2.1 Data used in this study

The hourly ERA5 reanalysis data (Hersbach et al. 2020) were used to describe the atmospheric conditions in this study. The ERA5 dataset is in a horizontal spatial resolution of $0.25^\circ \times 0.25^\circ$ and a temporal resolution of 1 hour with 37 vertical levels. It was considered to describe the features of the diurnal cycle of the lower-tropospheric conditions well with high spatiotemporal resolution (Chen et al. 2014, 2021; Du and Chen 2019).

To analyze rainfall activities, we used the satellite-derived rainfall product from the Tropical Rainfall Measuring Mission (TRMM 3B42 v7). TRMM has a horizontal spatial resolution of $0.25^\circ \times 0.25^\circ$ and a 3-hourly interval since 1998 (Huffman et al. 2007). It presents well the diurnal variations of rainfall on the south China coast (Zhou et al. 2008; Shen et al. 2010; Chen et al. 2018) and gives a good performance on capturing the events at a multiday time scale (He and Liu 2016; Chen et al. 2017; Guan et al. 2020), which is closely related to this paper.

In this study, we paid more attention to the early-summer season when both the seasonal change of atmospheric conditions over the SCS and the rainy season of South China are pronounced. The data from April to June in the past 20 years (1999–2018) were used for the climate analysis. The four synoptic hours 1400, 2000, 0200, and 0800 LST (LST=UTC+8) denote afternoon, evening, midnight, and morning, respectively. The anomalies are relative to the 20-year climatological mean.

2.2 Definition of southerly moisture surges

The definition of the southerly moisture surges is considered based on the key feature of moisture flux over the SCS. As shown in Fig. 1, the low-troposphere water vapor around 15°N in the central area of the SCS changes from zonal to meridional and provides moisture source for the downstream area (northern SCS and South China). Therefore, we can regard the central SCS as a key region ($12.5^\circ\text{--}17.5^\circ\text{N}$, $110^\circ\text{--}115^\circ\text{E}$; the black box in Fig. 1) for estimating the surge events. Given that most of the water vapor in the atmosphere is in the lower troposphere, the integrated water vapor flux is calculated from 1000 hPa to 750 hPa. We identify strong daily southerly moisture flux days with the integrated moisture fluxes averaged over the key region exceeding one standard deviation above the climate mean ($125 \text{ kg m}^{-1} \text{ s}^{-1}$). Then, the accumulated hour of strong moisture flux should exceed 48 hours, and two events with an interval of less than 2 days are merged into one event. We define the southerly moisture flux that satisfies the three conditions above as the surge events.

Figure 1 shows that the moisture transport patterns over the SCS exhibit diverse features from April to June, so we need to classify surge events into different flow patterns. The patterns of moisture flux in the key region can be determined by the different flow patterns of the zonal wind to the south of the key region. Meanwhile, the source of southerly moisture transport can be divided into two categories: one is the southeasterly flux from the Pacific, and the other is the southwesterly flux from the Indian Ocean. Therefore, we divide the south of the key region into two sub-areas: southeast area ($7.5^\circ\text{--}12.5^\circ\text{N}$, $112.5^\circ\text{--}117.5^\circ\text{E}$; the red boxes in Fig. 1) and southwest area ($7.5^\circ\text{--}12.5^\circ\text{N}$, $107.5^\circ\text{--}112.5^\circ\text{E}$; the blue boxes in Fig. 1) and thus the surge events are divided into three types. The first type is characterized by the southeasterly winds dominating both sub-areas, which can be called the southeasterly surge events. In the second type,

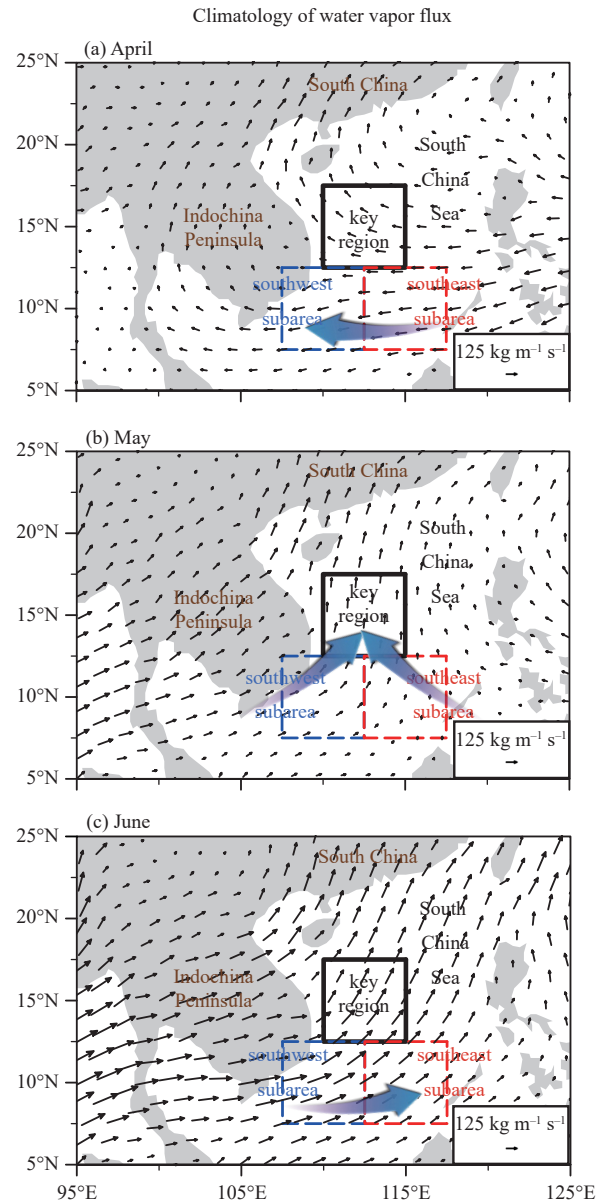


Figure 1. Horizontal patterns of mean moisture fluxes during (a) April, (b) May, and (c) June from 1999 to 2018. The black solid boxes represent the key region of the southerly moisture surges, while the blue and red dashed boxes represent the southwest sub-area and southeast sub-area, respectively.

southwesterly winds dominate both sub-areas, which can be called the southwesterly surge events. The third type is shown as the southeasterly winds dominate in the southeast sub-area, but southwesterly winds in the southwest sub-area, which can be called the mixed type.

Figure 2 shows an example of how we identify different types of surge events in 2010. The strong northward moisture fluxes and their variations can be seen in the central SCS in Fig. 2a. The first three events of strong moisture flux occurred in April and early May with a duration less than a week, while the other two events appeared from late May to June with a duration over two weeks. We further quantitatively estimate the strength of northward moisture fluxes averaged over the key region.

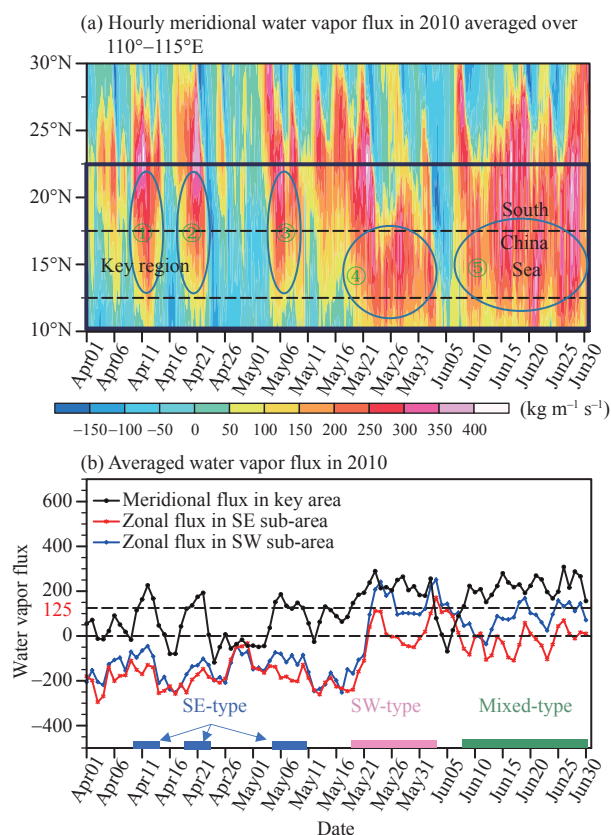


Figure 2. (a) Hourly evolution of the meridional moisture flux averaged over 110° – 115° E in 2010, and five events are circled. (b) Hourly evolution of the moisture flux averaged over the key region (black), southwest sub-area (blue), and southeast sub-area (red). The three types of events are labeled at the bottom of (b), blue for the southeasterly type, pink for the southwesterly type, and green for the mixed type.

Fig. 2b shows the occurrence days of five surge events (black solid line) are specified as April 10–13, April 19–22, May 4–10, May 18–June 2, and June 7–30, respectively. Then we classify the five surge events based on the zonal winds averaged over the two sub-areas to the south of the key region. The first three events are categorized as the southeasterly type because the zonal fluxes are easterlies over both sub-areas. The fourth event in late May is classified as categorized as the southwesterly type when the zonal fluxes are westerlies over both sub-areas. The fifth event in June is categorized as a mixed type, in which the zonal fluxes are westerlies over the southwest sub-area but easterlies over the southeast sub-area. Following such procedures, we identify a total of 92 surge events in the early summer of 20 years from 1999 to 2018. Among them, there are 22 southeasterly-type events, 50 southwesterly-type events, and 20 mixed-type events.

