Drivers of a sudden mesoscale rainstorm in arid and semi-arid regions at the edge of the western Pacific subtropical high

Jing Liu | Jinru Zhang | Fan Liu | Lianmei Yang

Institute of Desert Meteorology, China Meteorological Administration (CMA) and Center for Central Asia Atmosphere Science Research, Urumqi, China

Correspondence
Lianmei Yang, Institute of Desert Meteorology, China Meteorological Administration (CMA) and Center for Central Asia Atmosphere Science Research, Urumqi, China.
Email: yanglm@idm.cn

Funding information
the National Key Research and Development Program of China, Grant/Award Numbers: 2018YFC1507104, 2018YFC1507102; National Natural Science Foundation of China, Grant/Award Number: 41565003

Abstract
An extreme rainstorm occurred in southeastern Hami in Xinjiang, China, on July 31, 2018. The region experienced maximum accumulated precipitation of 110 mm over 12 h, causing a flood that killed 20 people and left eight missing. The present study uses multiple data sources in order to conduct an in-depth analysis of this extreme rainfall event. Results show that the western Pacific subtropical high (WPSH) could directly impact the arid and semi-arid areas under the certain circulation patterns. During the heavy rainfall period, the 500 hPa WPSH was anomalously northerly; several mesoscale cloud clusters generated in front of the 700 hPa Hexi corridor jet stream and then merged and developed along the 500 hPa steering flow. The atmosphere was conditionally unstable over the region, and unstable convective energy was triggered by warm frontogenesis at the low troposphere. Warm frontal frontogenesis was determined by the horizontal divergence and the tilt term during convective initiation, and deformation and tilt terms as convective cloud at matured. Additionally, the intensification of the 700 hPa Hexi corridor southeasterly jet and topographic uplifting were responsible for the long-term persistence of the mesoscale convective system, which should be paid more attention by forecasters in the future forecasting of this region.

KEYWORDS
arid and semi-arid area, mesoscale convective system, western Pacific subtropical high, trigger

1 | INTRODUCTION

With global warming and the acceleration of the water cycle, extreme precipitation events occurred frequently (Zhou et al., 2008; Shongwe et al., 2009; Shi and Durran, 2015). In the mid-latitudes, mesoscale convection systems are the main reason for summer heavy precipitation (Tao, 1980; Houze et al., 2004; Stevenson and Schumacher, 2014; Yang et al., 2014; Yang et al., 2019) and can result in catastrophic weather, including flooding, hail and strong winds (Weisman and Trapp, 2003; Zheng et al., 2010).

Xinjiang is an arid and semi-arid province of northwestern China that is indirectly affected by monsoon systems, especially in mountainous regions. The region has experienced frequent, short-duration heavy rainfall events in recent years (Zhang and Deng, 1987; Zhao et al., 2014);
However, little attention has been paid to the mesoscale convective systems in northwest China, despite the fact that the heavy precipitation could have significant social, economic and environmental consequences.

The inland region of Hami, situated on the eastern edge of Xinjiang province and adjacent to the Hexi corridor in Gansu province, has a typical arid and semi-arid climate. It is on the main road linking Xinjiang to China’s interior and is an important area for the Silk Road Economic Belt. The Tianshan Mountains divide the Hami region into northern and southern parts. Heavy rainfall is concentrated in Balikun county to the north of the Tianshan Mountains, with an average annual precipitation of 230.5 mm (Daoran and Li, 2007). South of Hami area is the Gobi Desert, which has no radar rainfall detection and sparse automated weather stations. In recent years, studies have focused on the characteristics of mesoscale convective systems in arid and semi-arid regions (Zhuang et al., 2006; Kong et al., 2011; Li et al., 2019). Studies in western Xinjiang province revealed the influence of a low-level convergence line and topography on the mesoscale convective system (Zeng and Yang, 2017; Zeng and Yang, 2018), and demonstrated the relation between cold fronts and the mesoscale convective system (Liu et al., 2019). Other studies have focused on the atmospheric circulation of heavy rainfall (Daoran and Li, 2007; Tu and Haijiang, 2014), and on the dynamic and thermodynamic conditions (Wang et al., 2010) in northern Hami. However, studies in the southern Hami area are scarce. Owing to the widespread distribution of Gobi and desert surfaces with sparse vegetation and low soil porosity, soil in the southern Hami region has poor water storage capacity. Combined with the primitive state of the local water facilities, the heavy precipitation in this region has the potential to cause flash flooding, mudslides and landslides, posing a significant risk to safety and infrastructure. Consequently, an understanding of extreme rainfall in the southern Hami region is particularly important for flood control and drought relief.

On July 31, 2018, an unexpectedly and sudden heavy rainfall event occurred in the Qingcheng area of southeastern Hami. The maximum 12 hr-accumulated precipitation reached 110 mm, causing a flood that killed 20 people and left eight missing. More than 8,700 houses and some farmland, roads, railways, and electricity and communication facilities were damaged. This event is used in the present study to examine the drivers and mechanisms of an extreme mesoscale rainfall event in the region because the maximum daily accumulated precipitation was extreme for the region and significantly affected the lives and property of residents. Furthermore, the mesoscale convective system that triggered the event was generated and strengthened on the edge of the western Pacific subtropical high (WPSH), suggesting that subtropical systems could have a direct impact on the region.

