Weekend effect in summertime temperature and precipitation over the Yangtze River Delta region

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Abstract
The Yangtze River Delta (YRD) region, located over East China, is an international urban agglomeration radiating Asia Pacific with convenient transportation, advanced manufacturing industry, and modern service industry. The intensive human activities have exerted substantial effects on the weather and climate over the YRD region during the past decades, thus bringing more challenges to accurate weather and climate forecasting. However, the weekly cycles of surface air temperature and precipitation linked closely to human activities and their corresponding physical processes remain insufficiently understood. Here, we investigate the weekly cycles of summertime surface air temperature and precipitation and the weekend effect over the YRD region for the period of 2008–2019 using high-resolution observational data and reanalysis data. The results demonstrate that lower surface air temperature and higher precipitation generally manifest during weekends compared to weekdays over the YRD region particularly over the areas with intensive human activities. Further analysis of the underlying physical processes points to the aerosol-cloud-radiation interaction which largely explains the weekend effect in summertime temperature and precipitation over the YRD region.

1 Introduction
For the past several decades, intensifying human activities accompanied by rapid urbanization have remarkably affected local and regional weather and climate variations by changing the atmospheric composition, radiation and cloud processes, land surface conditions, and so on (Ramanathan et al. 2001; Kalnay and Cai 2003; Zhou et al. 2004; Wu et al. 2013; Li et al. 2016), thus bringing more challenges to the accurate forecasting of weather and climate. Under the background of the long-term impact of urbanization on weather and climate, the meteorological variables also show obvious weekday-weekend differences (weekend effect) which are closely linked to the weekly cycles of human activities, providing evidence that human influence does play substantial roles in regulating the variations of weather and climate (Cerveny and Balling 1998; Forster and Solomon 2003; Sanchez-Lorenzo et al. 2012). However, the weekend effect and associated complex physical mechanisms remain insufficiently understood.

Weekend-weekday differences or weekend effects in surface air temperature and precipitation have been evidenced in many places of the world, though their magnitudes vary with the region and season (Zhou et al. 2004; Gong et al. 2006; Kim et al. 2009; Kim and Roh 2010; Sanchez-Lorenzo et al. 2012). For the corresponding physical mechanisms, the influence of human activities on the weekend effects lies in the changes of atmospheric thermal and dynamic conditions, which are mainly attributable to anthropogenic aerosols and anthropogenic heat release (Fujibe 1987; Simmonds and Keay 1997; Zhou et al. 2004; Sanchez-Lorenzo et al. 2008). Furthermore, previous studies have found that weekend-weekday differences in aerosol-cloud-radiation interaction related to human activities may play critical roles (Dai et al. 1997; Zhou et al. 2004; Gong et al. 2007; Sanchez-Lorenzo et al. 2008). Besides, the anthropogenic heat release also contributes to the weekend effect in some areas (Fujibe
1987, 1988a, b; Simmonds and Keay 1997). Over China, previous studies also have detected the weekend effect in surface air temperature and precipitation, corresponding to the direct and indirect effects of aerosols on radiation and cloud processes, and associated modified regional atmospheric circulations (Gong et al. 2006, 2007; Zhao et al. 2006; You et al. 2009; Li et al. 2011; Zhu et al. 2014). However, these previous studies are mainly based on observational data at relatively limited stations or remote sensing data and the physical mechanisms are not fully explained.

The Yangtze River Delta (YRD) region, one of the key regions with the most serious air pollution in the world, is located over East China, covering the Anhui, Jiangsu, and Zhejiang provinces and Shanghai municipality. The YRD region is an international urban agglomeration which is home to more than 220 million people. The intensive human activities over the YRD region have exerted certain effects on local and regional weather and climate (Chen et al. 2003; Gong et al. 2007; Zhang and Liang 2018). For example, Gong et al. (2007) demonstrated that weekday-weekend differences are obvious in summertime solar radiation, daily maximum temperature, diurnal temperature range, and precipitation over East China. Significant weekday-weekend differences and anthropogenic emissions related to the intensive human activities enable us to better understand the weekend effect and its corresponding physical mechanism over the YRD region.

