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Concurrent hot extremes and high ultraviolet radiation in summer over the Yangtze Plain and their possible impact on surface ozone

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Keywords: hot extremes, ultraviolet radiation, clouds, the Western Pacific Subtropical High, surface ozone, ERA5 reanalysis

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Abstract

Hot extremes, ultraviolet (UV) radiation, and surface ozone all have prominent effects on human health and ecosystems. Here we show evidence that both hot extremes and high surface UV radiation at noon time occur concurrently in summer over the Yangtze Plain. Composite analysis suggests that hot extremes in summer are primarily caused by the westward extension of the Western Pacific Subtropical High, which leads to less clouds and consequently more downward solar radiation on the surface over the Yangtze Plain. It is found that surface UV radiation may be dominated by cloud variations, instead of stratospheric ozone during the hot extremes. Further analysis indicates that the hot extremes and high UV radiation, which play important roles in photochemistry in the troposphere, may result in more surface ozone. The concurrent hot extremes, strong UV radiation, and severe ozone pollutions over the Yangtze Plain in summer are likely to have dramatical influences on human health, which should be paid more attention.

1. Introduction

Hot extremes have drawn extensive attention due to their harmful impacts on human health and regional terrestrial ecosystems (Coumou and Rahmstorf 2012, Gao *et al* 2015, Wang *et al* 2017, Yang *et al* 2019, Zhang *et al* 2021). Previous studies have found that hot extremes over the Yangtze Plain in summer are modulated by the soil moisture in eastern China (Wang *et al* 2018), the snow cover over the Qinghai–Tibetan Plateau (Wu *et al* 2016), the Indian Ocean sea surface temperature (Hu *et al* 2012), the Pacific decadal oscillation (Liu *et al* 2019), and El Niño–Southern Oscillation (Arblaster and Alexander 2012). All these factors could affect the summer hot extremes over the Yangtze Plain via the Western Pacific Subtropical High which has been demonstrated to be the key and most direct controlling circulation system (Wang *et al* 2016). For instance, the Western Pacific Subtropical High is found to be enhanced/weakened during the boreal summer following the peak of an/a El Niño/La Nina event (Wang *et al* 2000, Xie *et al* 2009). The westward extension of the Western Pacific Subtropical High, which leads to downward vertical motion and reduced rainfall over the Yangtze Plain (Ding *et al* 2010, Kosaka *et al* 2012), further causes less clouds and consequently more downward solar radiation at surface.

The solar ultraviolet (UV) radiation reaching the Earth's surface is known to have detrimental impacts on exposed life forms in the biosphere, crop failure, and air quality (Douglass *et al* 2011, Williamson *et al* 2014 and references therein). It is widely accepted that surface UV radiation is dominated by stratospheric ozone which effectively absorbs most of the solar UV radiation (McKenzie *et al* 2011). Furthermore, surface UV radiation is also strongly influenced by clouds as a result of scattering processes (Bais *et al* 1993, 2011, Calbó *et al* 2005, Watanabe *et al* 2011, López *et al* 2012, Williamson *et al* 2014). Recent research has shown that the cloud effect can strongly influence the surface UV radiation in certain regions, such as the Siberian Arctic in spring (Xia *et al* 2021a, 2021b). This begs the question whether the westward extension of the Western Pacific Subtropical High, by modulating the clouds, may lead to more surface UV radiation over the Yangtze Plain which is home of a population of about 600 million with population density of about 600 people km^{-2} and made up of many densely populated cities and intensive farming regions (Guo *et al* 2021, Yan *et al* 2021).

