

Article ID: 1006-8775(2026)03-0271-17

## Convection Initiation of Short-term Heavy Rainfall Events in Shanghai Under the Influence of the Western Pacific Subtropical High During the 2022 Extreme Heatwave

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**Abstract:** Downdrafts tend to suppress convection under the influence of the western Pacific subtropical high (WPSH); however, local short-term heavy rainfall (STHR) events still occur frequently in coastal cities, and predicting the convective initiation (CI) of such processes remains challenging. Based on ERA5 reanalysis data and an automatic weather station (AWS) network, the meteorological conditions of STHR and non-rainfall (NR) events were compared and analyzed using hourly synthesis analysis methods. The findings are as follows. (1) Suppression by the WPSH results in stronger vertical upward motion during STHR events, with  $-0.04 \leq \omega \leq -0.03 \text{ Pa s}^{-1}$ , than during NR events, with  $-0.03 \leq \omega \leq -0.015 \text{ Pa s}^{-1}$ . (2) STHR events, with over 80% AWSs  $\geq 38^\circ\text{C}$ , exhibit quicker temperature rises, higher peak temperatures, and more extensive areas of heat coverage compared to NR events, with only 16.5% AWSs  $\geq 38^\circ\text{C}$ . (3) STHR events, with a convergence of the  $\mathbf{Q}$  vector divergence of  $-0.4 \times 10^{-11} \text{ hPa}^{-1} \text{ s}^{-3}$ , compared to NR events, with a convergence of the  $\mathbf{Q}$  vector divergence of  $-0.2 \times 10^{-11} \text{ hPa}^{-1} \text{ s}^{-3}$ , are also accompanied by more intense surface convergence and upward motion, conditions which reveal the significance of local dynamics in triggering such weather events. (4) The weaker suppressive effect of the WPSH, combined with a significant mesoscale thermodynamic force near the ground, creates a multiscale resonance effect, which is a key condition for triggering local convection. (5) The lower temperature–dew point temperature spread ( $T - T_d$ ) at 2 m and relative humidity below 850 hPa for STHR events indicate that moisture conditions are sufficient, but not necessary, for triggering local convection. This study provides new insights into CI mechanisms under the influence of the WPSH for STHR events, thus offering important clues for future improvements in forecasting capabilities.

**Key words:** short-term heavy rainfall; western Pacific subtropical high; vertical upward motion; convection initiation

**CLC number:** P445

**Document code:** A

**Citation:** Chen, S. Q., C. J. Yue, and Y. Gao, 2026: Convection Initiation of Short-term Heavy Rainfall Events in Shanghai Under the Influence of the Western Pacific Subtropical High During the 2022 Extreme Heatwave. *J. Trop. Meteor.*, **32**, 271–287, <https://doi.org/10.3724/j.1006-8775.2026.016>.

## 1 INTRODUCTION

The western Pacific subtropical high (WPSH) is a key component of the Chinese summer climate, which influences the movement of rain belts and significantly impacts extreme heatwaves and severe convective weather in Eastern China. Specifically, under the influence of the WPSH, cold air tends to shift towards northern China. The WPSH is formed by the descending branch of the Hadley circulation, with affected areas mainly experiencing clear

and hot weather (Peixoto and Oort 1992; Zhou et al. 2022). Although convective activity is relatively weak under this meteorological background, local convective precipitation can still occur in the afternoon. For instance, in the summer of 2022, the Yangtze River Basin experienced an extraordinary heat wave (HW) that set new records in its intensity, duration, and spatial extent, leading to substantial societal and economic damage. The persistence and severity of this event were associated with the synergistic effects of abnormally high pressure in the Western North Pacific and the eastward extension of the South Asian High into the upper troposphere (Zhang et al. 2023). During this period, Shanghai, situated along China's eastern coastline, was subjected to successive extreme heatwaves, with daily peak temperatures frequently reaching or surpassing  $38^\circ\text{C}$ . The city also encountered multiple episodes of localized short-term intense rainfall, which presented significant challenges for forecasting.

Comprehensive elucidation of the mechanisms that trigger local convection is crucial for accurately predicting subsequent convective storm development and potentially severe weather (Markowski and Richardson 2010). Over

**Received** 2025-02-19; **Revised** 2025-06-19; **Accepted** 2025-11-03

**Funding:** Science and Technology Talent Project of Shanghai Meteorological Service (KJRC202408); National Natural Science Foundation of China (41875059, 41875071); AI for Science Program, Shanghai Municipal Commission of Economy and Informatization (2025-GZL-RGZN-BTBX-02034); Youth Innovation Team of China Meteorological Administration (CMA2024QN02)

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time, convection has been recognized to be caused by the multiscale coupling effects of large-scale and local meteorological circulation and surface conditions (Bai et al. 2021; Du and Chen 2019). Convection initiation (CI) is typically categorized into two primary types: surface-based and elevated convection. The former is often triggered by boundary layer convergence and can be observed in radar and satellite images (Wilson and Schreiber 1986). Conversely, elevated convection typically occurs under stable atmospheric conditions (Wilson and Roberts 2006). Surface-based convection has been extensively studied, indicating that its initiation typically requires a clear ascending mechanism such as large-scale fronts, low-level jets, outflow boundaries, land-sea breezes, and gravity waves (Bai et al. 2020; Du et al. 2020; Trier et al. 2017; Wilson and Roberts 2006). Simultaneously, the urban heat island (UHI) effect plays a significant role in convective enhancement in urban areas, enhancing low-level convergence and maintaining an unstable layer near the surface through thermal disturbances (Huang et al. 2019; Zhang et al. 2017). However, the lifting caused solely by UHI is typically insufficient to trigger or enhance deep moist convection. Therefore, combined with other external factors, including large-scale and mesoscale environments (Huang et al. 2019), terrain forcing (Wu et al. 2021), land-sea circulation (Sun et al. 2021), and forcing from existing precipitation systems, are conducive to triggering or enhancing urban convection. However, local situations are often complex and variable, and the interactions between these local changes and external factors pose significant challenges for accurately predicting the timing and location of convection.

As an important city on the southeastern coast of China, Shanghai is significantly affected by the WPSH during the summer. Short-term heavy rainfall (STHR) events under its influence are characterized by their locality and suddenness, thus necessitating the exploration of their CI mechanisms for weather forecasting and early warning systems. Traditional theories suggest that the center of the WPSH is dominated by descending airflows, which are not conducive to cloud formation and precipitation. Therefore, studies on clouds and precipitation within the center of the WPSH are limited. However, existing studies often utilize satellite products or spaceborne precipitation radar detection results. Research indicates that the occurrence of precipitation in the center of the WPSH is related to significant differences in atmospheric vertical motion (Feng and Fu 2009; Feng and Liu 2009; Wu and Liu 2003). Upward motion in the atmospheric environment is an important condition for convective precipitation in the center of the WPSH (Fu et al. 2006; Fu and Xian 2017). Moreover, the CI of such precipitation events is thought to be intricately linked to local atmospheric dynamics, including localized vertical motions (Yue et al. 2018), the development of surface

convergence lines (Qi and Chen 2009), and thermal disparities intensified by the UHI effect (Wang et al. 2015). Previous studies have focused on individual cases, revealing the main mechanisms triggering typical convective events; however, such processes have not been comprehensively elucidated. First, because the potential impact range of these processes is only 20–40 km, sparse radiosonde station data may fail to comprehensively capture the mesoscale meteorological conditions of CI. Radiosonde data, which are conventional observational datasets, exhibit relatively coarse spatial resolution, necessitating high spatial resolution and dense unconventional observations from automatic weather stations (AWSs). Second, under the influence of the WPSH, the warming effect is significant; in contrast with the conditions at the edge of the subtropical high, which have adequate water vapor transport, the moisture conditions may not be ideal. Meanwhile, phenomena such as UHIs and sea–land breezes can easily lead to upward motion but do not necessarily trigger convection. Therefore, exploration of the specific thresholds of dynamic and thermodynamic conditions that trigger local convection is essential. In addition, although there have been some statistical analyses (Gu et al. 2015; Ying and Cao 2010), they are mainly based on samples from different years and months, which may not eliminate the impacts of climate background differences. Therefore, a composite statistical analysis study based on STHR events in the same year and month will be more meaningful.

This study was based on the ERA5 reanalysis data and comprehensive AWS network observations in Shanghai, and both hourly and dynamic synthesis analyses were employed. Our objective was to compare and analyze the large-scale environment and mesoscale dynamic and thermodynamic characteristics of two distinct weather scenarios: 4 STHR events and 12 non-rainfall (NR) events that occurred during 16 high-temperature days in August 2022 under the influence of the WPSH. We aim to reveal the regularity and specificity of the CI of STHR events under the influence of the WPSH more objectively, providing scientific and technological support for precise forecasting and refined services for severe local convection in coastal megacities.

The rest of the article is organized as follows. In Section 2, the data and methods for STHR synthesis are described. In Section 3, we use hourly synthesis analysis to examine the differences in meteorological conditions between the STHR and NR events under the influence of the WPSH. In Section 4, dynamic synthesis analysis is used to discuss the key factors contributing to the CI of STHR events. Finally, the conclusions are presented in Section 5.

## 2 DATA AND METHOD

### 2.1 Data introduction

The local STHR events in this study were defined by the formation and development of local convective cloud

clusters within Shanghai under the influence of the WPSH. The radar reflectivity factor exceeded 35 dBZ, and the 1-h precipitation recorded at 3 or more AWSs surpassed 20 mm; meanwhile, a high-temperature day in Shanghai was characterized by conditions under which the maximum temperature at 2 m above ground level at three or more AWSs exceeded 35 °C under the influence of the WPSH.

For the main subject of this study, 16 high-temperature day samples occurring in Shanghai during August 2022 were selected (Table 1), with peak temperatures ranging from 35.4 to 42.9 °C. Of these days, 4 STHR events, occurring on August 11, 12, 13, and 23 from 11:00 to 15:00 LST (UTC+8), were chosen. During these events, recorded rainfall amounts were between 48.4 and 85.3 mm, and wind speeds peaked between 13.6 and 26.7 m s<sup>-1</sup>. We also included 12 NR events in this study for a comparative synthesis analysis. The ERA5 reanalysis used in this article features a 1-h temporal resolution and a 0.25° horizontal spatial resolution, providing 281 meteorological elements across 37 isobaric levels, including geopotential height, temperature, air pressure, wind, humidity, etc. (Hersbach et al. 2020). Recent studies have shown that the quality of ERA5 reanalysis data is superior to that of other reanalysis data, such as ERA-Interim (Albergel et al. 2018; Bian et al. 2021). The recently released ERA5 reanalysis, with its hourly resolution and fine horizontal spacing, enables the study of local convective environments in which prior reanalysis could not be achieved (Li et al. 2020; Taszarek et al. 2021a; Taszarek et al. 2021b).

More than 280 AWSs in Shanghai were selected for the study. First, the Barnes method (Barnes 1964) was used to interpolate and generate gridded data at a resolution of 5 km×5 km. Second, simple arithmetic accumulation averaging of 1-min average gridded data over six

consecutive time points was performed every 6 min to obtain gridded data, which were used for diagnostic calculations and synthesis analysis.

## 2.2 Method for synthesis of CI

As shown in Fig. 1, the initial positions of convection are mainly located at the junctions of the urban and suburban areas of Shanghai and are concentrated in the northern parts of Shanghai, such as Baoshan, Yangpu, and Northeastern Pudong. In this study, we focused primarily on severe convection events in the afternoon. Therefore, the hourly synthesis analysis method was used to synthesize meteorological elements such as temperature, pressure, wind, and humidity within this area (121.25°–

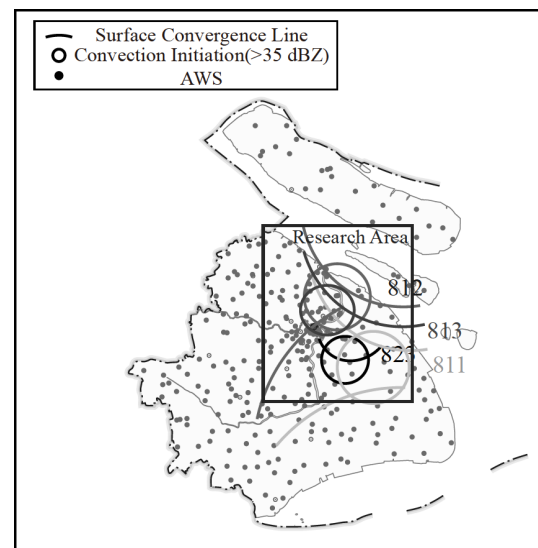


**Figure 1.** Locations of CI for STHR in August 2022 and distribution of AWS. The shading area represents the primary CI aggregation zone, while the gray shading denotes the Shanghai city center. This figure is based on the base map bearing the map review number GS(2019)3333.

