Roles of Anthropogenic Forcing and Natural Variability in the Record-Breaking Low Sunshine Event in January–February 2019 over the Middle-Lower Yangtze Plain

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The record-low January–February 2019 sunshine in the Middle-Lower Yangtze Plain was favored by a circulation pattern, while anthropogenic aerosols and greenhouse gases increased their probability in recent decades by 3.1 and 1.3 times, respectively.

In January–February 2019, the Middle-Lower Yangtze Plain, accounting for $\sim 1/8$ of China's territorial areas, endured the shortest sunshine duration (SD) since 1961 (Figs. 1a–b and Fig. ES1a). The regional average of daily SD (1.6 h) was approximately 57% shorter than the 1961–90 climatology (3.7 h). Due to the continuous rainy and low sunshine in early 2019, the acreage and yield per unit of early rice were reported to decrease by 341.3 thousand hectares and 64.8 kg ha⁻¹ compared with 2018, respectively (National Bureau of Statistics of China; www.stats.gov.cn/tjsj/sjjd/201908/t20190826_1693488.html).

Fig. 1. (a) Spatial distribution of the CMDC stations that registered record- and near-record (since 1961) SD for January–February 2019. (b) Time series of January–February mean SSR (in orange curve), SD (in green curve), and Z500 (in purple curve) anomalies averaged over the Middle-Lower Yangtze Plain (black box in Fig. 1a) from 1961 to 2019. The blue curve denotes the mean TCC from MODIS during the period of 2000–19. The pentagram represents the records broken in 2019. (c) Return period (in red curve) and 95% confidence intervals (in red dotted lines) for the observed regional mean SSR (red “+”) based on the GPD fit. The black line represents the observed SSR for January–February 2019. (d) Spatial distribution of Z500 anomalies (contours) and averaged TCC (shading) in January–February 2019. Dashed contours represent negative anomalies. Color-filled circles indicate the correlations between the detrended regional mean SSR and gridded Z500 anomalies ($p < 0.01$).

Sunshine is largely affected by cloud cover, which is regulated by regional atmospheric circulation (Christidis et al. 2016). At the end of 2018 and in early 2019, the equatorial Pacific entered an El Niño warm phase (index >0.5 , Fig. ES1d). Under this phase, the western Pacific subtropical high (WPSH) shifted northward and westward, then remained stable to form an anomalous anticyclonic circulation over and east of the Sea of Japan. The southwest airflow from anticyclonic circulation transported moisture from the northwest Pacific and the South China Sea to the Middle-Lower Yangtze Plain, resulting in continuous cloudy and rainy weather and thus the persistent low sunshine there (Fig. 1d and Fig. ES1c) (Rayner et al. 2003; Wu et al. 2009). Therefore, the contribution of the atmospheric circulation anomaly to the likelihood of such a short SD event is first investigated in this study.

With the rapid urbanization and industrial development in China, anthropogenic aerosols emissions are increasing in recent decades (Wang and Chen 2016). The direct and indirect radiative effects associated with this increase are most likely to reduce the SD (Kim and Ramanathan 2008; Sanchez-Romero et al. 2014; Christidis et al. 2016; He and Wang 2020). The direct effect means that solar radiation is directly scattered or absorbed by aerosols and the indirect effect refers to the effect of aerosols on solar radiation by altering properties of clouds (Boers et al. 2017). In addition, global warming due to greenhouse gas (GHG) emission is likely responsible for intensifying anticyclonic

circulation in recent decades by tropical oceanic warming (Zhou et al. 2009; He et al. 2015; Takahashi et al. 2019; Wang et al. 2020). Therefore, the roles of anthropogenic forcings including anthropogenic aerosols and GHGs in such a short SD event are also quantified in this study.

This study tries to explore three questions: 1) How extreme is low sunshine over the Middle-Lower Yangtze Plain in January–February 2019 in a historical context? 2) What are the contributions of the anomalous anticyclonic circulation over the northwest Pacific, anthropogenic aerosols, and GHGs to the probability of the event? 3) What are the roles of anthropogenic aerosols and GHGs for the development of the anomalous anticyclonic circulation?

Data and methods.

Daily SD observation data from 1961 to 2019 at ~2,000 meteorological stations in China (Fig. 1a) were obtained from the China Meteorological Data Service Center (CMDC; <http://data.cma.cn/en>). These data were subjected to quality control to eliminate spurious shifts in the time series (Zhou et al. 2018) and have complete temporal continuity at all the stations. A total of 744 stations in the study region (black box in Fig. 1a) were included in this study. Since CMIP6 does not provide SD data, we used surface incident solar radiation (SSR) as a proxy of SD. The SSR observation dataset was from He et al. (2018). The detrended January–February mean SSR has a strong correlation ($R = 0.98$, $p < 0.01$) with the detrended SD from 1961 to 2019 in the study region (Fig. ES1b).