Concurrent hot extremes and strong surface UV radiation in summer over the Yangtze Plain may cause more severe impacts on human health and even mortality than either of these factors alone. Moreover, both hot extremes and strong solar UV radiation are conductive to the photochemical reactions generating ground-level ozone (Lam *et al* 2005, Hodzic and Madronich 2018, Chen *et al* 2020) which is a secondary air pollutant and causes adverse effects on humans, crops, and ecosystems (Fann and Risley 2013, Tai *et al* 2014, Monks *et al* 2015, Fleming *et al* 2018). Recent studies have demonstrated that favorable meteorological conditions especially hot extremes have strong impacts on the formation of severe ground-level ozone pollution in China (Han *et al* 2020, Dang *et al* 2021, Wang *et al* 2022). It has been found that the western Pacific subtropical high plays a crucial role in the formation of high-level ozone over the Yangtze River Delta region in China (Shu *et al* 2016, Zhao and Wang 2017). Here we find that hot extremes and strong noon-time solar UV radiation occur simultaneously over the whole Yangtze River basin in summer, which is linked to severely high ozone episodes. Following sections describe the data, methods, and results in order.

2. Data and methods

2.1. Data

The monthly mean- noon-time (Beijing time 11:00–13:00) geopotential height, cloud fraction, total column ozone, 2 m air temperature (T2m), and downward solar and UV radiation at the surface analyzed here are from the fifth generation of the European Centre for Medium-Range Weather Forecasts (ERA5) reanalysis (Hersbach *et al* 2020) during the period 1979–2020. The analysis, which combines model data with observations, is produced hourly using an advanced 4D-var assimilation scheme. The horizontal resolution is 0.25° × 0.25°. In the ERA5 reanalysis, solar UV radiation flux is defined as radiation with a wavelength range of 200–440 nm.

To study the impact of hot extremes and strong UV radiation on surface ozone, a high-resolution (10 km) and high-quality daily maximum 8 h average ground-level ozone dataset covering China (ChinaHighO_3) from 2013 to 2020 is also used here. The ChinaHighO_3 dataset was generated from big data, including ground-based observations, remote sensing products, atmospheric reanalysis, and an emission inventory, using a novel spatiotemporal extremely randomized trees machine-learning model (Wei *et al* 2021, 2022). This dataset has been evaluated against surface observations at varying spatiotemporal scales and compared with previous related studies, and it has been found to have a high overall accuracy (Wei *et al* 2022).

2.2. Method

We use composite analysis to examine the concurrent hot extremes, strong UV radiation, and severe ozone pollutions in summer over the Yangtze Plain (black box in figure 1). The composite analysis is widely used in previous studies (Xie *et al* 2017, 2020, Xia *et al* 2021a). Here we use a T2m index, which is defined as the area-weighted spatial-mean T2m over 26° N–32° N and 100° E–120° E to composite the anomalies of T2m, surface UV radiation, and surface ozone in July, August, and September when hot extremes frequently occur. Linear trends and multi-year averages of each calendar month are removed because we mainly focus on the interannual variability. We define the monthly mean hot extreme events as years with the T2m index of greater than plus one standard deviation (the highest 15%) for each month (figure S1 available online at stacks.iop.org/ERL/17/064001/mmedia). The composite anomalies are computed by the difference between the hot extreme events and climatological mean over 1979–2020. The numbers of hot-extreme years are 7, 6, and 9 in July, August, and September, respectively. The statistical significance of the composite anomalies is assessed by the Student's *t*-test.

3. Results

Figure 1 shows the correlation coefficients between the monthly mean noon-time T2m and downward surface UV radiation over 1979–2020 in all months over China. During May–September, the surface UV radiation is positively correlated with the surface temperature in most regions in China, with maximum correlation coefficients of 0.92, 0.94, 0.96, 0.95, and 0.92 for the 5 months, respectively. The largest correlation coefficients are generally located over the Yangtze Plain, which indicates that hot extremes and