**Table 1.** Overview of local STHR and NR samples in Shanghai, August 2022.

| Heatwave date<br>(mm-dd) | CI time | Precipitation time | Total precipitation<br>(mm) | Extreme wind speed<br>(m s <sup>-1</sup> ) | Max temperature<br>(°C)/Time |
|--------------------------|---------|--------------------|-----------------------------|--------------------------------------------|------------------------------|
| 08-02                    | —       | —                  | —                           | —                                          | 38.9/14:13                   |
| 08-03                    | —       | —                  | —                           | —                                          | 38.9/14:33                   |
| 08-04                    | —       | —                  | —                           | —                                          | 39.8/15:01                   |
| 08-05                    | —       | —                  | —                           | —                                          | 42.4/14:51                   |
| 08-07                    | —       | —                  | —                           | —                                          | 41.0/14:58                   |
| 08-08                    | —       | —                  | —                           | —                                          | 40.3/15:17                   |
| 08-09                    | —       | —                  | —                           | —                                          | 41.7/15:50                   |
| 08-11                    | 13:35   | 13:42              | 63.2                        | 26.0                                       | 42.7/13:49                   |
| 08-12                    | 12:04   | 12:06              | 48.4                        | 22.0                                       | 41.7/13:33                   |
| 08-13                    | 13:04   | 13:12              | 71.5                        | 22.4                                       | 42.5/15:25                   |
| 08-14                    | —       | —                  | —                           | —                                          | 42.1/14:25                   |
| 08-15                    | —       | —                  | —                           | —                                          | 42.6/14:53                   |
| 08-18                    | —       | —                  | —                           | —                                          | 38.8/14:38                   |
| 08-19                    | —       | —                  | —                           | —                                          | 42.5/14:29                   |
| 08-22                    | —       | —                  | —                           | —                                          | 43.1/15:40                   |
| 08-23                    | 11:53   | 12:06              | 85.3                        | 19.8                                       | 43.6/12:33                   |

121.75°E, 31.0°–31.5°N). This method involves taking the arithmetic average of hourly meteorological elements from 08:00 to 12:00 LST.

### 2.3 Introduction to diagnostic analysis methods

In this study, we mainly used the non-geostrophic  $\mathbf{Q}$  vector divergence, temperature–dew point temperature difference, equivalent potential temperature, and other analytical diagnostic quantities, which are introduced as follows:

(1) Non-geostrophic  $\mathbf{Q}$  vector divergence that requires data from a single level

Starting from the fundamental equations for an  $f$ -plane, quasi-static, adiabatic, and frictionless atmosphere in pressure coordinates, and using the replacement balance approximation (i.e., replacing the actual wind vertical shear with the geostrophic wind vertical shear), a method for analyzing the non-geostrophic  $\mathbf{Q}$  vector divergence that requires data from a single level was derived (Yue et al. 2018). In the  $P$ -coordinates, the calculation formula is as follows:

$$\mathbf{Q}_x = -\frac{R}{P} \left( \frac{\partial u}{\partial x} \frac{\partial T}{\partial x} + \frac{\partial v}{\partial x} \frac{\partial T}{\partial y} \right) \quad (1)$$

$$\mathbf{Q}_y = -\frac{R}{P} \left( \frac{\partial u}{\partial y} \frac{\partial T}{\partial x} + \frac{\partial v}{\partial y} \frac{\partial T}{\partial y} \right) \quad (2)$$

The non-geostrophic  $\omega$  equation with  $\mathbf{Q}$  vector divergence as the force term is as follows:

$$\nabla^2 (\sigma\omega) + f^2 \frac{\partial^2 \omega}{\partial p^2} = -2 \nabla \cdot \mathbf{Q} \quad (3)$$

When the  $\omega$  field has wave-like characteristics, Eq. (3) is expressed as follows:

$$\nabla \cdot \mathbf{Q} \propto \omega \quad (4)$$

Equation (4) can be used to determine vertical motion. When  $\nabla \cdot \mathbf{Q} < 0$ ,  $\omega < 0$ , upward motion is indicated. When  $\nabla \cdot \mathbf{Q} > 0$ ,  $\omega > 0$ , downward motion is indicated.

#### (2) Temperature–dew-point difference ( $T-T_d$ )

Under normal conditions, the temperature–dew-point difference ( $T-T_d$ ) can be used to represent the relative humidity in the atmosphere. Relative humidity was inversely related to  $T-T_d$ . When  $T-T_d$  is close to 0 °C, the air humidity has reached a nearly saturated state. Usually, when  $T-T_d \leq 2$  °C, the air humidity is approximately saturated. When  $T-T_d$  is between 4 and 5 °C, the air is relatively moist. Many studies have indicated that the temperature–dew-point difference can be used as a forecasting parameter for severe convection (Yue et al. 2018).

#### (3) Equivalent potential temperature

The equivalent potential temperature is the temperature at a certain referential pressure height when air is lifted during a moist adiabatic process, and is a thermo-hygrometric quantity that can represent atmospheric instability. When the equivalent potential

temperature decreases with height, the air becomes unstable, which is conducive to the occurrence and development of convection. In this study, the equivalent potential temperature was calculated using the MetPy Library (May et al. 2022), as follows:

$$e_s = 6.112 \exp \left[ \frac{17.67(T-273.15)}{T-29.65} \right] \quad (5)$$

$$T_d = \frac{243.5 \log(\text{RH} \cdot e_s / 6112)}{17.67 - \log(\text{RH} \cdot e_s / 6112)} \quad (6)$$

$$T_L = \frac{1}{\frac{1}{T_d - 56} + \frac{\ln(T/T_d)}{800}} + 56 \quad (7)$$

$$\theta_{DL} = T \left( \frac{p_0}{p} \right)^{\frac{R_d}{c_p}} \left( \frac{T}{T_L} \right)^{0.28r} \quad (8)$$

$$r = \frac{0.622 e_s}{p - e_s} \quad (9)$$

$$\theta_e = \theta_{DL} \exp \left[ \left( \frac{3036}{T_L} - 1.78 \right) r (1 + 0.448r) \right] \quad (10)$$

where  $e_s$  is the saturated water vapor pressure,  $T$  is the atmospheric temperature,  $T_d$  is the dew point temperature, RH is the relative humidity,  $T_L$  is the temperature at the lifting condensation level (LCL temperature),  $p_0$  is the standard atmospheric pressure (taken here as 1000 hPa),  $p$  is the pressure,  $R_d$  is the specific gas constant for dry air (taken here as 287.04 J K<sup>−1</sup> kg<sup>−1</sup>),  $c_p$  is the specific heat capacity of dry air at constant pressure (taken here as 1005.7 J K<sup>−1</sup> kg<sup>−1</sup>),  $\theta_{DL}$  is the potential temperature at the LCL,  $r$  is the saturated mixing ratio, and  $\theta_e$  is the equivalent potential temperature.

Other diagnostic variables were included in the analysis. The disturbance temperature, disturbance dew-point temperature, and disturbance temperature dew-point difference ( $T-T_d$ ) collectively refer to the deviations from their respective baseline values at 08:00 LST. The convective available potential energy (CAPE) is a measure of the potential energy available for convection in the atmosphere and is typically expressed in joules per kilogram (J kg<sup>−1</sup>). The  $K$  index was used to assess the potential for convective weather, particularly thunderstorms. Diagnostic variables, including CAPE and the  $K$  index, were acquired directly from ERA5; therefore, they are not introduced in detail here.

## 3 HOURLY SYNTHESIS ANALYSIS

### 3.1 Analysis of large-scale environment

In August, the Shanghai region was influenced by the WPSH (Figs. 2a and 2b). At 850 hPa, both STHR and NR conditions were dominated by warm and moist southwesterly airflow, with temperatures maintained above 22 °C and relative humidity around 50%–60% (Figs. 2c and 2d). Additionally, the CAPE for STHR conditions

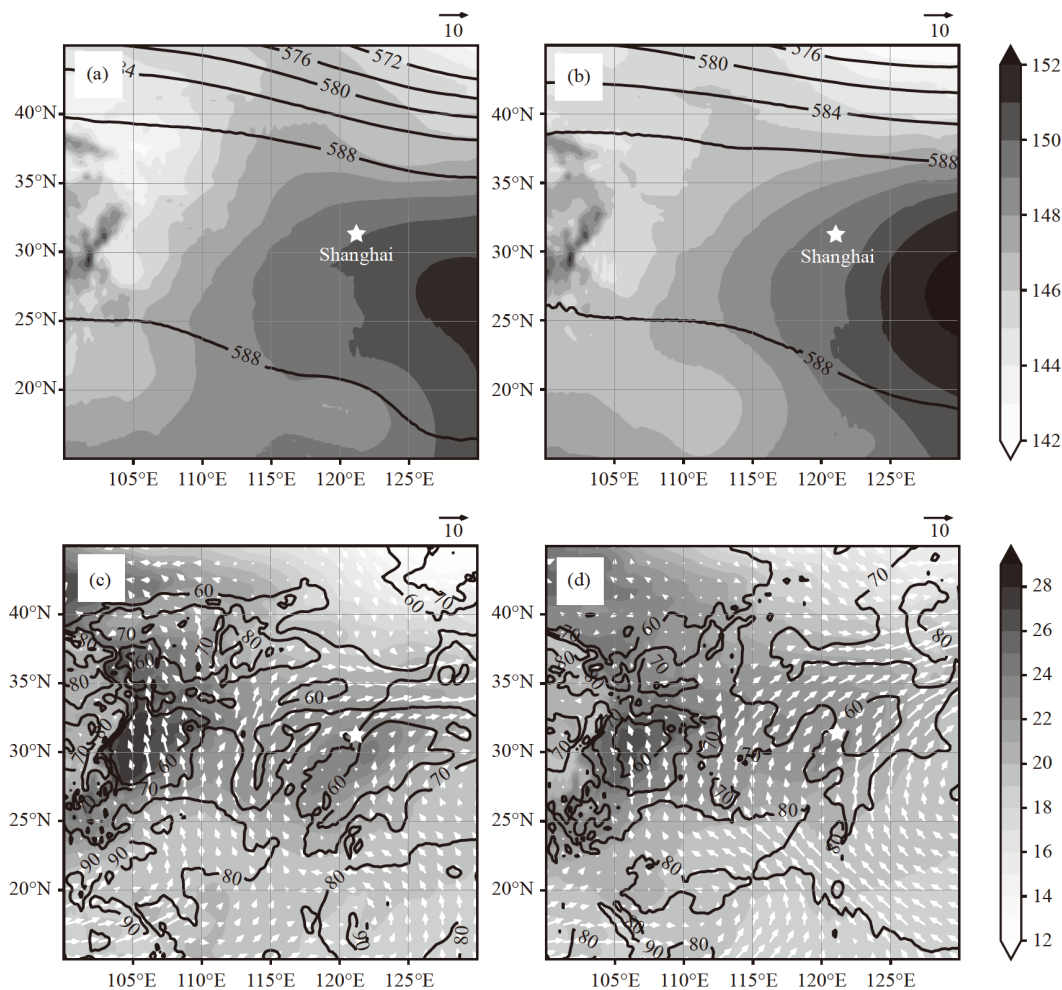


**Figure 2.** Circulation pattern fields for August 2022: (a, b) overlaid maps of 500 hPa geopotential height (contours; units: gpm) and 850 hPa geopotential height (shading; units: gpm); and (c, d) overlaid maps of 850 hPa relative humidity (contours; units: %), temperature (shading; units: °C), and wind field (vectors; units:  $\text{m s}^{-1}$ ). The left column shows STHR events; the right column shows NR events.

ranged between 2500 and 3000  $\text{J kg}^{-1}$ , and the  $K$  index between 35 and 40 °C. The CAPE for NR conditions ranged between 1000 and 1500  $\text{J kg}^{-1}$ , and the  $K$  index was around 30 °C (Fig. 3). Both scenarios exhibited relatively stable CAPE and  $K$  index values over time, and the values at 08:00 LST were indicative of the differences in energy conditions between the STHR and NR events, indicating that in both scenarios, the Shanghai region is controlled by

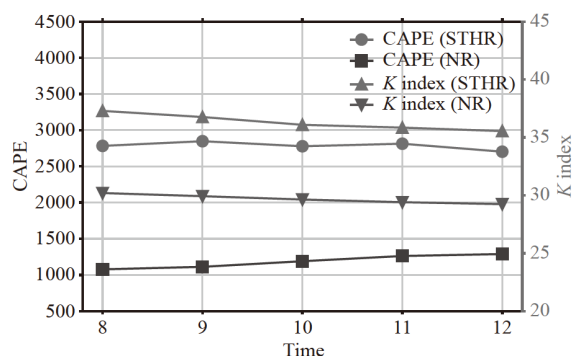


**Figure 3.** Time series of CAPE (units:  $\text{J kg}^{-1}$ ) and  $K$  index (units: °C).

a similar large-scale environment, affected by high temperatures, thermal instability, and generally moderate relative humidity. The STHR conditions exhibited relatively significant unstable energy and stratification; however, owing to the significant suppression of the subtropical high, sufficient lifting conditions were lacking. Therefore, it is necessary to focus on the impact of mesoscale systems on the CI of STHR events. Subsequent analyses will focus on the local dynamic factors within Shanghai, including the impacts of UHI circulation and land-sea breezes on the boundary layer convergence line, as well as assess the spatial and temporal patterns of regional heat, humidity, and momentum transfer. By synthesizing and analyzing the differences in the physical parameters between the two scenarios, the key regulatory mechanisms causing event differences are expected to be revealed.