3 CLIMATOLOGY OF SOUTHERLY MOISTURE SURGES

In this section, we examine the spatiotemporal variations of the surge events, focusing on their synoptic and diurnal variations. Fig. 3a shows the climatology of

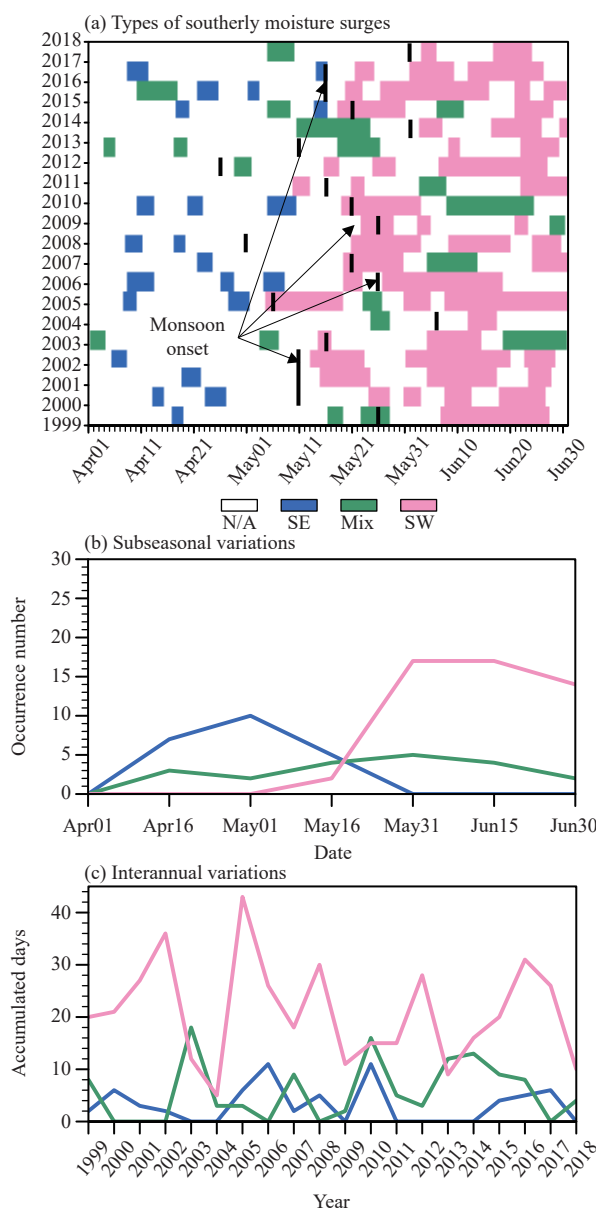


Figure 3. (a) Occurrence of the three types of surge events, with black lines indicating the onset of the SCS monsoon (represented by the first day of each pentad). (b) Subseasonal variation in the occurrences of surge events. (c) Interannual variation in the cumulative days of surge events.

surge events in the 20 years from 1999 to 2018. The cumulative duration of the 92 surge events is approximately 618 days, which accounts for 34% of the total days within the study period. The climate-mean duration of these events is about 6.7 days. The southeasterly-type events have an average duration of about 3 days, and the mixed-type events are about 6 days. The southwesterly-type events last for about 8.5 days that are much longer than the average duration. In particular, there are 8 extreme events that can last for more than 15 days, and most of them are southwesterly-type events.

Figure 3b shows the subseasonal variations of the surge events. Most of the southeasterly-type events occur before mid-May. In contrast, the southwesterly-type events

dominate in late May and June. The mixed-type events are the least frequent and appear relatively evenly from April to June. Such a pronounced subseasonal variation is thought to be related to monsoon activities. We further examine the relationship between surge events and the SCS summer monsoon, in which the first day of monsoon onset is indicated by the black vertical lines in Fig. 3a. All the southeasterly-type events occur before the onset of the monsoon, and up to 95% of southwesterly-type events occur after the monsoon onset. Notably, the surge events before the onset have shorter durations, while those after the onset have much longer durations. We also examine the interannual variations of the surge events. Fig. 3c shows that the southwesterly-type events are recorded every year, with an average occurrence of 20 days per year. The number of accumulated days show an apparent interannual variation, ranging from 5 days to more than 40 days. In contrast, both the southeasterly-type and mixed-type events are less than 20 accumulated days and even they are absent in some years. In this study, we mainly focus on the climatology at synoptic and shorter time scales, while the other longer time scales such as interannual variations may be studied in the future.

Figure 4 shows a week window with the composite variations of each type of events before and after the first day of the moisture surges. During the first day (day 0), the maximum of the southeasterly-type events is established with values over $260 \text{ kg m}^{-1} \text{ s}^{-1}$ near the coastline at around 22°N (Fig. 4a). The northern boundary of strong moisture flux is observed at 28°N . During the surge event, the maximum center moves southward and gradually extends to the key region (central SCS). The maximum flux decays to $120 \text{ kg m}^{-1} \text{ s}^{-1}$ on day +4, corresponding to an average duration of 3 days. Meanwhile, the northern boundary of strong moisture flux moves southward from 28°N to 22°N (the coastline), which may indicate the southward shift of the westerly disturbance.

During the southwesterly-type events, the maximum flux is established near 15°N in the key region (Fig. 4b), which is much more south than the southeasterly-type events. The span of the large value exceeding $220 \text{ kg m}^{-1} \text{ s}^{-1}$ expands from $12^\circ\text{--}17^\circ\text{N}$ on day +1 to $12^\circ\text{--}22^\circ\text{N}$ on day +2. Meanwhile, the maximum center moves slowly northward, and the northern boundary of large moisture flux also moves northward and maintains near the coastline. We also note that the moisture flux decays slightly on day +4, but it still exceeds $200 \text{ kg m}^{-1} \text{ s}^{-1}$, which is much stronger than that during southeasterly-type events. The position and movement of maximum flux as well as the northern boundary during southwesterly-type events are different from those during the southeasterly type. As indicated, they may be regulated by different large-scale atmospheric conditions, which will be discussed later.

During the mixed-type events, the maximum flux is located at 19°N , with a slight southern movement from day +1 to day +2 (Fig. 4c). The position of maximum flux is

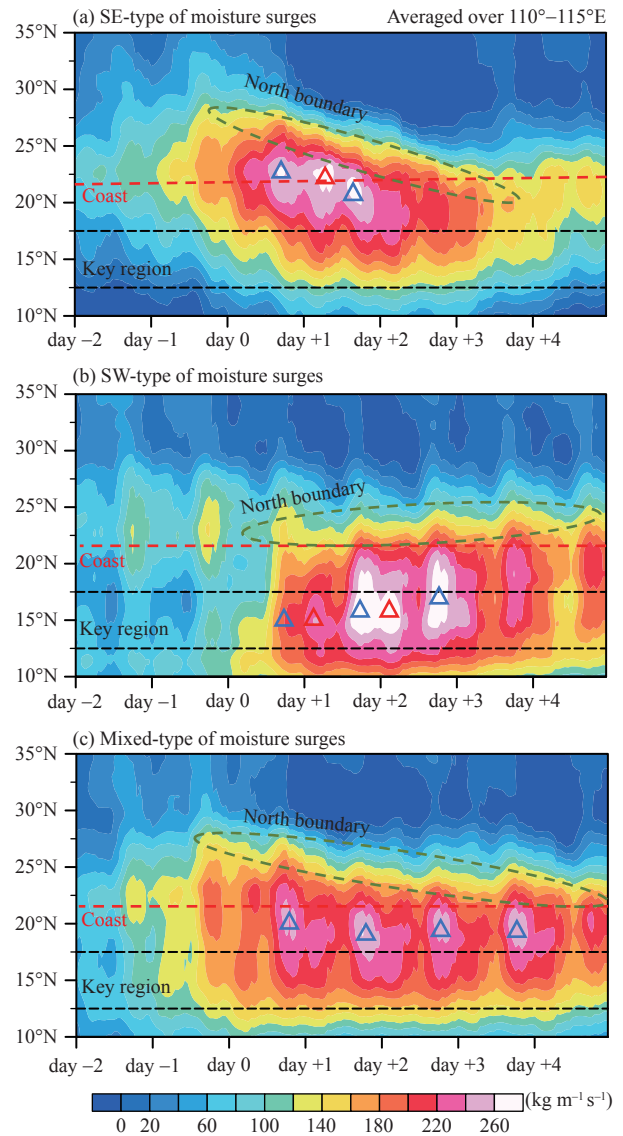


Figure 4. Hourly evolution of the meridional moisture flux averaged over $110^\circ\text{--}115^\circ\text{E}$ of the surge events of (a) southeasterly type, (b) southwesterly type, and (c) mixed type. With the first day of surge events being day 0, day -1 is one day before the first day, and day +1 is one day after the first day. Each day refers to the period from 0800 LST to 0700 LST the following day. The black dashed lines represent the latitude of the key region, the red dashed lines represent the coastline, and the green dashed lines represent the area with strong flux convergence. The blue triangles indicate the early morning peaks of the flux, while the red triangles indicate the afternoon peaks.

between the first two types and has no obvious movement. The northern boundary is established near 25°N and it shows a southward movement with a speed much slower than southeasterly-type events. The maximum of day +4 can still exceed $220 \text{ kg m}^{-1} \text{ s}^{-1}$, which is stronger than the first two types although it has decreased compared with the previous days. Notably, the intensity of moisture flux on day -1 in the key region is much stronger than the first two types. The position of the maximum and moving direction of this type lie intermediate between those of the first two types, so it can be considered as a transitional

state between the first two types.

The temporal evolution of moisture flux in the key region is further examined (Fig. 5a). During the southeasterly surge (blue line), the moisture flux increases from $40 \text{ kg m}^{-1} \text{ s}^{-1}$ to $150 \text{ kg m}^{-1} \text{ s}^{-1}$ after the first day and decays apparently on day +3. The moisture flux of the southwesterly surge (red line) increases from $50 \text{ kg m}^{-1} \text{ s}^{-1}$ on day -1 to $230 \text{ kg m}^{-1} \text{ s}^{-1}$ on day +1, and the amplitude is estimated $180 \text{ kg m}^{-1} \text{ s}^{-1}$, which is larger than the increase ($110 \text{ kg m}^{-1} \text{ s}^{-1}$) in the southeasterly surges. In particular, the southwesterly surge shows a large increase of $100 \text{ kg m}^{-1} \text{ s}^{-1}$ on day +1 and still maintains a values of more than $150 \text{ kg m}^{-1} \text{ s}^{-1}$ on day +3. During the mixed-type surges (green line), the increase of moisture flux is relatively slow, with an increase from $100 \text{ kg m}^{-1} \text{ s}^{-1}$ on day -1 to $200 \text{ kg m}^{-1} \text{ s}^{-1}$ on day +1. The feature of growth before day +1 is similar to the southeasterly surges, and then maintains about $200 \text{ kg m}^{-1} \text{ s}^{-1}$ from day +1 to day +4, which is higher than that of southeasterly surges but weaker than that of southwesterly surges. We also note that, such variations of moisture flux are mainly contributed by the change in the low-level southerly wind speed (Fig. 5c), and they are less contributed by the change in specific humidity (Fig. 5b). Specific humidity has different mean values among the three types of events likely in association with seasonal

change, but its variations for event's days and diurnal cycles are quite small. Therefore, we consider that the synoptic and diurnal variations of surge events are mainly related to the low-level southerly winds.

We further examine the variations of key region in the diurnal scale by subtracting the averaged value (dashed lines in Fig. 5a) from the hourly moisture flux (solid lines in Fig. 5a). Fig. 5d shows that each type exhibits two peaks at early morning (0400 LST) and afternoon (1300 LST) but shows different features in the relative importance of the two peaks. The southeasterly surges are dominated by the afternoon peak, while the southwesterly surges are dominated by the early morning peak. The mixed-type events exhibit an afternoon peak before day 0 and shift to an early morning peak after day +1. Additionally, there is a notable amplitude before both the early morning and afternoon peaks in each type. The amplitude before the early morning peaks is consistently greater than that in the afternoon, and a notable increase can be observed after day 0 of the surge events.

