

# 2021: A Year of Unprecedented Climate Extremes in Eastern Asia, North America, and Europe

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(Received 8 March 2022; revised 22 March 2022; accepted 29 March 2022)

## ABSTRACT

The year 2021 was recorded as the 6th warmest since 1880. In addition to large-scale warming, 2021 will be remembered for its unprecedented climate extremes. Here, a review of selected high-impact climate extremes in 2021, with a focus on China, along with an extension to extreme events in North America and Europe is presented. Nine extreme events that occurred in 2021 in China are highlighted, including a rapid transition from cold to warm extremes and sandstorms in spring, consecutive drought in South China and severe thunderstorms in eastern China in the first half of the year, extremely heavy rainfall over Henan Province and Hubei Province during summer, as well as heatwaves, persistent heavy rainfall, and a cold surge during fall. Potential links of extremes in China to four global-scale climate extremes and the underlying physical mechanisms are discussed here, providing insights to understand climate extremes from a global perspective. This serves as a reference for climate event attribution, process understanding, and high-resolution modeling of extreme events.

**Key words:** climate extremes, detection and attribution, climate change, natural internal variability

**Citation:** Zhou, T. J., and Coauthors, 2022: 2021: A year of unprecedented climate extremes in Eastern Asia, North America, and Europe. *Adv. Atmos. Sci.*, **39**(10), 1598–1607, <https://doi.org/10.1007/s00376-022-2063-9>.

## 1. Introduction

The average temperature across global surfaces in 2021 was 1.04°C above the average of 1880–1900, according to the US National Oceanic and Atmospheric Administration assessment report<sup>a</sup>. This puts 2021 on track to be the 6th warmest year recorded during the period 1880–2021. In addition to a large-scale warming trend, 2021 will be remembered for its unprecedented extremes. Extreme events, such as extreme rainfall and devastating floods, droughts, heatwaves, cold waves, and storms were seen in different regions across the globe throughout the year (World Meteorological Organization, 2021). In China, 2021 will also be remembered for its unusual spring to winter period (Fig. 1). The annual mean surface temperature, averaged over continental China for 2021, was the warmest since 1961, at an estimated 1.0°C above normal (1981–2010) levels. Devastating extreme weather and climate events were also observed, including cold spells, sandstorms, heatwaves, and floods (China Meteorology Administration, 2022).

The provisional WMO State of the Global Climate 2021 report released by the World Meteorological Organization (WMO) at a press conference on the opening day of the 2021 United Nations climate change conference, known as COP26

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<sup>a</sup> <https://www.ncei.noaa.gov/news/global-climate-202112>

(Conference of the Parties, 26th annual summit), provided a review of high-impact events based on data for the first nine months of 2021. The report highlights the impacts of climate change and is presented from a global view. Here, we present a review of selected high-impact climate extremes in 2021, with a focus on China along with an extension to extreme events in North America and Europe (Fig. 2). This serves as a reference for climate event attribution, process understanding, and high-resolution modeling of extreme events.

## 2. High-impact climate extremes in China

In the following section, we review the climate extremes in China from a seasonal time-sequence perspective. As

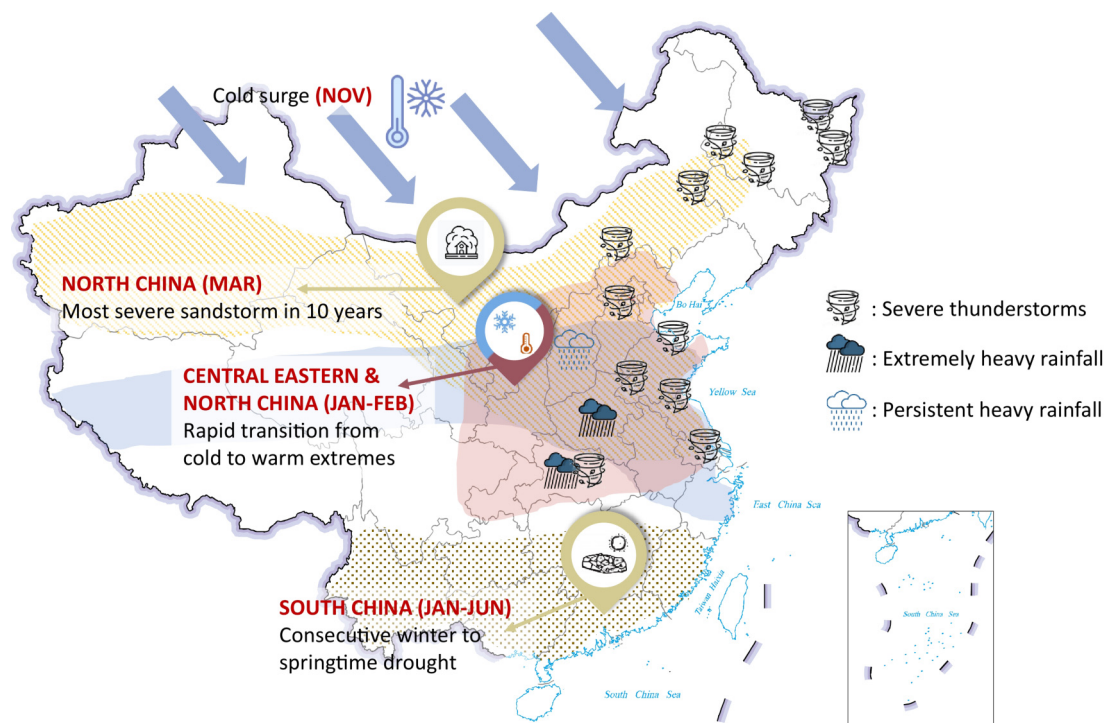


Fig. 1. High-impact climate extremes in China during 2021.