The monthly geopotential height at 500 hPa (Z500) from 1961 to 2019 was downloaded from the JRA-55 reanalysis product (https://jra.kishou.go.jp/JRA-55/index_en.html) (Kobayashi et al. 2015; Harada et al. 2016). The circulation anomaly pattern in January–February 2019 is shown in Fig. 1d. The monthly total cloud cover (TCC) data from 2000 to 2019 were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS, <https://modis.gsfc.nasa.gov/data/dataproduct/mod08.php>) (Platnick et al. 2015).

CMIP6 model outputs (<https://esgf-node.llnl.gov/projects/cmip6/>) (Eyring et al. 2016) were used to quantify the roles of internal atmospheric variability, GHG-based warming, and anthropogenic aerosols in the 2019 low sunshine event, including historical all-forcing (ALL), historical anthropogenic aerosol-only (AER), and historical greenhouse gas-only (GHG) simulations. The AER (GHG) simulation is forced by anthropogenic aerosol (well-mixed greenhouse gas) forcing only and does not include natural forcing, so the preindustrial control (PIC) simulation was used as a reference to quantify the impacts of anthropogenic aerosols and GHGs on this event. To ensure an equal weight for different CMIP6 models, the “r11plf1” realizations were adopted in this study. We selected 17 models (see Table ES1) based on two steps referring to the method of Zhou et al. (2020). First, 31 out of 34 models were selected by comparing the January–February SSR and Z500 anomalies from CMIP6 ALL runs with those from observations via a Kolmogorov–Smirnov test ($h = 0$, $p > 0.05$). Second, 17 out of 31 models were selected with a significant negative correlation ($p < 0.05$) between the detrended January–February SSR and Z500 anomalies. SSR and Z500 from these models have similar probability density distribution to those from observation (Fig. ES2). The temporal correlation coefficients between area averaged SSR and Z500 over the study region from multi-model means of the ALL runs and observations are 0.448 ($p < 0.01$) and 0.447 ($p < 0.01$), respectively. The SSP2–4.5 runs (the combination of the second type of the shared socioeconomic pathways (SSP), i.e., the fossil-fueled development pathways, and the 4.5 forcing levels of the representative concentration pathways (RCP)) (O’Neill et al. 2016) were used to extend the ALL runs through 2019. To be consistent, all the observations and model data were converted as anomalies relative to the 1961–90 climatology and then integrated on the $2.5^\circ \times 2.5^\circ$ grids, which were averaged as regional time series with area as weight.

We used the generalized Pareto distribution (GPD) (Schaller et al. 2016) to fit the distribution of SSR from 1961 to 2019 in order to estimate the event probabilities (P)

and return periods. Figures ES2c and ES2d show that GPD has a good ability to fit SSR and Z500 anomalies in the study region. Probability ratios (PRs) were adopted to assess the contributions of atmospheric circulation, anthropogenic aerosols, and GHGs to the event probability. To estimate the contribution of the anomalous circulation to the likelihood of this event, $P_{\text{ALL-highZ500}}/P_{\text{ALL-neutralZ500}}$ was calculated. Here, $P_{\text{ALL-highZ500}}$ and $P_{\text{ALL-neutralZ500}}$ represent the probabilities under the high-correlation and neutral-correlation Z500 regimes from ALL simulations, respectively. A trend in Z500 would have little impact on the calculation of the PR relative to the contribution of an anomalous circulation. The high-correlation Z500 regimes from CMIP6 individual model run denote similar circulation patterns to that from JRA-55 in January–February 2019 (pattern correlation ≥ 0.5 , $p < 0.05$), and the neutral-correlation Z500 regimes are with pattern correlations of -0.1 to 0.1 (Christidis and Stott 2015; Zhou et al. 2020). The spatial patterns of the multimodel mean Z500 anomalies from the ALL runs under two regimes are shown in Figs. ES3a and ES3b. The effect of anthropogenic aerosols (GHGs) on the likelihood of this event was calculated as $P_{\text{AER}}/P_{\text{PIC}} (P_{\text{GHG}}/P_{\text{PIC}})$, where P_{PIC} and $P_{\text{AER}} (P_{\text{GHG}})$ indicate the probabilities under the PIC and AER (GHG) runs, respectively. The 95% confidence intervals (CIs) of the probabilities were estimated via bootstrap random resampling 1,000 times.

Results.

From January to February 2019, the almost entire Middle-Lower Yangtze Plain (black box in Fig. 1a) experienced the shortest or near-shortest mean SD since 1961 (Fig. 1a). New historical record lows of -2.1 h and -37.9 W m $^{-2}$ were observed for SD and SSR anomalies relative to the 1961–90 climatology in the study region, respectively (Fig. 1b). The observed regional mean values of SSR anomaly were used as a threshold (i.e., -37.9 W m $^{-2}$) to depict this extremely low SD event in the following analyses. A GPD fit of the observed SSR anomalies indicates that the extremely low SSR event in 2019 is a 1-in-265-year event (95% CI: $66-\infty$) for the Middle-Lower Yangtze Plain (Fig. 1c), which may be overestimated due to small sample size.