Recently, the China Meteorological Administration (CMA) developed a high-resolution (0.1°) gridded hourly precipitation dataset using the observations of 30,000–40,000 automatic stations over China and the Climate Prediction Center (CPC) morphing technique (CMORPH) dataset (Joyce et al. 2004; Janowiak et al. 2005; Buarque et al. 2011; Qian et al. 2015; Trenberth and Zhang 2018). In this study, we used the new hourly precipitation dataset combined with the high-resolution ERA5 reanalysis data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) to investigate the weekend effect during summertime over the YRD region for 2008–2019 and further discuss associated underlying physical processes. Employing these fine-resolution data allows us to explore detailed characteristics of the summertime weekend effect over the YRD region.

## 2 Data and methods

The weekend effect of summertime precipitation over the YRD region is investigated by using the hourly gridded precipitation data (0.1°) from the CMA. To analyze the weekend effect in summertime surface air temperature, we adopted hourly 2-m temperature at a resolution of 0.25° from the ERA5 reanalysis (Hersbach et al. 2018a; Bassett et al. 2021).

This study focuses on the summer season including June, July, and August for the period of 2008–2019. In total, there are 1677 (including 3 abnormal hourly data) missing hourly precipitation data over the YRD region for the study period. The missing rate of 6.33% is small, so we removed these days with missing data. Additionally, because the huge impact of typhoons may weaken the effect of human activities on precipitation, according to the historical typhoon data provided by the Shanghai Typhoon Institute of the China Meteorological Administration (Ying et al. 2014; Lu et al. 2021), we also removed the influence of typhoon precipitation associated with the YRD region (Table 1). For consistency, we also removed these days in the analysis of the weekend effect in surface air temperature and the discussion of the associated physical processes.

To describe the human activities over the YRD region, we applied the gridded population data of 2015 with a resolution of 1 km from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (RESDC-CAS), GTOPO30 topographical height data with a resolution of 30 s (about 1 km) from the US Geological Survey (USGS), and DMSP-OLS nighttime lights time data of 2013 with a resolution of 30 s (about 1 km) collected by the US Air Force Weather Agency.

### Table 1 The main typhoon events and their corresponding impact periods during 2008–2019

| Year | Typhoon number (name) | Impact period (LST) |
|------|-----------------------|---------------------|
| 2008 | 0807 (Kalmaegi)       | 7.18–7.20           |
| 2008 | 0808 (Fung-wong)      | 7.28–8.2            |
| 2009 | 0908 (Morakot)        | 8.8–8.11            |
| 2011 | 1105 (Meari)          | 6.23–26             |
| 2011 | 1109 (Mifua)          | 8.6–8.7             |
| 2012 | 1209 (Suola)          | 8.2–8.3             |
| 2012 | 1210 (Damrey)         | 8.2–8.3             |
| 2012 | 1211 (Haikui)         | 8.7–8.8             |
| 2012 | 1214 (Tembin)         | 8.28–8.29           |
| 2012 | 1215 (Bolaven)        | 8.26–28             |
| 2013 | 1307 (Soulik)         | 7.13–7.15           |
| 2013 | 1312 (Trami)          | 8.21–8.23           |
| 2014 | 1410 (Matmo)          | 7.23–7.25           |
| 2014 | 1412 (Nakri)          | 7.31–8.03           |
| 2015 | 1509 (Chan-hom)       | 7.10–7.12           |
| 2015 | 1513 (Soudelor)       | 8.08–8.11           |
| 2015 | 1515 (Goni)           | 8.21–8.24           |
| 2016 | 1601 (Nepartak)       | 7.09–7.12           |
| 2017 | 1709 (Nesat)/1710 (Haitang) | 7.30–8.02 |
| 2018 | 1810 (Ampil)          | 7.21–7.23           |
| 2018 | 1812 (Jongdari)       | 8.2–8.3             |
| 2018 | 1814 (Rumbia)         | 8.12–8.19           |
| 2019 | 1909 (Lekima)         | 8.9–8.11            |
Hourly low, medium, and high cloud cover, surface and 850 hPa winds, vertically integrated moisture divergence, surface downward short-wave radiation, surface net short-wave radiation and surface net long-wave radiation at a resolution of 0.25° from the ERA5 reanalysis dataset (Hersbach et al. 2018a, b; Bassett et al. 2021), and three-hourly aerosol optical depth (AOD) product at 550 nm at a resolution of 0.75° from the EAC4 reanalysis dataset (Inness et al. 2019) were also used to explore the possible physical mechanisms. AOD is defined as the integral of the extinction coefficient of the medium in the vertical direction, which describes the reduction effect of aerosol on light. The AOD product of EAC4 is proved to be accurate and is evaluated with ground-based observations of the AErosol RObotic NETwork (AERONET), which is a network of about 400 stations measuring spectral AOD with sun photometers (Holben et al. 1998; Inness et al. 2019).