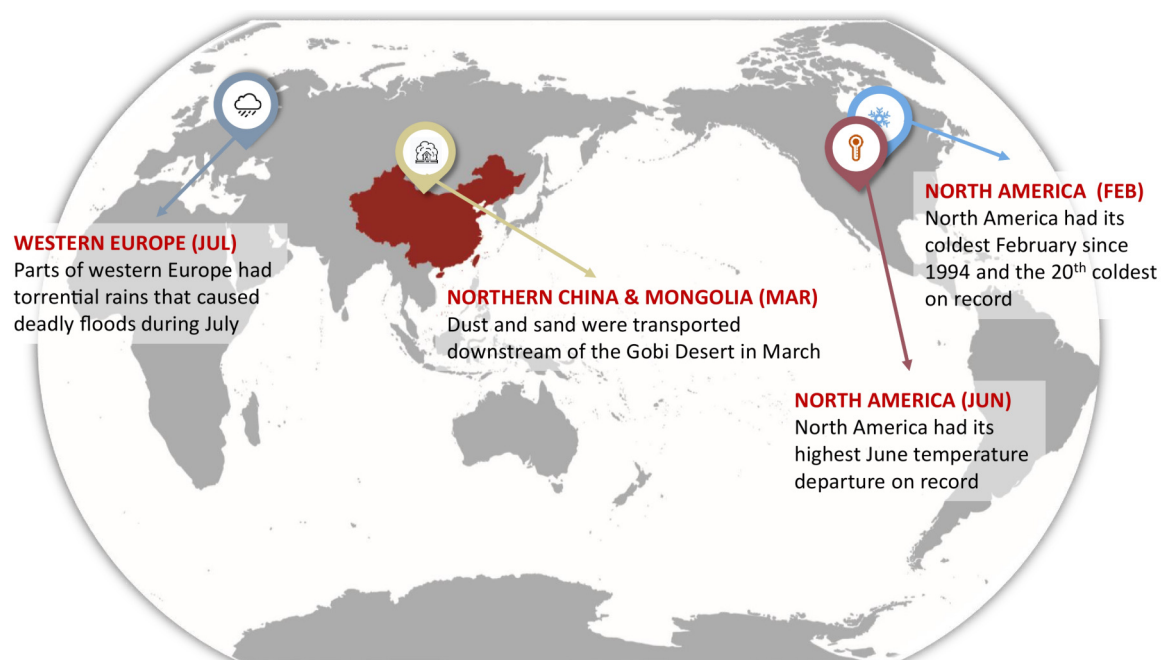


Fig. 2. Selected global climate extreme events in 2021 reviewed in this study.

shown in Fig. 3, nine extreme events are highlighted.

### 2.1. Rapid transition from cold to warm extremes during January and February

A cold surge hit North China on 6–8 January 2021, with large parts of the country experiencing temperature decreases of 6°C–12°C. Temperatures reached or broke records in more than 50 cities and counties. Beijing, for example, had a minimum temperature of –19.6°C on 7 January, which was the third coldest day since 1951. The cold conditions, however, quickly relented, and the following month, February, became the warmest since 1961 in terms of national average, with daily maximum temperature records being exceeded in 787 cities and counties. From 18–21 February, extreme warm events occurred in northern China. February records of daily maximum temperature were breached at 905 stations in North China. Parts of northern China reached 25°C–29°C on 21 February, with Beijing at 25.6°C and Xixia in Henan at 30°C (China Meteorology Administration, 2022).

The occurrence of the strong cold surge seen in January 2021 in China appears to have been related to the negative phase of the Arctic Oscillation and an intensified Siberian High (Wang et al., 2021; Zheng et al., 2022). The “Warm Arctic–Cold Siberia” pattern has also been mentioned as a possible contributing factor to the intensity of the cold surge (Zhang et al., 2021b). The transition from cold to warm appears to have been associated with an enhanced and subsequently weakened Ural blocking high and surface Siberian high before and after mid-January 2021 (Yu et al., 2022). The extreme warmth in February in China was remotely connected to the exceptionally cold February in North America by the anomalous weakening of the polar vortex and the resulting intensified meridional flows (see section 3.1). Other contributing factors also deserve to be explored, which is out of the scope of this study.

### 2.2. The strongest sandstorm in March

Sandstorms are frequent phenomena during spring in northern China in most years. Nine spring sandstorms occurred in 2021 over China according to the 2021 China Climate Bulletin<sup>b</sup>. In 2021, the first sandstorm occurred on 10 January, 38 days earlier than the 2000–20 normal and the earliest since 2002. Two severe sandstorms occurred in March, the largest number since 2000. The strongest sandstorm swept northern China from 13–18 March 2021 and became the most severe of the past decade. Nineteen provinces, including Inner Mongolia, Hebei, Ningxia, Shanxi, and Beijing, covering 4 562 000 km<sup>2</sup>, were impacted, with direct economic losses exceeding 30 billion RMB<sup>c</sup>. The event began on 14 March over the Mongolian Plateau and spread to North China around 15 March. The PM<sub>10</sub> concentration broke the monitoring record in Ulanqab (>9985 µg m<sup>-3</sup>) on 14 March and exceeded 7400 µg m<sup>-3</sup> in Beijing on 15 March. For comparison, the historical March mean is less than 200 µg m<sup>-3</sup> (Yin et al., 2022). The lowest visibility in Beijing dropped to 500–800 m. On 16 March, the sandstorm reached western South Korea<sup>d</sup>.