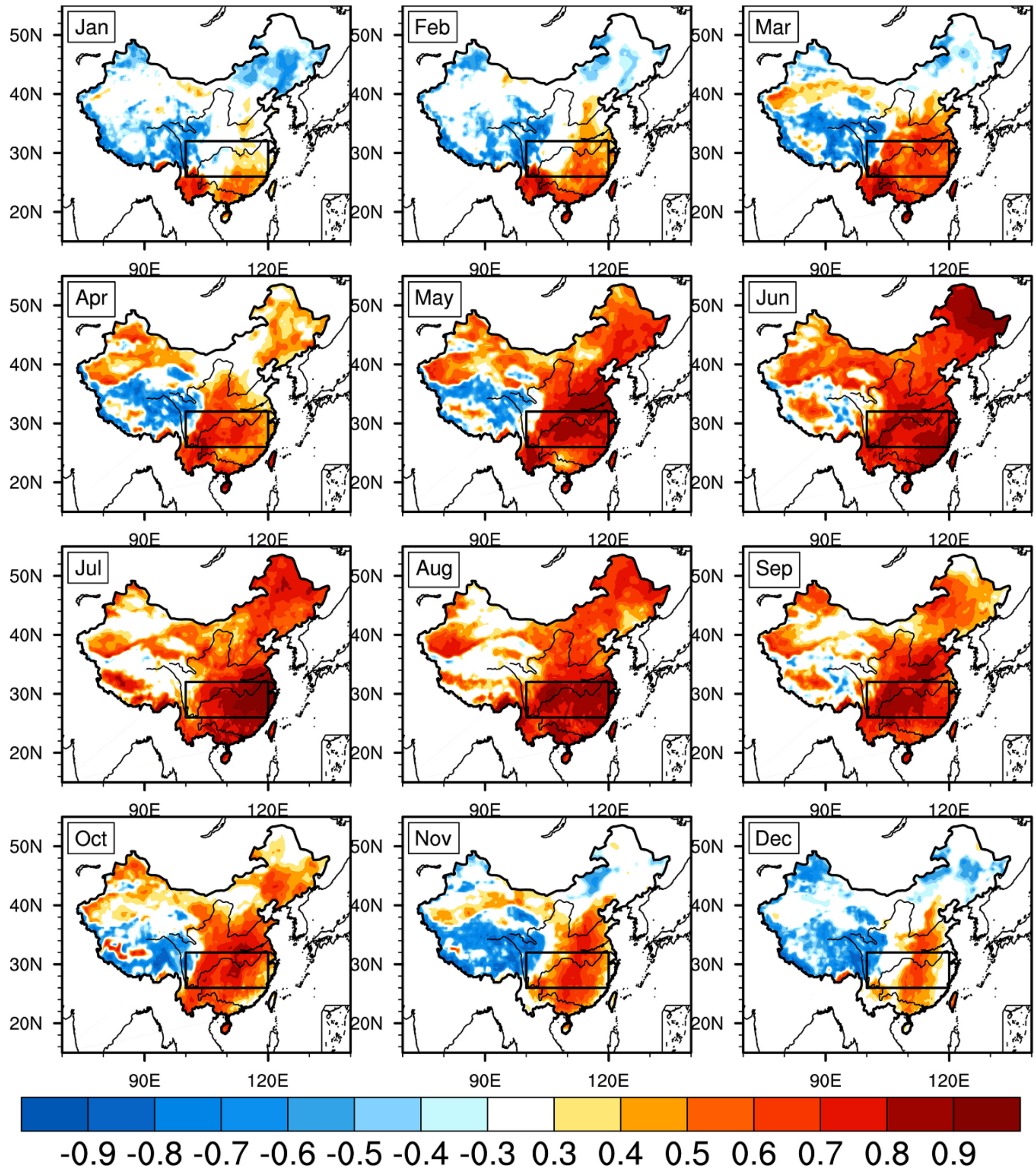

Figure 1. Geographic distributions of the correlation coefficients between the monthly mean noon-time T2m and downward surface UV radiation at each grid over 1979–2020 in all months over China based on ERA5 reanalysis. Black boxes indicate the concerned Yangtze Plain region over 26° N–32° N and 100° E–120° E. The correlation coefficient of ±0.3 corresponds to the 95% confidence level for the 42 years.

strong UV radiation probably occur concurrently in summer over the Yangtze Plain. Similar results can also be seen in the correlation coefficients between the monthly mean T2m and downward surface UV radiation, which shows very similar spatial patterns with that from noon-time mean (figure S2). It is interesting to note that surface UV radiation is negatively correlated with surface temperature over Tibetan Plateau and Northeast China especially during winter, which indicates that high surface temperature and strong surface UV radiation do not always occur simultaneously. The reason for this negative correlation is still unclear and warrants further investigation in future. We note that the correlation between T2m and total column ozone is insignificant over the Yangtze Plain (figure S3) where is covered by plenty of cloud cover (figure S4). It indicates that the significantly positive correlation between T2m and surface UV radiation over the Yangtze Plain may be caused by the variations of clouds.

