Meteorological impacts on the unexpected ozone pollution in coastal cities of China during the unprecedented hot summer of 2022

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Key Points:

- A shift of distribution patterns of O_3 concentrations in coastal cities of China in the unprecedented hot summer of 2022 were investigated.
- Meteorological changes caused 15.6% increase in O_3 concentrations in southern coastal cities and 3.34% decrease in northern coastal cities.
- Extreme heat events increase the difficulty of O_3 pollution mitigation, especially in the coastal areas with low O_3 precursor's emissions.

Abstract

Surface ozone pollution under climate warming has become a serious environmental issue. In the summer of 2022, abnormal warming spread over most of the Northern Hemisphere and resulted in the abnormal increase in O_3 concentration. In this study, we focused on the coastal cities in China and investigated the O_3 trends in July during 2015 to 2022. Four regions with different locations and emission levels were selected for comparison. A significant increase of O_3 concentration in July 2022 were observed in the southern coastal cities (16.7-22.8 μg m^{-3}) while the opposite characteristics were found in the northern coastal cities (decrease of 0.26-2.18 μg m^{-3}). The results indicated various distribution patterns of the O_3 concentrations responded to heat wave across China. The weakening of East Asian summer monsoon, extension of the western Pacific subtropical high, significant warming, stronger solar radiation, lower relative humidity, less rainfall and sinking motion of atmosphere in 2022 were beneficial for O_3 generation and accumulation in the southern coastal areas. Meteorological changes during July 2022 could lead to an increase of 15.6% in O_3 concentrations in southern coastal cities compared to that in 2015-2021, based on the analysis of machine learning. Air temperature was the main contributor to high O_3 concentrations in the coast of Fujian province, while other coastal cities depended on relative humidity. This study indicated the challenge of O_3 pollution control in coastal areas under global warming, especially in extreme heat wave events.

Plain Language Summary

The variations of surface ozone are affected by emission levels and meteorological conditions. China experienced a record-breaking hot summer in 2022 and abnormal increase in O_3 concentrations in the southern coastal cities. Compared with meteorological conditions from 2015 to 2021, the weakening of East Asian summer monsoon, extension of the western Pacific subtropical high, significant warming, strong solar radiation, low relative humidity, less rainfall and sinking motion of atmosphere in 2022 were beneficial for O_3 formation and accumulation in the southern coastal cities. We furtherly applied a machine-learning based approach to evaluate the meteorological impact on O_3 trends during 2015 to 2022, and found that the meteorological changes in July 2022 resulted in an 15.6% increase of daytime O_3 concentrations in southern coastal cities. O_3 variations in the coastal area of Fujian province are strongly dependent on air temperature. This study implied the necessary for local governments to consider climate change for mitigating O_3 pollution.

1 Introduction

Surface ozone (O_3), primarily generated through a series of complex photochemical reaction involving carbon monoxide, volatile organic compounds (VOCs) and nitrogen oxides (NO_x) in the troposphere, is an air pollutant that be harmful to both human health and ecosystems (C. Li et al., 2022; Wang et al., 2022; Weng et al., 2022). Along with the global warming, heat waves have occurred more frequently in most part of Europe, Asia and Australia along with the ascendance of O_3 concentrations (Pu et al., 2017). Meteorological conditions accompanied with heat waves, including sustained high temperature, strong solar radiation, weak wind speed and little cloud coverage, could enhance O_3 production (Ma et al., 2019). Heat wave has gradually become a common danger in the world (Zhang et al., 2023) and the risk of temperature-related O_3 pollution may be greatly increased in the future. Although the important role of meteorology in O_3 pollution under heat wave is widely acknowledged, its mechanisms and quantitative contribution under extreme weather remains highly uncertain. Thus, it is vital to investigate the meteorological impact and possible mechanisms leading to high O_3 levels in extreme weather events.

The effectiveness of O_3 production is mainly controlled by not only the levels of precursors emissions, but also meteorological conditions (Weng et al., 2022; Zhang et al., 2018). Meteorological impacts on O_3 are attracting more attentions from researchers (Y. Dong et al., 2020; Gao et al., 2021; Liu et al., 2019). It has been proved that meteorological factors could have remarkable impact on O_3 concentrations, but temperature and solar radiation were indicated to be the prevailing variables (Pu et al., 2017; Yin et al., 2019; Yu et al., 2019). Since O_3 levels are significantly impacted by changes of precursor's emission and meteorological condition, it is important to split the effect of meteorology and emissions while evaluating the O_3 trends. Statistical analysis methods including Kolmogorov-Zurbenko (KZ) filter model(Ma et al., 2016; Yin et al., 2019; Yu et al., 2019), multiple linear regression (MLR) (Han et al., 2020; Qian et al., 2022) and machine learning (ML) (Vu et al., 2019; Wang et al., 2020; Weng et al., 2022) have been widely used to study the meteorological impact on O_3 concentrations. It was suggested that quantified meteorological contributions could vary regionally due to various climate conditions along with the rapid but regionally imbalanced economic developments across China (C. Li et al., 2022).

Over the last decade, the concentrations of ambient fine particulate matter ($PM_{2.5}$) in China have been decreased since the successful implement of air pollution control policies (C. Li et al., 2022; Yang et al., 2022b). However, O_3 concentrations increased, especially during summer time when the local photochemical process is the strongest (Ma et al., 2019; Zhang et al., 2018). This indicates the greater urgency for O_3 pollution control. In the summer of 2022, abnormal warming spread over most of the Northern Hemisphere, with Europe and China especially suffering from the record-breaking heat wave (Ma & Yuan, 2023; Zhang et al., 2023). The lasting of high temperature has resulted in widespread O_3 pollution (Zheng et al., 2023). This event provided an opportunity to study the response of O_3 concentrations to extremely high temperatures and related circulations. The significant impact of meteorological conditions on O_3 variabilities in coastal areas has been confirmed in our previous studies, especially in the areas with relatively low precursor's emissions (Ji et al., 2023), and this study aims to further explore the impact mechanism of meteorological changes on O_3 pollution in different coastal cities.