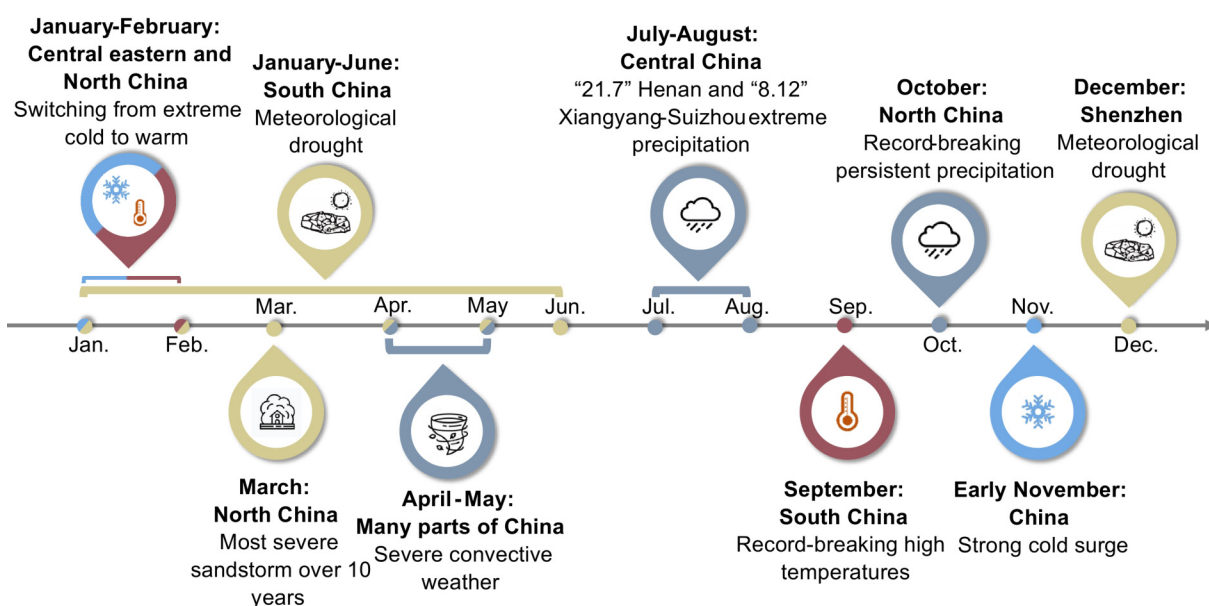


Fig. 3. Climate extremes that hit China during 2021 listed in temporal sequence.

<sup>b</sup> [http://zwgk.cma.gov.cn/zfxgk/gknr/qxbg/202203/t20220308\\_4568477.html](http://zwgk.cma.gov.cn/zfxgk/gknr/qxbg/202203/t20220308_4568477.html) (in Chinese)

<sup>c</sup> <https://www.119.gov.cn/article/42hYuGBMi7t> (in Chinese)

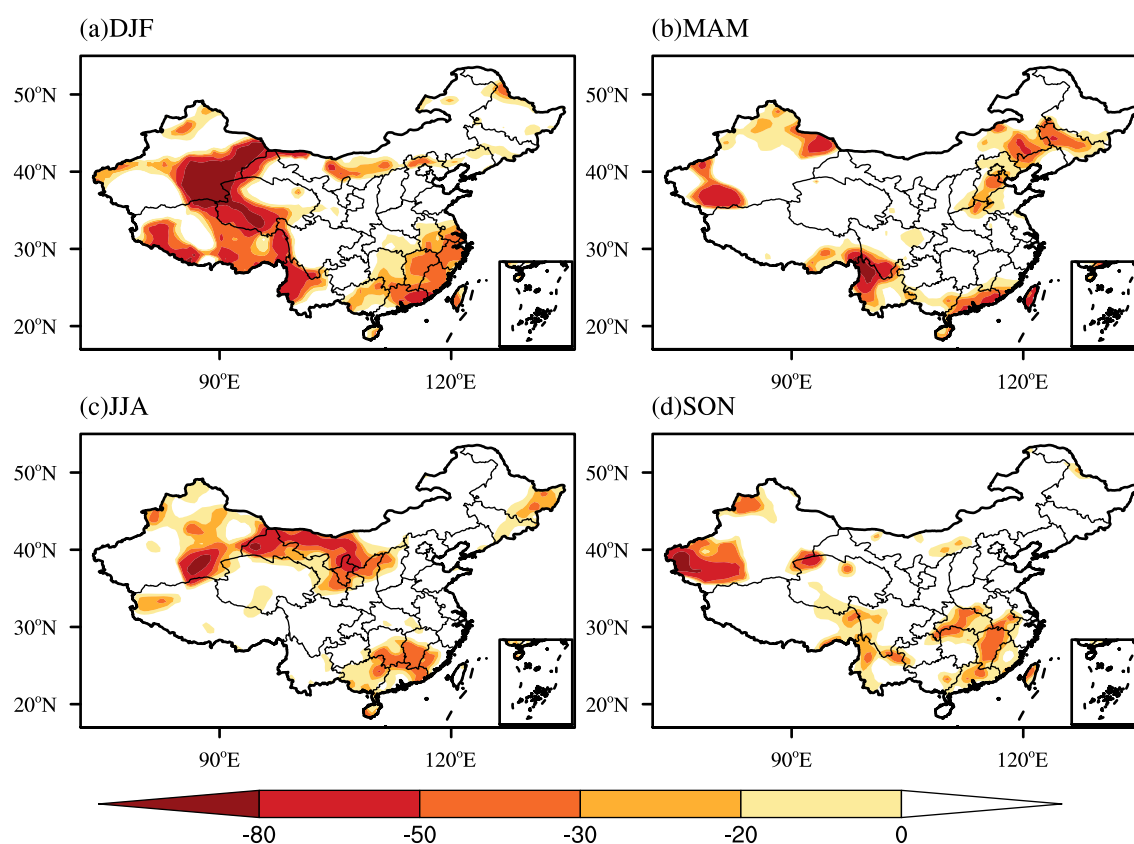
<sup>d</sup> <https://www.euroweeklynews.com/2021/03/16/south-korea-blanketed-by-massive-yellow-dust-storm-blown-in-from-China/>