### 3.2 Atmospheric vertical upward motion and equivalent potential temperature

Our analysis shows that atmospheric vertical upward motion was more active during STHR events than during NR events (Fig. 4), thus suggesting a weaker suppression

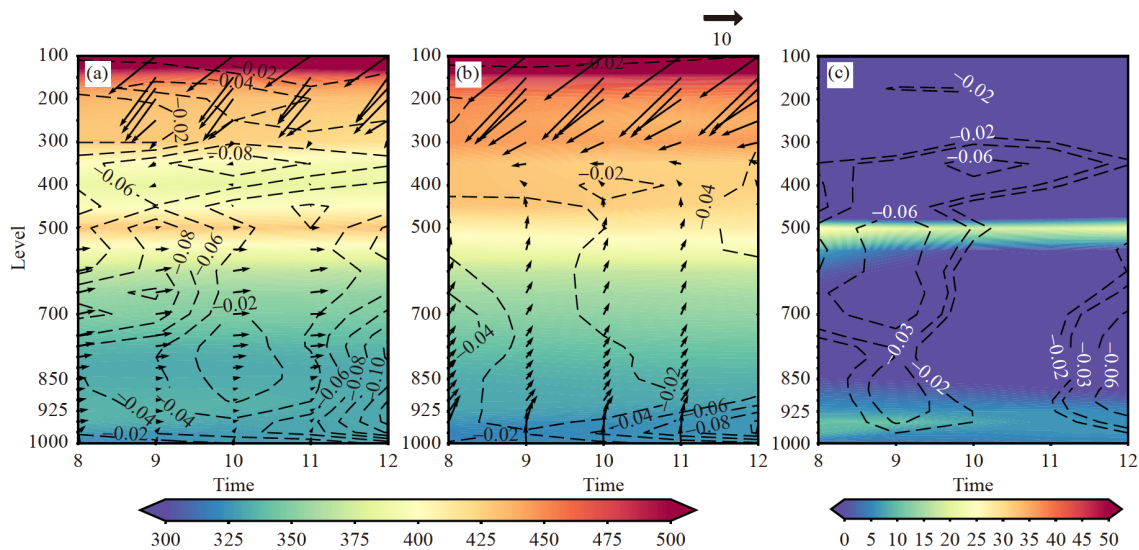


**Figure 4.** Time series for vertical velocity (black contours; units:  $\text{Pa s}^{-1}$ ), equivalent potential temperature (shading; units: K), and wind field (vectors; units:  $\text{m s}^{-1}$ ): (a) STHR events, (b) NR events, and (c) difference between STHR and NR events. The y-axis represents level (units: hPa).

effect caused by WPSH, which is consistent with previous research findings (Feng and Fu 2009; Feng and Liu 2009). In particular, during two periods (08:00–09:00 LST and 11:00–12:00 LST), the vertical upward motion between 1000 and 300 hPa was more active (Fig. 4c). Between 11:00 and 12:00 LST, the upward motions during both the STHR and NR events intensified rapidly owing to boundary layer convergence. In the case of STHR events, the upward motions extended from the lower layers above 700 hPa and were significantly greater than those observed during NR events (Figs. 4a and 4b). At these times, the average  $\omega$  (from 100 to 1000 hPa) for the entire layer ( $\omega_{\text{avg}}$ ) of STHR events was the highest at  $-0.08 \text{ Pa s}^{-1}$ , while, for NR events, it was only  $-0.041 \text{ Pa s}^{-1}$  (Fig. 5). At 10:00 LST, the upward motion weakened during the STHR events. Concurrently, downward motion intensified. Additionally, STHR events show more significant vertical wind shear in the lower and middle layers than NR events, but significantly less than the wind shear required for the development of common multicellular (approximately  $10 \text{ m s}^{-1}$  for 0–6 km wind

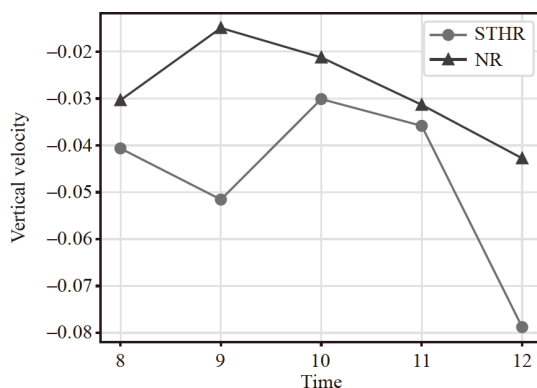


**Figure 5.** Time series of the whole-layer average vertical velocity (units:  $\text{Pa s}^{-1}$ ).

shear) and supercell (approximately  $20 \text{ m s}^{-1}$ ) storms (Markowski and Richardson 2010). At the same time, the equivalent potential temperature ( $\theta_e$ ) for STHR events ranged between 1000 and 850 hPa and, at 500 hPa, was higher than that for NR events (Fig. 4). Commencing at 08:00 LST, the vertical decrement rate of  $\theta_e$  at 850 hPa, and around 400 hPa for STHR events, exceeded 0, which indicates a distinct convective instability stratification conducive to the development of convective systems. The above analysis indicates that weaker suppression by the WPSH, significant boundary layer convergence, and unstable stratification contributed to the CI of STHR events.

### 3.3 Atmospheric humidity conditions

Humidity conditions during the STHR and NR events differed significantly. The RH, below 850 hPa for STHR events, was sustained between 50% and 70%, which was slightly lower than that for NR events, and the STHR conditions exhibited a deeper moist layer (Fig. 6). The specific humidity (SH) for STHR conditions (at 850 hPa) ranged from 14.0 to 14.5  $\text{g kg}^{-1}$ , and the average SH below 500 hPa ( $\text{SH}_{\text{avg}}$ ) ranged from 11.0 to 11.5  $\text{g kg}^{-1}$  (Fig. 7), values which were notably greater than those for NR scenarios. Furthermore, starting at 08:00 LST, STHR conditions exhibited significant vertical upward moisture transport; the SH for STHR conditions at 850 hPa increased, from 13.8 to 14.5  $\text{g kg}^{-1}$ , and the  $\text{SH}_{\text{avg}}$  increased, from 11.2 to 11.6  $\text{g kg}^{-1}$ . Between 11:00 and 12:00 LST, the SH at 850 hPa showed a sharp increase of 0.5  $\text{g kg}^{-1}$ . The  $\text{SH}_{\text{avg}}$  values for the NR conditions remained relatively unchanged, and the SH at 850 hPa showed a downward trend (Fig. 7). These results indicate that abundant atmospheric moisture content, combined with appropriate vertical moisture transport, is key to triggering STHR events, a process that is not necessarily

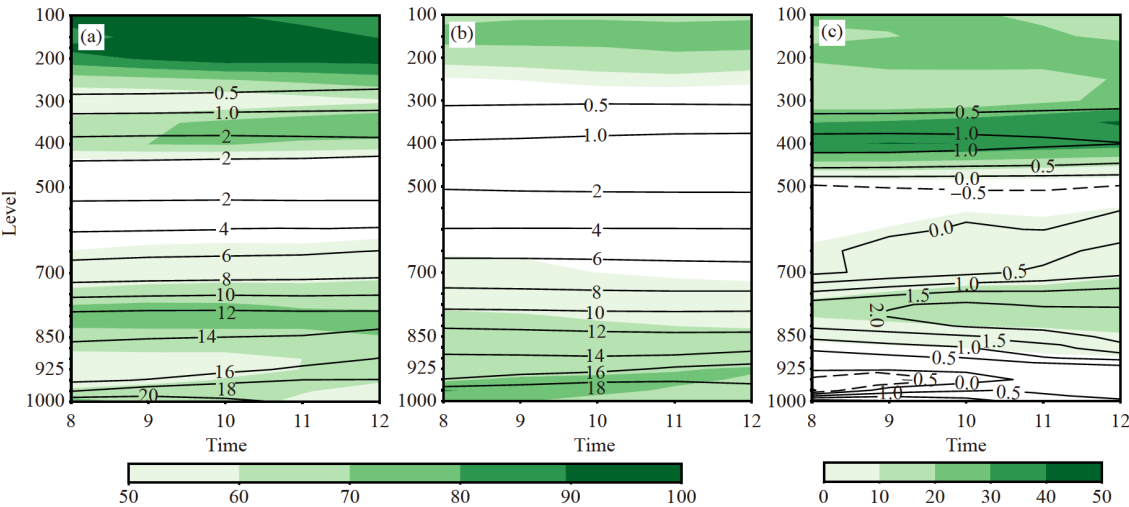


**Figure 6.** Time series for SH (contours; units:  $\text{g kg}^{-1}$ ) and RH (shading; units: %): (a) STHR events, (b) NR events, and (c) difference between STHR and NR events. The y-axis represents level (units: hPa).

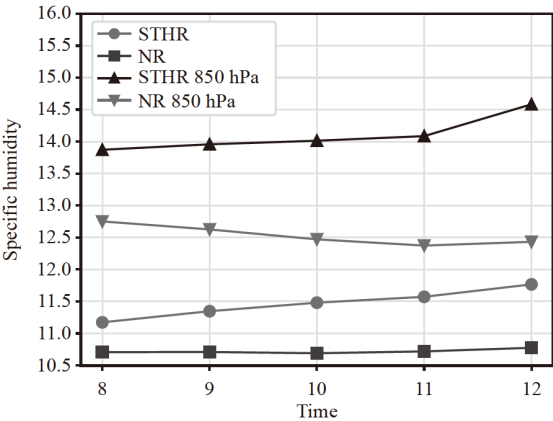


**Figure 7.** Time series of whole-layer average SH below 500 hPa (units:  $\text{g kg}^{-1}$ ).

associated with high low-level relative humidity.