Due to the lack of temporal and spatial resolution of station data, AOD based on satellite is widely used to estimate the concentrations of particle matters, especially the fine particulate matters (PM2.5) observed on the surface (Shao et al. 2017). Take Shanghai as an example; it is shown that the annual mean concentration of PM2.5 observed in Shanghai is similar to the AOD-derived (Shao et al. 2017; Wang et al. 2013). In addition, many researchers also have found that AOD has a strong positive relationship with the other PM concentrations observed on the surface, especially in eastern China, where PM concentrations have the same pattern as AOD (Guo et al. 2009; Shao et al. 2017; Yang et al. 2019). Besides, compared with one single air pollutant, AOD can comprehensively measure the climate effect of various aerosols and is now widely used in the meteorological research (Kaufman et al. 2002; Deng et al. 2012; Inness et al. 2019; Tariq and ul-Haq 2020).

In this study, considering that Monday and Friday are transitional periods between weekdays and weekends, we define Tuesday through Thursday as the weekdays and Saturday through Sunday as the weekend. The weekend effect refers to their difference value (weekend minus weekdays). In addition, using the large sample data to detect the weekend effect closely associated with periodic human activities can largely remove the impacts of natural variability of weather-scale atmospheric circulation.

### 3 Results

The YRD region is an alluvial plain before the estuary of the Yangtze River, which is intermittently distributed with low elevation (Fig. 1a). The YRD region is highly populated...
and urbanized, especially in the eastern coastal area, forming megacities centered on Shanghai radiating outward (Fig. 1b and c). Under the background of the East Asian monsoon, the southwest warm and humid airflow brings sufficient moisture to the region (Fig. 1d). As a result, the YRD region has generally higher surface air temperature and more precipitation during summertime (Fig. 1e and f).

Figure 2 shows spatial distributions of the day of week with maximum and minimum 2-m surface air temperature and precipitation over the YRD region in the summertime of 2008–2019. The surface air temperature is maximal on Tuesday and Thursday from south to north of the YRD region and consistently minimal on Sunday throughout the YRD region except for a few locations. Compared with temperature, precipitation exhibits less spatial consistency. Saturday and Sunday are wetter than other weekdays over most areas of the southern and northern parts, while Thursday is the driest day of the week over most areas of the YRD region. In general, weekends have relatively lower surface air temperature and stronger precipitation compared to weekdays over the YRD region in summertime of 2008–2019.

Figure 3 shows weekly cycles of regional mean 2-m surface air temperature and precipitation over the YRD region in summertime for 2008–2019. There are clear weekly cycles in 2-m surface air temperature and precipitation. Surface air temperature increases from Sunday to Thursday and then decreases with a maximum on Thursday and minimum on Sunday. Comparatively, precipitation has an opposite pattern of weekly cycle. The precipitation decreases from Sunday to Thursday as a whole and then increases with peaks on the weekend. In general, both surface air temperature and precipitation exhibit distinct weekend-weekday differences.

Figure 4 shows the weekend effect in surface air temperature and precipitation over the YRD region in summertime of 2008–2019. The surface air temperature has a negative weekend effect all over the YRD region, with the average value of −0.22 °C. On the contrary, precipitation exhibits a positive weekend effect over most areas of the YRD region, and the average value is 0.05 mm/h, about 21% relative to the climatology mean of regional precipitation. It is worth noting that the areas where a relatively large weekend effect in surface air temperature and precipitation mainly occurred are consistent with those with large population densities and nighttime lights (Fig. 1b and c). These results imply that the weekend effect in surface air temperature and precipitation is tightly associated with intensified human activities, which is also revealed in the previous research of other areas (Rosenfeld 2000; Gong et al. 2006).

Further, we explore the possible interpretation responsible for the colder and wetter weekend compared to weekdays.
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Over the YRD region in summertime of 2008–2019, aerosol-cloud-radiation interaction and land-air interaction are considered to be the main reasons affecting regional temperature and precipitation. Cloud development related to aerosols is beneficial to more precipitation, while the reduction of downward short-wave radiation flux may decrease the surface air temperature (Gong et al. 2006; Ekman et al. 2007).