The sandstorm itself was due to strong northwesterly winds associated with Mongolian cyclones (Duan et al., 2021). A particularly dry period of weather and early snowmelt over the dust source region was crucial for the formation of this sandstorm. It left the soil surface desiccated, lacking in spring vegetation, and prone to sand transport (Duan et al., 2021; Yin et al., 2022). A persistent drier and warmer climate in Mongolia in 2020 and early 2021 was crucial for the creation of this North China sandstorm; the climate conditions in Mongolia are discussed in section 3.2.

### 2.3. Consecutive winter to springtime drought in South China

From October 2020 to April 2021, precipitation in southern China was significantly less than normal and 20%–50% less than the climate mean in South China and Yunnan Province (Fig. 4a). The average precipitation for the seven provinces, including Zhejiang, Fujian, Jiangxi, Hunan, Guangdong, Guangxi, and Yunnan, reached its lowest value since 1961. The precipitation in Fujian Province was 224.8 mm and in Guangdong Province, 216.0 mm, which were 60% and 53.4% less than the climate mean, respectively. Continuous low precipitation led to continued drought and severe impacts in part of South China in the spring of 2021. The water surface area of Poyang Lake in Jiangxi Province on 15 January (1044 square kilometers) was 40% smaller than the climate mean. Large and medium-sized reservoirs in Zhejiang and Fujian provinces had less water storage in early February than in normal conditions, and some regions experienced a scant supply of water (Fig. 4b). Taiwan Island, one of the rainiest places in the world, in June 2021 faced its worst drought of the past 56 years. Because there were no landfalling typhoons on the island in 2020 and little rainfall until the spring of 2021, many reservoirs in Taiwan province were at less than 20% capacity. The Sun and Moon Lake in Taiwan province reached its lowest water level in the past 56 years, and some parts actually dried up in the spring of 2021 (Fig. 4b).

The drought was caused by a low-level anomalous cyclonic circulation over the Northwest Pacific. Anomalous northerly winds on the northwest side of the cyclone prevailed over South China, inhibiting water vapor transport from the ocean. The cyclone circulation had persisted since October 2020 and intensified in the winter of 2020/21. The circulation anomalies were forced by sea surface temperature anomalies associated with La Niña. The persistence of the large-scale circulation since the end of the rainy season in 2020 led to continuous low precipitation and high temperature until the spring of



**Fig. 4.** Precipitation anomalies (units: %) in 2021 (a) preceding winter, (b) spring, (c) summer, and (d) autumn relative to the climatology of 1991–2020. The precipitation data is from Climate Prediction Center (CPC) Unified Gauge-Based Analysis of Global Daily Precipitation (Xie et al., 2007).



2021<sup>e</sup>.

In addition, although the onset of the South China Sea summer monsoon in late May 2021 partly alleviated the dry conditions, South China precipitation was still 20%–50% below normal in the summer and autumn of 2021, particularly over Guangdong Province (Figs. 4c and 4d). The associated warmer temperature and heatwaves in 2021 further enhanced evaporation, which then reduced the surface water, dried out soils, and affected the vegetation. The lack of water supply and enhanced water demand from autumn 2020 to 2021 in the upstream region of Dongjiang, a Pearl River tributary that supplies 90% of the water needs of two metropolises, Shenzhen and Hong Kong, led to a severe water shortage in Shenzhen in December. To deal with the worst drought in the past four decades, Shenzhen City announced emergency measures to cut water consumption.