The study addresses two main research questions:

- What is the trigger for the mesoscale convective system that caused the extreme rainstorm over Qingcheng?
- Is there a potential linkage between local convective initiation in arid and semi-arid area and large-scale circulations?

The paper is structured as follows. Section 2 describes the data and methods employed. Section 3 describes the weather processes and atmospheric circulations. Section 4 discusses the drivers of the convective system. Section 5 summarizes.

## 2 | DATA AND METHODS

To analyse the convective initiation of the mesoscale systems and its relationship with large-scale synoptic systems during the heavy rainfall period in southeastern Hami, several types of data are combined in the study: reanalysis, merged product, satellite and observation station data. The reanalysis product is the Final (FNL) Operational Global Analysis data from the National Center for Environmental Prediction (NCEP) with a horizontal grid spacing of 0.25° × 0.25°. The merged product is the ground multisource merged hourly precipitation made available by the China Meteorological Administration (CMA). The satellite data are hourly black body temperature-equivalent (TBB) data from FY-2G geostationary satellites with a 0.1° × 0.1° spatial resolution from the National Satellite Meteorological Center of the CMA. The hourly precipitation data are obtained from the regional meteorological stations in the Hami area.

The frontogenesis formula in natural co-ordinates (Miller, 1948; Keyser et al., 1988) was used to determine the frontogenesis function. Pseudo-equivalent potential temperature was used instead of potential temperature. The wet frontogenesis function was obtained as follows:

\[
F = \frac{d}{dt} \left( \nabla \theta_{se} \right) = F_1 + F_2 + F_3 + F_4
\]

\[
F_1 = \frac{D}{2} \left( \nabla \theta_{se} \right)
\]

\[
F_2 = -\frac{1}{2\left| \nabla \theta_{se} \right|} \left[ E_{st} \left( \frac{\partial \theta_{se}}{\partial x} \right)^2 + 2E_{st} \frac{\partial \theta_{se}}{\partial x} \frac{\partial \theta_{se}}{\partial y} - E_{st} \left( \frac{\partial \theta_{se}}{\partial y} \right)^2 \right]
\]
LIU ET AL.

where \( F_1 \) is the divergence term; \( F_2 \) is the deformation term; \( F_3 \) is the tilt term; \( F_4 \) is the non-adiabatic heating term (an item that cannot be ignored under wet adiabatic conditions); \( D \) is the horizontal divergence; \( E_{\text{de}} = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \) denotes horizontal extensional deformation; and \( E_{\text{sh}} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \) denotes horizontal shear deformation.

A suitable local precipitation classification was used for the climate characteristics of Xinjiang, proposed by a Xinjiang meteorologist (Zhang and Deng, 1987; Xiaokaiti et al., 1997): for 24 hr accumulation of rainfall, 0.1–6.0 mm are classified as light rain; 6.1–12.0 mm as moderate rain; and 12.1–24.0 mm as heavy rain. Precipitation > 24 and 48 mm are classified as a rainstorm and a heavy rainstorm, respectively.

3 | OVERVIEW OF THE WEATHER PROCESSES

3.1 | Precipitation

During the heavy rainfall event (July 30–31, 2018), the position of the WPSH was anomalously northerly. Convective cloud clusters were generated in front of the southeasterly jet in the lower Troposphere and moved northeast (Figure 2a, b), causing 15 regional automatic meteorological stations in Hami to record heavy rainfall within 12 hr, and four stations to record rainfall exceeding heavy rainstorm levels. Of these four stations, the accumulated precipitation at Qinchengxiangxiaoobao station (hereafter, Qin station: the precipitation centre) reached 115.5 mm between 0100 and 1400 LST on July 31 (Figure 1c). (The time below is local standard time (LST) is UTC + 8 hr.) Precipitation at Qin station was mainly concentrated between 0600 and 0800 LST (accumulated precipitation of 58.4 mm). Precipitation at Naoliu Highway station (hereafter, Nao station) began at 0300 LST, with the strongest precipitation (58.8 mm) occurring between 0600 and 0900 LST. After 1400 LST, the convective system gradually moved out of the rainstorm area and the heavy rainfall in Hami weakened.

3.2 | Large-scale circulations

At 0200 LST on July 31, 2018 (Figure 2a), the 200 hPa South Asian high was belt shaped and moving north of 35 °N. The 500 hPa Iran high and the WPSH (Figure 2b) were anomalously north of their mean positions, with centres located around 40 °N. The rainstorm area was located to the west of the WPSH at 500 hPa and in front of the 700 hPa Hexi corridor southeasterly jet (Figure 2c). The 700 hPa specific humidity at Hami sounding station increased from 5 to 11 g kg\(^{-1}\) from 2000 LST on July 30 to 0800 LST on July 31 (data not shown), indicating an obvious humidification in the lower Troposphere. Transportation of warm and wet air from low latitudes resulted in the formation of unstable convective stratification over the rainstorm area. The strong convergence of low-level water vapour, and the development of ascending motion caused the generation of several convective cloud clusters in front of the 700 hPa Hexi corridor southeasterly jet. Cloud clusters then moved and developed to the northeast along the 500 hPa steering flow. Furthermore, the Hami area was positioned north of the surface inverted trough (Figure 2d), where a warm moisture mass met with cold air from the north. In short, the circulation configuration of the large-scale synoptic system from high to low levels was conducive to the development of a convective system and the occurrence of heavy precipitation.