Figure 5(a) indicates that more aerosols are released into the atmosphere during the weekend. Consequently, the concentration of aerosols serving as cloud condensation nuclei (CCN) increases the regional cloud cover (Fig. 5b, c and d), especially in the low and medium cloud cover (Twomey 1977; King et al. 1993; Zhao et al. 2014), which provides a good background for more precipitation during the weekend (Fig. 4b). Meanwhile, the increase in aerosols during the weekend leads to less surface downward short-wave radiation, decreasing the surface air temperature (Fig. 5e, Fig. 4a).

4 Conclusions and discussion

Using the 0.1° high-resolution hourly observational precipitation data from CMA and the 0.25° hourly surface temperature from ERA5 reanalysis data provided by ECMWF, we investigate the weekend effect in summertime surface air temperature and precipitation over the YRD region for 2008–2019. The results show that lower surface air temperature and higher precipitation generally appear during weekends compared to weekdays over the YRD region. Moreover, strong spatial differences in the weekend effect in summertime surface air temperature and precipitation are clearly identified.

Further, we explain the possible physical processes explaining the weekend effect in surface climate over the YRD region. Consistent with previous studies (Zhou et al. 2004; Gong et al. 2006, 2007), the results show that the aerosol-cloud-radiation interaction may make a critical contribution to the weekend effect over the YRD region. Different from the non-rainy days with more high cloud cover and less low and medium cloud cover (Fig. S1), appropriate aerosol emissions associated with intense human activities tend to increase the cloud cover amount and decrease the net radiation reaching the surface (Fig. 5), which may subsequently lead to more precipitation and lower surface air temperature during weekends.

Fig. 3 Weekly cycles of regional mean summertime (a) precipitation (blue histogram, unit: mm/h) and (b) 2-m surface air temperature (red solid line, unit: °C) over the YRD region for 2008–2019. Error bars indicate the 95% confidence intervals, respectively.

Fig. 4 Weekday effect in (a) 2-m surface air temperature (unit: °C) and (b) precipitation (unit: mm/h) over the YRD region for 2008–2019. The stippled areas are significant at the 99% confidence level by Student’s t test. The weekend effect is calculated by subtracting the average for Tuesday through Thursday from the average for Saturday through Sunday.
It is worth noting that the study area contains some hills, which may result in mountain and valley wind and topographic effects. Besides, there is also a sea-land breeze effect over the YRD region due to its proximity to the East China Sea. These effects can be found in climatological fields of meteorological variables (Fig. 1). Using the large sample data to calculate the weekend-weekday differences in this study may largely eliminate these effects on our analysis of weekend effect, since very similar effects of mountain-valley and sea-land breezes and terrain exist in terms of their climatologies during weekends and weekdays. For example, Figs. 3 and S2 show that the weekly cycles of regional mean surface air temperature and precipitation with and without these grids of high terrains above 500 m are quite consistent; the effects of terrains on our analysis of weekend effect are small.

However, the relationships between the weekend effect and human activities remain not to be a direct one-to-one correspondence since the human activities can produce both local and nonlocal impacts on the atmospheric circulation via complex physical processes over the YRD region.

Apart from the atmospheric circulation, atmospheric microphysical processes associated with air pollutants resulting from human activities also play a role. Many previous studies show that human activities are beneficial to the precipitation in the urban area and its downwind direction (Lowry 1998). However, Rosenfeld (2000) pointed out that the addition of ice cores and cloud condensation nodules transformed from air pollutants associated with the intensive human activities makes the stratiform cloud produce more small cloud droplets and the cloud droplet spectrum distribution more uniform, which reduces the conversion efficiency from cloud water to rainwater and suppresses the precipitation in the downwind direction of the city. Additionally, despite the effect of aerosols on precipitation, precipitation also has a certain feedback on aerosols. In other words, aerosol and precipitation may interact and restrict each other. An appropriate amount of aerosol provides good conditions for precipitation (Jin et al. 2005; Shepherd 2005), while precipitation is also conducive to clear aerosol (Chate and Pranesha 2004; Chate et al. 2011). In all, as mentioned above, the impact of human activities on the weekend effect