The differences in maximum latitude, propagation, and diurnal variations of moisture transport among the three types imply that they may be influenced by different types of atmospheric conditions and regional forcings. The variations of the northern boundary of moisture flux may imply changes in the convergence zones of moisture flux,

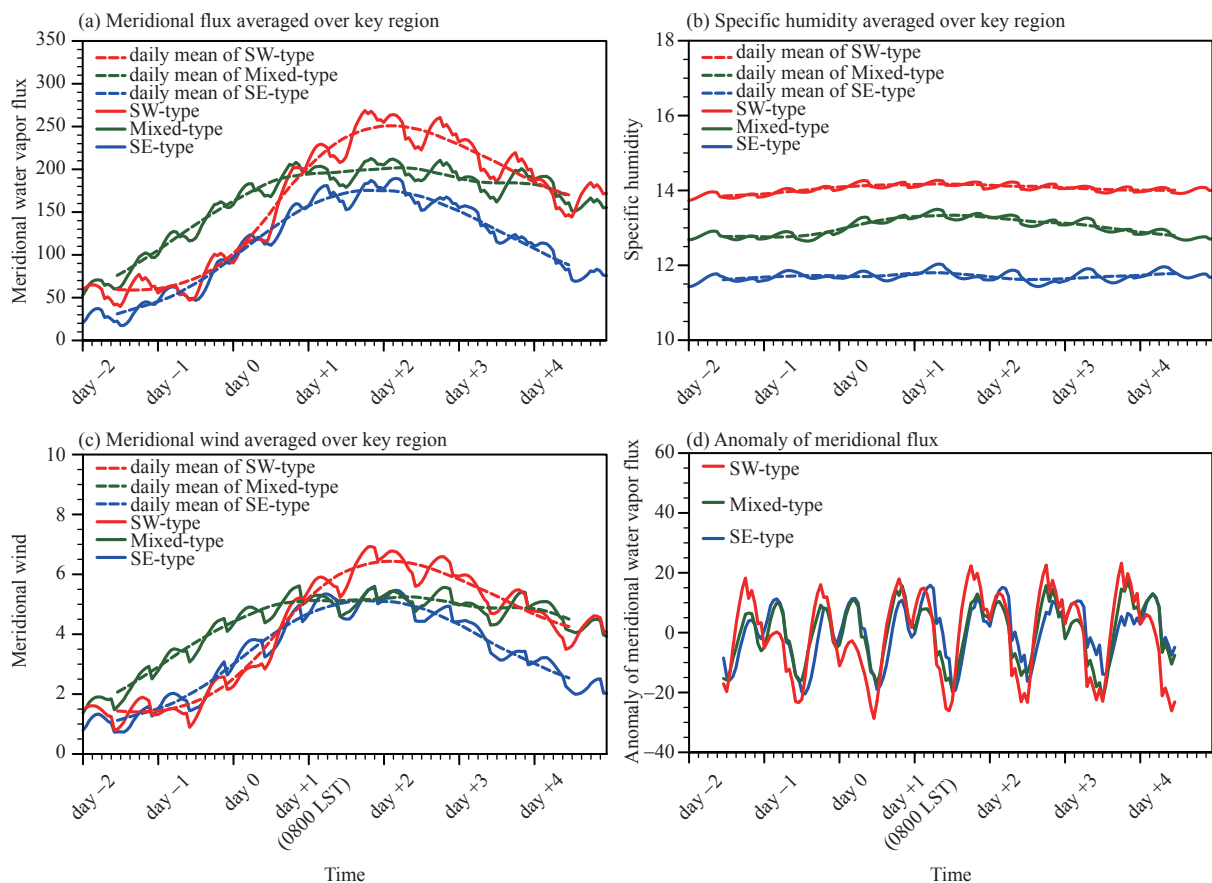


Figure 5. Temporal variations of hourly (a) meridional moisture flux, (b) specific humidity, and (c) meridional wind averaged in key region. The meridional wind and specific humidity are averaged over 750–1000 hPa. Dashed lines denote the series of 24-h running mean. (d) Diurnal deviation of hourly meridional moisture flux with 24-h running mean removed.

which may be related to the impacts on rainfall activities. These issues will be further analyzed in the following sections.

4 SPATIOTEMPORAL EVOLUTION OF ASSOCIATED ATMOSPHERIC CONDITIONS

4.1 Synoptic disturbances and quasi-biweekly oscillation

In this subsection, we examine the large-scale atmospheric conditions associated with the three types of surge events and further clarify how they regulate the surge events. Fig. 6a shows that before the first day of southeasterly surge events, the high-pressure anomaly of geopotential height at 850 hPa dominates in most areas of the SCS. After day 0, the high-pressure anomaly weakens and becomes a low-pressure anomaly in the western area of the SCS (near 105°E), while the positive anomaly remains in the eastern area (near 120°E). Such a pattern of high- and low-pressure anomalies helps to establish an east-west gradient that strengthens the southerly wind over the key region. To trace the source of low-pressure disturbance, we investigate the meridional gradients of geopotential height (Fig. 6d). The low-pressure disturbance appears at high latitudes on day -1 and gradually moves south to near 20°N, indicating the approaching westerly disturbances. These features agree with previous studies on the possible impact of westerly disturbances on moisture transport (Wu et al. 2015; Chen

et al. 2017).

As for the mixed-type events (Fig. 6b), the geopotential height undergoes an evident transition from high- to low-pressure anomaly from day -4 to day +1 over the western SCS (near 105°E). This may be affected by the westerly disturbances, which is somewhat similar to the southeasterly type. Then, the enhanced low-pressure disturbance over the western SCS strengthens the east-west gradient, which strengthens southerly wind over the key region. However, the high-pressure anomaly over the eastern SCS is much weaker than that during the southeasterly type, which may result in the appearance of the southwesterly wind. Its anomalous low-pressure disturbance appears in high latitudes on day -2 and gradually moves south to near 15°N (Fig. 6e), similar to the southeasterly type (Fig. 6d).

During the southwesterly-type events, a low-pressure disturbance locates near 120°E on day -3 and then develops and moves northwestward (Fig. 6c). After day +1, the low-pressure disturbance moves to near 110°E and reaches the maximum. It enhances the east-west gradient between 110°–125°E and intensifies the southerly wind over the SCS. Fig. 6f shows that the entire SCS is affected by a low-pressure disturbance coming from the tropics. It indicates that the southwesterly-type events seem to be affected by the tropical disturbances, which is different from the first two types affected by the mid-latitude

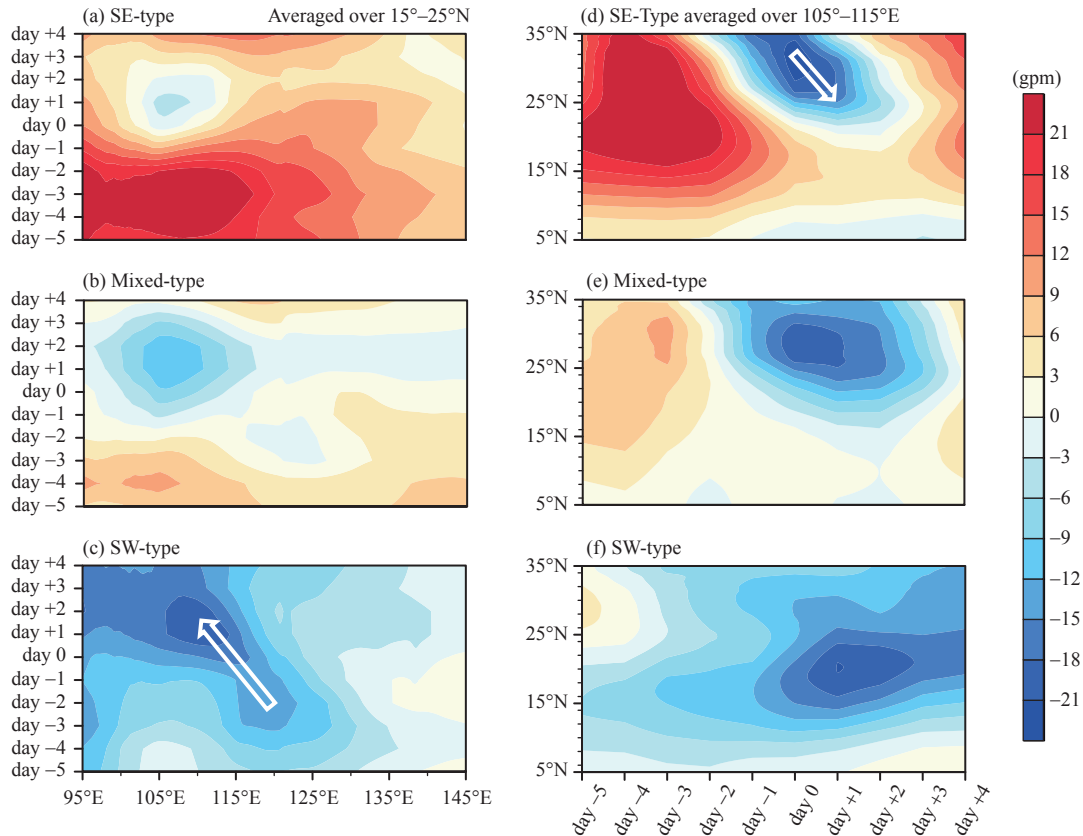


Figure 6. Anomaly of 850-hPa geopotential height during day -5 to day +4 averaged over (a–c) 15°–25°N and (d–f) 105°–115°E for the surge events of (a) and (d) southeasterly type, (b) and (e) mixed type, and (c) and (f) southwesterly type. The arrows indicate the movement of the low-pressure anomaly.

westerly disturbances. In particular, the atmospheric circulations show remarkable differences between the surge events of southeasterly type (Figs. 6a and 6d) and southwesterly type (Figs. 6c and 6f), which are quite similar to those differences before and after the onset of SCS summer monsoon (Gu et al. 2024). They also correspond to that the southeasterly (southwesterly) type of surge events mainly occur before (after) the monsoon onset (Fig. 3a).

Figure 7 shows how the westerly disturbances affect the southeasterly-type events. The high-pressure disturbance spans across 5° – 20° N on day -3 , with an anomalously strong East Asian trough established at 125° E (Fig. 7a). On day -1 , a low-pressure disturbance occurred near 35° N, 105° E, which is accompanied by the weakening of the high-pressure anomaly over the SCS (Fig. 7b). After day $+1$, the low-pressure disturbance moves southeastward to near 30° N, 110° E, while the high-pressure anomaly maintains over the SCS with weak intensity (Fig. 7c). The invasion of low-pressure disturbances in the mid-latitude indicates the movement of the westerly disturbances, which may be the main atmospheric condition affecting the southeasterly-type events. As for 850 hPa, the high-pressure disturbance is located over South China on day -3 (Fig. 7d), and gradually moves southeastward to the east of the SCS on day $+1$ (Fig. 7f). A low-pressure disturbance occurs in the mid-latitude regions and intrudes into South China on day

-1 (Fig. 7e). It is located over South China after day $+1$ and strengthens the east-west pressure gradient over the SCS with the high-pressure disturbance (Fig. 7f). As a result, the southerly winds over the key region are intensified. The cold air behind the trough also invades to southeast China from day -3 to day $+1$ because of the guidance of the upper trough.