In this study, we characterized O_3 trends in July during 2015 to 2022 in four adjacent coastal regions in Southern and Northern China. The exceptional O_3 variabilities and meteorological conditions during the heat wave in 2022 were analyzed to study the meteorological factors that possibly contributed to the high O_3 levels during the extremes. In addition, a ML-based weather normalization was applied to assessing the meteorological contribution on O_3 variabilities in coastal cities.

2 Materials and Methods

2.1 Surface ozone and meteorological datasets

In order to study the meteorological impact on O_3 pollution during heat waves in coastal area, two southern coastal areas (the coast of Fujian Province (c-FJ) and the coast of Yangtze River Delta region (c-YRD)) and two northern coastal areas (the coast of Shandong Peninsula (c-SD) and Beijing-Tianjin-Hebei (c-BTH)) were selected for comparison. Totally 25 coastal cities were picked as typical cities representative of the studied regions (Zhangzhou, Xiamen, Quanzhou, Putian, Fuzhou and Ningde in c-FJ; Wenzhou, Taizhou, Ningbo, Zhoushan, Jiaxing, Shanghai, Nantong, Yancheng and Lianyungang in c-YRD; Rizhao, Qingdao, Weifang, Weihai, Yantai and Dongying in c-SD; Cangzhou, Tianjin, Tangshan and Qinhuangdao in c-BTH) and the data was averaged to obtain the O_3 concentrations and meteorological conditions regionally. The locations of the four regions are shown in Figure 1 and the precursor's emission levels are listed in Table S1. The BTH and the YRD are usually regarded as one of the most densely populated regions in China, and Fujian province is a southern coastal region with relatively low pollutants emission levels.

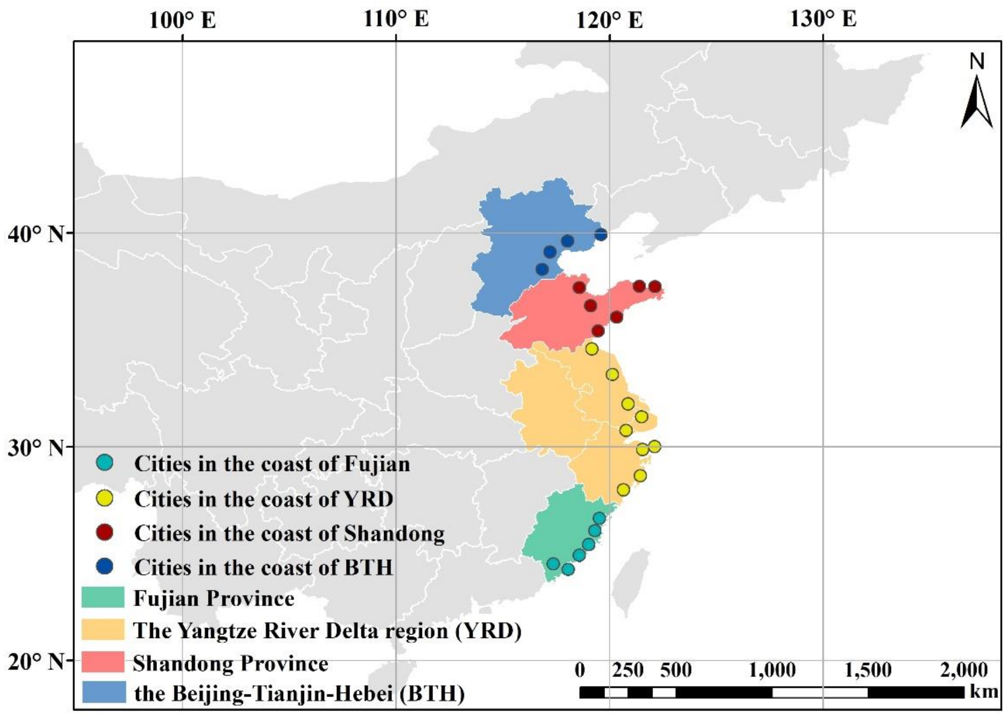

Figure 1. Geographic location of the studied area and cities.

Hourly ground-level O_3 concentrations used in this study were obtained from https://quotsoft.net/air/ (last access: 24 March 2023) which is a mirror of the data from the Ministry of Ecology and Environment (MEE) of China. The meteorological factors including temperature at 2 m (T_2), relative humidity (RH), U and V wind components at 10 m (U_{10} and V_{10}, respectively), surface solar radiation downward (SSRD), sea level pressure (SLP), low cloud cover (LCC), precipitation (P), boundary layer height (BLH), vertical velocity and wind divergence were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 hourly reanalysis dataset with a spatial resolution of 0.25°×0.25°.

2.2 Weather Normalization

A weather normalization approach based on random forest (RF) was applied to decouple the effect of meteorological condition from the observed O_3 series and investigate the meteorological impact on O_3 variabilities investigate the meteorological impact on O_3 variabilities in each study region. It was implemented using the "rmweather" R package developed by Grange et al. (2018), aiming to develop a statistical model that predicts O_3 concentrations under constant meteorological conditions. RF models which used O_3 concentrations as the dependent variable for each of the 4 study regions were grown. All RF models used the same explanatory variables to predict hourly O_3 concentrations. We used the hourly meteorological data including temperature at 2 m (T_2), relative humidity (RH), U and V wind components at 10 m (U_{10} and V_{10}, respectively), surface solar radiation downward (SSRD), sea level pressure (SLP), low cloud cover (LCC), precipitation (P) and boundary layer height (BLH) between 6:00 to 18:00 in July during 2015 to 2022 as input data for the model. It has been proved that the data of these hours is sufficient to cover the daytime hours when O_3 is produced by photochemical process (Weng et al., 2022). In addition, time variables were added to the explanatory variables as proxies of time-related variables such as emission intensity. We applied Unix time (number of seconds since 1 January 1970) as the linear trend component, Julian day (day of the year) as the seasonal component, day of the week as the weekly component and hour of the day as the diel-cycle component.