4 | TRIGGERS AND DRIVERS OF THE CONVECTIVE SYSTEM

4.1 | Mesoscale cloud clusters

Based on the FY2G satellite, the TBB product and the 700 hPa wind field, it was found that several meso-β- and meso-γ-scale cloud clusters with a TBB ≤ −56°C were generated in front of the Hexi corridor southeasterly jet stream at 700 hPa. The mesoscale cloud clusters gradually moved to the northeast along with the 500 hPa steering flow and passed through the rainstorm area in turn, causing extremely heavy short-term rainfall.

At 0200 LST on July 31 (Figure 3a), the meso-γ-scale clouds A–E generated in front of the 700 hPa southeasterly jet, and then developed rapidly to the northeast along the 500 hPa steering flow at 0300 LST (data not shown). The maximum TBB of cloud D decreased from −16 to −28°C as it moved to Qin station. At 0400 LST (Figure 3b), clouds D and A moved northeast towards Nao and Qin stations, respectively, with a maximum TBB of −28°C. Meanwhile, clouds B and E merged into meso-γ-scale cloud cluster F, moving northeast along the 500 hPa steering flow with a maximum TBB of −36°C. At 0600 LST (Figure 3c), clouds F and C merged into meso-β-scale cloud cluster G, with a maximum TBB of −52°C. At this time, cloud cover and intensity increased markedly. The Qin and Nao stations were controlled by cloud
G and the large TBB gradient area at the northeast cloud G, respectively. As the 700 hPa southeasterly jet gradually turned into a southerly jet (Figure 3d), the cloud cover and intensity of cloud G was the strongest at 0800 LST, with a maximum TBB of \(-56^\circ C\). In summary, multiple meso-\(\gamma\) and meso-\(\beta\) convective cloud clusters moved through the rainstorm area in sequence, and a training effect was apparent. Convection initiation was triggered at 0200 LST on July 31. The cloud clusters merged and strengthened to its strongest with a maximum TBB of \(-56^\circ C\) at 0800 LST on July 31.

### 4.2 Convective instability

Atmospheric stratification over the rainstorm area showed strongly convective instability. The mesoscale convective cloud cluster was triggered by the vigorous vertical movement near the warm frontal zone. Figure 4a shows that when the convective cloud initially developed (0200 LST on July 31), the frontal zone inclined to the north and the rainstorm area was in a dense zone of pseudo-equivalent potential temperature \(\theta_{se}\). The \(\theta_{se}\) increased with height \(\frac{\partial \theta_{se}}{\partial p} < 0\) between 850 and 700 hPa and decreased with height \(\frac{\partial \theta_{se}}{\partial p} > 0\) between 700 and 500 hPa, suggesting that the lower atmosphere was stable while the lower-middle atmosphere displayed convective instability. At the same time, there was an intense cold–warm interaction at the edge of the 700 hPa warm front. As the vertical movement rapidly increasing with maximum of \(-0.8\) Pa·s\(^{-1}\), convective initiation was triggered and several mesoscale cloud clusters developed. At 0800 LST on July 31 (Figure 4b), the warm front in the lower Troposphere climbed and moved northward to approximately 44 \(^\circ\) N with the height of the frontal zone decreasing. The instability of atmospheric stratification at the middle and lower Troposphere was further strengthened \(\frac{\partial \theta_{se}}{\partial p} > 0\). Under the front uplifting, the convection movement developed to its strongest, and released convective available potential energy (CAPE). Meanwhile, the wet potential vorticity equation by Wu et al. (1995) applied at the centre of the rainstorm showed that during the heavy rainfall in the rainstorm area (data not shown), low-level barotropic component of the moist
potential vorticity \( (M_{pv1}) \) was negative, the baroclinic component of the moist potential vorticity \( (M_{pv2}) \) was positive, and \(|M_{pv1}|>|M_{pv2}|\), indicating that convective instability predominated in the lower Troposphere, providing favourable thermodynamic instability conditions for the occurrence and development of convective clouds.

According to the height-time evolution of \( \theta_{se} \) (Figure 4c) over Qin station (43.8 ° N, 82.52 ° E), it is apparent that the entire layer over the rainstorm area had stable atmospheric stratification before the rainstorm (0800–2000 LST on July 30). At 0200 on July 31, the atmospheric stratification gradually transformed from stable to conditional instability \((\partial \theta_{se}/\partial \rho > 0)\) between 700 and 500 hPa. Warm front frontogenesis in the lower Troposphere triggered the convective initiation, and several mesoscale cloud clusters developed, resulting in severe short-term rainfall from 0200 to 1400 LST at Qin station. The entire atmospheric stratification at Nao station (located northeast of Qin station) was stable from 0800 LST on July 30 to 0200 LST on July 31. During the heavy rainfall period, the atmospheric stratification gradually became unstable between 700 and 500 hPa (Figure 4d). As the convection was initiated, the height of the unstable atmospheric stratification decreased with time, with severe short-term rainfall continuing until 1400 LST on July 31.