As for the mixed-type events, an anomalously strong East Asian trough is also observed on day -3 (Fig. 8a), but the high-pressure anomaly over the SCS is much weaker than the southeasterly type (Fig. 7a). The movement of mid-latitude westerly disturbance is also evident, with the low-pressure disturbance appearing near 30° N, 85° E before day 0 and thus intruding to southeastern China on day $+1$ (Figs. 8b and 8c). In the lower level (850 hPa), the low-pressure disturbance locates over South China on day -1 (Fig. 8e) and gradually enhances over 14 gpm on day $+1$ (Fig. 8f). Then, the southerly wind over the key region is strengthened at the southern flank of the low-pressure disturbance. Additionally, the high-pressure disturbance at 850 hPa is also weaker than the southeasterly type, moving from southeastern China to the ocean from day -3 to day $+1$ (Figs. 8d and 8f). There is also some shallow cold air behind the trough which invades southward. In summary, both the southeasterly and mixed types are affected by the westerly disturbance, but the southeasterly type has a stronger high-pressure anomaly over the SCS.

Previous studies have noticed that the impacts of

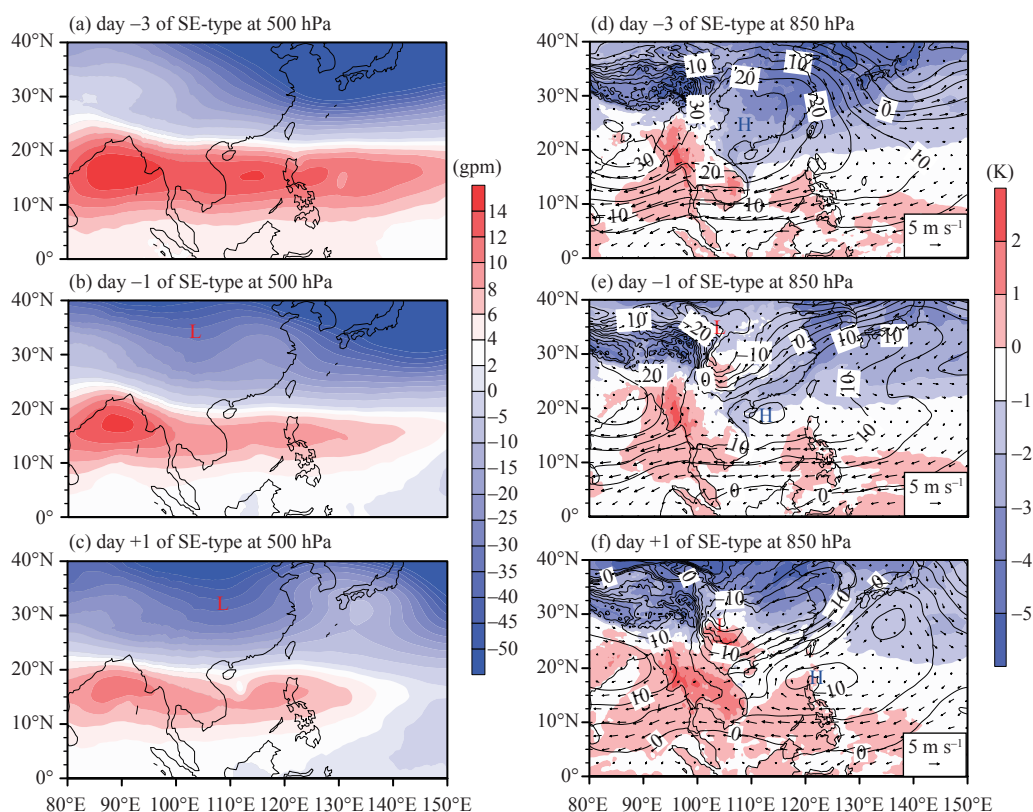


Figure 7. Anomaly of (a–c) 500-hPa geopotential height and (d–f) 850-hPa geopotential height (contour), wind field (vector), and 2-m temperature (shaded) of the southeasterly surge events. The anomaly value is obtained by subtracting the average value of April–June from the original value from 1999–2018. (a) and (d) day -3 , (b) and (e) day -1 , and (c) and (f) day $+1$.

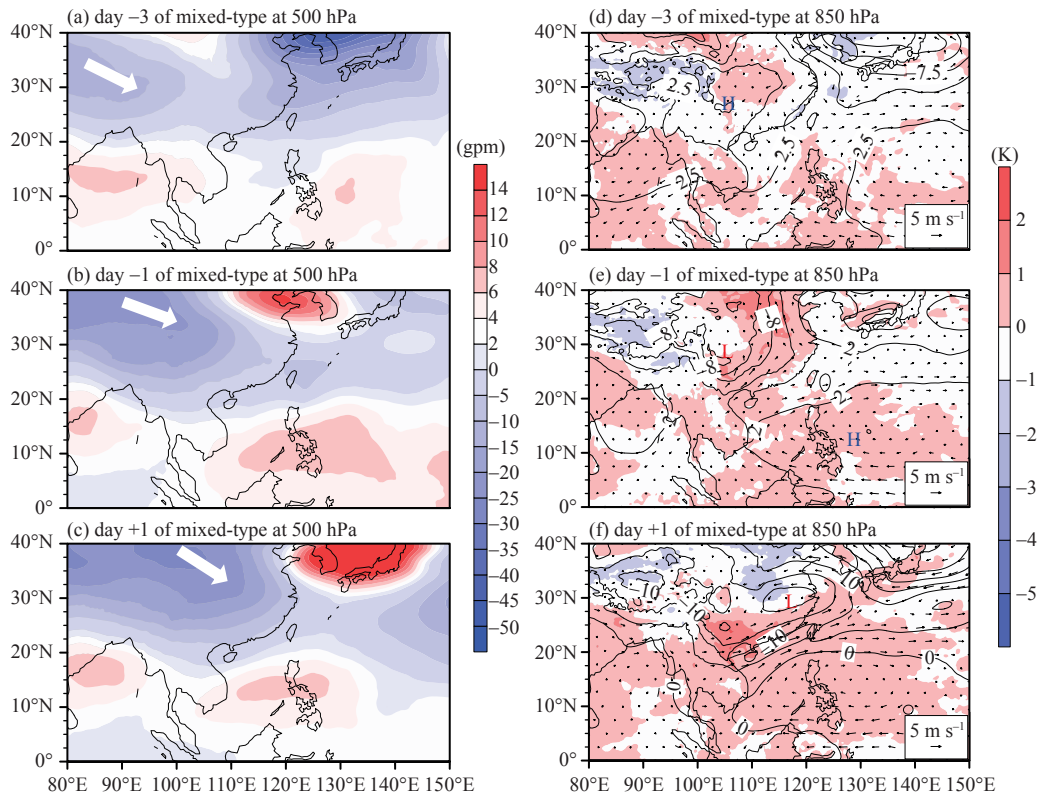


Figure 8. As Fig. 7, but for the mixed surge events. The arrows indicate the movement of the low-pressure anomaly.

tropical disturbances on the winds over the SCS are primarily contributed by the monsoon trough, and QBWO is one of the main sources of tropical disturbances (Wu et al. 2015; Chen et al. 2017; Zhang et al. 2023). Here, we carry out 10–20-day band-pass filtering analysis on the wind of southwesterly-type events, and it shows a clear 12-day cycle in the vorticity field in Fig. 9. During day –8 and day –7, a weak anticyclonic vorticity is located over the SCS and induces the weak southwesterly winds in the key region (Fig. 9a). During day –6 and day –5, a cyclonic vorticity is strengthened over the western Pacific (Fig. 9b) and then develops and moves westward to around 120°E, leading to a strong northerly wind anomaly over the key region (Fig. 9c). Then, the cyclonic system moves westward and reaches the Indochina Peninsula (Figs. 9d and 9e), causing a southerly wind anomaly over the key region. During day +2 and day +3, the cyclonic system in the western SCS weakens but the anticyclonic vorticity in the eastern SCS intensifies, resulting in the continuous strengthening of the southerly wind anomaly (Fig. 9f). Meanwhile, a new cyclonic vorticity signal appears over the western Pacific, indicating the beginning of a new 12-day cycle, which can represent a period of QBWO. Therefore, we can conclude that the southwesterly-type events are affected by the monsoon trough in association with tropical disturbances. The findings agree with previous studies in that the westward-moving tropical waves from Pacific may play a key role in regulating the moisture transport over the SCS (Huangfu et al. 2022; Chen et al. 2023; Hu et al. 2023).

4.2 Diurnal variations

In this subsection, we examine the diurnal variations of the moisture flux. Figs. 10a–10c show the climatic mean diurnal cycle of moisture flux. All three types of surge events show a large value of the diurnal amplitudes over the plain of the Indochina Peninsula and the western SCS, which may relate to the thermal contrast of the land and sea. Meanwhile, the southerly moisture fluxes over the key region reach the maximum around 0200 LST, which is consistent with previous studies (Chen 2020; Chen et al. 2013). There are also some differences in the diurnal amplitudes of three months, with the amplitude over the key region gradually increasing from April to June. Such an increase is mostly obvious in the western and northern SCS. It is also notable that the diurnal amplitude of the region north of 12.5°N is larger than that of the south.

Figures 10d–10f show the diurnal cycle of different types of surge events. The southerly moisture fluxes of each type have obvious diurnal amplitude over the central SCS, and the southwesterly-type events are the largest. In specific, the diurnal amplitude of the southeasterly-type events, which mainly occur in April (Fig. 3b), is much stronger than the climate mean in April (Figs. 10a and 10d). Meanwhile, the diurnal amplitude of the southwesterly-type events, which mainly occurs in June, is stronger than that of the climate mean in June (Figs. 10c and 10f). The position of the maximum of each type's amplitude is different: the southeasterly type is centered over the western SCS, while the mixed type and the southwesterly type expand to the central and northern SCS.