Training of the models was conducted on 80% of the input data and the remaining 20% was used to test the model. The hyper-parameters for all the models were consistent with previous studies: the number of variables used to grow a tree was set to three, the number of trees within a forest was set to 300 and the minimum size of terminal nodes was five (Grange et al., 2018; Wang et al., 2020). For O_3 series in each study region, the weather normalization was achieved by repeatedly sampling and predicting using RF models. After weather normalization, the O_3 trends that are solely caused by the emission changes were singled out and identified as "de-weathered O_3", then the difference with the observed O_3 can represent the meteorological impact (C. Li et al., 2022). The de-weathered concentrations at a particular hour were calculated by averaging 1000 predictions from the meteorological factors (excluding all time variables) randomly resampled from the whole period. Thus, this presented the O_3 trend disentangling the meteorological impacts.

2.3 Definition of heat wave, O_3 standard-exceeding days and East Asian summer monsoon index

Heat waves can be broadly defined as a period of consecutive days with higher air temperature than normal. World Meteorological Organization (WMO) suggests that daily maximum air temperature higher than 32 °C and last for more than three days can be regarded as heat waves (Pu et al., 2017). The heat waves episodes in this study were defined according to this standard.

O_3 standard-exceeding days were defined as days when the maximum daily 8-h average (MDA8) O_3 concentrations of a city were above 160 μg m^{-3}, according to the Technical Regulation on Ambient Air Quality Index of China publisher by the Ministry of Environmental Protection of China in 2012 (GB 3095-2012) (Yueming Dong et al., 2020; Yan et al., 2023).

To achieve a comprehensive indication of the East Asian summer monsoon (EASM) features, we calculated the EASM index based on the rules suggested by Wang et al. (2008). It is defined by the U_{850} in (22.5° - 32.5° N, 110° E-140° E) minus U_{850} in (5° - 15° N, 90° E-130° E). Here, U_{850} presents the zonal winds in 850 hPa.

3 Results and discussion

3.1 Overview of surface ozone and temperature

Fig. 2 shows the comparisons of MDA8 O_3, average O_3 standard-exceeding ratio, daily mean NO_2 and hourly air temperature in July from 2015 to 2021 and 2022 in the four coastal regions. The O_3 concentrations in c-BTH and c-YRD with high population density and economic development level were higher than those in c-FJ. A significant increase of both O_3 concentrations and air temperature in July 2022 were observed in the southern coastal cities (c-FJ and c-YRD). The monthly average MDA8 O_3 during 2015-2021 are shown in Fig. S1 and it is found that the monthly variations of O_3 concentrations in the southern coastal cities tended to show a “double-peak pattern”, with peak values occurring in Spring and Autumn, while a “single-peak pattern” that peaked in Summer was found in the northern coastal cities (c-SD and c-BTH) (Fig. S1). The O_3 concentrations were relatively low in July in the southern coastal cities during the past few years. However, the average MDA8 O_3 in July 2022 (108.42 ± 38.79 μg m^{-3} in c-FJ and 121.13 ± 33.26 μg m^{-3} in c-YRD) increased significantly, compared to those during 2015-2021 (85.65 ± 26.35 μg m^{-3} in c-FJ and 104.48 ± 32.02 μg m^{-3} in c-YRD), even approaching the highest concentration in the Spring (103.57 ± 32.02 μg m^{-3} in April in c-FJ and 127.17 ± 27.26 μg m^{-3} in May in c-YRD). The O_3 standard-exceeding ratios raised from 9.44% to 14.5% in c-FJ and 13.3% to 17.7% in c-YRD. In the northern coastal cities, the average MDA8 O_3 in July 2022 showed a slight decrease (-2.18 μg m^{-3} in c-SD and -0.26 μg m^{-3} in c-BTH), compared to those from 2015 to 2021. The O_3 standard-exceeding ratios decreased from 21.0% to 16.7% in c-SD and 36.1% to 33.1% in c-BTH. A decrease of NO_2 (one of the important precursors of O_3) concentrations was observed in all the four regions (Fig. 2). Temperature in southern coastal cities showed a significant increase compared to that during 2015-2021, while the temperature changed slightly in the northern coastal cities. These may indicate the important role of meteorological conditions on O_3 variations in coastal areas and the various distribution patterns of the O_3 concentrations under different heating amplitudes.

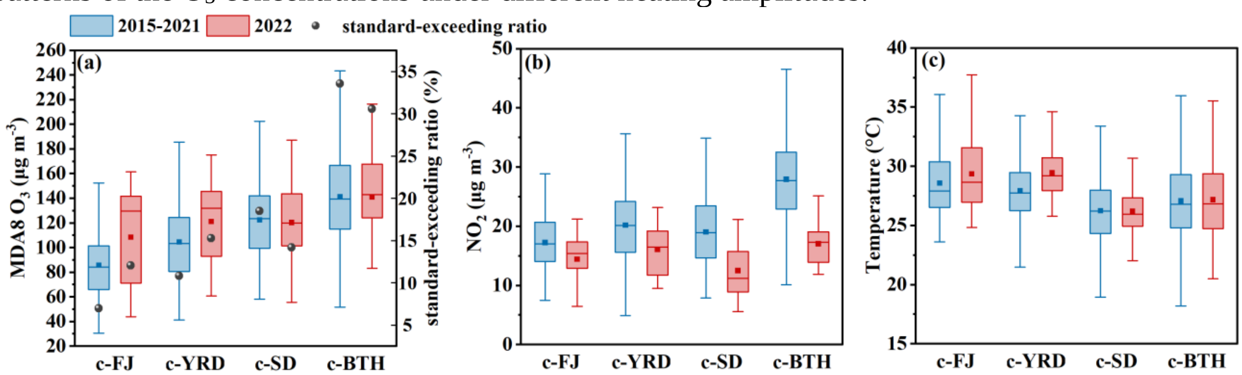

Figure 2. Comparisons of MDA8 O_3 and standard-exceeding ratio (a), daily mean NO_2 (b) and hourly air temperature (c) in July from 2015 to 2021 and 2022 in the coastal regions.