Since the late winter 2018, the WPSH has been strong and close to mainland China. The Z500 anomaly in the Middle-Lower Yangtze Plain in January–February 2019 also registered a new record in the historical context (Fig. 1b). The mean January–February 2019 total cloud cover data are close to 1 in the study region to explicitly demonstrate that it is cloudy weather affected by the WPSH (Fig. 1d). The changes in TCC are opposite to those in SSR and SD from 2000 to 2019 (Fig. 1b). We also found that the gridded Z500 anomalies (associated with local anticyclonic circulation) have significantly negative correlations with the detrended regional mean SSR over the Middle-Lower Yangtze Plain (Fig. 1d), which indicates the anomalous anticyclonic circulation is probably responsible for this low sunshine event. The detrended time series of January–February SSR anomaly significantly correlates with that of the Z500 anomaly ($R = -0.38$, $p < 0.01$) (Fig. ES1b). To quantify the role of the anticyclonic circulation, we compared the probabilities of this short SD event between from high- and neutral-correlation Z500 regimes and found the PR to be approximately 4.8 (95% CI: 1.6–9.3) (Figs. 2a,d), indicating that the anomalous anticyclonic circulation is a main driver of the extreme event.

To assess the influence of anthropogenic aerosols, based on the GPD fit, the best estimate of the probabilities of the SSR anomalies to be less than the 2019 threshold is 0.84% (0.24%–1.55%) and 0.27% (0.10%–0.42%) for the AER and PIC runs, respectively (Fig. 2b). In other words, anthropogenic aerosols increase the probability of the extremely short SD in 2019 to 3.1 (95% CI: 0.9–5.9) (Fig. 2d) through their direct and indirect radiative effects. We further estimated the PR due to GHGs and found it to be 1.3 (95% CI: 1.2–5.8) (Figs. 2b,d). Stronger impact of anthropogenic aerosols on the likelihood of the low SSR anomalies is also reflected in the significant decline trend [-2.6 W m $^{-2}$ (10 yr) $^{-1}$, $p < 0.01$] of SSR from 1961 to 2019 in the AER runs, while SSR trend in the GHG runs is non-significant [-0.5 W m $^{-2}$ (10 yr) $^{-1}$, $p > 0.1$].

Anthropogenic forcing has been argued to contribute to increase the likelihood of anomalous atmosphere circulation (Horton et al. 2015; Zhang et al. 2020; Zhou et al. 2020). Compared with multimodel mean Z500 anomalies under the AER and PIC runs, the spatial distribution of Z500 anomalies simulated by the GHG runs shows an enhanced anticyclonic circulation in the northwest Pacific (Fig. ES3d). The regional mean Z500 anomaly in the GHG runs also displays a significant increase [$6.7 \text{ m (10 yr)}^{-1}$] from 1961 to 2019. The probabilities of Z500 anomalies to exceed the threshold of the observed Z500 anomaly in January–February 2019 (i.e., 56.4m) are 0.1% (95% CI: 0.0%–0.2%), 1.3% (0.4%–2.1%), and 0.3% (0.0%–0.7%) for AER, GHG, and PIC runs, respectively (Fig. 2c). It is concluded that GHGs emissions might have increased the likelihood of the extreme Z500 anomaly to 4.6 times (95% CI: 0.6–10.6), while anthropogenic aerosols seem to have no significant contribution to it (PR = 0.04, 95% CI: 0.003–2.4).

Conclusions.

The SD in January–February 2019 hit a record low in the Middle-Lower Yangtze Plain and its return period was estimated to 1-in-265-years based on the generalized Pareto distribution fit. Based on analyses of reanalysis data, the strengthening of the anomalous anticyclonic circulation caused the extreme Z500 anomaly in January–February 2019 to show the highest record since 1961. The SSR (as a proxy of SD) and Z500 anomalies from 1961 to 2019 show a significantly negative correlation ($R = -0.38$, $p < 0.01$).

Fig. 2. (a) Probability density of the January–February mean SSR anomalies under high-correlation (solid purple) and neutral-correlation (dashed purple) Z500 regimes in historical all-forcing (ALL, purple) runs from 1961 to 2019. (b) Probability density of the January–February mean SSR anomalies in the preindustrial control (PIC, gray), historical anthropogenic aerosol forcing-only (AER, blue), and historical GHG forcing-only (GHG, red) runs from 1961 to 2019. The black line represents the observed SSR for January–February 2019. (c) As in (b), but for Z500 anomalies. (d) Probability ratio (PR) of the extremely low SSR event in 2019 due to anticyclonic circulation (Anticyclone, purple), anthropogenic aerosols (Anthro-aerosol, blue), and greenhouse gases (GHGs, red). The bottom and top edges of the bar indicate the 95% confidence intervals. The black dashed line represents the PR equal to 1. (e) PR of the extreme Z500 anomaly in 2019 due to anthropogenic aerosols and GHGs.

Through the analyses using CMIP6 model simulations, it is found that the anomalous anticyclonic circulation might have increased the probability of this low SSR event to be 4.8 times, making it the main driver for this extreme event. Furthermore, anthropogenic aerosols and greenhouse gases might have increased the probability of this event by a factor of 3.1 and 1.3, respectively. Besides, greenhouse gases may have potential impacts on the likelihood of extreme Z500 anomalies.

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