Figure 2 shows the composite anomalies of noon-time mean T2m and surface UV radiation for hot extreme events over the Yangtze Plain in July, August, and September. We find that the significant surface warming is mainly located over the Yangtze Plain, which extends to Northwestern China in August and September. The maximums of the surface warming are 2.0 K, 2.8 K, 2.2 K in July, August, and September, respectively. Interestingly, a significant increase in surface UV radiation occurs simultaneously with

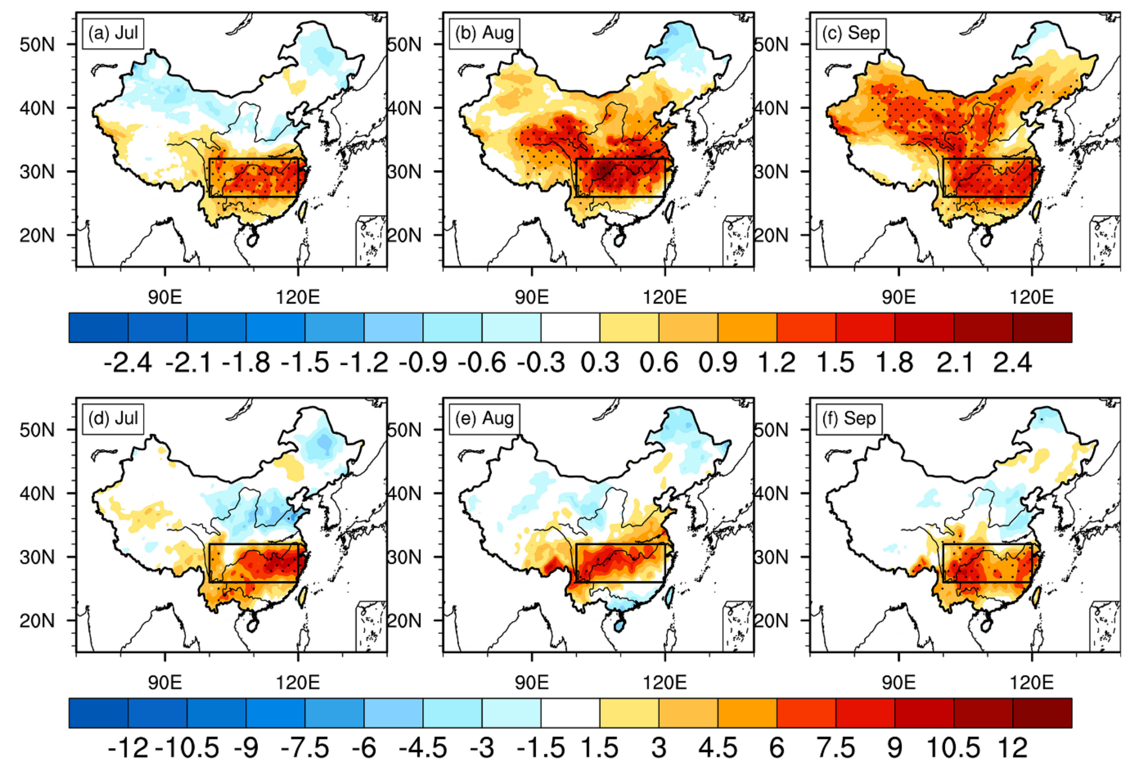

Figure 2. Geographic distributions of composite anomalies of noon-time (a)–(c) T2m (unit: K) and (d)–(f) surface UV radiation (unit: W m^{-2}) for hot extreme events in July, August, and September based on ERA5 reanalysis. Regions with dots are the places where composite anomalies have statistical significance levels higher than the 95% confidence level.