We furtherly investigated the daily MDA8 O_3 concentrations, max temperature, average wind speed and total precipitation in July 2022 in the four regions are shown in Fig. S2. It was indicated that the temperature in c-FJ and c-YRD were much higher than that in c-SD and c-BTH. There were 24 and 20 days of heat wave in c-FJ and c-YRD, respectively, with daily maximum temperature higher than 32 °C. The O_3 concentrations in c-SD and c-BTH showed more obvious fluctuations. High O_3 concentrations tended to occur during the periods of high temperature, weak wind speed and less precipitation. Precipitation could have a strong scavenging effect on O_3, thereby, the more precipitation in northern coastal cities responsible for the decrease of O_3 concentrations. Meanwhile, the extremely high temperature and stagnant conditions in southern coastal cities were beneficial for the generation and accumulation of O_3.

The correlation coefficients between MDA8 O_3 and daily maximum 2 m temperature in all the four regions show significant increase in 2022, compared to that from 2015 to 2021 (Fig. 3). The correlation coefficient in 2022 in c-FJ (r=0.80) was obviously higher than that from 2015 to 2021 (r=0.67) and those in other regions (r=0.73 in c-YRD, r=0.62 in c-SD and r=0.74 in c-BTH), suggesting the significant influence of temperature on O_3 varieties. The regression slope in southern coastal cities in 2022 (12.62 μg m^{-3} °C^{-1} in c-FJ and 18.42 μg m^{-3} °C^{-1} in c-YRD) were higher than that in 2015-2021 (7.16 μg m^{-3} °C^{-1} in c-FJ and 8.02 μg m^{-3} °C^{-1} in c-YRD) and that in northern coastal cities. The results demonstrated the large impacts of temperature on O_3 concentrations under the heat wave of 2022 in southern coastal cities. The observed abnormal O_3 concentrations made the distribution patterns different, which might be associated with the intensified heat wave along with the related atmospheric circulations and meteorological anomalies.

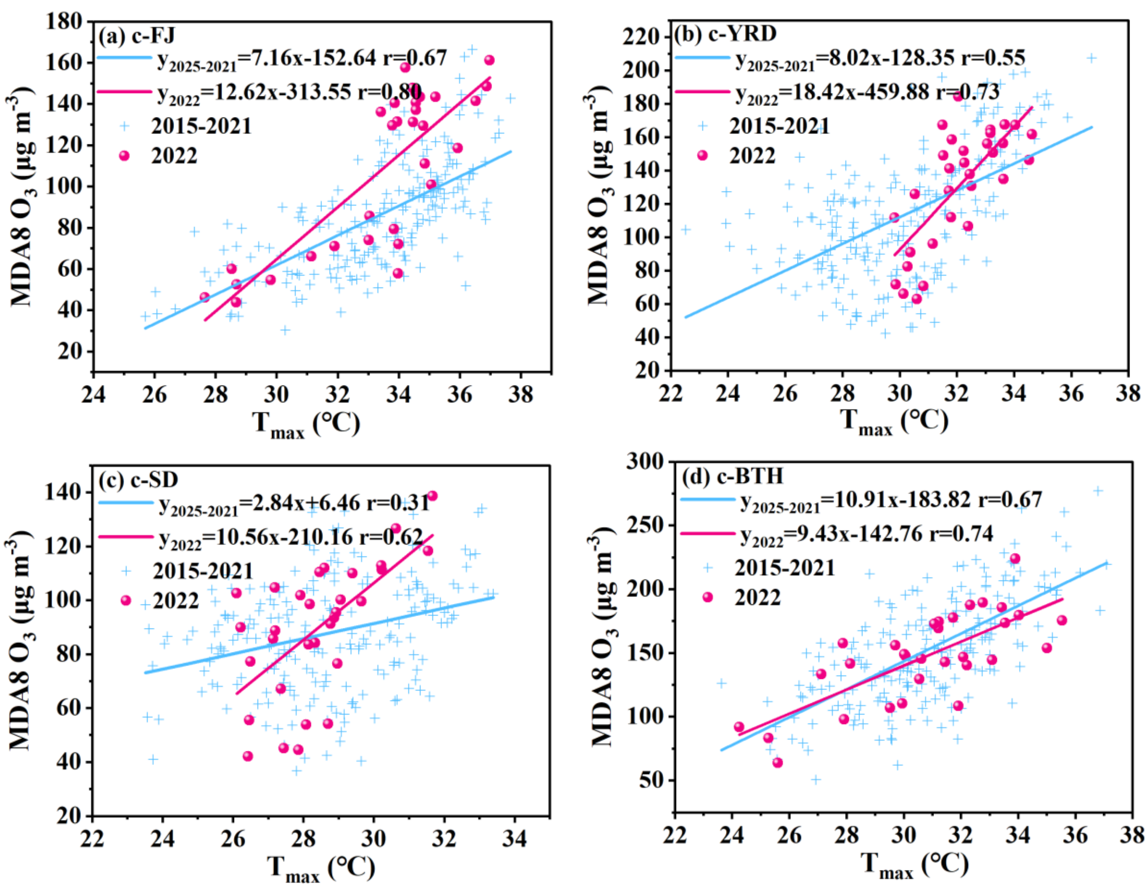

Figure 3. The correlations between MDA8 O3 and daily maximum temperature during 2015 to 2021 and 2022 in the four regions.