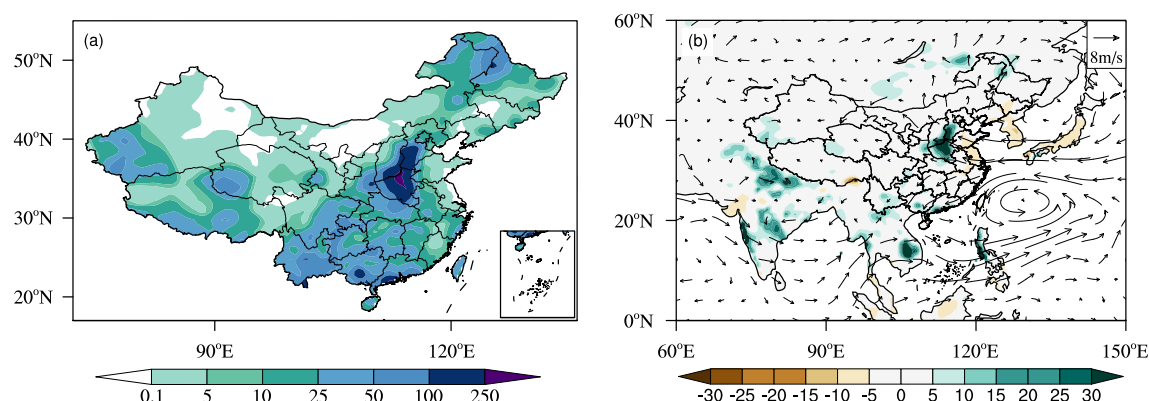
#### **2.4. Severe thunderstorms in eastern China in the first half of 2021**

Thunderstorms are mesoscale or small-scale weather phenomena, and since they occur frequently and can be widespread, they are also considered as main contributors to continental extreme precipitation events. They are severe and disruptive weather hazards that change rapidly on the time scale of minutes to hours or a few days, and they have high impacts on society. Recent research has demonstrated that 63.2% of hourly extreme precipitation was associated with thunderstorms during the warm season in 1980–2011, as recorded by 653 stations in China (Ng et al., 2022). In southern China, this rate may reach to 70%–80% (Xu, 2020). The record-breaking extreme precipitation event and extreme high wind event that occurred in 2021 were associated with thunderstorms in China. There were multiple severe thunderstorm outbreaks in eastern China in the first half of the year (China Meteorology Administration, 2022). A severe thunderstorm within a squall line struck parts of Shandong Province, Jiangsu Province, and Anhui Province in central and eastern China on 30 April, leading to major damage and 15 reported deaths. A maximum wind speed of 47.9 m s<sup>-1</sup> was reported in Nantong of Jiangsu Province. Large hail (3–5 cm in diameter) was reported in Suqian of Jiangsu Province. In China, thunderstorms within squall lines are common in Jiangsu and are reported every year. However, high-impact squall lines causing extensive damage, such as this event, are rare. The occurrence of this squall line was also earlier than normal. An EF3 tornado hit Wuhan of Hubei Province and Suzhou of Jiangsu Province on 14 May, causing high impacts. Ten deaths in Wuhan and four deaths in Suzhou were reported, as were economic losses due to gales and floods. The middle and lower reaches of the Yangtze River valley are frequently hit by tornados. However, the distance between Wuhan and Suzhou is approximately 1000 km, and a case where two strong tornadoes hit those two places almost at the same time (with only a 1–2-h delay) is unlikely. The two tornadoes were dominated by the same synoptic low-level jet, which provided the warm moisture and strong dynamic forcing needed to generate the severe thunderstorms. The total rainfall amount was 231 mm, and maximum daily precipitation amounts of 40–70 mm were reported at a local station in Hubei Province. While attributions for individual thunderstorms imbedded in synoptic weather systems remain a challenging issue, the increased synoptic variability associated with global warming should be a concern of both the scientific community and policy makers (Zhang et al., 2021a).

#### **2.5. Extremely heavy rainfall over Henan Province in July**

Extreme rainfall hit Henan Province of China from 17 to 24 July. After this event accumulated rainfall in 39 counties had reached or exceeded half of the climatological mean annual rainfall; of these, 10 counties, including Zhengzhou, Huixian, and Qixian, had received accumulated rainfall more than the climatological mean annual rainfall. Approximately 32.8% of the land in Henan Province had received accumulated rainfall of more than 250 mm (China Meteorology Administration, 2022). The most severely affected area was around the city of Zhengzhou, which is the capital of Henan Province and has a population of 12.6 million. On 20 July, the city received 201.9 mm of rainfall in one hour, 382 mm in 6 hours, and 552.5 mm in 24 hours. The one-hour rainfall broke the record of observation in continental China since 1951. The daily rainfall of 552.5 mm also broke the July record. In addition to Zhengzhou, the daily rainfall broke records in 18 surrounding counties. The three-day consecutive rainfall broke records in 32 counties. From 18 to 22 July, Zhengzhou received a total rainfall of 820.40 mm, which is far larger than the climatological monthly mean (1991–2020) of 138.82 mm for July and even more than its climatological annual average of 640.8 mm (Fig. 5). Extreme flash flooding inundated many buildings, roads, and subways. The official death toll from the floods reached 380 in Zhengzhou and 398 in the whole province. Approximately 1.48 million people were affected and had to be relocated, and hundreds of thousands lost their homes. The direct damage caused by the floods amounted to 40.9 billion RMB in Zhengzhou and more than 120 billion RMB in Henan Province.