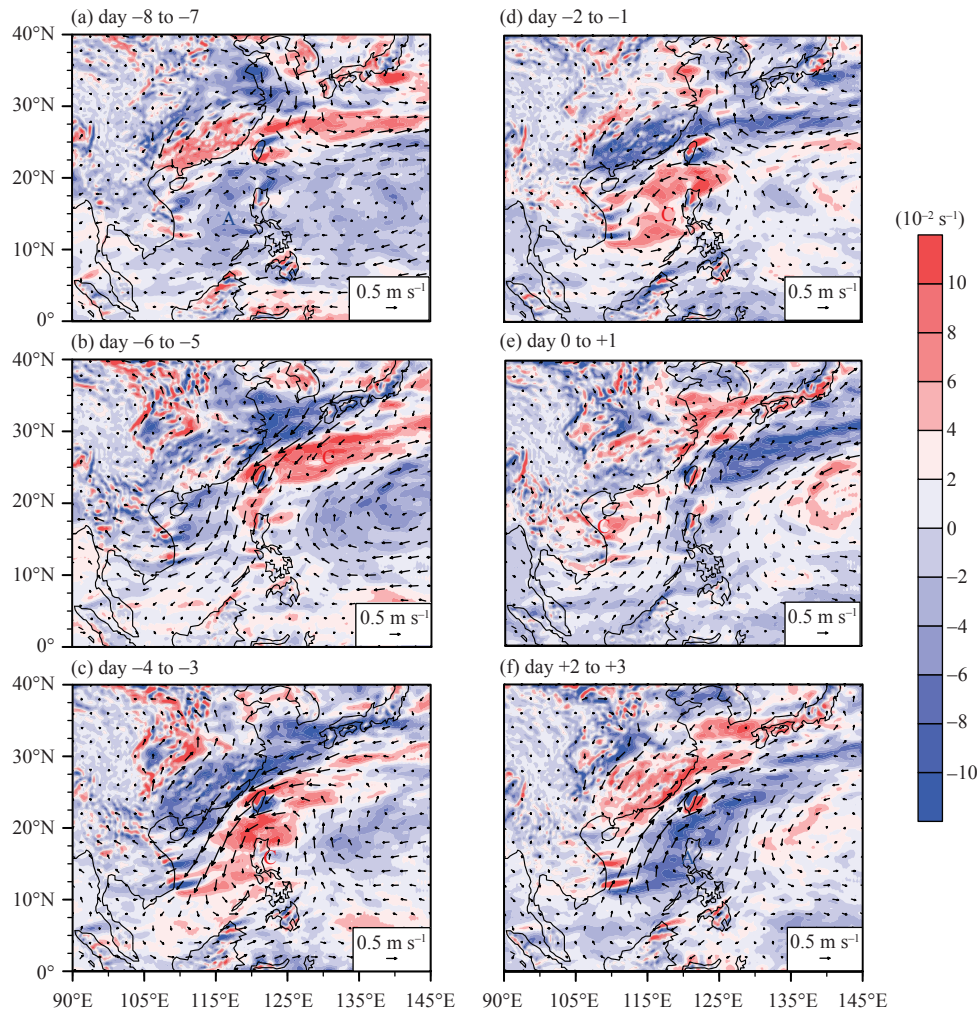


Figure 9. 10–20-day filtered low-level winds (vector) and vorticity (shading) during the southwesterly type of surge events. Two-day average is applied with respect to the occurrence day (day 0 to day +1) of surge events. “A” and “C” denote the center of anticyclone and cyclone of filtered wind patterns, respectively.

Given that the diurnal variations of low-level winds express as a response of local circulations to the land-sea thermal contrast (Fujinami et al. 2022; Liu et al. 2022), we examine the vertical structure of low-level winds and temperature near the key region. Fig. 11a shows a 925-hPa westerly anomaly occurring at 110°E, which indicates the establishment of land breeze due to the cooling effect of the Indochina Peninsula at night. The strong warming of the land occurs in the daytime and the easterly anomaly appears near 110°E and develops upward to 850 hPa at 2000 LST, which indicates a strong sea breeze (Fig. 11b). There is also a center of an easterly anomaly in the plain of the Indochina Peninsula (near 103°E) because of the enhancement of friction. At the same time, the Indochina Peninsula and the SCS show a northerly wind anomaly and a weak southerly wind anomaly appears at 110°E (Fig. 11c). Then, two centers of the strong easterly wind anomaly in Fig. 11b are shifted into a southerly wind anomaly over the Indochina Peninsula and the SCS at 0200 LST and extend upward to about 850 hPa (Fig. 11d). Such a clockwise rotation of wind vectors from 2000 LST to 0200 LST indicates that the southerly wind anomaly at

0200 LST is mainly driven by the inertial oscillation.

We further examine the time evolution of diurnal features near the coast of the Indochina Peninsula after the first day of surge events. The values at 875–975 hPa have the largest diurnal variations (Fig. 11), and thus, they are averaged for analysis. Fig. 12a shows that the maximum temperature of day 0 (over 298.8 K) appears near 1700 LST with an obvious temperature gradient at 108°–112°E. The region of temperature maximum at 1700 LST is increased on day +1, and the strength of the temperature gradient along the coast is also enhanced. The zonal wind gradient of day 0 near 110°E is largest at 2000 LST (Fig. 12b), and the easterly wind along the coast corresponds to the land heating effect in Fig. 12a. On day +1, the easterly wind near the coast is weakened at 2000 LST because of the enhancement of the background westerly wind. The meridional wind has a maximum at 0200 LST near 112°E on day 0 (Fig. 12c), showing a nighttime enhancement, and the nighttime peak at day +1 is further enhanced. The meridional moisture fluxes in Fig. 12d also show a nighttime enhancement, which is highly similar to the meridional wind, indicating that the southerly wind

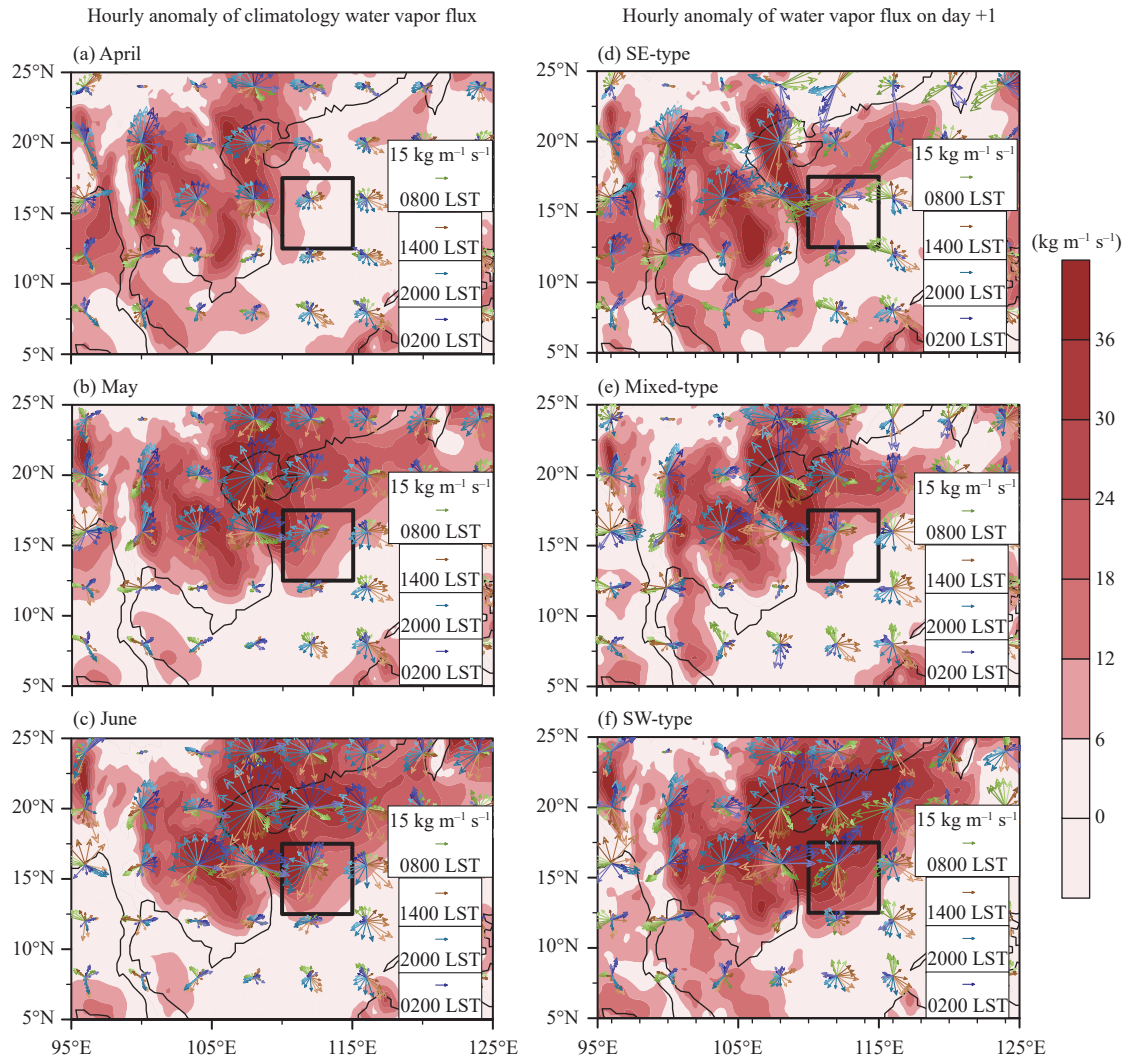


Figure 10. Diurnal deviation of hourly moisture flux (vectors) and diurnal amplitude at 02 LST (shading). (a–c) Averaged for April, May, and June of 1999–2018, and (d–f) three types of events on day +1. The legend shows the vectors at four synoptic hours.

anomaly plays a crucial role in the moisture flux anomaly. As both winds and temperature show evident diurnal variations, we will further analyze the relationship between them.

We further examine how the change of thermal contrast is related to the response in low-level winds. Fig. 13 uses the zonal wind anomaly at the left boundary of the key region as an index and calculates its relationship with surrounding temperature and meridional wind. The zonal wind and temperature of the three types show a significant correlation exceeding 0.4 near the western SCS (Figs. 13a–13c). It indicates that the stronger land surface heating during the day can induce the stronger onshore easterly wind. The zonal wind of the southeasterly type is highly correlated with the meridional wind over the western SCS (Fig. 13d), which indicates that the daytime easterly wind can lead to the southerly wind in the following early morning through inertial oscillation. The region with a high correlation of the other two types extends eastward, with the region of the southwesterly type located over the central SCS (Figs. 13e and 13f). This difference in

locations of high correlation may be related to the momentum transport of the background southwesterly winds (Zeng et al. 2019). In summary, the thermal contrast between the Indochina Peninsula and the SCS can induce the response in diurnal variations of low-level winds.