3.2 Meteorological contributions to O_3 variations

3.2.1 Climate and synoptic conditions

Climate in coastal area of China is significantly dominated by Asian monsoon system (He et al., 2007). On seasonal to inter-annual scales, the East Asian summer monsoon (EASM) was found to have a close link with O_3 concentrations over coastal regions of China (Zhou et al., 2013). The EASM index was calculated and shown in Fig. 4(a). It is indicated that the EASM index tended to be positive during summer and negative during other seasons, reaching the max in August from 2015 to 2021. The EASM brings clean, warm and humid air from the ocean to eastern (Zhou et al., 2022). A strong EASM year has been proved to be associated with the abundant rainfall in southern China during June and July (Wu et al., 2008) and more northward transport of pollutants induced by strong southerly winds (Xie et al., 2016). These may explain the lower O_3 concentrations in summer in the past few years in the southern coastal cities. However, a significantly weakening of EASM (Fig. 4(a)) and southwesterly winds (Fig. S3) were observed in July 2022, which made the southern coastal areas experience hot, sunny and stable weather at the time. The decrease of precipitation and weakening of southwesterly winds over southern China could reduce the dilution of pollutants and lead to an anomalous O_3 flux convergence in the southern areas (Xie et al., 2016; Yang et al., 2022a).

As one of the most important components of EASM, the western Pacific subtropical high (WPSH) also plays a key role in meteorological conditions in Southern China during the monsoon season (Zhao & Wang, 2017). The WPSH is the most direct circulation system that be responsible for the heat wave. As shown in Fig. 4(b), the geopotential height at 500 hPa in 2022 was higher than those from 2015 to 2021 around the country. The WPSH ridge tended to be defined as the line within the range of 5880 gpm and it was usually located over the ocean (Mao et al., 2020). However, the abnormal extension was found in July of 2022, even adjoined together with the Iran high (Lu et al., 2023). It was found that the WPSH covered the southern coastal cities and contributed to heat wave via compression of sinking air, enhancement of solar radiation and modulation of East Asian monsoon rain belt (Lu et al., 2023; Zhang et al., 2023). These could promote the generation and accumulation of O_3 in the southern coastal cities, and the details will be discussed in section 3.2.2. In addition, the movement of WPSH over the southern coastal cities strengthened the westerly winds and a convergence of westerly and southerly winds was found near the coastline (Fig. S3). This may also enhance the local accumulation of O_3.

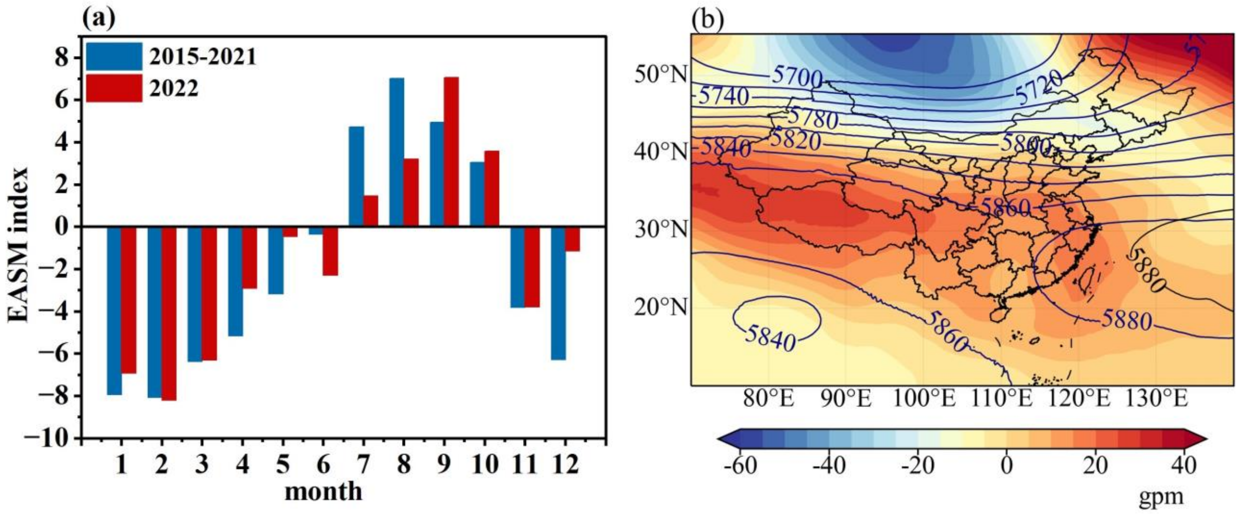

Figure 4. Comparison of EASM index between 2015-2021 and 2022 (a) and the changes of geopotential height at 500 hPa in 2022 compared with those from 2015 to 2021(b). The black lines represent the geopotential height in 2022 and the blue lines represent the average values of the geopotential height from 2015 to 2021.

3.2.2 Local meteorological conditions

To explore the changes on local meteorological condition and the underlying mechanisms that may be responsible for the high O_3 concentration in the southern coastal areas during the heat wave of 2022, we quantify the changes in various local meteorological factors in July between 2015-2021 and 2022 (Fig. 5). Most regions in China showed increase of air temperature at 2 m, and the highest anomalies occurred in YRD, which could be higher than 2.5 °C. However, the coastal areas of BTH and Shandong province showed slight increase of temperature, even negative anomalies. In addition, reduced relative humidity, strong solar radiation, less precipitation, less cloud cover and weak wind speed in southern coastal area were observed. Fig. S4 showed the difference of the average temperature, vertical velocity and wind divergence from 117°N to 122°N in July between 2022 and 2015-2021. Under the control of abnormally strong WPSH and record-breaking heat, the atmosphere in most of southern coastal cities were dominated by sinking motion. The vertical velocity was higher than that from 2015 to 2021 under 500 hPa (Fig. S4(b)), indicating the stronger sinking motion under heat wave in southern coastal cities. Correspondingly, positive anomalies of divergence were observed in these areas and there exited two divergence centers at 1000-925 hPa between 20-28°N (Fig. S4(c)). The warming center between 850-700 hPa in c-FJ made the sinking airflow close to the surface. The vertical structure enhanced the stability of the atmosphere and favored the O_3-benefiting sinking motion, usually leading to O_3 pollution episodes (Y. Li et al., 2022; Mao et al., 2020). These characteristics of meteorological conditions in southern coastal cities were favorable for the photochemical reaction but adverse to the removal and diffusion of O_3, leading to the enhancement of O_3 pollution. The changes in meteorological factors in the northern coastal cities exhibited the opposite patterns, and this may explain the decrease in O_3 concentrations.