During this extreme event, the western Pacific subtropical high (hereafter referred to as WPSH), the continental subtropical high over northwestern China, the trough in the midlatitudes, and the inverted trough over South China formed a saddle-type large-scale circulation pattern (Fig. 5b). Due to this the saddle-type circulation pattern, the low vortex over Henan Province was stable and persisted for six days. The southeasterlies at the west side of the WPSH transported water vapor to Zhengzhou and converged there. In addition, the moisture ahead of Typhoon “In-Fa” (2021) also contributed to the extreme rainfall by strengthening the southeasterlies via its outer airflow. The orographic lifting of the high mountains located to the west of Zhengzhou is also favorable for torrential rainfall. Extreme rainfall poses challenges to both numerical weather prediction and high-resolution climate modeling.



**Fig. 5.** (a) Accumulated precipitation (units: mm) from 18 to 22 July 2021. (b) Precipitation anomalies (units:  $\text{mm d}^{-1}$ ) and 850-hPa wind anomalies (units:  $\text{m s}^{-1}$ ) from 18 to 22 July 2021 relative to the July mean from 1991–2020. Precipitation and wind fields are derived from CPC data and ERA5 reanalysis (Hersbach et al., 2019), respectively.

## 2.6. Extreme rainfall over Hubei Province in August 2021

Following the devastating extreme rainfall in Henan in July, southwest China and the middle and lower reaches of the Yangtze River valley were again hit by torrential rainfall between 10 and 14 August. The maximum accumulated rainfall occurred in Xiangyang and Suizhou, Hubei Province, with an accumulation of between 490 mm and 556 mm during this period. The daily maximum rainfall at Yicheng station, 305.9 mm, broke the observational record. In particular, the torrential rainfall in Xiangyang and Suizhou poured down at nighttime between 2300 LST (LST = UTC + 8 h) 11 August and 0700 LST 12 August. During this period in Liulin Town in Suizhou, hourly rainfall exceeded 50 mm for five consecutive hours between 0300 LST and 0800 LST and even exceeded 100 mm for two consecutive hours between 0400 LST and 0600 LST 12 August. This resulted in a rainfall accumulation of 462.6 mm within six hours in Liulin Town in Suizhou. The sudden outbreak of torrential rainfall at night exacerbated socioeconomic losses, as prompt solutions and rescues were almost impossible. According to statistics, in Liulin Town in Suizhou, over 8000 people were impacted, with 21 dead and 4 missing.

This torrential rainfall event along the Yangtze River valley was closely related to the strengthened WPSH. Located at the edge of the WPSH, the Yangtze River valley was fed by continuous and abundant moisture from the southwesterlies, which carried warm and moist air from the Pacific. When this condition was confronted with cold air advection from the mid-latitudes, heavy rainfall developed.

## 2.7. High temperatures in South China throughout September 2021

Vast areas of South China were under the influence of high temperatures throughout September 2021. High-temperature days (defined as daily maximum temperatures reaching or exceeding  $35^{\circ}\text{C}$ ) accounted for more than 10–20 days in September in large parts of South China and exceeded 20 days in parts of Hunan, Guangdong, Guangxi, and Jiangxi Provinces. Compared to the normal climate state, the number of high-temperature days in September was 3–10 days above normal over large parts of South China and exceeded 10 days above normal in parts of Hunan, Jiangxi, Guangxi, and Guangdong Provinces.

Meanwhile, the accumulated rainfall amount in parts of South China and south of the Yangtze River valley was less than the climatological average by 50%–90% in September. The high temperatures, in combination with the rainfall deficit, resulted in meteorological droughts in parts of Guangdong, Guangxi, Jiangxi, and Hunan Provinces in September.

The exceptionally hot September was directly related to the WPSH, which was steadily located more northwestward than its climatology with a stronger than normal intensity. South China was impacted by subsidence from the WPSH and was hence repeatedly hit by high temperatures. It is worth noting that the hot September in South China and the excessively wet October in North China are intrinsically linked; both are related to the anomalous behavior of the WPSH. The underlying mechanism of the anomalous WPSH is crucial for understanding the climate background of the extreme events.

## 2.8. Persistent heavy rainfall in North China in September and October 2021

A large part of North China received excessive rainfall in the early autumn of 2021. During 1 September and 10 October, the total rainfall amount in northern China was 1.5 times more than the climatology for the same period, ranking the highest on record. A total of nine provinces (cities), including Beijing, Tianjin, Hebei, Henan, Shaanxi, Shanxi, Liaoning, Shandong, and Gansu, saw total rainfall amounts which broke records from 1961. In particular, rainfall accumulation in Shanxi (310.2 mm) and Shaanxi (396.4 mm) was 3 and 2.3 times greater than the normal climatology, respectively (China Meteorology Administration, 2022; Fig. 6).

During this excessively wet autumn, Shanxi was hit by persistent heavy rainfall during 2 and 6 October. The total rainfall amount in Shanxi Province reached 119.5 mm between 2000 LST 2 October and 0800 LST 7 October, which was more

than three times the climatological monthly rainfall accumulation in October. Among the 117 counties (cities or districts) in Shanxi Province, 18 saw a rainfall accumulation of more than 200 mm, with the maximum reaching 285.2 mm. A total of 63 national meteorological observation stations recorded maximum historical rainfall accumulations for the same period. In addition, the daily rainfall amounts at 59 stations broke historical records for the same period. The persistent rainfall resulted in waterlogging, floods, and geological disasters in Shanxi. The heavy rainfall event affected 1.76 million people in Shanxi Province, with 15 dead, 3 missing, and 120 100 relocated. The direct economic loss was estimated to be 5.03 billion RMB.