Strong convective instability stratification was apparent between the lower to middle layers of the rainstorm area. Warm front frontogenesis in the lower Troposphere triggered convective initiation at the initial stage of the precipitation. At the strongest stage of the rainstorm, the unstable warm air mass was forced to climb above the cold air mass at the bottom, leading to the release of CAPE over the rainstorm area.

4.3 | Triggers and drivers of convection

The frontal system is a common weather system at mid-latitudes. It often plays an important role in the occurrence and development of mesoscale convective systems (Xu et al., 2002; Zhao et al., 2017; Capet et al., 2017). Frontogenesis functions consider both the dynamic and thermodynamic characteristics of the atmosphere. They

FIGURE 2 (a) 200 hPa and (b) 500 hPa geopotential (contour, unit: Dagpm) and wind fields, shaded for wind speeds ≥ 30 m·s⁻¹ in (a) and for wind speeds ≥ 10 m·s⁻¹ in (b); (c) distribution of the 200 hPa jet stream (contour, unit: M·s⁻¹) and 700 hPa jet stream (shaded for wind speeds ≥ 10 m·s⁻¹); and (d) sea level pressure field (contour, unit: hPa) at 0200 LST on July 31, 2018. The red rectangle represents the Hami area.
are an important indicator for diagnosing frontal intensity and the spatial–temporal distribution. The distribution of the frontogenesis function over the rainstorm region is shown in Figure 5. Warm front frontogenesis at 700 hPa was an important trigger for the convective initiation. The frontogenesis sector (the sum of the horizontal divergence, horizontal deformation and tilt terms) was in the high-energy region of strong θse at 340–348 K. At 1400 LST on July 30 (data not shown), there was a northeast–southwest belt-shaped frontogenesis zone near the 600 hPa dense isentropes region (42°N, near 95°E), which was fractured into two segments with a maximum of $2 \times 10^{-8}$ K·s$^{-1}$·m$^{-1}$ in the eastern part. The warm air mass then pushed the cold air northwest, and the 600 hPa eastern part of warm front moved into northeastern Hami at 2000 LST on July 31 (Figure 5a), maintaining its strength. Meanwhile, at 700 hPa, there was a belt-shaped frontogenesis zone in a northeast–southwest direction near the southeastern Hami area with an intensity of $2.5 \times 10^{-8}$ K·s$^{-1}$·m$^{-1}$, accompanied by the dense isentropic zone (Figure 5c). The warm frontal zone inclined northwest from lower to middle layers. At 0200 LST on July 31 (Figure 5b), the 600 hPa eastern part of the warm front moved less, with a maximum of $2 \times 10^{-8}$ K·s$^{-1}$·m$^{-1}$. Meanwhile, the 700 hPa dense isentropic zone was broken into two parts, and the eastern segment was located near Qin station (Figure 5d). The dense isentropic zone stretched to the northeast with height. As the warm air mass climbed above the cold air mass, the warm frontogenesis further strengthened, with the frontogenesis function up to $3 \times 10^{-8}$ K·s$^{-1}$·m$^{-1}$. Warm low-level frontogenesis stimulated the development of frontal secondary circulation, which released the CAPE and triggered the convective initiation. At 0800 LST on July 31 (data not shown), as the 700 hPa Hexi corridor southeasterly jet stream extended further to the northeast, the low-level convergence area and wet tongue invaded southeastern Hami. Warm frontogenesis strengthened the frontal secondary circulation and developed the convective cloud cluster to its strongest stage, resulting in heavy short-term rainfall in southeastern Hami.

**FIGURE 3** Distribution of black body temperature-equivalent (TBB, shaded, unit: °C) and wind field (vector, unit: M·s$^{-1}$): (a) 0200 LST on July 31; (b) 0400 LST on July 31; (c) 0600 LST on July 31; and (d) 0800 LST on July 31. The red and blue points denote Qin and Nao stations, respectively.
At 1400 LST on July 30 (Figure 6a), the frontogenesis was mainly concentrated at the middle Troposphere (around 600 hPa), corresponding with strong warm air advection (Figure 7a) and the ascending branch of frontal secondary circulation > 600 hPa. As the southerly wind at the lower layer gradually strengthened, a warm front frontogenesis occurred near 700 hPa, while the 600 hPa warm front moved northeast (Figure 6b) at 2000 LST on July 30. The warm air advection expanded and extended to the northeast with height, and the ascending branch of frontal secondary circulation concentrated at 700–600 hPa (Figure 7b). The southerly wind at the lower Troposphere then rapidly increased at 0200 LST on July 31 (Figure 6c). The maximum southeasterly speed was up to 12 m·s⁻¹ at 700 hPa, while the northerly wind was concentrated at <750 hPa. At the same time, the warm air mass in the lower Troposphere with maximum warm air advection of $30 \times 10^{-8}$ K·s⁻¹·m⁻¹ climbed above the underlying cold air mass (Figure 7c). The meeting of cold and warm air led to a further warm front frontogenesis with the height extending to 600 hPa. The superposed ascending motion at the lower and middle Troposphere facilitated the development of frontal secondary circulation. At 0800 LST on July 31 (Figure 6d), the warm front in the lower Troposphere moved northeast, with a maximum frontogenesis function of $3.0 \times 10^{-8}$ K·s⁻¹·m⁻¹ over southeastern Hami. Meanwhile, warm air advection in