the hot extremes and is confined to the Yangtze Plain. The increase in surface UV radiation shows high spatial consistency with the surface warming with spatial correlation coefficients of 0.64, 0.77, and 0.71 in July, August, and September, respectively. In July, the increase in surface UV radiation is mainly located over the lower reaches of the Yangtze River with a maximum value of 10.2 W m^{-2}. In contrast, the high-value center is shifted to the upper reaches of the Yangtze River in August with a maximum of 10.1 W m^{-2}. In September, the strong surface UV radiation occurs in most of the Yangtze Plain with a maximum value of 9.9 W m^{-2}. The fractional increase of surface UV radiation can reach about 12.8%, 14.9%, and 21.4% in July, August, and September, respectively. Further analysis indicates that this increase in surface UV radiation is not associated with the change in stratospheric ozone (figure S5).

As mentioned in the introduction section, the concurrent hot extremes and strong surface UV radiation may be caused by changes in the Western Pacific Subtropical High. Figure 3 shows the composite anomalies of geopotential height at 500 hPa, total cloud fraction, and downward surface solar radiation for the hot extreme events in July, August, and September. In terms of the climatological mean, the Western Pacific Subtropical High is shifted eastward gradually from July to September. It is found that significant positive anomalies of geopotential height occur in the northwest of the climatological mean of the Western Pacific Subtropical High for the hot extreme events (figures 3(a)–(c)), which suggests a northwestward extension of the Western Pacific Subtropical High. The climatological pattern shows that the Yangtze Plain is covered by plenty of high, middle, and low clouds with maximum values of about 79%, 67%, and 83%, respectively (figure S4). The changes in the Western Pacific Subtropical High leads to a reduction of clouds during the hot extreme events (figures 3(d)–(f)). The center of this reduction, which can reach about −11%, is mainly located in South China, which is likely due to the spatial inhomogeneity of the climatology of clouds (figure S6). In July, the reduction of the high clouds in Southwest China over the Pearl River Basin contributes to most of the changes in total clouds (figures S5(a), (d) and (g)). However, middle and low clouds have stronger (around double) effects on scattering solar radiation especially UV radiation than high clouds (Calbó *et al* 2005). The reduction of middle and low clouds over the Yangtze Plain (figures S5(d) and (g)) explains the enhanced downward solar and UV radiation (figures 3(g) and 2(d)). Similarly, the increase in surface solar and UV radiation over the Yangtze Plain in August and September may also result from the decrease in middle and low clouds over there (figure S7). Moreover, the increases in surface solar radiation, which can reach about 86.1, 84.7, and 89.3 W m^{-2} in July, August, and September,