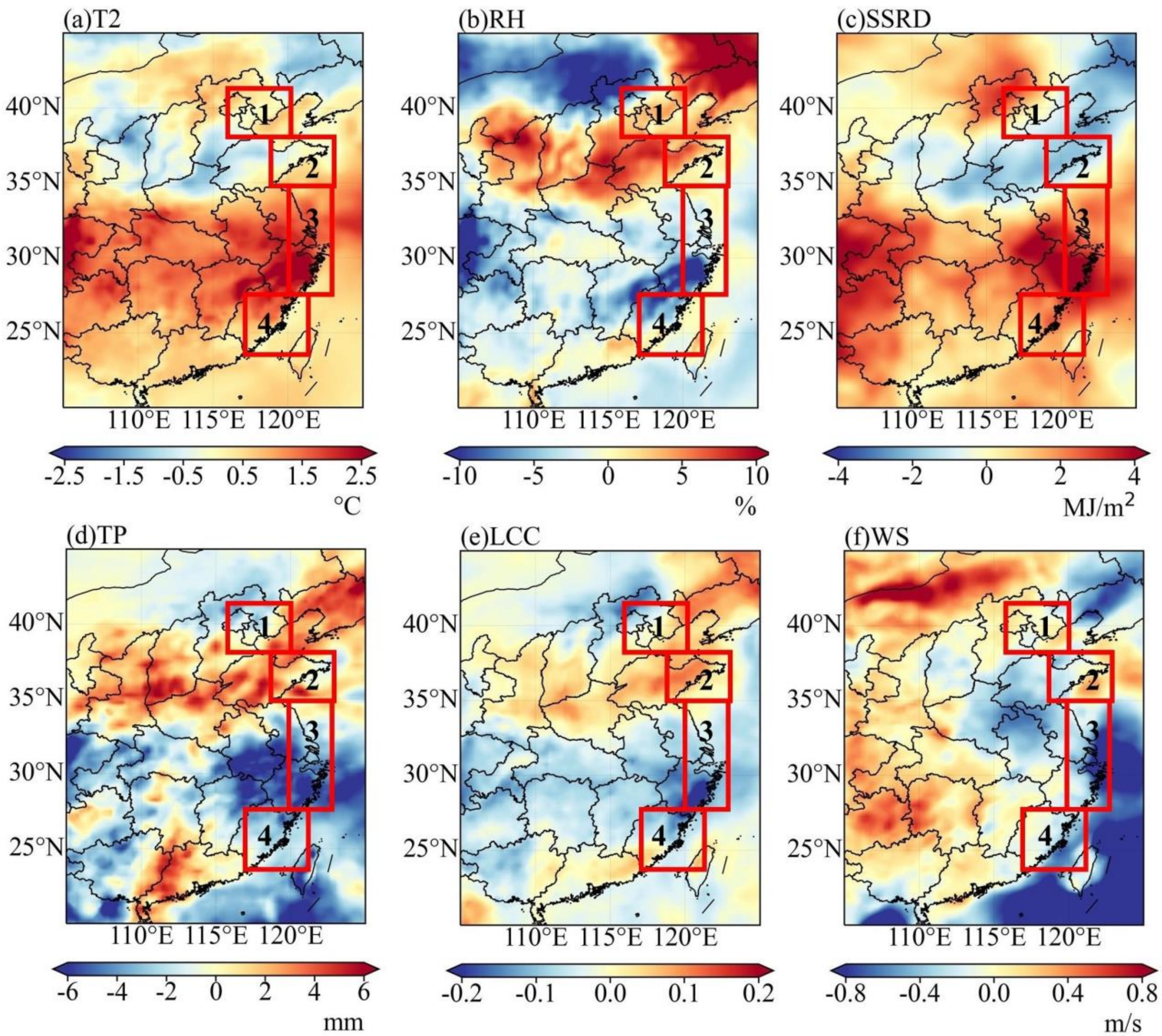

Figure 5. Spatial distribution in the difference between meteorological factors in July 2022 and the average value in July from 2015 to 2021. The meteorological factors included air temperature at 2 m (a), relative humidity at 1000 hPa (b), surface solar radiation downwards (c), total precipitation (d), low cloud cover (e) and wind speed (f). The red boxes represent the four regions: (1) c-BTH, (2) c-SD, (3) c-YRD and (4) c-FJ.

3.3 Evaluating the effectiveness of meteorological factors

The diurnal variations of O_3 concentrations during the daytime in July 2022 showed obvious increase in southern coastal cities, while a decrease could be found in the northern coastal cities (Fig. S5). These results indicated the differences in regional photochemical reaction processes, due to the changes of meteorological conditions. In order to quantify the impact of meteorological conditions to the O_3 variations during the daytime, the ML-based weather normalization was applied. Fig. 6 shows the observed and de-weathered O_3 concentrations in July in the four regions. It can be found that the de-weathered O_3 concentrations in July 2022 increased slightly in the four regions (3.51 μg m^{-3} in c-FJ, 0.89 μg m^{-3} in c-YRD, 3.29 μg m^{-3} in c-SD and 4.98 in c-BTH), compared to the average values from 2015 to 2021. Compared to the de-weathered concentrations, the observed O_3 showed a significantly increase in the southern area (9.85 μg m^{-3} in c-FJ and 12.98 μg m^{-3} in c-YRD). Thus, the unfavorable meteorological conditions during the heat wave leaded to 14.2% and 15.6% of O_3 increase in c-FJ and c-YRD, respectively. In the contrary, the O_3 concentrations in c-SD and c-BTH decreased 3.35 μg m^{-3} (3.34%) and 2.18 μg m^{-3} (1.96%) due to the meteorological variabilities. The changes of meteorological conditions under heat wave in July 2022 made different impact on O_3 trends in the southern and northern coastal cities. These results indicated the possibility of distribution pattern changes under climate warming, which were consistent with the discussion of meteorological changes in section 3.2. In addition, although the enhancement of temperature in c-YRD was more significant, the meteorological contribution to the elevated O_3 was comparable to that in c-FJ, suggesting the strong dependence of O_3 variations on air temperature in c-FJ.