5 INFLUENCE OF SOUTHERLY MOISTURE SURGES ON DOWNSTREAM RAINFALL

The moisture flux from the SCS to the downstream area can be crucial to the occurrence of heavy rain in South China (Simmonds et al. 1999; Li 1999; Du and Chen 2018, 2019; Sun et al. 2019). Here, we examine whether the different types of surge events have different effects on rainfall in the downstream areas. Fig. 14 shows the spatial distributions of rainfall associated with the three different types. During the southeasterly-type events, the rainfall is weak on day –1 (Fig. 14a) and then increases remarkably on day +1. The largest increment of rainfall occurs over the inland region at 28°N with the maximum rainfall exceeding 22 mm day^{–1} and a relatively small increment occurs along the coast (Fig. 14b). During the

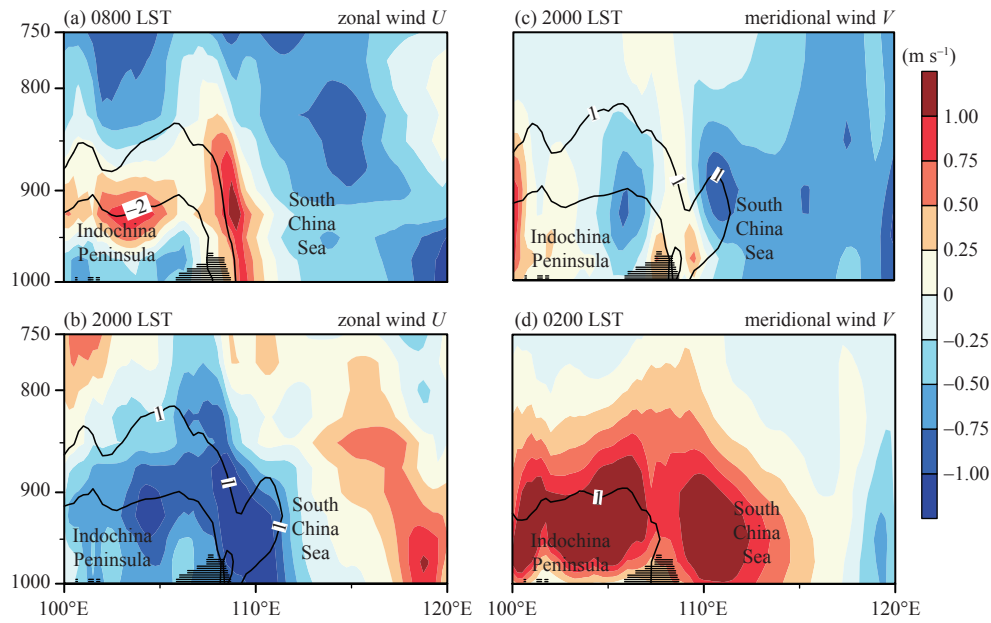


Figure 11. Longitude-vertical cross section of (a) zonal wind anomaly at 0800 LST on day +1 (shading), and 12-h temperature increment (black contours) averaged over 12.5° – 17.5° N. (b) Zonal wind anomaly (shading) at 2000 LST on day +1, 12-h temperature increment (black contours), and temperature zonal anomaly (purple contours). (c) is the same as (b) but for meridional wind anomaly (shading) at 2000 LST on day +1. (d) is the same as (c), but for the meridional wind anomaly (shading) at 02 LST on day +2. The black-filled areas denote the coastal orography of the Indochina Peninsula.

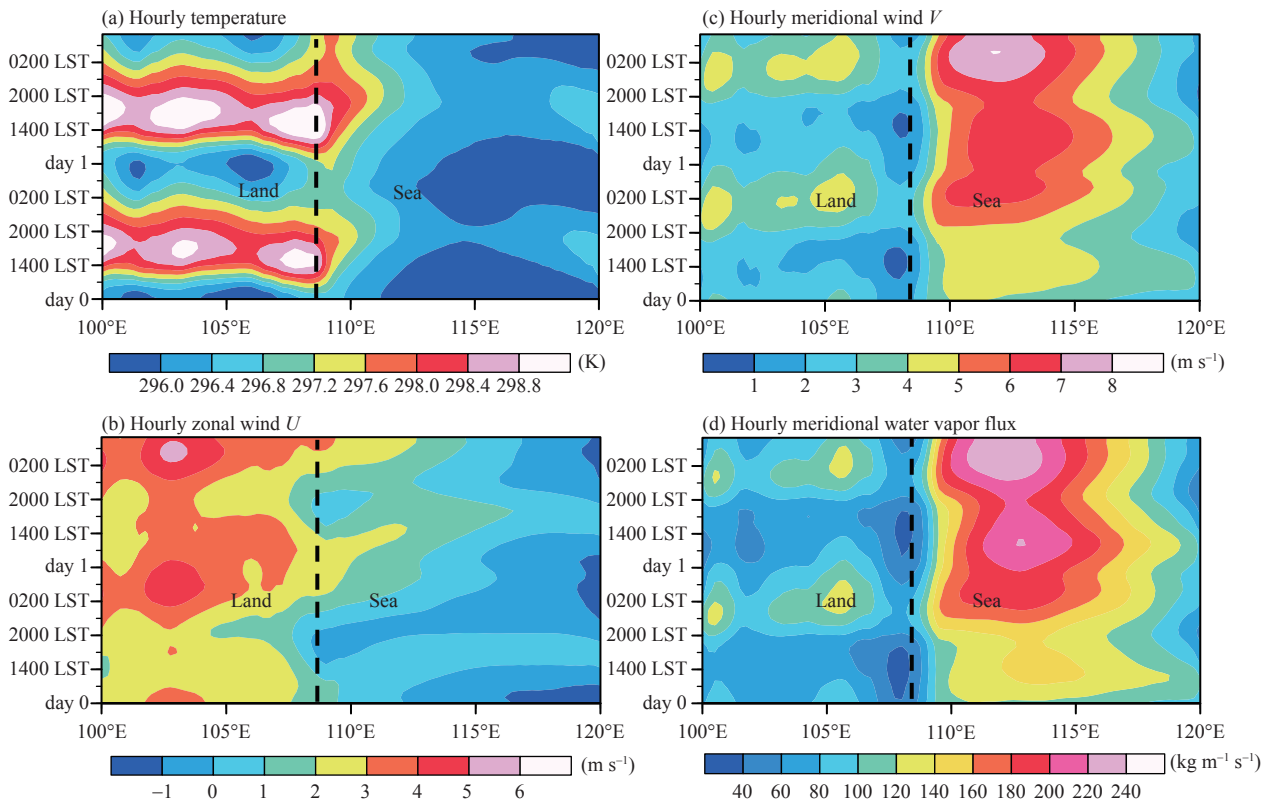


Figure 12. Temporal evolution of (a) temperature, (b) zonal wind, (c) meridional wind, and (d) meridional moisture flux averaged over 875–975 hPa at the latitudes of 12.5° – 17.5° N from day 0 to day +1.

southwesterly-type events, large rainfalls are observed over the central SCS near 10° N on day -1 and then move northward remarkably to the coastal region near 22° N on day +1, with a large value over 22 mm day^{-1} . There are

also some apparent rainfalls over the SCS and eastern Indochina Peninsula, which is different from the southeasterly-type events. As for the mixed-type events, strong rainfall occurs off the coast of South China around

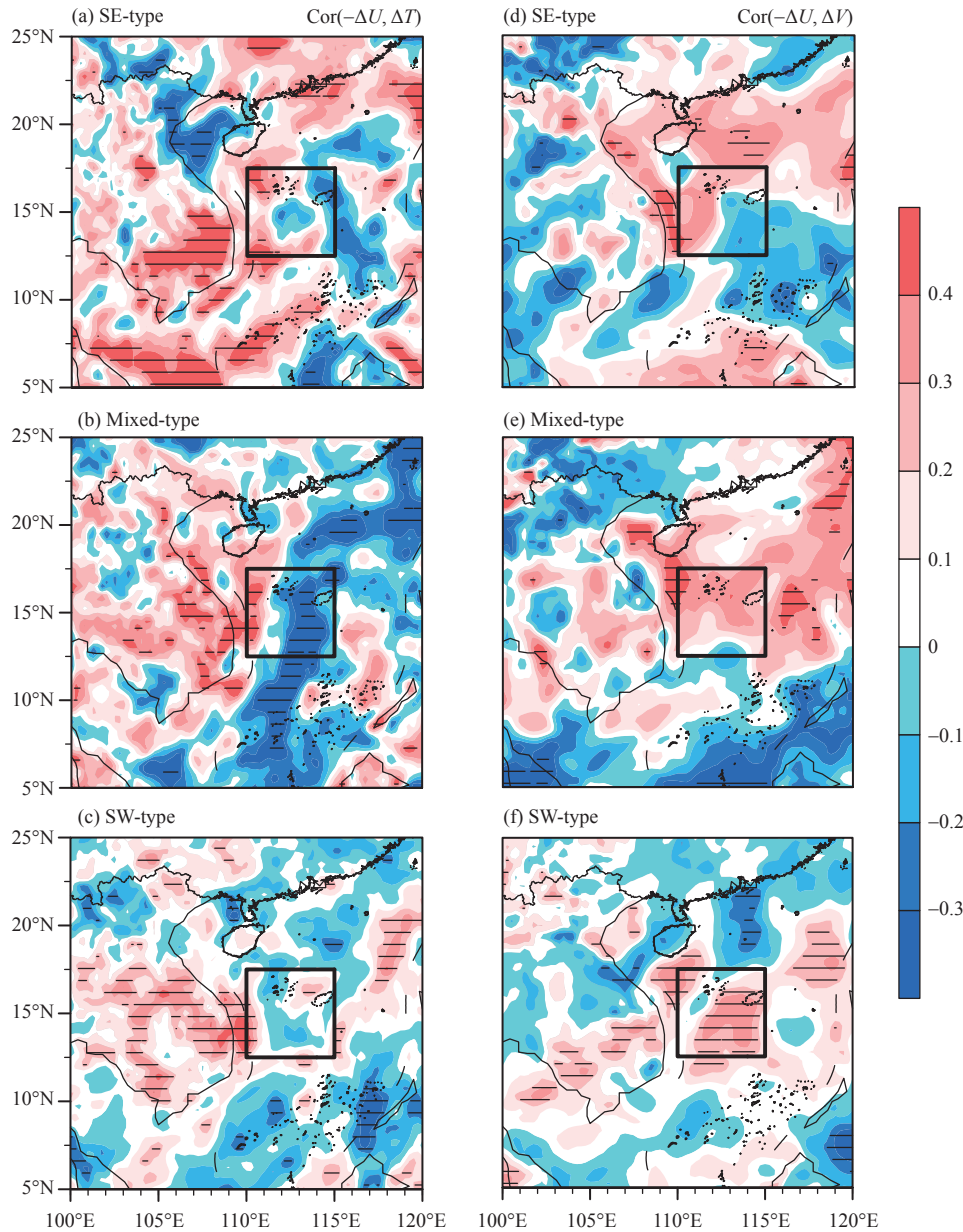


Figure 13. Correlation coefficient between the daytime easterly wind increment $-\Delta U$ (i.e., 2000 LST minus 0800 LST) average over at $12.5^{\circ}\text{--}17.5^{\circ}\text{N}$ of 110°E . (a–c) The daytime temperature increase ΔT (i.e., 1700 LST minus 0800 LST), and (d–f) the nighttime southerly wind increment ΔV (i.e., 0200 LST minus 2000 LST). The hatching denotes the values with statistically significance at the 99% confidence level. The black solid boxes represent the key region.

20°N on day -1 , and some weak rainfalls occur over the inland region. Then, the large rainfalls move northward to 22°N on day $+1$ and there is also an increment of inland rainfall. The coastal rainfall of mixed-type events is weaker than the southwesterly-type events, due to the moisture flux of the mixed type is also weaker. In conclusion, the rainfall of the southeasterly type mainly occurs over the inland region, the southwesterly type mainly occurs over the coastal region, and the mixed type has two large values over the coastal and inland regions.