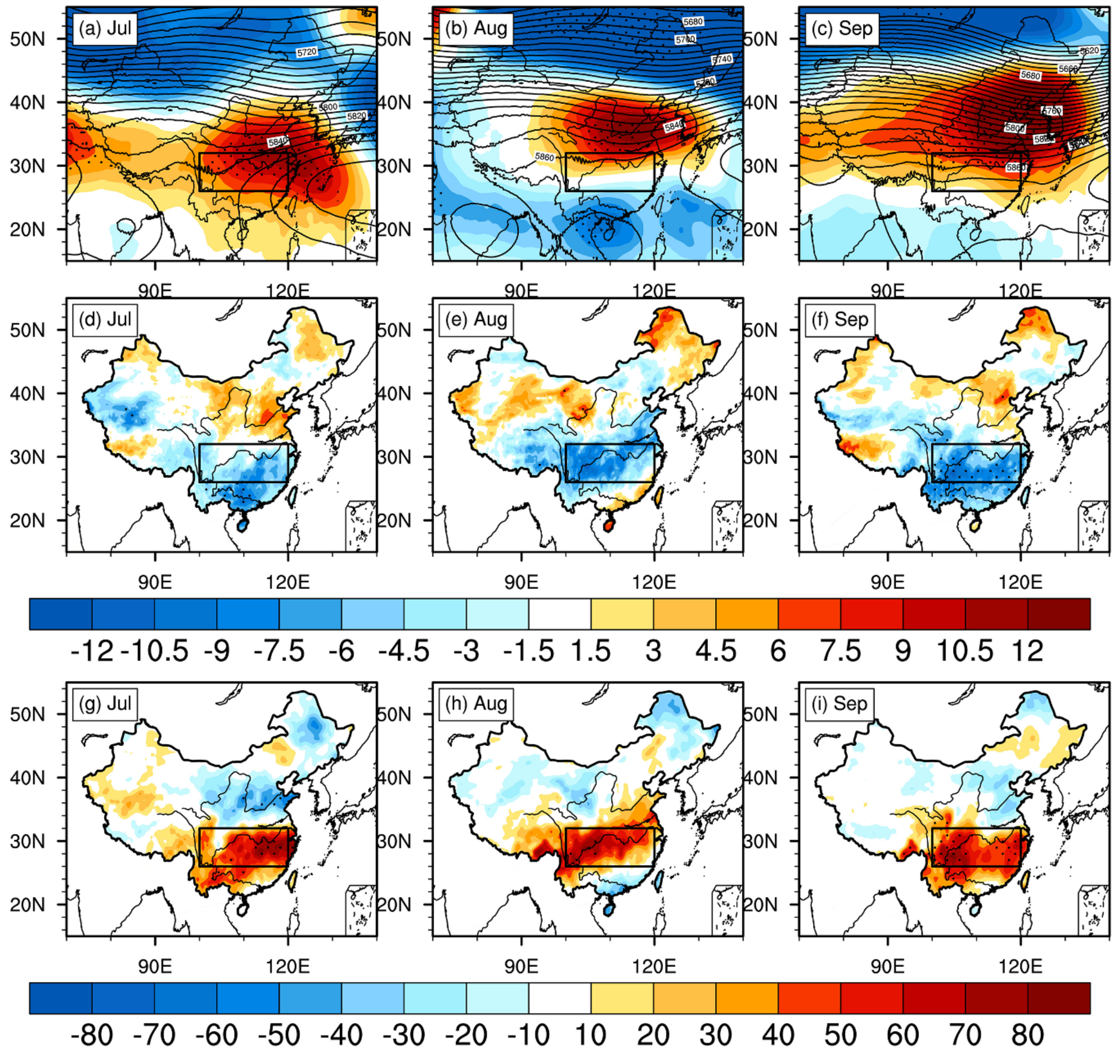

Figure 3. Geographic distributions of composite anomalies of noon-time (a)–(c) geopotential height at 500 hPa (unit: m), (d)–(f) total cloud fraction (unit: %), and (g)–(i) downward surface solar radiation (unit: W m^{-2}) for the hot extreme events in July, August, and September based on ERA5 reanalysis. The contour lines in panels (a)–(c) the climatological mean geopotential height at 500 hPa. Regions with dots are the places where composite anomalies have statistical significance levels higher than the 95% confidence level.

respectively (figures 3(g)–(i)), play an important role in hot extremes over the Yangtze Plain.

Since the ground-level ozone dataset (ChinaHighO_3) is available from 2013 to 2020, we perform composite analysis of T2m, surface UV radiation, and ground-level ozone over 2013–2020 to examine the impact of hot extremes and strong UV radiation on surface ozone over the Yangtze Plain. The hot-extreme years are identified as 2013, 2017, and 2018 in July, 2013 and 2016 in August, and 2014, 2017, and 2019 in September.