---

**FIGURE 4** Vertical cross-sections of $\theta$ (contour, unit: K) and vertical velocity (shaded, unit: Pa·s⁻¹) along 94.75° E at (a) 0200 LST on July 31; and (b) 0800 LST on July 31. The southeastern Hami is located between 42 and 44° N. Height-time evolution of the $\theta$ (contour, unit: K) at (c) Qin and (d) Nao stations. The grey shaded area at the bottom of each graph shows a cross-section of the terrain.
the lower Troposphere was enhanced (Figure 7d) and inclined to the northeast with height. The warm front in the lower Troposphere developed to its strongest level. Between 1400 and 2000 LST on July 30, the warm frontogenesis in the middle Troposphere moved northeast and inclined to the north with height, stimulating the development of frontal secondary circulation in the middle Troposphere. Between 0200 and 0800 LST on July 31, the 700 hPa southeasterly jet stream of the Hexi corridor rapidly strengthened, carrying warm and humid air to the rainstorm area. Enhanced warm air advection in the lower Troposphere led to the horizontal frontogenesis of the warm front, favourable to the development of the frontal secondary circulation.

**FIGURE 6** Frontogenesis function (shaded, unit: $10^{-8} \text{K s}^{-1} \text{m}^{-1}$) and meridional wind (contour, unit: $\text{M s}^{-1}$) profile along the red line in Figure 3c at (a) 1400 LST on July 30; (b) 2000 LST on July 30; (c) 0200 LST on July 31; and (d) 0800 LST on July 31. The grey shaded area at the bottom of each graph shows a cross-section of the terrain.

**FIGURE 7** As for Figure 6, but for temperature advection (shaded, unit: K s$^{-1}$) and wind speed field (stream)
Figure 8a shows that at 0200 LST on July 31, the divergence term of the frontogenesis function was concentrated at 750–700 hPa with a maximum of $2.5 \times 10^{-8} \text{ K s}^{-1} \text{ m}^{-1}$. The same effect is seen with the tilt term, with a maximum of $2.0 \times 10^{-8} \text{ K s}^{-1} \text{ m}^{-1}$ (Figure 8e), while the horizontal deformation term had a smaller effect ($1.5 \times 10^{-8} \text{ K s}^{-1} \text{ m}^{-1}$) (Figure 8c), indicating that the warm frontogenesis was triggered by the divergence and tilt terms at the primary stage of the convective initiation. At 0800 LST on July 31 (Figures 8b, d, f), the warm front moved over southeastern

Figure 8  Vertical cross-sections of the divergence term (a, b, shaded, unit: $10^{-8} \text{ K s}^{-1} \text{ m}^{-1}$), deformation term (c, d, shaded, unit: $10^{-8} \text{ K s}^{-1} \text{ m}^{-1}$), tilt term (e, f, shaded, unit: $10^{-8} \text{ K s}^{-1} \text{ m}^{-1}$), and $\theta_{se}$ (contour, unit: K) along the red line in Figure 3c. The three graphs on the left show 0200 LST on July 31; and the three graphs on the right show 0800 LST on July 31. The grey shaded area at the bottom of each graph shows a cross-section of the terrain.

Figure 9  300 hPa (contour) and 700 hPa (shaded $\leq -3 \times 10^{-5} \text{ s}^{-1}$) divergence field (unit: $\times 10^{-5} \text{ s}^{-1}$) at (a) 0200 and (b) 0800 LST on July 31. The red rectangle delineates Hami. The vertical profile of positive vorticity (shaded, unit: $\times 10^{-5} \text{ s}^{-1}$) and vertical velocity (dotted line, unit: Pa s$^{-1}$) along the red line in Figure 3c at (c) 0200 and (d) 0800 LST on July 31. The grey shaded area at the bottom of graphs (c) and (d) shows a cross-section of the terrain.
Hami. The divergence term at 700 hPa slightly decreased to $2.0 \times 10^{-8}$ K s$^{-1}$ m$^{-1}$ (Figure 8b) and shrank to < 600 hPa. The tilt term over southeastern Hami increased to $3 \times 10^{-8}$ K s$^{-1}$ m$^{-1}$ under the strongly anomalous convective motion (Figure 8f), and the deformation term rapidly increased to $2.5 \times 10^{-8}$ K s$^{-1}$ m$^{-1}$ (Figure 8d).