3.4 Local thermal conditions

By 09:00 LST, approximately 60% of the AWSs recorded temperatures exceeding  $35^{\circ}\text{C}$  during STHR events; by 12:00 LST, approximately 85% surpassed  $38^{\circ}\text{C}$ , with 11.6% even exceeding  $40^{\circ}\text{C}$  (Fig. 8a). Conversely, during NR events at 09:00 LST, temperatures remained below  $35^{\circ}\text{C}$ , and by 12:00 LST, only 16.5% reached  $38^{\circ}\text{C}$  (Fig. 8b). From 09:00 to 12:00 LST, the disturbance temperature for STHR events increased, from 1.7 to  $5.4^{\circ}\text{C}$ , and the gap with disturbance temperature for NR events widened, from 0.5 to  $1^{\circ}\text{C}$  (Fig. 9), a trend which suggests a comparatively accelerated warming rate for STHR events. Furthermore, under the influence of extreme HWs, temperatures increased significantly under STHR conditions, resulting in notable temperature gradient

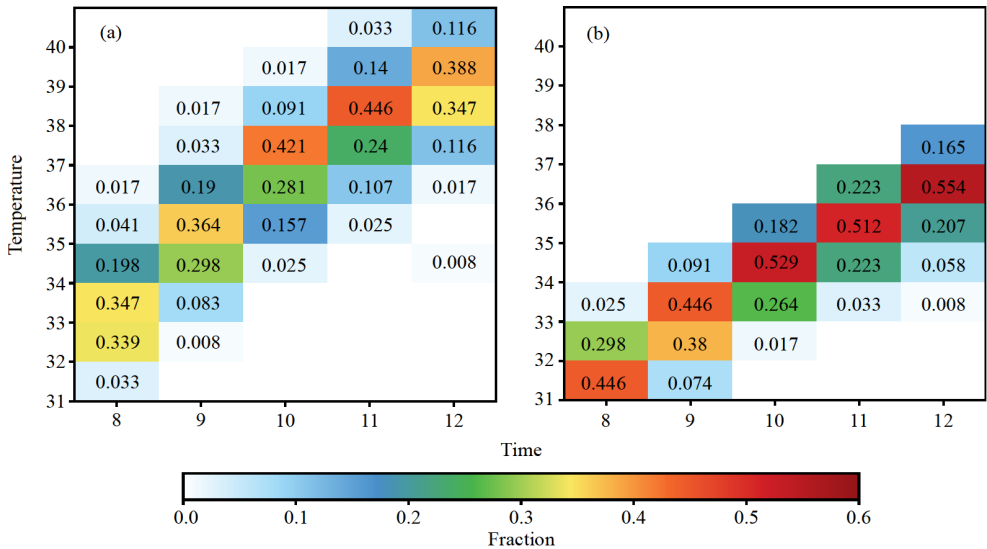


**Figure 8.** Time series for high-temperature frequency distribution at AWSs: (a) STHR events and (b) NR events. The y-axis represents temperature (units:  $^{\circ}\text{C}$ ).

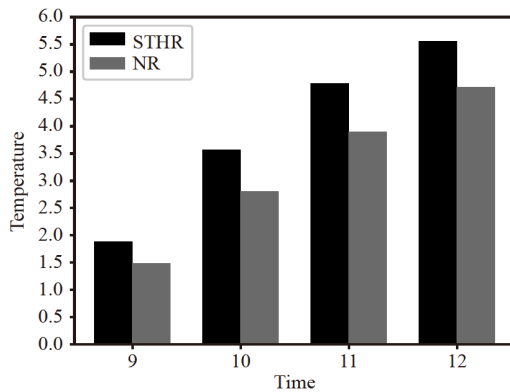


**Figure 9.** Time series of disturbance temperature (units: °C).

changes at the junctions of riverside, coastal, and urban district areas. Higher temperatures were observed near the main urban areas of Shanghai, while surface warming during NR events was relatively weaker (Fig. 10). Additionally, owing to land–sea thermal differences and rapid surface warming, from 09:00 to 12:00 LST in the northern riverside areas of Shanghai, a distinct sea breeze phenomenon was observed during STHR events, characterized by a shift in the coastal wind direction from southerly to easterly–southeasterly winds, with wind velocities rising to  $4\text{--}5\text{ m s}^{-1}$ ; however, from 08:00 to 12:00 LST during NR events, wind speeds exhibited minimal variation, thus maintaining a southerly direction without discernible sea breeze occurrence (Fig. 10).

Further analysis of the differences indicates that, under the influence of an extreme HW, STHR conditions experience a faster warming rate, higher temperatures, and a broader coverage of high temperatures. The temperature differences between land and sea in the north also promote

the formation of sea breezes, thereby favoring the formation of convergence lines, such as sea breeze fronts, indicating that stronger thermal forcing is one of the important factors triggering convection during STHR events.

### 3.5 Local dynamics and humidity conditions

In both the STHR and NR scenarios, Shanghai exhibited pronounced near-surface convergence characteristics; however, the range and intensity of convergence were greater during STHR events. Our analysis revealed that, from 10:00 to 12:00 LST, the convergence area for STHR events, where the convergence of the  $\mathbf{Q}$  vector divergence reached  $-0.2 \times 10^{-11}\text{ hPa}^{-1}\text{ s}^{-3}$ , increased from 10.7% to 21.5%, with stronger convergence areas where the convergence of the  $\mathbf{Q}$  vector divergence exceeded  $-0.4 \times 10^{-11}\text{ hPa}^{-1}\text{ s}^{-3}$ , reaching 5% (Fig. 11a). Conversely, for the NR events, the convergence area increased from 2.5% to 8.3% (Fig. 11b). In terms of relative humidity conditions, at 08:00 LST, the  $T-T_d$  ( $\leq 6^\circ\text{C}$ ) area for STHR events accounted for 40.5%, compared with 32.3% for NR events, indicating slightly better relative humidity conditions for STHR events at the time. From 10:00 to 12:00 LST, the  $T-T_d$  ( $8\text{--}10^\circ\text{C}$ ) area for STHR events decreased, from 45.5% to 6.7%, and the  $T-T_d$  ( $\geq 10^\circ\text{C}$ ) area increased, from 48.8% to 93.4% (Fig. 11c); the  $T-T_d$  ( $8\text{--}10^\circ\text{C}$ ) area for NR events decreased, from 75.2% to 13.2%, and the  $T-T_d$  ( $\geq 10^\circ\text{C}$ ) area increased, from 19.8% to 86.8% (Fig. 11d). In terms of disturbance  $T-T_d$ , from 08:00 to 12:00 LST, the gap between STHR and NR conditions increased, from 0.5 to  $1^\circ\text{C}$  (Fig. 12a); from 09:00 to 12:00 LST, the relative humidity conditions for STHR events were

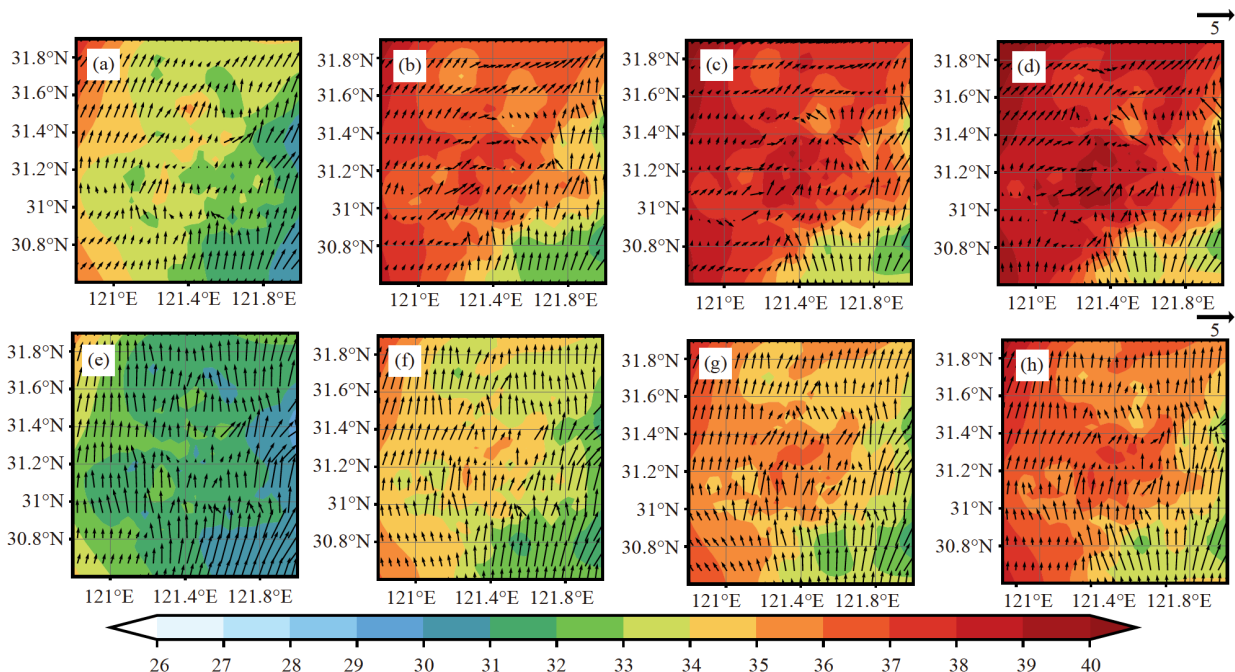


**Figure 10.** Spatiotemporal overlay of 2 m temperature (shading; units: °C) and wind field (contours; units:  $\text{m s}^{-1}$ ) at 08:00, 10:00, 11:00, 12:00 LST under (a–d) STHR and (e–h) NR conditions.

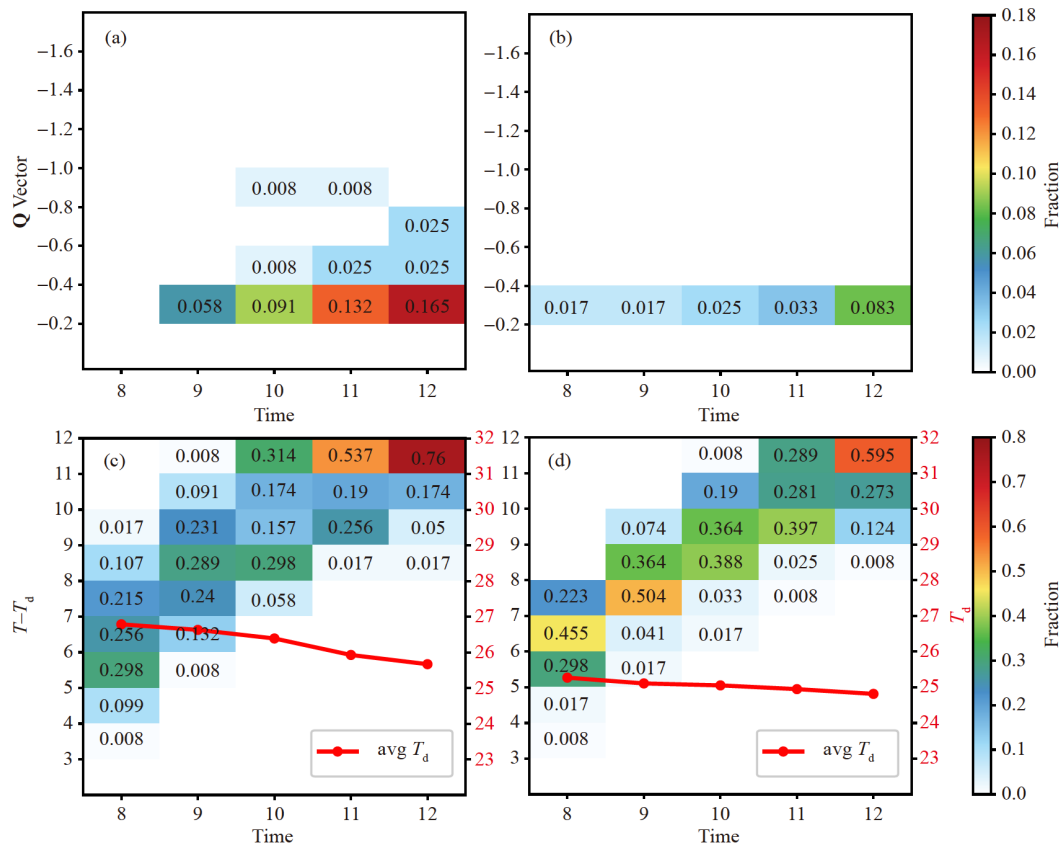


**Figure 11.** Frequency distribution time series for  $Q$  vector divergence (units:  $10^{-11} \text{ hPa}^{-1} \text{ s}^{-3}$ ) and  $T-T_d$  (units:  $^{\circ}\text{C}$ ): (a)  $Q$  vector divergence for STHR events, (b)  $Q$  vector divergence for NR events, (c)  $T-T_d$  for STHR events, and (d)  $T-T_d$  for NR events.