Figure 4 shows the composite anomalies of noon-time mean T2m, surface UV radiation, and monthly-mean ground-level ozone for hot extreme events over the Yangtze Plain in July, August, and September over 2013–2020. It is found that an increase in surface UV radiation occurs concurrently with surface warming over the Yangtze Plain (figures 4(a)–(f)), which is consistent with the above results based on ERA5 reanalysis over 1979–2020. In July, the concurrent strong surface UV radiation and hot extremes are mainly located in the Yangtze Delta, while they spread to the upper reaches of the Yangtze River in August. In September, the affected area is shifted to the south of the Yangtze River. The surface warming and increase of surface UV radiation can reach about 2.6 K and 14.4 W m^{-2}, respectively, over the Yangtze Plain. Such meteorological conditions favor the photochemical reactions of ground-level ozone and thus ozone pollution. The composite analysis indicates that severe ozone pollution occurs in the major cities along the Yangtze River such as Nanjing, Wuhan, Chongqing, and Chengdu (black triangles in figure 4) in July and August for the hot extreme events with maximum increases of 33.2 and 37.3 $\mu g\ m^{-3}$, respectively (figures 4(g)–(h)). The cities in the south of the Yangtze River experience serious ozone pollution in September with a maximum

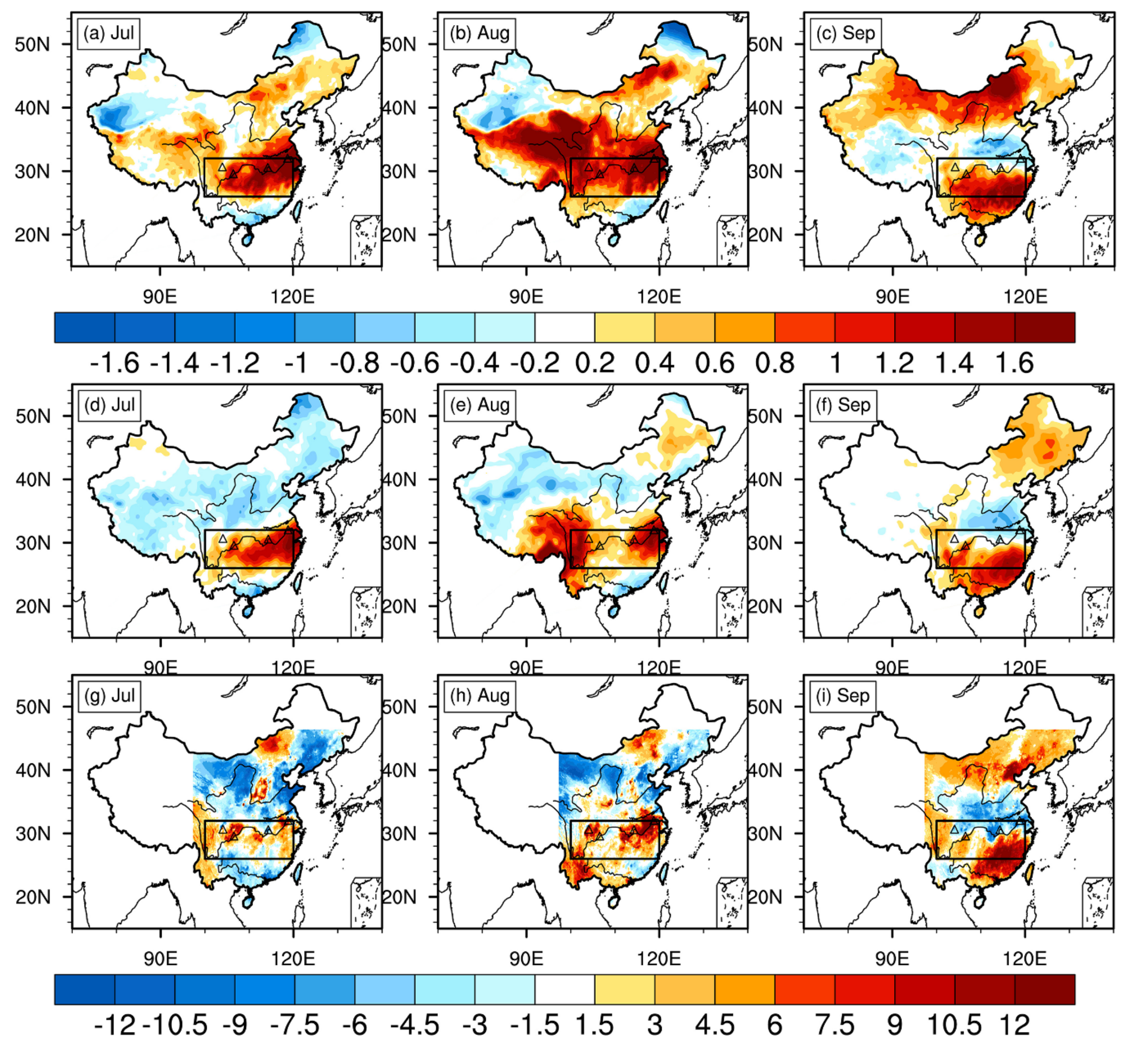

Figure 4. Geographic distributions of composite anomalies of (a)–(c) T2m (unit: K), (d)–(f) surface UV radiation (unit: W m^{-2}), and (g)–(i) ground-level ozone (unit: μg m^{-3}) for hot extreme events in July, August, and September over 2013–2020. Black triangles mark the major cities along the Yangtze River from east to west: Nanjing, Wuhan, Chongqing, and Chengdu.

anomaly of 23.7 μg m^{-3} (figure 4(i)) associated with the concurrent hot extremes and strong surface UV radiation.

4. Conclusions and discussions

The correlation analysis shows that strong surface UV radiation occurs simultaneously with hot extremes during May–September especially over the Yangtze Plain. The composite analysis further verifies the results and indicates high spatial consistency between the increase of surface UV radiation and surface warming over the Yangtze Plain. We find that this is mainly caused by a northwestward extension of the Western Pacific Subtropical High which leads to downward vertical motion and less clouds over the Yangtze Plain. The reduction of clouds especially middle and low clouds allows more solar radiation and even UV radiation to reach surface. The increase in surface solar radiation, which can reach about 89.3 W m^{-2}, plays an important role in the occurrences of hot extremes over the Yangtze Plain (see the schematic diagram in figure S8).