The above analysis shows that during the initial stages, the warm frontogenesis in the lower Troposphere was mainly determined by the divergence and tilt terms. As the warm air advection in the lower Troposphere strengthened, atmospheric stratification in the lower Troposphere was conditional convective instability over the rainstorm area. Convergence in front of the Hexi corridor southeasterly airflow facilitated the warm frontogenesis. The rising warm air strengthened vertical frontogenesis and further promoted the development of small- and medium-scale systems. At the mature stage, the low-level wet tongue extended northeast as the low-level southeastern jet gradually turned into a southerly jet. The frontogenesis deformation term led to a dense of the $\theta_{se}$ near the warm front area, further strengthening the warm frontogenesis.

The long-lived mesoscale convective cloud cluster that was generated, developed and then moved northeast over the rainstorm area was triggered by the warm front frontogenesis in the lower Troposphere. Thus, a clear answer emerges regarding the triggers and drivers of the mesoscale convective system. During the initial stage (0200 LST on July 31) (Figure 9a), there was a strong horizontal convergence at 700 hPa near the southeastern Hami area of up to $-13 \times 10^{-5}$ s$^{-1}$. At the same time, the deep cyclonic vortex column of > 700 hPa near the rainstorm area (Figure 9c) inclined northeast and extended to 300 hPa. The positive vorticity centre was located near 700 and 450 hPa with centres of $14 \times 10^{-5}$ s$^{-1}$ and $16 \times 10^{-5}$ s$^{-1}$, respectively. The deep cyclonic vortex column and horizontal convergence caused a positive vorticity column near the frontal area. The vorticity centre corresponded

---

**FIGURE 10** 700 hPa wind field (vector, unit: M s$^{-1}$) and $\theta_{se}$ field at (a) 0200 and (b) 0800 LST on July 31

**FIGURE 11** Conceptual model during the extreme short-term rainfall
with forceful vertical motion. At 0800 LST on July 31 (Figure 9b), the convergence area at 700 hPa expanded northeast with a maximum of $-11 \times 10^{-5} \text{ s}^{-1}$. The vorticity column changed from a previously inclined structure to one that was perpendicular to the ground (Figure 9d). Strong low-level convergence maintained and strengthened frontal secondary circulation. Thus, convective motion developed to its strongest stage.

The strengthening of the southeasterly jet at 700 hPa during heavy rainfall was one of the main reasons for the long-term persistence of the mesoscale convective system. At 0200 LST on July 31 (Figure 10a), there was a dense zone of $\theta_{se}$ in front of the Hexi corridor southeasterly jet stream with a maximum of 18 m s$^{-1}$. The warm tongue extended to the rainstorm area along the jet, which was favourable to the generation of warm front frontogenesis. At the same time, the aggregation of low-level water vapour was intensified by convergence and topographic uplifting (data not shown) in southeastern Hami. This was conducive to the convection initiation. At 0800 LST on July 31 (Figure 10b), the low-level southeasterly jet stream gradually turned into a southerly jet. Meanwhile, a dense zone of pseudo-equivalent potential temperature near the mesoscale cloud cluster G (Figure 3d) was apparent. As the warm air advection intensified and the specific humidity of Hami sounding station reached 11 g kg$^{-1}$ at 700 hPa, the warm front frontogenesis and frontal secondary circulation were strengthened. These were responsible for the convective cloud cluster developing to its strongest stage, resulting in extremely strong short-term precipitation in southeastern Hami.

During the early stages of precipitation, the warm tongue penetrated northward into the rainstorm area. Under the convergence and topographic uplifting, the warm and wet airflow from lower latitude converged and gathered strongly between the Tianshan Mountains and the southeasterly jet at 700 hPa, which was conductive to warm front frontogenesis and the convection initiation. At the strongest stage, the warm tongue in the lower Troposphere extended northeast obviously. Warm frontogenesis and frontal secondary circulation were strengthened in the lower Troposphere, favouring the development of the convective system. The strengthening of the low-level southeasterly jet and the topographic uplifting were the main reasons for the long-term persistence of the mesoscale convective system.

5 CONCLUSIONS

The heavy rainfall event in southeastern Hami on July 31, 2018, was an unexpectedly event in terms of its location and severity. Maximum accumulated precipitation reached 110 mm over 12 hr, well exceeding the threshold for extreme daily precipitation. Unlike previous events in the northern Hami region, there were several mesoscale convective systems that were generated and strengthened on the edge of the western Pacific subtropical high (WPSH). Atmospheric instability and frontal frontogenesis during the heavy rainfall period were discussed, and it was confirmed that the development of the mesoscale convective system was triggered by warm frontogenesis in the lower Troposphere. The strengthening of the low-level southeasterly jet accompanied by the topographic uplifting were the main drivers sustaining the mesoscale convective system. Based on the above analysis, a conceptual model of the extremely heavy short-term rainfall in southeastern Hami is shown in Figure 11. The 500 hPa WPSH was anomalously northerly, permitting the southerly jet stream in the west peripheral of the WPSH to control the Hami region. The warm front in the middle Troposphere stimulated the frontal secondary circulation and then moved northeast. As the low-level southeasterly jet strengthened, the middle and lower warm front was superposed, accompanied by a convergence zone between the Tianshan Mountains and the low-level jet. At the same time, the low-level southeasterly jet at 700 hPa transported the warm and humid air from the low latitude, and the lower level warm tongue extended northwest along the jet stream, which resulted in conditional instability over southeastern Hami. The characteristics of dynamical forcing (convergence in the lower Troposphere) and thermodynamic (the conditional instability) forcing were the favourable factors for the initiation of convection. Moreover, the surface-inverted trough passed into the Hami region. As such, the Troposphere experienced bottom to top warm frontogenesis. Several mesoscale convective systems were generated and moved towards the northeast in sequence along the southerly airflow in the western periphery of the WPSH at 500 hPa. The convective cloud clusters merged, developed and persisted, resulting in extremely strong precipitation lasting for 12 h in southeastern Hami.