This persistent heavy rainfall event was dominated by a stable atmospheric circulation configuration. The stronger-than-normal WPSH remained stable over the Huang–Huai region, which, combined with the low-pressure systems in the west-erly, gave rise to the persistent heavy rainfall. In addition, the complex topography of Lvliang Mountains and Taihang Moun-tains in Shanxi enhanced the rainfall.

### 2.9. Cold surge in early November

A strong cold surge swept through eastern and northwestern China during 4–9 November 2021. This event ranks 4th since 1961 on the comprehensive strength index. During this event, daily mean temperatures dropped by more than 8°C for over 80% of the nation, in which some regions experienced a drop of more than 16°C. The drop in temperature at 116 stations reached or exceeded previous records. Meanwhile, the amount of daily precipitation at 151 national stations exceeded the November maximum in northeastern and northern China, most of which was induced by blizzards. The depth of snow in some areas exceeded 10 cm and was up to 50 cm locally. The cryogenic freezing rain and snow caused widespread disruptions to transport, power supply, and public services and damage to agriculture in northern and northeastern China and the eastern part of northwestern China (China Meteorology Administration, 2022).

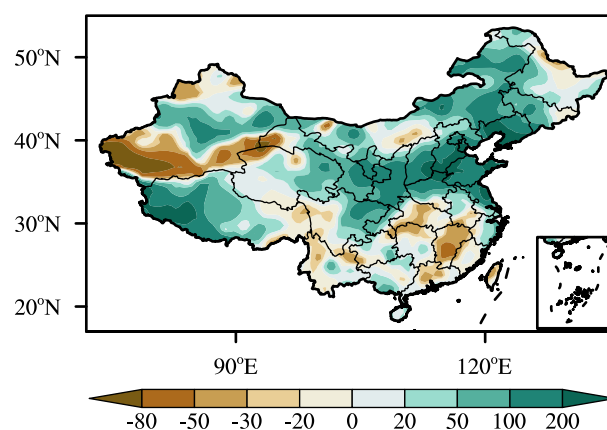
The cryogenic freezing rain and snow during this event reminded us of a previous extreme cold event that had occurred in January 2008 (Ding et al., 2008), when more than 100 people died. Fortunately, benefitting from the successful forecast and the preventative action taken this year, no mortality was reported during the event.

## 3. Links to global-scale climate extremes

### 3.1. Exceptionally cold North American February 2021

Beyond China's borders, 2021 was also a year of several exceptional events in parts of the Northern Hemisphere (Fig. 2). In early January, the polar vortex, a robust, climatological circulation in the stratosphere encircling the North Pole, became highly distorted and weakened (Lee, 2021; Lu et al., 2021; Rao et al., 2021), resulting in the usually zonal flow of the midlatitude jet stream becoming sharply meridional, particularly over North America. By February, the effects of this had descended to the surface, ushering in exceptionally cold conditions throughout Canada and the United States, with conditions widely being between 15°C and 25°C colder than normal, especially in central and southern states, where the cities of Oklahoma City, Dallas, and Houston experienced their coldest days since 1899, 1930, and 1989, respectively.

The impacts of the low temperatures on energy supplies and travel were exacerbated by exceptionally widespread snow cover, which at one point covered 73% of the contiguous US (Doss-Gollin et al., 2021; Jackson, 2021), as the result of a winter storm that traversed the US from the Pacific to the Atlantic. The weakening of the polar vortex was also notable for its occur-



**Fig. 6.** Precipitation anomalies (units: %) for September to October 2021 relative to the climate mean of 1991–2020 derived from CPC precipitation data.

rence during a period in which the usual precursors [an easterly QBO based on Baldwin and Dunkerton (1998), for example] in the tropics for such events were absent. Lu et al. (2021) instead attributed the event partly to anticyclonic blocking over the Urals during December 2020.

### 3.2. *Mongolian dust event in March 2021*

Drier and increasingly warm summers have been a persistent aspect of the climate in Mongolia in recent decades (Meng et al., 2020; Han et al., 2021), accompanied by degradation of the natural environment. The past five years and summer of 2020 have been no exception, with drought persisting throughout what is climatologically the wettest season of each year. After an unusually warm February in 2021 with earlier than normal snow melt, which left the soil exposed to the atmosphere, the region experienced a persistent longitudinal dipole in mid-March between an anticyclone to the west and an unusually vigorous low pressure system over northeast China; surface winds generated by the pressure gradient over the Gobi Desert exceeded  $80 \text{ km h}^{-1}$  (Filonchyk and Peterson, 2022). Dust and sand transported downstream of the desert resulted in unprecedented daily average  $\text{PM}_{10}$  concentrations of over  $1000 \mu\text{g m}^{-3}$  in 42 Chinese cities, with two locations having at least  $10\,000 \mu\text{g m}^{-3}$  (see section 2.2).