Fig. 5 Weekend effect in summertime (a) aerosol optical depth at 550 nm (AOD<sub>550</sub>), (b) low cloud cover, (c) medium cloud cover, (d) high cloud cover, (e) surface downward short-wave radiation (unit: W·m⁻²), and (f) surface net radiation (unit: W·m⁻²) over the YRD region for 2008–2019. The stippled areas are significant at the 90% confidence level with Student’s t test.
Weekend effect in summertime temperature and precipitation over the Yangtze River Delta region does not have the obvious weekday-weekend differences, the intensive human activities make the weekend temperature generally lower than weekdays over the YRD region (Fig. 4a), which reduces the land-sea thermal difference and further weakens the monsoon, resulting in northerly wind anomalies (Fig. 6). Due to the different intensity of human activities resulting from different urbanization levels, the inhomogeneous distribution of thermal anomalies leads to convergence and divergence of northerly winds, which makes the AOD accumulation (Figs. 5 and 6). Figure 6 shows that the weekend effect of the wind field is very complex, particularly during the daytime. The weekend effect of the wind field during the nighttime is mainly manifested in the northwest wind anomaly, that is, the weakening of the southeast summer monsoon, indicating the consistent cooling trend of the region as a whole. The daytime wind field shows the weekend effect of the northerly wind anomaly, and the directions and intensities of

![Fig. 6 Distributions of summertime 10-m surface wind (vector, unit: m/s) and its divergence (unit: 10^-6 s^-1) during (a–c) weekends (Saturday through Sunday) and (d–f) weekdays (Tuesday through Thursday) and (g–i) their difference field (weekends minus weekdays) of

(a, d, g) the whole day, (b, e, h) daytime (6:00–17:00 LST), and (c, f, i) nighttime (18:00–5:00 LST) over the YRD region for 2008–2019. The areas passing the 95% confidence level are shown.](image-url)
the wind vary with regions, which may be associated with the inhomogeneous distribution of human activities. Additionally, there are other factors linked to the surface wind over the coastal area of the YRD region. For example, the lake-air interaction may lead to strong local divergence anomalies.

Besides, the human activities also exert effects on land surface processes such as soil types (Thielen et al. 2000; Hu et al. 2017; Song and Zhang 2020), soil moisture (Doville et al. 2001; Koster et al. 2010; Sun and Wang 2012; Wei and Dirmeyer 2012), soil temperature (Zhang and Wu 2014), and the vegetation (Lee et al. 2012; Wei and Dirmeyer 2012), leading to changes in aerosol-cloud-climate interaction and land-air interaction (Rosenfeld 2000; Jin et al. 2005; Menon et al. 2008; Rosenfeld et al. 2014). These changes can influence radiation, energy balance, moisture, atmospheric boundary layer, and regional atmospheric circulations, and further modulate temperature and precipitation variations over the YRD region. It also needs to be noted that weekday-weekend differences in anthropogenic heat release may play an important role in highly urbanized areas (Simmonds and Keay 1997). These complex physical progresses involved should be explored by combined diagnosis methods and numerical simulations in the future.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00704-022-04173-7.

Author contribution Jingyong Zhang and Ziyi Song conceived the study. Ziyi Song performed the data analysis and prepared the first draft. Ziyi Song and Jingyong Zhang revised the manuscript. All authors contributed to the writing of the paper.

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Data availability The hourly high-resolution precipitation data is available at http://data.cma.cn/site/showSubject/sid/101.html. The historical typhoon data is stored at https://tcddata.tpyphoon.org.cn/dfrdqy_zl.html. The gridded population data is available at https://doi.org/10.12078/2017121101. GTOPO30 topographical height data is stored at https://doi.org/10.5066/F7DF6PQS and DMSP-OLS nighttime lights time data is from https://www.ngdc.noaa.gov/eog/dmsp/downloadV4composites.html. The hourly ERA5 reanalysis variables of low cloud cover, medium cloud cover, high cloud cover, 2-m temperature, vertically integrated moisture divergence, surface downward short-wave radiation, surface net long-wave radiation, surface winds, and 850-hPa wind flows are available at https://doi.org/10.24381/cds.adbb2d47 and https://doi.org/10.24381/cds.bd0915c6 respectively. The three-hourly aerosol optical depth product at 550 nm of the EAC4 reanalysis dataset is stored at https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-reanalysis-eac4?tab=overview.

Code availability All the figures were produced using NCL. The code used in this study will be available on reasonable request.

Declarations

Ethics approval The authors paid attention to the ethical rules in the study. There is no violation of ethics.

Consent to participate All the authors admitted that they have contributed to the study.

Consent for publication All the authors agree with the publication of the content of the manuscript.

Conflict of interest The authors declare no competing interests.

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