At least two recommendations from the study can be applied to nowcasting:

- During heavy rainfall, the position of the 500 hPa WPSH was anomalously northerly, and the warm tongue extended northwest along the 700 hPa southeasterly jet in the Hexi corridor. The strengthening of the 700 hPa southeasterly jet and the topographic uplifting were the main drivers sustaining the long-term persistence of the mesoscale convective system.
- Warm front frontogenesis in the lower Troposphere was the main trigger for the development of mesoscale convective cloud clusters. During the initial stages of
precipitation, the convective initiation was mainly determined by the divergence and tilt terms of the frontogenesis function. Enhanced warm air advection and the convergence of the southerly airflow in the lower Troposphere were conducive to horizontal warm front frontogenesis. The tilting up of warm air further enhanced atmospheric instability, favouring convective initiation. During the mature stage, the frontogenesis deformation term resulted in a dense zone of $\theta_{se}$ in southeastern Hami. The deformation and tilt terms of the frontogenesis function further strengthened frontal secondary circulation.

The study found that the WPSH could directly impact the arid and semi-arid areas under certain circulation patterns, complementing theoretical research on arid and semi-arid areas. Consequently, forecasters should be cautious about the influence of the WPSH and Hexi corridor southeasterly jet stream on local weather forecasting. In future studies, a comprehensive analysis of these results using current and future weather forecasting models is planned to provide more subtle three-dimensional structural characteristics of these mesoscale systems.

ACKNOWLEDGEMENTS
The study was supported by the National Key Research and Development Program of China (grant numbers 2018YFC1507104 and 2018YFC1507102). The authors thank the anonymous reviewers for constructive comments; and Editage (www.editage.cn) for English language editing.