From the spatial distribution, we can see that there are obvious differences in the rainfall of the three types in the coastal areas, so we further examine the impact of surge events on coastal rainfall. Fig. 15 shows the frequency

distribution of coastal rainfall (black boxes in Fig. 14) of various rain rates. During the southeasterly-type events, the frequency of rainfalls which is less than 10 mm day^{-1} can be up to 70% before day 0 (Fig. 15a). Then the maximum frequency reaches 75% with the value of rainfalls increases from 7 mm day^{-1} to 15 mm day^{-1} after day $+1$, which shows the enhancement effect of the southeasterly-type events on coastal rainfalls. During the southwesterly-type events, the frequency of rainfalls which is less than 15 mm day^{-1} can increase up to 65% before day 0 (Fig. 15b). Then, the maximum frequency accounts for 55% with the value of rainfalls increases from 13 mm day^{-1} to 20 mm day^{-1} after day $+1$. Moreover, there is a notable increase in high rainfall values, which exceeds

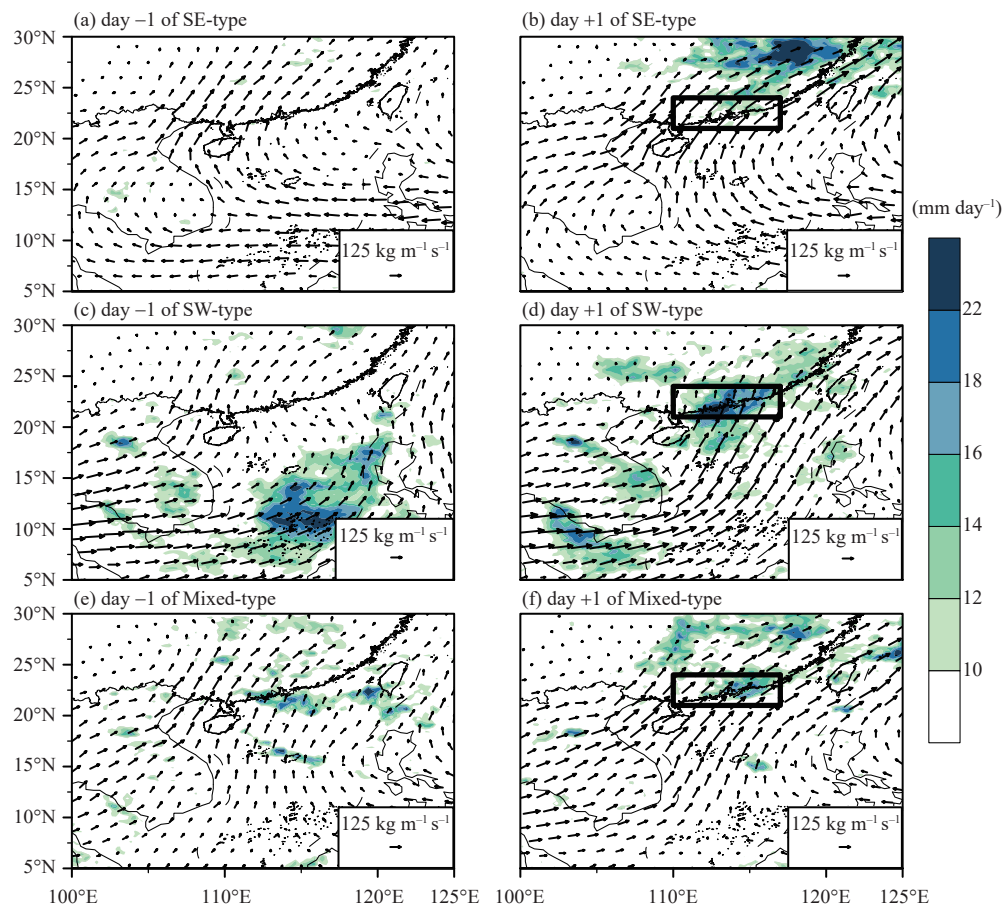


Figure 14. Horizontal distribution of rainfall (shading) and moisture flux (vectors) on day -1 (left panel) and day +1 (right panel) of (a–b) southeasterly-type events, (c–d) southwesterly-type events, and (e–f) mixed-type events. The black boxes indicate the coastal area (21°–23°N, 110°–120°E).

20 mm day⁻¹ in 3 hours, with the frequency increase from 25% to 40%. During the mixed-type events, the maximum frequency of coastal rainfalls decreases from 18 mm day⁻¹ to 10 mm day⁻¹ (Fig. 15c) due to the rainfall moving from the coast into the land after day 0 (Figs. 14e and 14f). Therefore, different types of surge events have different impacts on coastal rainfall.

Figure 16 shows the spatial and temporal evolution of rainfall and moisture convergence in different types of surge events in a 5-day window before and after the first day of the surge events. During the southeasterly-type events, the rainfalls increase obviously after day 0, and the large rainy region moves from north to south (Fig. 16a), which indicates the southward movement of westerly disturbance (Fig. 6d). To the diurnal variations, the rain over the inland regions (around 28°N) develops at night, peaks in the morning, and decays in the afternoon during day 0 and day +1. Then, the large rainy region moves southward to 24°N on day +2, with a peak occurring at 1400 LST and a small rainfall peak occurring near 22°N in the morning. The features of moisture convergence are highly similar to the rainfall, the convergence is enhanced remarkably to $0.07 \times 10^{-3} \text{ kg m}^{-2} \text{ s}^{-1}$ and gradually moves southward after day 0 (Fig. 16d). There are also two morning peaks of inland moisture convergence from day

+1 to day +2, and the morning peak along the coast on day +2 is observed. Furthermore, the northern SCS and coastal area (south of 22°N) show obvious moisture divergence, while the regions north of 22°N show obvious convergence.

The rainfall also increases after the first day of the southwesterly-type events. The coastal rainfall develops rapidly from early morning and then propagates inland and offshore during day +1 and day +2 (Fig. 16b). The coastal rainfall (around 22°N) is stronger than that of the inland region (around 28°N), which is different from the southeasterly-type events. The features of moisture convergence are also similar to rainfall, with the regions of large convergence mainly located on the coast (Fig. 16e). Due to the impacts of the tropical disturbances, the northern SCS shows obvious moisture convergence near the coast in the morning of this type, which is different from the southeasterly-type events.

During the mixed-type events, there are two rainfall bands over the inland (around 28°N) and coastal region (around 22°N), and the inland rain increases firstly since day 0 (Fig. 16c). The inland rain band intensifies at night and reaches its maximum in the morning. There is also an obvious morning rain peak along the coast on day -1, which is consistent with the feature in Fig. 14e. It shows an

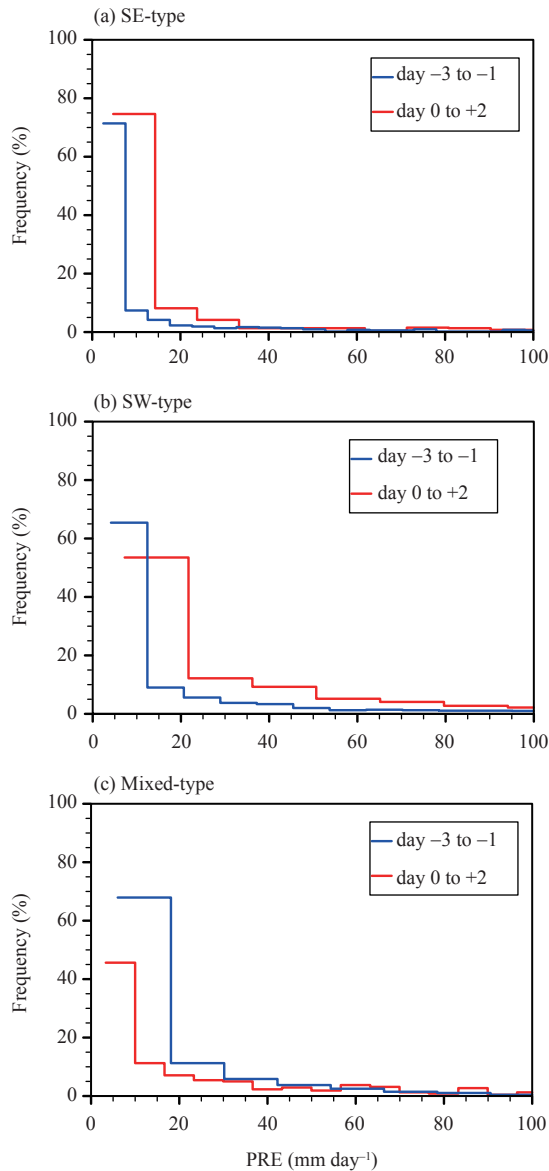


Figure 15. Frequency distribution of average 3-hour cumulative rainfall in the coastal area (21° – 23° N, 110° – 120° E) from day -3 to day -1 (blue line) and day 0 to day $+2$ (red line) for (a) southeasterly-type events, (b) southwesterly-type events, and (c) mixed-type events.

offshore propagation before day 0 but exhibits an inland propagation from day $+1$ to day $+2$. The moisture convergence also shows two large value regions along the coast and inland, and the maximum appears in the morning (Fig. 16f). The rainfall of all three types exhibits a clear diurnal variation, with the rainfall peaks in the morning (around 0800 LST) at 22° N and 28° N and in the afternoon (around 1400 LST) at 24° N.

Due to the evident variations of the rainfalls near the coast, we further examine the role of the surge events in the diurnal variation of coastal rainfalls, we analyze the features of the moisture budget there (black boxes in Fig. 14). Fig. 17 shows that the moisture flux increases remarkably after day $+1$, with the mean value increasing from $80 \text{ kg m}^{-1} \text{ s}^{-1}$ to $200 \text{ kg m}^{-1} \text{ s}^{-1}$, and the maximum

appears during 0200–0400 LST in the early morning. The moisture convergence is also enhanced, with the mean value increasing from $1 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$ to more than $3 \times 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$. The peak of convergence also appears in the early morning, and the amplitude of diurnal variation shows a slight increase. Due to the obvious enhancement of moisture flux and convergence, the rainfall increases remarkably, with the mean value increasing from 17 mm day^{-1} to 40 mm day^{-1} . Meanwhile, the diurnal amplitude of rainfall is increased with an afternoon peak. The rainfall begins to increase rapidly from 1100 LST on day $+1$, following the peak of convergence during 0800–1000 LST, and the rainfall begins to increase rapidly from 0500 LST on day $+2$, following the peak of convergence during 0200–0400 LST. Therefore, the rainfall will reach the peak with a lag of about 3 hours to the maximum moisture convergence. In summary, the enhancement of moisture transport caused by the southwesterly-type events makes strong moisture convergence, leading to increased rainfall and its diurnal variation. The southeasterly-type events show similar features with the southwesterly type but with a smaller increment, while the rainfall of the mixed type is reduced to some extent (figures not shown), which is consistent with the features in Fig. 15c.

6 SUMMARY AND DISCUSSION

This study evaluates the southerly moisture surge events that can last for a few days in the central SCS during April and June from 1999 to 2018. The surge events are categorized into three types: southeasterly-type events, southwesterly-type events, and mixed-type events. The differences and impacts of these three types of events, in terms of multiscale activity features, associated atmospheric conditions, and the impacts of the surge events on rainfall, are clarified. The main findings are summarized as follows.