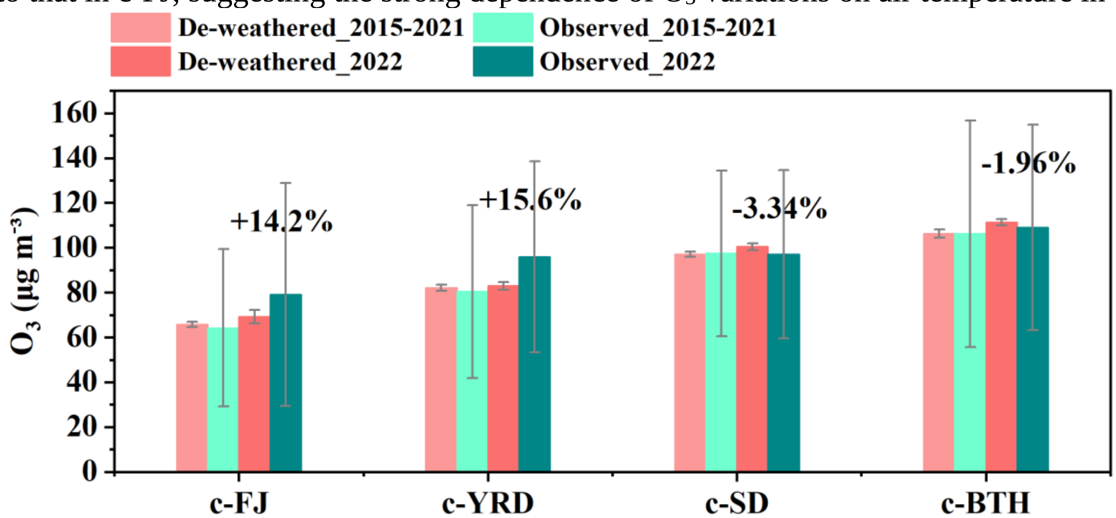

Figure 6. The observed O_3 concentrations and de-weathered O_3 concentrations in July from 2015 to 2021 and in 2022.

We furtherly calculated the relative importance of each meteorological variables input into the models of weather normalization (Fig. 7). In c-FJ, air temperature is the most important variable (35.7%), followed by solar radiation (19.2%) and relative humidity (14.5%). The partial dependence plots of the most important variable in each region are shown in Fig. S8, which present the dependence of O_3 concentrations on one meteorological factor if all other factors are fixed at their average values. O_3 concentrations would increase with the range of temperature between 28°C ~35°C in c-FJ, due to the increased rates of photochemical reaction, biogenic and anthropogenic activities emissions (such as solvent evaporation) (Weng et al., 2022). As shown in Fig. S6, O_3 concentrations in c-FJ also could keep in high level under low RH, and high RH is beneficial for O_3 removal. In c-YRD, the O_3 trends were mainly affected by relative humidity (29.8%), air temperature (23.8%) and u-component of wind (11.6%), which implied the important roles of local photochemical reactions along with regional transport. The relationship between O_3 concentrations and RH in c-YRD was similar to that in c-FJ, but a decrease of O_3 concentrations was found when air temperature increases from 24°C to 28 °C. This indicated that the increase of O_3 concentrations in c-YRD not only depended on air temperature, but also affected by other factors. The O_3 concentrations tends to be high under low wind speed (~2m/s) which creates a more stagnant condition. West wind (positive values of U_{10}) could bring more air pollutants from inland areas and leaded to high O_3 concentrations, while east wind was favorable for the removal of O_3 due to the clean air masses from the sea (Weng et al., 2022). In c-SD, relative humidity showed the largest contribution to O_3 trends (33.5%), and O_3 concentrations in c-BTH mainly depended on relative humidity (31.1%), air temperature (23.4%) and boundary layer height (12.4%). The O_3 concentrations were enhanced with the increase of the boundary layer height, which associated with hot, sunny and deep convective boundary layer conditions in the daytime (Grange et al., 2018). Previous studies reported that O_3 variations in the relatively dry regions depended more on temperature and solar radiation instead of relative humidity (Weng et al., 2022). In this study, meteorological changes during the hot summer of 2022 led to high humidity and more precipitation in northern coastal areas (Fig. 5), which resulted in O_3 variations in northern coastal areas were much different from southern coastal areas.

Therefore, the highest O_3 concentrations were observed when air temperature reached its maximum value in all the coastal cities, indicating the large possibility of O_3 pollution under heat waves. Under the heat wave conditions, the contribution of air temperature to high O_3 concentrations in c-FJ was higher than those in other regions. This study implied that O_3 concentrations in coastal areas with low O_3 precursors' emission levels could present strong sensitivity to global warming.