### 3.3. *North American heatwave in June 2021*

During June 2021, the tropospheric polar vortex at 100 hPa was split (Overland, 2021), with large-scale centers of negative geopotential height over the high northern latitudes of both the Pacific and Atlantic Oceans. Over North America, this allowed a longitudinally oriented omega ( $\Omega$ ) block of low–high–low pressure to form at the surface, resulting in persistent anticyclonic anomalies over northwestern states of the US and the Canadian provinces of Alberta and British Columbia. Persistence of the block allowed adiabatic heating due to descent in the region and incoming solar radiation to progressively warm the troposphere close to the surface with devastating consequences for the local environment with temperatures widely being in excess of  $45^\circ\text{C}$  and even attaining a remarkable  $49.6^\circ\text{C}$ , a new record in Canada, which exceeded the previous record by  $6^\circ\text{C}$ . Associated impacts on health and from forest fires were widespread, affecting human populations, fauna, and flora.

### 3.4. *European floods during July 2021*

For residents of Germany and Belgium, the summer of 2021 will be remembered for its torrential rainfall, which saw many regions receive more than their climatological mean July rainfall (approximately 100 mm) in a single day during 17–19 July. In one part of eastern Belgium's Liège province, rainfall of more than 271 mm was recorded in a 48-hour period, while in Reifferscheid, in Germany's western Rhineland–Palatinate state, 207 mm fell within a nine-hour period. In eastern Germany, 87 mm fell in two hours in the Ore mountains, and 43 mm fell in just 30 minutes in the Bavarian city of Hoferland in southern Germany (Jungbänel et al., 2021). The flooding arose from a slow-moving cutoff low pressure system from the Atlantic that stalled over Germany. Flooding from the system also impacted several other countries in its path, including the UK, France, the Netherlands, and Switzerland, and it even extended as far as Romania.

## 4. **Concluding remarks**

The past year of 2021 is remembered for its unprecedented extremes from both global and regional viewpoints. Extreme events, by nature, are strongly affected by internal climate variability. For example, studies have shown that the extreme cold surges in January 2021 in China were associated with the negative phase of the Arctic Oscillation and the enhancement and movement of the Siberian High (Wang et al., 2021; Zheng et al., 2022). ENSO, another internal mode, is also an important driver of interannual variability. In the observations, La Niña conditions emerged in mid-2020 and peaked in October–December at moderate strength. La Niña weakened through the first half of 2021, reaching an ENSO-neutral state in May, but then enhanced after mid-year and approached the La Niña threshold again by October 2021. La Niña conditions may partly affect consecutive winter to springtime droughts in South China, but further studies are needed to clarify the mechanism.

Apart from internal variability, whether and to what extent human activities have altered the likelihood and/or magnitude of observed climate extremes has been of great concern to the public. While no attribution conclusions have been reached to date on the selected events in China (which often takes a longer time), the detection and attribution of climate extremes at the scales of the selected events are challenging. Across a wider area of eastern China, significant trends in extreme events such as extreme precipitation and temperature were identified (e.g., Ma et al., 2017b; Qian et al., 2019), and some could be attributed to human-induced climate change (Ma et al., 2017a, b; Sun et al., 2022). There is high confidence that anthropogenic influence has increased the probability and intensity of high temperature extremes (e.g., Ma et al., 2017c; Ren et al., 2020) and extreme drought in China (Zhang et al., 2017, 2020a), but meanwhile, it has also decreased the probability and intensity of cold extremes (e.g., Qian et al., 2018; Liu et al., 2021). In contrast, the attribution of extreme precipitation events exhibits larger uncertainty depending on the temporal and spatial scales of events and has lower confidence (Zhang et al.,



2020b; Sun et al., 2022). For example, human-induced climate change, including GHG and aerosol emissions, has been concluded to change the likelihood of persistent heavy rainfall extremes, such as those along the Yangtze River valley in 2020 (Zhou et al., 2021) and in southwestern China in 2020 (Qian et al., 2022).

There is pressing demand for the scientific community to provide timely event attribution statements. Thus, an urgent need exists to develop an operational real-time extreme event attribution system to quantify the risks of extremes caused by climate change or anthropogenic forcing in a timely manner by using a pre-established methodology. Rapid attribution systems, which allow rapid attribution assessments based on peer-reviewed methods to reach conclusions within a few days of a record-breaking extreme event, have been used in the attributions of the summer heatwave in northwest America<sup>f</sup> and the floods in western Europe<sup>h</sup> in July 2021. Such attribution systems are, however, still not available and need to be developed for China. The number of climate centers or consortia that carry out global climate simulations has grown rapidly in China. In CMIP6, which supported the climate change assessment of IPCC AR6, there are eight climate/Earth system models from mainland China (see Zhou et al., 2020 for a review). The quick developments of both supercomputers and climate models are expected to drive the establishment of a rapid attribution system in China.

**Acknowledgements.** This work is supported by the Second Tibetan Plateau Scientific Expedition and Research (STEP) program (Grant No. 2019QZKK0102) and the K. C. WONG Education Foundation. This work also contributes to the U.K.–China Research and Innovation Partnership Fund through the Met Office Climate Science for Service Partnership (CSSP) China as part of the Newton Fund.

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<sup>f</sup> <https://blog.metoffice.gov.uk/2021/06/29/heatwave-record-for-pacific-north-west/>

<sup>g</sup> <https://www.worldweatherattribution.org/western-north-american-extreme-heat-virtually-impossible-without-human-caused-climate-change/>

<sup>h</sup> <https://www.worldweatherattribution.org/heavy-rainfall-which-led-to-severe-flooding-in-western-europe-made-more-likely-by-climate-change/>

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