Both strong UV radiation and hot extremes favor the generation of ozone pollution. We find that severe ozone pollution occurs in the major cities around the Yangtze River during the hot extreme events based on composite analysis over 2013–2020. It is found that the increase in ground-level ozone can reach about 37.3 μg m^{-3} in summer over the Yangtze Plain, which is associated with surface warming and increases in surface UV radiation with maximums of about 2.6 K and 14.4 W m^{-2}, respectively. Figure S9 shows the probability distributions functions of the anomalies of ground-level ozone over the Yangtze Plain (26° N–32° N and 100° E–120° E) and North China (37° N–41° N and 100° E–120° E) during July–September over 2013–2020. We find that the anomalously high ozone events (higher than 20 μg m^{-3}) occur with higher probability over the

Yangtze Plain than that in North China, which may be caused by the concurrent hot extremes and strong surface UV radiation and needs further investigation in future.

Generally, low surface wind speeds favor the occurrence of high concentrations of ozone (Tang *et al* 2012). The composite anomalies of 10 m wind speed for hot extreme events are also investigated here (figure S10). It is found that the surface wind speeds are enhanced over the Yangtze Plain for the hot extreme events in July (figure S10(d)), which may have negative impact on the ozone pollution. On the contrary, surface wind speeds have little variation in August and September (figures S10(e) and (f)), which contributes little to the ozone pollution.

It is important to note that the concurrent hot extremes, strong surface UV radiation, and severe ozone pollution all have harmful effects on human health. Our results suggest that the westward shift of the Western Pacific Subtropical High is a very good predictor for the hot extremes, strong surface UV radiation, and severe ozone pollution over the Yangtze Plain. It is important to note that the meteorological condition may lead to severe health impacts on the vast population living in this region and should continue to be monitored and studied in future.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset&text=ERA5.

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