We identified a total of 92 surge events. Among them, there are 22 southeasterly-type events, 50 southwesterly-type events, and 20 mixed-type events. The mixed-type events appear relatively evenly from April to June with a duration of 6 days. The frequency and duration of the occurrence of another two types show subseasonal changes. The southeasterly-type events primarily occur in April with a duration of 3 days, while the southwesterly-type events mainly occur in June with a longer duration of 8.5 days.

Our study mainly focuses on the synoptic scale and diurnal variations of the surge events. On the synoptic scale, the maximum of northward flux in the southeasterly-type events is located around 22° N and gradually extends to the key region. Meanwhile, there is a large gradient near 27° N, and gradually shifts southward to the coast. As for the southwesterly-type events, the maximum of northward flux is around 15° N and gradually shifts northward. The northern boundary of strong moisture flux for this type is in the coastal area and gradually shifts northward. The mixed-type events are a transitional state, which combines

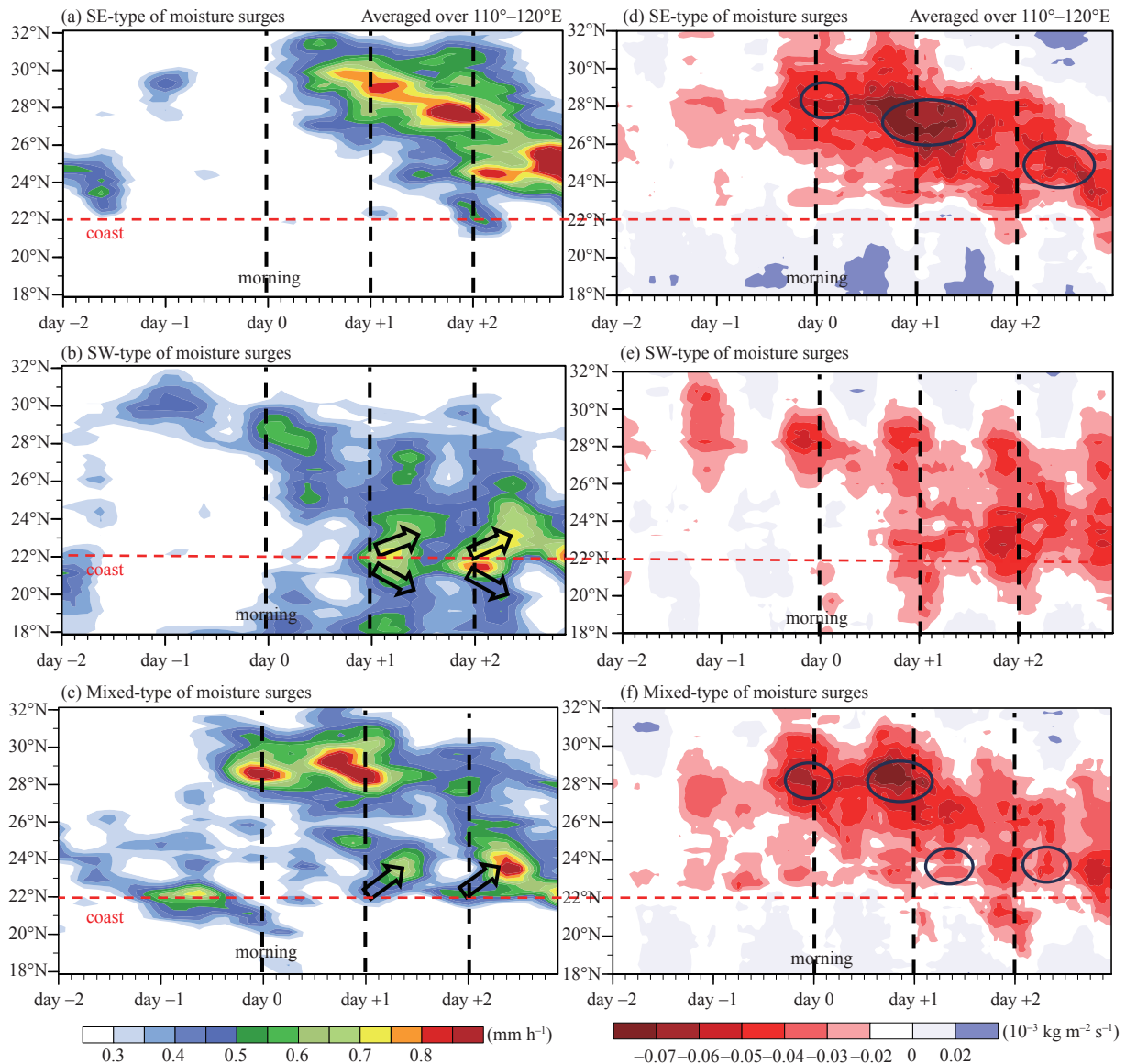


Figure 16. Average 3-hour cumulative rainfall at 110° – 120° E from day -2 to day $+2$ (a) southeasterly-type events, (b) southwesterly-type events, and (c) mixed-type events. (d–f) are the same as (a–c), but for moisture convergence. The arrows indicate the propagation direction of rainfalls, and the circles indicate the large center of convergence.

features of the first two types. On the diurnal scale, each type exhibits two peaks, one in the early morning and the other in the afternoon. The southeasterly surges are dominated by the afternoon peak, while the southwesterly surges are dominated by the early morning peak. However, the mixed-type events have a dominant afternoon peak before the events' occurrence and are shifted to a dominant early-morning peak during the surge events.

The difference in the activities in each type is due to the different associated atmospheric conditions. Both the southeasterly-type events and mixed-type events are affected by the disturbance of westerlies, but the high-pressure anomaly over the SCS is stronger during the southeasterly-type events. In contrast, the southwesterly-type events are mainly affected by the monsoon trough associated with the westward-moving QBWO. As for the

diurnal variation, the amplitude of the moisture flux increases north of 15° N during all three types, with the maximum of southerly transport anomalies occurring at 0200 LST. The early morning southerly wind anomaly is mainly caused by the thermal effects along the eastern coast of the Indochina Peninsula, which leads to the enhancement of the easterly wind, and then the southerly wind is enhanced by inertial oscillation.

The impacts of the three types of surge events on rainfall in downstream areas is also different. In terms of the spatial distribution of rainfall, the rainfall is centered over inland areas with a little rainfall along the coast during the southeasterly-type events. However, more intense rainfall is seen over the coastal area during the southwesterly-type events. During the mixed-type events, there are two rain bands along the coast and inland. There is a distinct difference between coastal and inland rainfall

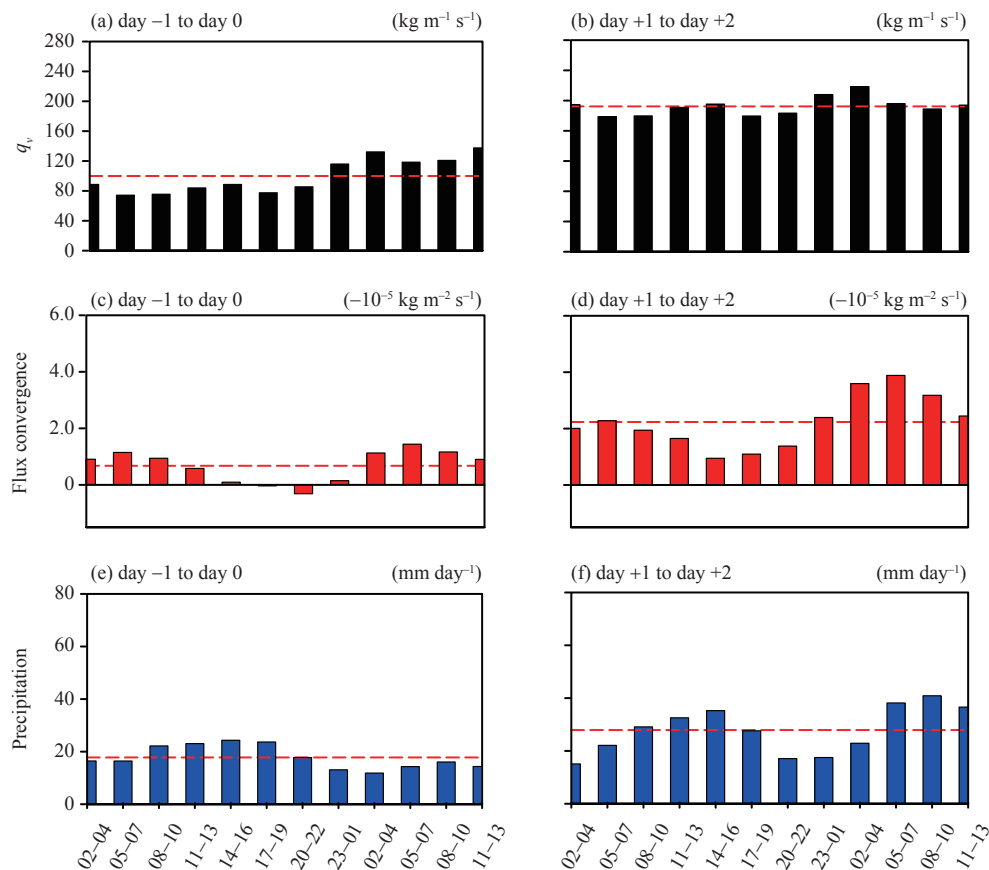


Figure 17. (a–b) northward moisture flux at 21°N averaged every 3 hours, (c–d) moisture convergence averaged every 3 hours, and (e–f) 3-hour cumulative rainfall averaged over ($21^\circ\text{--}23^\circ\text{N}$, $110^\circ\text{--}120^\circ\text{E}$) of the southwesterly-type events. (a), (c), and (e) from day -1 to day 0 , while (b), (d), and (f) from day $+1$ to day $+2$. The red dashed lines represent the mean value of the selected period.

peaks for all types: the rainfall at 22°N and 28°N is peaked at 0800 LST, but it peaked at 1400 LST near 24°N . The rainfall developing in the morning and peaking in the afternoon is caused by the increasement of the mean northward moisture flux and convergence along the coast after the first day of surge events.

Our study identifies southerly moisture surges in central SCS during April and June from 1999 to 2018, clarifies their diverse features and associated atmospheric conditions from diurnal to subseasonal scales, and examines their distinct impacts on downstream rainfall. Although there are some apparent differences among each type of surge events, they all contribute to the generation of rainfall in downstream areas and play a crucial role in understanding the mechanism of heavy rain in South China. Our research focuses on the impacts of synoptic disturbances, QBWO, and local thermal forcing on moisture transport. However, other synoptic weather systems including atmospheric rivers, LLJs, cross-equatorial flow, and tropical cyclones may also affect the moisture transport (Acosta and Huber 2017; Albano et al. 2017; Barbero et al. 2019; Hu et al. 2018). Previous studies also pointed out that sea surface temperature and the SCS summer monsoon onset may have important impacts on moisture transport (Mo and Juang 2003; Huangfu et al.

2022; Gu et al. 2024). We shall carry out studies of synoptic weather systems and oceanic influence in the future and further analyze the multi-scale features of moisture transport over the SCS.

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