ORCID
Jing Liu https://orcid.org/0000-0002-2485-7207

REFERENCES
Capet, X., Mcwilliams, J.C., Molemaker, M.J. and Shchepetkin, A.F. (2017) Mesoscale to submesoscale transition in the California current system. Part II: frontal processes. Journal of Physical Oceanography, 38(4), 44–64. https://doi.org/10.1175/2007JPO3672.1.
Daoran, C.G. and Li, R.Q. (2007) Analysis of summer heavy rainfall in eastern Xinjiang (in Chinese with an English abstract). Meteorological Monographs, 33(2), 62–69. https://doi.org/10.7519/j.issn.1000-0526.2007.02.010.
Houze, B.F., Smull, P. and Dodge, R.A., Jr. (2004) Mesoscale convective systems. Rev. Geophys, 42, RG4003.
Keyser, D., Reeder, M.J. and Reed, R.J. (1988) A generalization of Petterssen's frontogenesis function and its relation to the forcing of vertical motion. Monthly Weather Review, 116, 762–780.
Kong, Q., Zheng, Y.G. and Chen, C.Y. (2011) Synoptic scale and mesoscale characteristics of 7-17 Urumqi heavy rainfall in 2007 (in Chinese with an English abstract). Journal of Applied Meteorology Science, 22(1), 12–22.
Li, J.G., Yang, L.M., Liu, W. and Jiang, C. (2019) Spatiotemporal distribution characteristics of mesoscale convective systems producing short-duration heavy rainfall over the Tianshan Mountain area. Advances in Meteorology, 1, 1–19.
Liu, J., Zhou, Y.M., Yang, L.M., Zeng, Y. and Liu, W. (2019) Analysis on the instability and trigger mechanism of extreme precipitation event in Yili river valley on July 31, 2016(in Chinese with an English abstract). Chinese Journal of Atmospheric Sciences, 43(5), 959–974. https://doi.org/10.3878/j.issn.1006-9895.1901.18155.
Miller, J.E. (1948) On the concept of frontogenesis. Journal of Meteorology, 5(4), 169–171.
Shi, X.M. and Durran, D.R. (2015) Estimating the response of extreme precipitation over Midlatitude Mountains to global warming. Journal of Climate, 28(10), 4246–4262.
Shongwe, M.E., van Oldenborgh, G.J. and van den Hurk, B. (2009) Projected changes in mean and extreme precipitation in Africa under global warming. Part I: southern Africa. Journal of Climate, 22(13), 3819–3837.
Stevenson, S.N. and Schumacher, R.S. (2014) A 10-year survey of extreme rainfall events in the central and eastern United States using gridded multisensor precipitation analyses. Monthly Weather Review, 142, 3147–3162.
Tao, S.Y. (1980) Chinese Rainfall (in Chinese). Beijing: Science Press, p. P225.
Tu, Y.Q. and Huijiang, K. (2014) Atmospheric circulation classification of large precipitation in Hami of Xinjiang (in Chinese with an English abstract). Journal of Arid Meteorology, 32(4), 642–648. https://doi.org/10.11755/j.issn.1006-7639(2014)-04-0642.
Wang, R.M., Ran, D. and Tu, Y.Q. (2010) Analysis of rainfall on 7th July 2007 in Hami area (in Chinese with an English abstract). Desert and Oasis Meteorology, 4(1), 36–40. 10.1002/0799(2010)01-0036-05.
Weisman, M.L. and Trapp, R.J. (2003) Low-level mesovortices within squall lines and bow echoes. Part I: overview and dependence on environmental shear. Monthly Weather Review, 131, 2779–2803.
Wu, G.X., Cai, Y.P. and Tang, X.J. (1995) Moist potential vorticity and slantwise vorticity development (in Chinese with an English abstract). Acta Meteorological Sinica, 53(4), 387–405. http://doi.org/10.11676/qxbh1995.045.
Xiaokaiti, D., Tang, H., Li, X., and Bai, H.X. (1997) Study on the vapor condition of “967” heavy rainfall in Xinjiang (in Chinese with an English abstract). Xinjiang Meteorite, 20(1), 8–11.
Xu, X.D., Weng, Y.H. and Meng, Z.Y. (2002) Characteristics of the convection in the Meso-scale front of the serious storm rainfall over the Wuhan–Huangshi region during July of 1998 through Variational analysis by satellite data (in Chinese with an English abstract). Chin. Journal of the Atmospheric Sciences, 26(6), 845–856. https://doi.org/10.3878/j.issn.1006-9895.2002.06.12.
Yang, Y., Wang, H., Chen, F., Zheng, X., Fu, Y. and Zhou, S. (2019) TRMM-based Optical and Microphysical Features of Precipitating Clouds in Summer over the Yangtze-Huaihe River Valley, China. Pure and Applied Geophysics, 176(1), 357–370. http://doi.org/10.1007/s00024-018-1940-8.
Zeng, Y. and Yang, L.M. (2017) Mesoscale characteristic analysis of a severe convective weather with torrential rain in the west of southern Xinjiang (in Chinese with an English abstract). Arid Meteorite, 35(3), 475–484.
Zeng, Y. and Yang, L.M. (2018) Analysis on the causes of an extreme rainfall event in the west of Xinjiang (in Chinese with
an English abstract). *Plateau Meteorology*, 37(5), 1220–1232. https://doi.org/10.7522/j.issn.1000-0534.2018.00014.

Zhang, J.B. and Deng, Z.F. (1987) *Introduction to Precipitation in Xinjiang (in Chinese)*. Beijing: China Meteorological Press.

Zhang, Y.J., Fu, Y.P., Chen, F.G., Zheng, X.Y. and Chen, Y.L. (2014) Spectral characteristics of precipitating clouds during the Meiyu over the Yangtze–Huaihe river valley from merged TRMM precipitation radar and visible/infrared scanner data. *Proceedings of SPIE*, 9259, 92591K1-12.

Zhao, Y., Huang, A.N., Zhou, Y., Huang, D.Q., Yang, Q., Ma, Y.F., Li, M. and Wei, G. (2014) Impact of the middle and upper tropospheric cooling over Central Asia on the summer rainfall in the Tarim basin, China. *Journal of Climate*, 27, 4721–4732.

Zhao, Y., Pei, C.C. and Yang, C.F. (2017) Observational analysis of initiation and organization of meso-scale convective systems in a heavy rainfall event associated with Meiyu front (in Chinese with an English abstract). *Acta Meteorologica Sinica*, 75(5), 700–716. http://doi/10.11676/qxxb2017.051

Zheng, Y.G., Zhang, X.L., Zhou, Q.L., Duan, Y.H., Chen, Y. and He, L.F. (2010) Review on severe convective weather short term forecasting and Nowcasting (in Chinese with an English abstract). *Meteorological Monographs*, 36(7), 33–42. https://doi.org/10.7519/j.issn.1000-0526.2010.7.008.

Zhou, T.J., Li, L.J., Li, H.M. and Bao, Q. (2008) Progress in climate change attribution and projection studies (in Chinese with an English abstract). *Chinese Journal of the Atmospheric Sciences*, 32(4), 906–922. https://doi.org/10.3878/j.issn.1006-9895.2008.04.17.

Zhuang, W., Liu, L.P. and Wang, N. (2006) Study on three-dimensional wind fields of mesoscale convective systems in Xinjiang (in Chinese with an English abstract). *Journal of Applied Meteorology*, 17(4), 444–451.

How to cite this article: Liu J, Zhang J, Liu F, Yang L. Drivers of a sudden mesoscale rainstorm in arid and semi-arid regions at the edge of the western Pacific subtropical high. *Meteorol Appl*. 2020;27:e1884. https://doi.org/10.1002/met.1884