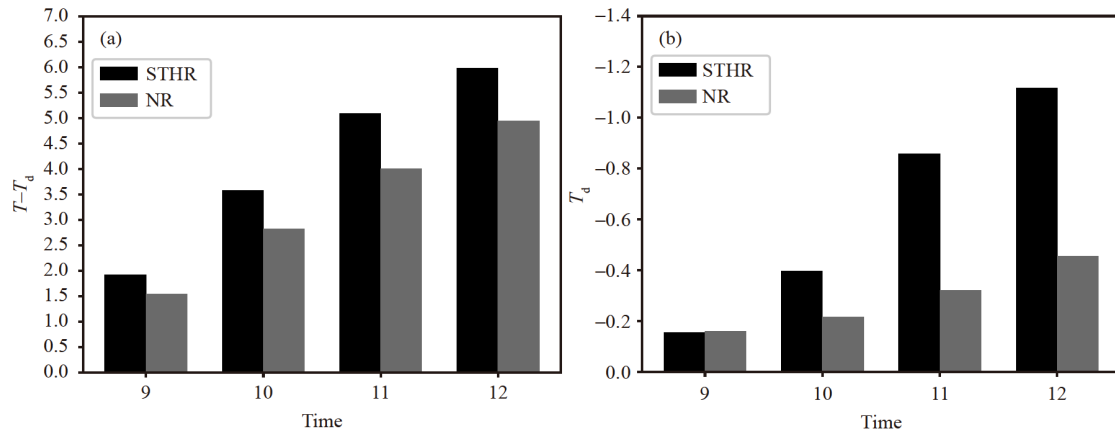


**Figure 12.** Time series for disturbance temperature-dew point temperature difference and disturbance dew point temperature-temperature (units:  $^{\circ}\text{C}$ ): (a)  $T-T_d$  and (b)  $T_d$ .

consistently weaker than those for NR events, and the decline rate of  $T-T_d$  was faster for STHR events. Observing the trend of  $T_d$ , both STHR and NR events displayed a decreasing trend in  $T_d$  as temperature significantly rose ( $T_d$  for STHR events decreased, from 26.9 to 25.6  $^{\circ}\text{C}$ ); however, the  $T_d$  values for STHR conditions were consistently higher than those for NR conditions (Figs. 11c and 11d). In terms of disturbance  $T_d$ , there was no significant difference between STHR and NR

conditions at 09:00 LST. However, from 10:00 to 12:00 LST, the gap in disturbance  $T_d$  between STHR and NR conditions increased from  $-0.2$  to  $-0.8$   $^{\circ}\text{C}$  (Fig. 12b), indicating that the decrease in  $T_d$  for STHR events was also faster than that for NR events. In summary, the humidity conditions for STHR events remained consistently better than those for NR events, accompanied by more significant vertical moisture transport on the surface.

The spatiotemporal overlay of  $Q$  vector divergence

and  $T-T_d$  shows that from 10:00 to 12:00 LST, the convergence area for NR events, with a convergence of the  $\mathbf{Q}$  vector divergence of  $0.02 \times 10^{-11} \text{ hPa}^{-1} \text{ s}^{-3}$ , was sparsely distributed and significantly weaker in both intensity and coverage compared to that for STHR events, suggesting that the weaker upward motion is insufficient to trigger the release of unstable energy, leading to convection (Fig. 13). Additionally, although the significant convergence areas were present in both the northern and southern riverside and coastal regions during STHR events, the convergence and upward motion were stronger in the northern areas, where the convergence of the  $\mathbf{Q}$  vector divergence reached  $-0.04 \times 10^{-11} \text{ hPa}^{-1} \text{ s}^{-3}$ . In terms of humidity, owing to the increase in solar radiation absorption and evaporation from the urban surface, Shanghai's urban areas tend to be warmer and drier (Zhang et al. 2009). From 08:00 to 11:00 LST, the low-humidity areas for both scenarios expanded, but the humidity decline rate was faster for the STHR events (Fig. 13).

Further analysis of the differences revealed that the intensity and range of near-surface convergence and upward motion during STHR events were superior to those during NR events, indicating that they were more significantly affected by the dynamic force of mesoscale systems. In addition, STHR events are characterized by greater moisture availability and vertical moisture transport rates than NR events, although they exhibit worse relative humidity conditions.

### 3.6 Multiscale impact analysis of the differences between STHR and NR events

Starting at 08:00 LST, STHR events ( $-0.04 \leq \omega \leq -0.03 \text{ Pa s}^{-1}$ ) exhibited more significant upward motion compared to NR events ( $-0.03 \leq \omega \leq -0.015 \text{ Pa s}^{-1}$ ), thus reflecting a dynamically active atmosphere that effectively

mitigated the inhibitory feedback on CI, typically imposed by subsidence airflows within the WPSH. Moreover, this internal vertical motion difference within the WPSH did not significantly affect cloud coverage and therefore did not influence the warming effect of solar radiation on the underlying surface. On the contrary, STHR conditions experienced stronger solar radiation, leading to a broader occurrence of extreme heatwaves (85% AWS  $\geq 38^\circ\text{C}$ , 11.6% AWS  $\geq 40^\circ\text{C}$ ), which significantly enhanced surface evaporation. Additionally, between 10:00 and 12:00 LST, with the emergence of ground convergence lines and UHI effects, the STHR scenarios were subject to noticeable meso-scale thermodynamic forces, particularly evident with widespread convergence and upward motions, whereby the convergence of the  $\mathbf{Q}$  vector divergence reached  $-0.4 \times 10^{-11} \text{ hPa}^{-1} \text{ s}^{-3}$ , which contributed to the release of unstable energy. In summary, the weaker suppressive effect of the WPSH, combined with significant meso- and micro-scale thermodynamic forces, creates a multiscale resonance effect, which is a key condition for triggering local convection events.

## 4 DISCUSSION AND CONCLUSION

Under the influence of the WPSH, downdrafts tend to suppress convection; however, local STHR events in coastal cities still occur frequently, and predicting the CI of these processes remains a challenge. This study was based on local STHR events that occurred multiple times in Shanghai in August 2022. Based on the ERA5 reanalysis data and AWS network data, we employed hourly and dynamic synthesis analysis methods to compare and analyze the large-scale environment as well as the mesoscale dynamic and thermodynamic conditions

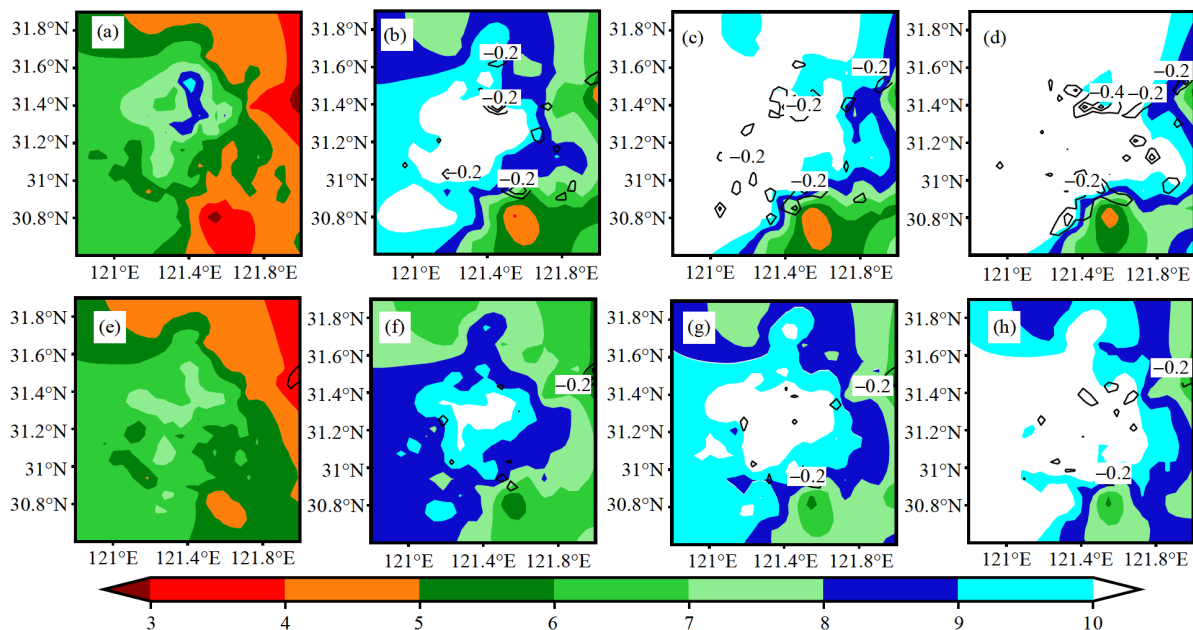


**Figure 13.** Spatiotemporal overlay of  $\mathbf{Q}$  vector divergence field (contours; units:  $10^{-11} \text{ hPa}^{-1} \text{ s}^{-3}$ ) and temperature-dew point difference (shading; units:  $^\circ\text{C}$ ) at 08:00, 10:00, 11:00, and 12:00 LST under (a–d) STHR and (e–h) NR conditions.

during STHR and NR events to identify key triggers for CI.

In our research, we identify that, before the effect of the boundary layer convergence line (08:00–10:00 LST), the atmospheric vertical upward motions during STHR events, with  $-0.04 \leq \omega \leq -0.03 \text{ Pa s}^{-1}$ , were more significant compared to NR events, with  $-0.03 \leq \omega \leq -0.015 \text{ Pa s}^{-1}$ , indicating weaker suppression by the WPSH on STHR events; meanwhile, STHR events, with over 80% AWSs  $\geq 38^\circ\text{C}$ , show quicker warming rates, higher temperatures, and a broader coverage of high temperatures than NR events, with only 16.5% AWSs  $\geq 38^\circ\text{C}$ . Furthermore, STHR events, for which CAPE  $> 2500 \text{ J kg}^{-1}$ ,  $K > 35^\circ\text{C}$ , and vertical decrement rate  $\theta_e > 0$ , are characterized by more significant unstable energy and unstable stratification compared to NR events, for which  $1000 < \text{CAPE} < 1500 \text{ J kg}^{-1}$  and  $K \approx 30^\circ\text{C}$ ; these results indicate that superior thermal conditions and unstable stratification are important prerequisites for CI. Second, the non-geostrophic  $\mathbf{Q}$  vector divergence can effectively reflect local dynamic disturbances. STHR conditions, with a convergence of the  $\mathbf{Q}$  vector divergence of  $-0.4 \times 10^{-11} \text{ hPa}^{-1} \text{ s}^{-3}$ , were accompanied by stronger, broader near-surface convergence and upward motions than NR conditions, with a convergence of the  $\mathbf{Q}$  vector divergence of  $-0.2 \times 10^{-11} \text{ hPa}^{-1} \text{ s}^{-3}$ , revealing the key role of local force mechanisms, such as UHI circulation and land–sea breeze, under the influence of the WPSH. In summary, a weaker suppressive effect of the WPSH combined with a significant mesoscale thermodynamic force creates a multiscale resonance effect, which is a key condition for triggering local convection events. Additionally, the locations of CI were mainly concentrated in the north and east of the city center, related to the overall northward position of the central city. The central urban area of Shanghai is closer to the northern waters, and thus experiences more pronounced effects from the UHI and land–sea breeze (sea breeze front) effects. This situation facilitates the occurrence of marked low-level convergence between the northern waterfront and urban hub, which promotes the liberation of unstable energy, thereby contributing to the formation of convective cloud clusters and subsequently instigating the STHR phenomenon.

Although  $T - T_d$  at 2 m and relative humidity conditions below 850 hPa are marginally lower for STHR compared to NR events, the overall SH and  $T_d$  are more favorable for STHR events, owing to the fact that they have  $\text{SH}_{\text{avg}} > 11.5 \text{ g kg}^{-1}$ ,  $T_d > 25.5^\circ\text{C}$ , while NR events have  $10.5 < \text{SH}_{\text{avg}} < 11.0 \text{ g kg}^{-1}$ ,  $T_d \approx 25^\circ\text{C}$ ; moreover, the influence of more intense heatwaves leads to a further decline in  $T_d$ , indicative of enhanced near-surface moisture evaporation, which, in turn, contributes to vertical moisture transport within the boundary layer. The above observations imply that under the influence of the WPSH, significant vertical moisture transport and sufficient atmospheric moisture are crucial for the CI, whereas

relative humidity is not necessarily a determining factor.

While this research offers fresh perspectives on the emergence of severe convection under the influence of the WPSH, the findings presented here lay a scientific foundation for enhancing the precision of severe convection forecasts. Future research will use numerical simulation methods to quantitatively analyze the relative contributions of different mechanisms, which will be a key step in further improving the forecasting capabilities for local severe convective weather.

## REFERENCES

- Albergel, C., E. Dutra, S. Munier, J. C. Calvet, J. Muñoz-Sabater, P. de Rosnay, and G. Balsamo, 2018: ERA-5 and ERA-Interim driven ISBA land surface model simulations: Which one performs better? *Hydrol. Earth Syst. Sci.*, **22**, 3515–3532, <https://doi.org/10.5194/hess-22-3515-2018>.
- Bai, L. Q., G. X. Chen, and L. Huang, 2020: Convection initiation in monsoon coastal areas (South China). *Geophys. Res. Lett.*, **47**, e2020GL087035, <https://doi.org/10.1029/2020GL087035>.
- Bai, L. Q., G. Chen, Y. Huang, and Z. Meng, 2021: Convection initiation at a coastal rainfall hotspot in South China: Synoptic patterns and orographic effects. *J. Geophys. Res. Atmos.*, **126**, e2021JD034642, <https://doi.org/10.1029/2021JD034642>.
- Barnes, S. L., 1964: A technique for maximizing details in numerical weather map analysis. *J. Appl. Meteor.*, **3**, 396–409, [https://doi.org/10.1175/1520-0450\(1964\)003<0396:atfmdi>2.0.co;2](https://doi.org/10.1175/1520-0450(1964)003<0396:atfmdi>2.0.co;2).
- Bian, G. F., G. Z. Nie, and X. Qiu, 2021: How well is outer tropical cyclone size represented in the ERA5 reanalysis dataset?. *Atmos. Res.*, **249**, 1–13, <https://doi.org/10.1016/j.atmosres.2020.105339>.
- Du, Y., and G. X. Chen, 2019: Heavy rainfall associated with double low-level jets over Southern China. Part II: Convection initiation. *Mon. Wea. Rev.*, **147**, 543–565, <https://doi.org/10.1175/MWR-D-18-0102.1>.
- Du, Y., G. X. Chen, B. Han, C. Mai, L. Bai, and M. Li, 2020: Convection initiation and growth at the coast of South China. Part I: Effect of the marine boundary layer jet. *Mon. Wea. Rev.*, **148**, 3847–3869, <https://doi.org/10.1175/MWR-D-20-0089.1>.
- Feng, S., and Y. F. Fu, 2009: Seasonal characteristics of precipitation occurrences in the core area of the subtropical high. *Acta Meteor. Sin.*, **23**, 681–690. (in Chinese)
- Feng, S., Q. Liu, and Y. F. Fu, 2009: Precipitation under subtropical high conditions: Evidence and implications. *Atmos. Ocean. Sci. Lett.*, **2**, 244–249, <https://doi.org/10.1080/16742834.2009.11446807>.
- Fu, Y. F., J. Y. Feng, H. F. Zhu, R. Li, and X. D. Liu, 2006: Precipitation structures of a thermal convective system happened in the central western subtropical Pacific anticyclone. *Acta Meteor. Sin.*, **20**, 232–243.
- Fu Y. F., and T. Xian, 2017: Review and prospect of climate characteristics of cloud and precipitation in subtropical high center. *Torrential Rain Disasters*, **36**, 489–497, <https://doi.org/10.3969/j.issn.1004-9045.2017.06.001>. (in Chinese)
- Gu, W., J. G. Tan, and Y. Y. Chang, 2015: Characteristics of heavy rainfall events in Shanghai region from 1981 to 2013.

- J. Meteor. Environ.*, **31**, 107–114, <https://doi.org/10.3969/j.issn.1673-503X.2015.06.014>. (in Chinese).
- Han, J. Y., J. J. Baik, and A. P. Khain, 2012: A numerical study of urban aerosol impacts on clouds and precipitation. *J. Atmos. Sci.*, **69**, 504–520, <https://doi.org/10.1175/JAS-D-11-071.1>.
- Hersbach, H., and Coauthors, 2020: The ERA5 global reanalysis. *Quart. J. Roy. Meteor. Soc.*, **146**, 1999–2049, <https://doi.org/10.1002/qj.3803>.
- Huang, Y. J., Y. B. Liu, Y. W. Liu, H. Y. Li, and J. C. Knierel, 2019: Mechanisms for a record-breaking rainfall in the coastal metropolitan city of Guangzhou, China: Observation analysis and nested very large eddy simulation with the WRF model. *J. Geophys. Res. Atmos.*, **124**, 1370–1391, <https://doi.org/10.1029/2018JD029668>.
- Huff, F. A., and S. A. Changnon, 1973: Precipitation modification by major urban areas. *Bull. Amer. Meteor. Soc.*, **54**, 1220–1233, [https://doi.org/10.1175/1520-0477\(1973\)054<1220:PMBMUA>2.0.CO;2](https://doi.org/10.1175/1520-0477(1973)054<1220:PMBMUA>2.0.CO;2).
- Li, F. N., D. R. Chavas, K. A. Reed, and D. T. Dawson, 2020: Climatology of severe local storm environments and synoptic-scale features over North America in ERA5 reanalysis and CAM6 simulation. *J. Climate*, **33**, 8339–8365, <https://doi.org/10.1175/jcli-d-19-0986.1>.
- Markowski, P., and Y. Richardson, 2010: *Mesoscale Meteorology in Midlatitudes*. Wiley, 430.
- May, R. M., and Coauthors, 2022: MetPy: A meteorological Python library for data analysis and visualization. *Bull. Amer. Meteor. Soc.*, **103**, E2273–E2284, <https://doi.org/10.1175/BAMS-D-21-0125.1>.
- Mölders, N., and M. A. Olson, 2004: Impact of urban effects on precipitation in high latitudes. *J. Hydrometeor.*, **5**, 409–429, [https://doi.org/10.1175/1525-7541\(2004\)005<0409:IOUEOP>2.0.CO;2](https://doi.org/10.1175/1525-7541(2004)005<0409:IOUEOP>2.0.CO;2).
- Peixoto, J. P., and A. H. Oort, 1992: *Physics of climate*. American Institute of Physics Press, 520.
- Qi, L. B., and L. Chen, 2009: Local severe convective weather in Shanghai and its nowcasting summary. *Meteor. Mon.*, **35**, 11–17, <https://doi.org/10.7519/j.issn.1000-0526.2009.9.002>. (in Chinese)
- Reif, D. W., H. B. Bluestein, 2017: A 20-year climatology of nocturnal convection initiation over the central and southern Great Plains during the warm season. *Mon. Wea. Rev.*, **145**, 1615–1639, <https://doi.org/10.1175/MWR-D-16-0340.1>.
- Sun, X. Y., Y. L. Luo, X. Y. Gao, M. W. Wu, M. X. Li, L. Huang, D. L. Zhang, and H. M. Xu, 2021: On the localized extreme rainfall over the Great Bay Area in South China with complex topography and strong UHI effects. *Mon. Wea. Rev.*, **149**, 2777–2801, <https://doi.org/10.1175/MWR-D-21-0004.1>.
- Taszarek, M., J. T. Allen, H. E. Brooks, N. Pilguy, and B. Czerneck, 2021a: Differing trends in United States and European severe thunderstorm environments in a warming climate. *Bull. Amer. Meteor. Soc.*, **102**, E296–E322, <https://doi.org/10.1175/bams-d-20-0004.1>.
- Taszarek, M., J. T. Allen, M. Marchio, and H. E. Brooks, 2021b: Global climatology and trends in convective environments from ERA5 and rawinsonde data. *npj Climate Atmos. Sci.*, **4**, 35, <https://doi.org/10.1038/s41612-021-00190-x>.
- Trier, S. B., J. W. Wilson, D. A. Ahijevych, and R. A. Sobash, 2017: Mesoscale vertical motions near nocturnal convection initiation in PECAN. *Mon. Wea. Rev.*, **145**, 2919–2941, <https://doi.org/10.1175/MWR-D-17-0005.1>.
- Wang, X. F., P. Wang, L. Zhang, X. L. Xu, and J. Li, 2015: Numerical simulation of ‘7·31’ severe convection event in Shanghai using rapid refresh technique. *Plateau Meteor.*, **34**, 124–136, <https://doi.org/10.7522/j.issn.1000-0534.2013.00202>. (in Chinese)
- Wilson, J. W., and W. E. Schreiber, 1986: Initiation of convective storms at radar-observed boundary-layer convergence lines. *Mon. Wea. Rev.*, **114**, 2516–2536, [https://doi.org/10.1175/1520-0493\(1986\)114<2516:IOCSAR>2.0.CO;2](https://doi.org/10.1175/1520-0493(1986)114<2516:IOCSAR>2.0.CO;2).
- Wilson, J. W., and R. D. Roberts, 2006: Summary of convective storm initiation and evolution during IHOP: Observational and modeling perspective. *Mon. Wea. Rev.*, **134**, 23–47, <https://doi.org/10.1175/MWR3069.1>.
- Wu, G. X., and Y. M. Liu, 2003: Summertime quadruplet heating pattern in the subtropics and the associated atmospheric circulation. *Geophys. Res. Lett.*, **30**, 1201, <https://doi.org/10.1088/1748-9326/acba30>.
- Wu, Y. L., J. Z. Sun, Z. M. Ying, L. Xue, D. Chen, and W. Lin, 2021: Effects of local-scale orography and urban heat island on the initiation of a record-breaking rainfall event. *J. Geophys. Res. Atmos.*, **126**, e2021JD034839, <https://doi.org/10.1029/2021JD034839>.
- Ying, H. P., and X. G. Cao, 2010: Summary on subtropical high severe convection during midsummer in Shanghai area. *Meteor. Mon.*, **36**, 19–25, <https://doi.org/10.7519/j.issn.1000-0526.2010.8.003>. (in Chinese)
- Yue, C. J., W. Gu, Y. Q. Tang, Z. H. Han, and X. F. Wang, 2018: Analyzing the cause of a local short-lived severe precipitation in Shanghai under the control of western Pacific subtropical high based on **Q** vector. *J. Trop. Meteor.*, **34**, 610–625, <https://doi.org/10.16032/j.issn.1004-4965.2018.05.004>. (in Chinese)
- Zhang, C. L., F. Chen, S. G. Miao, Q. C. Li, X. A. Xia, and C. Y. Xuan, 2009: Impacts of urban expansion and future green planting on summer precipitation in the Beijing metropolitan area. *J. Geophys. Res. Atmos.*, **114**, D02116, <https://doi.org/10.1029/2008JD010328>.
- Zhang, D. Q., L. J. Chen, Y. Yuan, J. Q. Zuo, and Z. J. Ke, 2023: Why was the heat wave in the Yangtze River valley abnormally intensified in late summer 2022? *Environ. Res. Lett.*, **18**, 034014, <https://doi.org/10.1088/1748-9326/acba30>.
- Zhang, Y. Z., S. G. Miao, Y. J. Dai, and R. Bornstein, 2017: Numerical simulation of urban land surface effects on summer convective rainfall under different UHI intensity in Beijing. *J. Geophys. Res. Atmos.*, **122**, 7851–7868, <https://doi.org/10.1002/2017JD026614>.
- Zhou, W. D., N. Han, J. H. Dai, H. Chen, C. J. Yue, and R. Y. Zhang, 2022: Investigation of rainstorm warning and its difference under different synoptic conditions in Shanghai. *Torrential Rain Disasters*, **41**, 405–412, <https://doi.org/10.3969/j.issn.1004-9045.2022.04.005>. (in Chinese)

**Citation:** Chen, S. Q., C. J. Yue, and Y. Gao, 2026: Convection Initiation of Short-term Heavy Rainfall Events in Shanghai Under the Influence of the Western Pacific Subtropical High During the 2022 Extreme Heatwave. *J. Trop. Meteor.*, **32**, 271–287, <https://doi.org/10.3724/j.1006-8775.2026.016>.

## APPENDIX

In Section 3, a comparison and analysis of atmospheric environmental fields, as well as surface dynamics and thermal characteristics, between the STHR and NR conditions was conducted from 08:00 to 12:00 LST. To further reveal the causes of convection initiation, we employed a dynamic synthesis analysis method outlined in the following section. In this method, the time of precipitation occurrence is denoted as  $t_0$ , and time points as hour 1, hour 2, ..., hour 6 before precipitation as  $t_{-1}$ ,  $t_{-2}$ , ...,  $t_{-6}$ , and then the arithmetic average of the hourly meteorological elements is calculated. Starting from the time of convection occurrence and focusing on the period of 0–6 h before the onset of convection, we aimed to reveal the atmospheric environment fields, surface dynamics, and thermal characteristics that occur during this period, thereby providing valuable insights for practical operational forecasting.

### APPENDIX A1 ATMOSPHERIC VERTICAL UPWARD MOTION, EQUIVALENT POTENTIAL TEMPERATURE, AND HUMIDITY CONDITIONS

Through our examination of the vertical upward motion during STHR events, we determined that it could be divided into two phases. From  $t_{-6}$  to  $t_{-4}$ , the middle and upper atmospheric motions were more active, with vertical upward motion primarily occurring above 850 hPa (Fig. A1a); however, during this phase, there was a weakening trend in  $\omega_{\text{avg}}$ , decreasing from  $-0.042 \text{ Pa s}^{-1}$  at  $t_{-5}$  to  $-0.025 \text{ Pa s}^{-1}$  at  $t_{-4}$ . From  $t_{-3}$  to  $t_0$ , while upper-level upward motion was less pronounced, the influence

of boundary layer convergence led to a gradual intensification of the middle and lower layer upward motions, extending up to approximately 700 hPa, and the peak vertical velocity increased, from  $-0.08$  to  $-0.24 \text{ Pa s}^{-1}$  (Fig. A1a). Concurrently, the  $\omega_{\text{avg}}$  for STHR events showed a significant upward trend, increasing from  $-0.042 \text{ Pa s}^{-1}$  at  $t_{-3}$  to  $-0.118 \text{ Pa s}^{-1}$  at  $t_0$  (Fig. A2). In terms of humidity conditions, the high-RH area (70%–80%) for the STHR conditions was located between 850 and 750 hPa. With the warming of the surface, there was a pronounced vertical moisture transport process, which elevated the  $\text{SH}_{\text{avg}}$ , from  $11.25 \text{ g kg}^{-1}$  at  $t_{-6}$  to  $12.1 \text{ g kg}^{-1}$  at  $t_0$  (Figs. A1b and A2). The analysis of equivalent potential temperature was similar to that presented in Section 3.2; from  $t_{-6}$  to  $t_0$ , the vertical decrement rates of equivalent potential temperature at 850 and 400 hPa for STHR events were greater than 0, indicating an atmosphere with convective instability stratification (Fig. A1b). Additionally, the vertical wind shear condition was similar to that discussed in Section 3.2, and was characterized by an overall weak shear environment. The above results indicate that vertical moisture transport, combined with pronounced convective instability stratification and enhanced vertical upward motion, favors the initiation of convection during STHR events.

### APPENDIX A2 LOCAL THERMAL CONDITIONS

Our analysis showed that at  $t_{-4}$ , 86% of AWSs recorded temperatures higher than  $35^\circ\text{C}$ , with 2.5% exceeding  $38^\circ\text{C}$ . At  $t_0$ , 84.3% of AWSs recorded temperatures above  $35^\circ\text{C}$ , with 18.2% reaching over  $40^\circ\text{C}$  (Fig. A3a). In terms of the disturbance temperature,

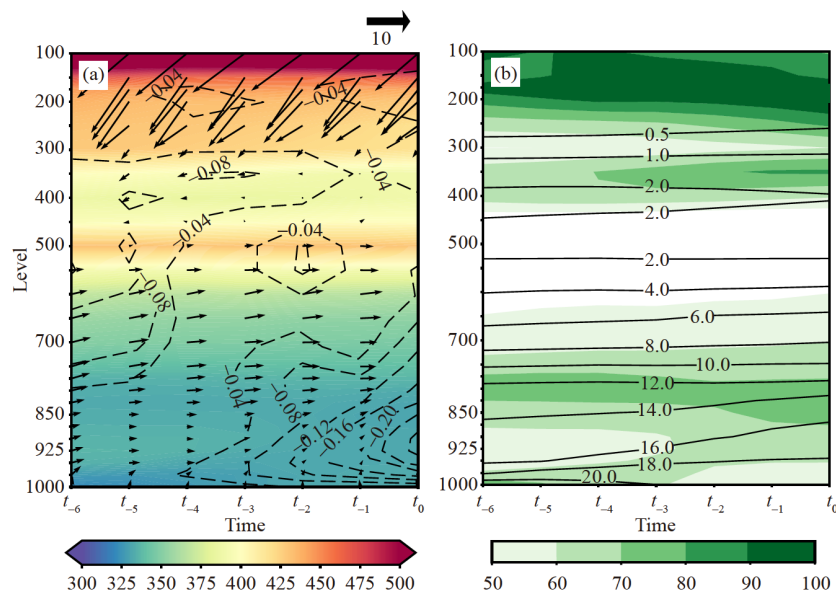


**Figure A1.** (a) Dynamic synthesis time series for vertical velocity (black contours; units:  $\text{Pa s}^{-1}$ ), equivalent potential temperature (shading; units: K), and wind field (vectors; units:  $\text{m s}^{-1}$ ). (b) Dynamic synthesis time series for SH (contours; units:  $\text{g kg}^{-1}$ ) and relative humidity (shading, units: %). The y-axis represents the pressure level (units: hPa).

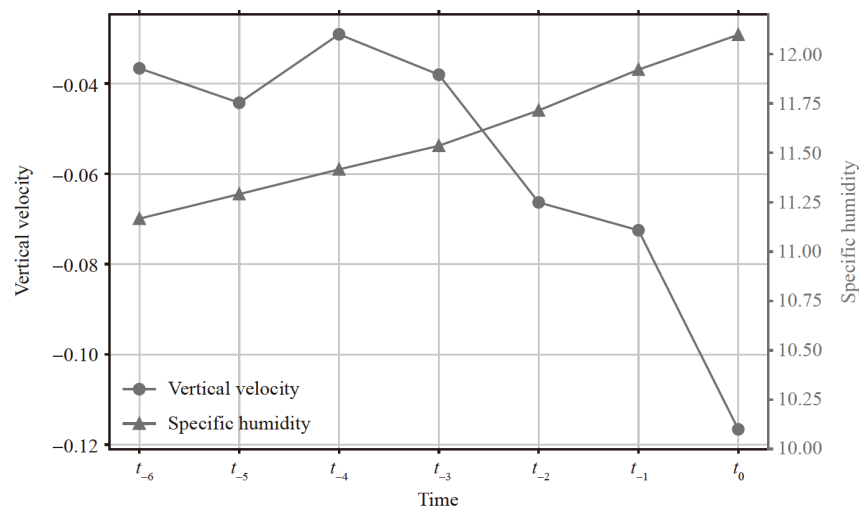


**Figure A2.** Dynamic synthesis analysis time series for the whole-layer average vertical velocity (units:  $\text{Pa s}^{-1}$ ) and average SH (below 500 hPa, units:  $\text{g kg}^{-1}$ ).

there was an increasing trend from  $t_{-5}$  to  $t_{-1}$ , but the rate of increase gradually weakened, and at  $t_0$ , there was a slight decrease due to precipitation (Fig. A3b). The dynamic synthesis of 2 m temperature and wind field spatiotemporal changes showed that the positions where the CI of STHR events occurred (Fig. 1) were all located in the urban-suburban junction areas with large temperature gradients. Moreover, from  $t_{-3}$  to  $t_{-1}$ , under the combined influence of the sea breeze and urban heat island effects, wind field convergence occurred near the northern urban areas of Shanghai (Fig. A4). The wind speed was gradually increased to over  $5 \text{ m s}^{-1}$ . Notably, the wind-field convergence phenomenon revealed by the dynamic synthesis method is more significant than that revealed by the hourly synthesis method (Section 3.5).

The results indicate that extreme heatwaves, with temperatures soaring above  $40^\circ\text{C}$ , play a critical role in triggering convection by significantly disrupting local atmospheric circulation through thermal force.

Additionally, as the main urban area of Shanghai is generally located to the north, adjacent to the northern Yangtze River estuary, the convection initiation of STHR events is concentrated near the urban agglomeration areas, under the combined influences of terrain-urban (including the actual coastline) distribution, the urban heat island effect, and land-sea breeze. This is qualitatively consistent with previous observations in other regions, where heavy rainfall often occurs inside or on the downwind side of cities (Huff and Changnon 1973; Han et al. 2012; Mölders and Olson 2004; Sun et al. 2021). Following the onset of precipitation, a pronounced cooling effect occurs, driven by microphysical processes intimately linked with descending moist air (such as raindrop evaporation and hail melting) (Sun et al. 2021), leading to a rapid temperature decline in the zones affected by STHR events, resulting in the formation of cold pools; consequently, temperatures in urban areas experience a significant drop.

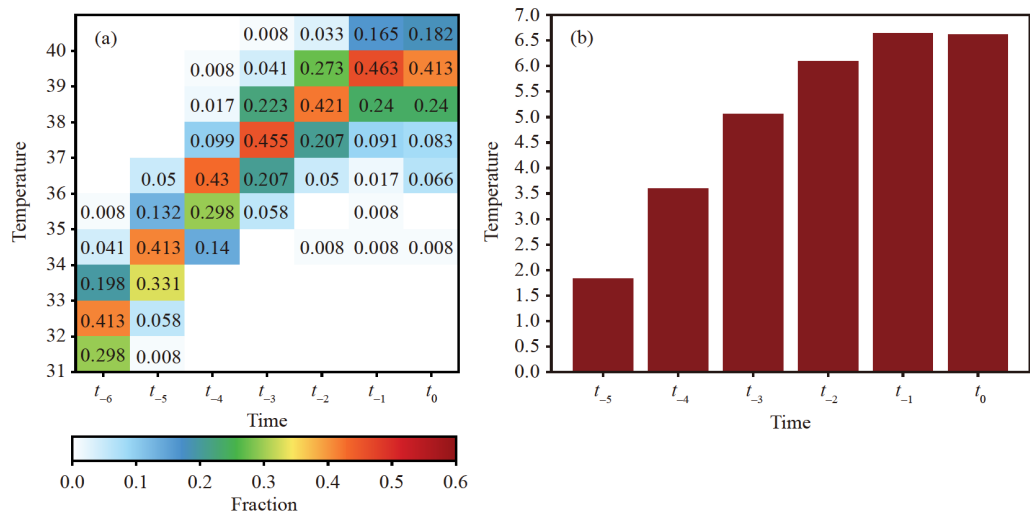


**Figure A3.** (a) Dynamic synthesis time series of high-temperature frequency distribution in AWSs. (b) Dynamic synthesis time series for disturbance temperature. The y-axis represents the temperature (units:  $^\circ\text{C}$ ).

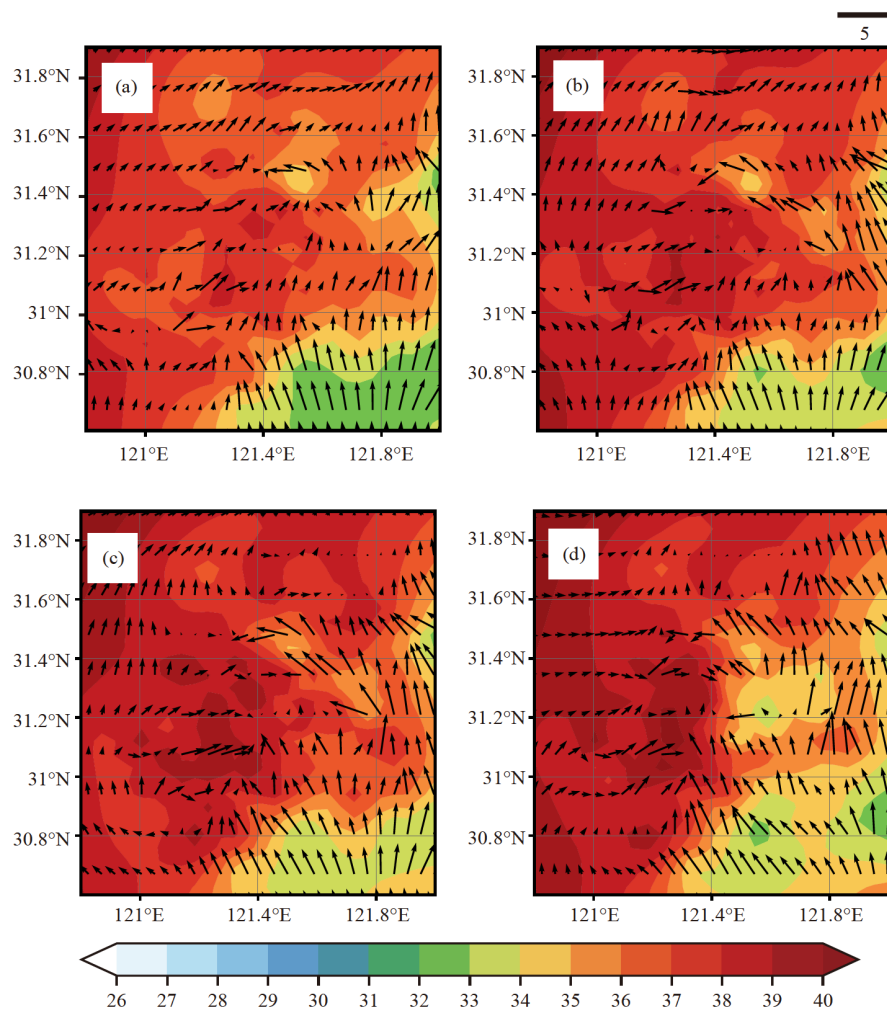


**Figure A4.** Spatiotemporal overlay of dynamic synthesis of 2 m temperature (shading; units:  $^{\circ}\text{C}$ ) and wind field (contours; units:  $\text{m s}^{-1}$ ). (a)  $t_{-3}$ , (b)  $t_{-2}$ , (c)  $t_{-1}$ , and (d)  $t_0$ .

### APPENDIX A3 LOCAL DYNAMICS AND HUMIDITY CONDITIONS

Our analysis indicates that, at  $t_{-5}$ , only 3.3% of the area exhibited convergence, but thereafter, the range and intensity of convergence continuously increased. From  $t_{-2}$  to  $t_0$ , the convergence area grew from 14% to 53%, with a

stronger convergence zone where the convergence of the  $\mathbf{Q}$  vector divergence reached  $-0.4 \times 10^{-11} \text{ hPa}^{-1} \text{ s}^{-3}$ , expanding from 5.7% to 25.7% (Fig. A5a). In terms of humidity conditions,  $T - T_d$  consistently fell prior to the onset of precipitation; by  $t_{-1}$ , the  $T - T_d$  remained above  $8^{\circ}\text{C}$ , with the proportion of  $T - T_d (\geq 11^{\circ}\text{C})$  increasing to

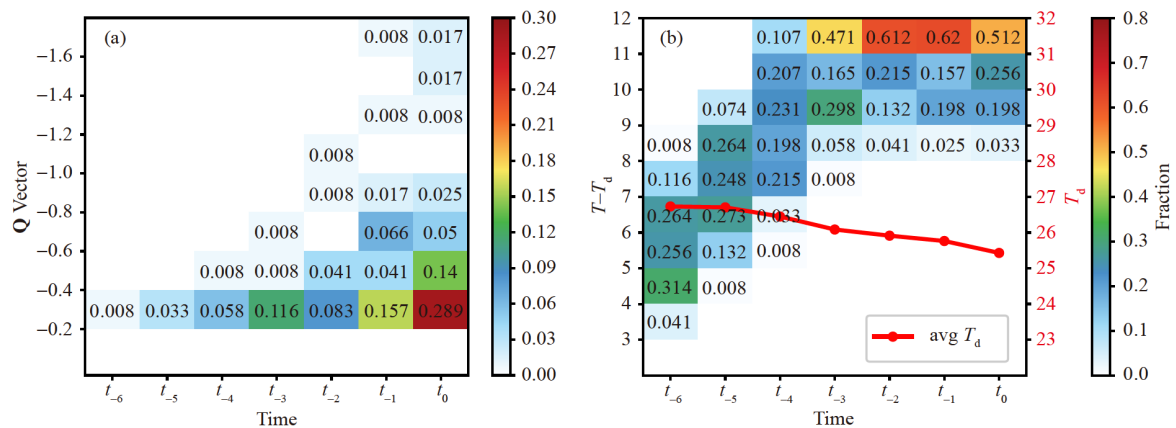


**Figure A5.** Dynamic synthesis time series of frequency distribution for  $\mathbf{Q}$  vector divergence and  $T - T_d$ : (a)  $\mathbf{Q}$  vector divergence (units:  $10^{-11} \text{ hPa}^{-1} \text{ s}^{-3}$ ) and (b)  $T - T_d$  (units:  $^{\circ}\text{C}$ ).

62%. Following precipitation at  $t_0$ , humidity slightly rose, with the  $T-T_d$  ( $\geq 11^\circ\text{C}$ ) area decreasing to 51.2% (Fig. A5b); concurrently, as the ground surface rapidly warmed, vertical moisture transport intensified, leading to decreases in both  $T_d$  and disturbance  $T_d$  (from 26.9 to 25.3  $^\circ\text{C}$ ); this gradual increase in disturbance  $T_d$  was observed before precipitation (Fig. A6, similar to the results of Section 3.5). The overlay of dynamic synthesis spatiotemporal

changes in  $\mathbf{Q}$  vector divergence and  $T-T_d$  revealed that, from  $t_{-3}$  to  $t_{-2}$ , the convergence uplift zones were concentrated in the northern riverside and southern coastal areas (Figs. A7a and A7b). Stronger convergence zones, with convergence of the  $\mathbf{Q}$  vector divergence values of  $-0.4 \times 10^{-11} \text{ hPa}^{-1} \text{ s}^{-3}$ , were located to the north, accompanied by distinct  $T-T_d$  gradient shifts. As the convective clouds reached maturity and precipitation

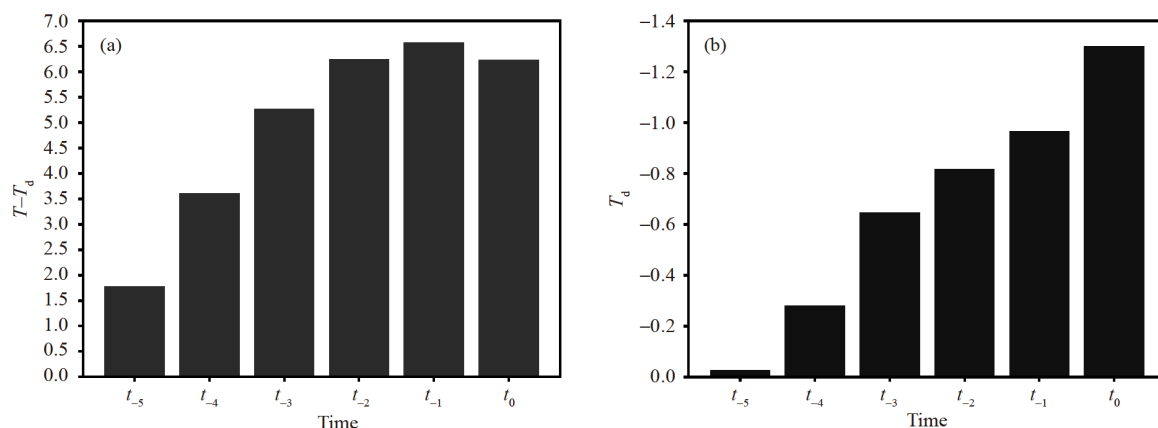


**Figure A6.** Dynamic synthesis evolution diagrams for disturbance  $T-T_d$  and disturbance  $T_d$ : (a)  $T-T_d$  and (b)  $T_d$  (units:  $^\circ\text{C}$ ).

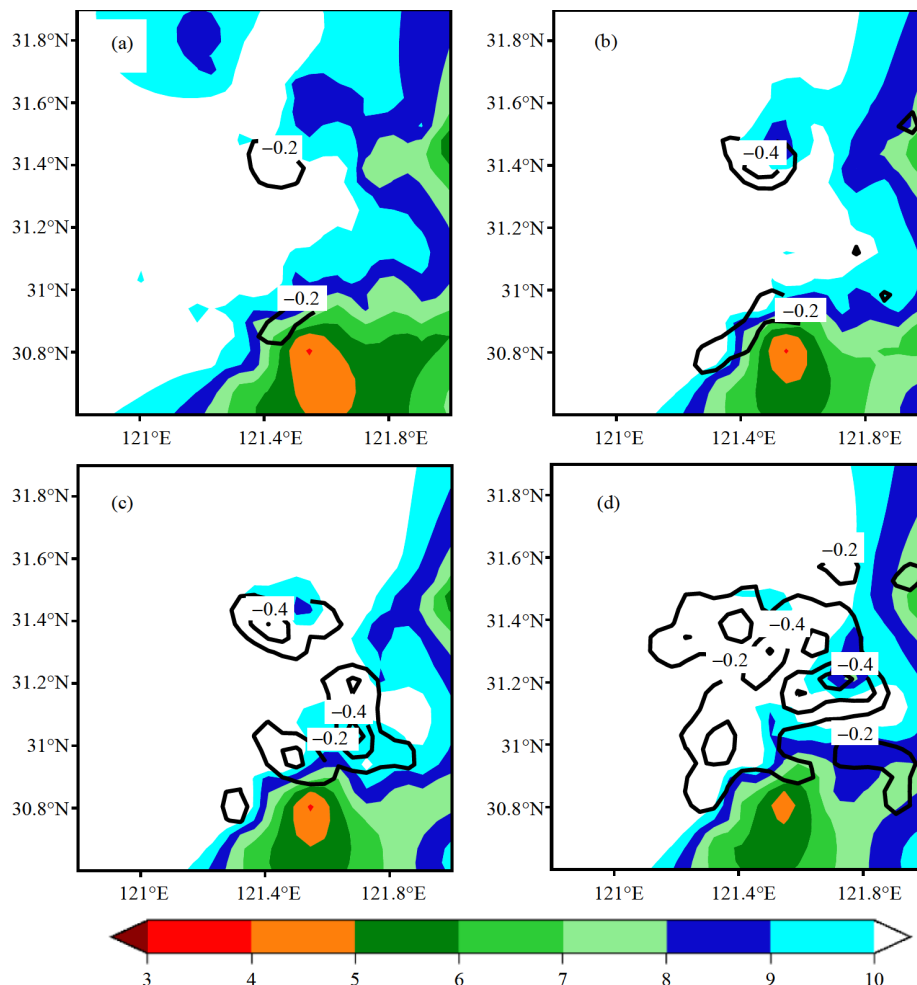


**Figure A7.** Spatiotemporal overlay of dynamic synthesis for  $\mathbf{Q}$  vector divergence field (contours; units:  $10^{-11} \text{ hPa}^{-1} \text{ s}^{-3}$ ) and temperature-dew point temperature difference (shading; units:  $^\circ\text{C}$ ): (a)  $t_{-3}$ , (b)  $t_{-2}$ , (c)  $t_{-1}$ , and (d)  $t_0$ .

occurred (from  $t_{-1}$  to  $t_{-0}$ ), the convergence area gradually covered the entire Shanghai urban area (Figs. A7c and A7d).

In summary, the riverside and coastal areas of Shanghai are the first to exhibit convergence; then, as the sea breeze front (convergence line) develops and strengthens inland, its impact area expands, and convection also forms near the sea breeze front (Reif and Bluestein 2017; Wilson and Schreiber 1986). This process is largely driven by the interaction between the cool, moist air mass trailing the sea breeze front and the warm, dry air mass over the urban region, the latter of which is continuously lifted, leading to a strengthening of the convergence uplift motion and triggering an intense release of unstable energy in that area, thereby resulting in

the formation and rapid development of thunderstorm cells. Additionally, the urban heat island effect can also intensify thermal instability near urban areas, and the combination of the sea breeze front and convergence uplift caused by the urban heat island is conducive to the initiation of convection near urban areas.

Combined with the analysis results from Section 3, our dynamic synthesis analysis confirms that weaker suppression by the WPSH local convergence uplift, thermal force conditions, and unstable stratification are important factors in triggering STHR events. Moreover, extreme temperatures lead to more significant vertical moisture transport before the CI of such events, thus resulting in consistently worse 2 m relative humidity conditions.