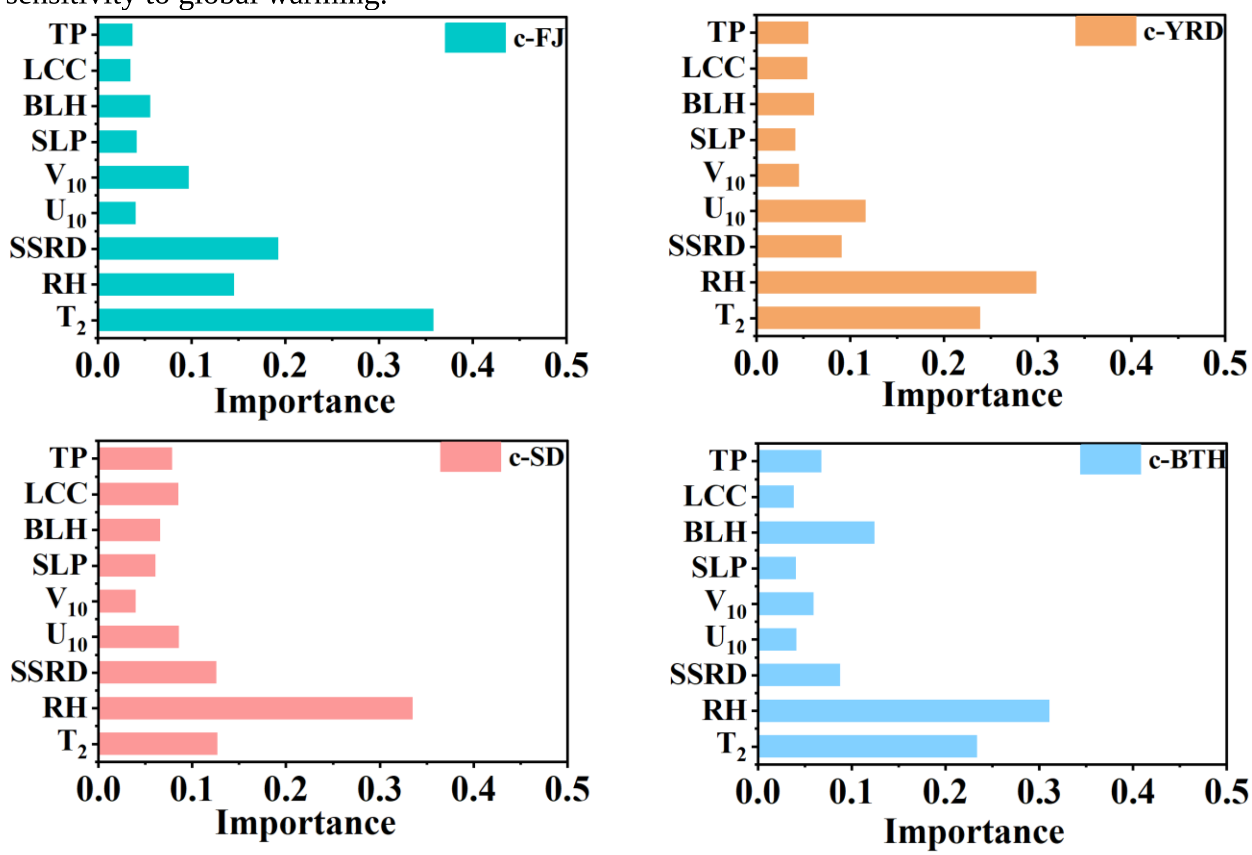

Figure 7. The relative importance of different meteorological factors in the four study areas in 2022.

4 Conclusions

The impact of meteorological changes on O_3 concentrations in the coastal cities of China under heat wave in summer of 2022 was evaluated. The O_3 trends in July during 2015 to 2022 were investigated in four coastal areas with different geolocations and emission magnitudes in China. Compared to that during 2015-2021, a significant increase of O_3 concentrations (16.7~22.8 μg m^{-3}) in the southern coastal cities, while a slight decrease in the northern coastal cities were observed. The results indicated a shift of distribution patterns of O_3 concentrations in coastal cities of China in the unprecedented hot summer of 2022 and suggested the varied mechanism O_3 concentrations responded to heat wave around the country. The enhancement of O_3 concentration mainly occurred during the days with higher temperature, low wind speed and less rainfall.

The year 2022 featured a weakened East Asian summer monsoon and abnormal extension of the western Pacific subtropical high. Associated with the changes of climate and synoptic conditions, the record-breaking warming, strong solar radiation, low relative humidity, less rainfall and deep sinking motion of atmosphere in the southern coastal cities made a favorable condition for the O_3 formations and accumulations.

According to the results of machine-learning based weather normalization, we found that the unfavorable meteorological conditions in July 2022 could lead to a 15.6% increase in O_3 concentrations during the daytime in the southern coastal cities and a 3.34% decrease in the northern coastal cities. Totally, air temperature, relative humidity, solar radiation, zonal wind and boundary layer height could have overwhelming impact on the O_3 variations in coastal areas. Heat wave made the meteorological condition and drivers of O_3 variations different across the country. Air temperature was the main contributor in the coast of Fujian province (35.7%), while the other areas depended on relative humidity (29.8%~33.5%). Although the enhancement of temperature in c-YRD was more significant, c-FJ experienced the highest O_3 concentrations ascend rate. This suggested large possibility of O_3 pollution under heat waves in the coastal areas with lower precursor's emission. This study demonstrated the meteorological impact on O_3 concentrations enhancement during heat wave, and implied the challenge of mitigating O_3 pollution under global warming.

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Open Research

A dataset for this paper can be accessed at (Ji et al., 2023).

References

Dong, Y., Li, J., Guo, J., Jiang, Z., Chu, Y., Chang, L., Yang, Y., & Liao, H. (2020). The impact of synoptic patterns on summertime ozone pollution in the North China Plain. *Science of The Total Environment*, *735*. https://doi.org/10.1016/j.scitotenv.2020.139559

Dong, Y., Li, J., Guo, J., Jiang, Z., Chu, Y., Chang, L., Yang, Y., & Liao, H. (2020). The impact of synoptic patterns on summertime ozone pollution in the North China Plain. *Sci Total Environ*, *735*, 139559. https://doi.org/10.1016/j.scitotenv.2020.139559

Gao, D., Xie, M., Liu, J., Wang, T., Ma, C., Bai, H., Chen, X., Li, M., Zhuang, B., & Li, S. (2021). Ozone variability induced by synoptic weather patterns in warm seasons of 2014–2018 over the Yangtze River Delta region, China. *Atmospheric Chemistry and Physics*, *21*(8), 5847-5864. https://doi.org/10.5194/acp-21-5847-2021

Grange, S. K., Carslaw, D. C., Lewis, A. C., Boleti, E., & Hueglin, C. (2018). Random forest meteorological normalisation models for Swiss PM₁₀ trend analysis. *Atmospheric Chemistry and Physics*, *18*(9), 6223-6239. https://doi.org/10.5194/acp-18-6223-2018

Han, H., Liu, J., Shu, L., Wang, T., & Yuan, H. (2020). Local and synoptic meteorological influences on daily variability in summertime surface ozone in eastern China. *Atmospheric Chemistry and Physics*, *20*(1), 203-222. https://doi.org/10.5194/acp-20-203-2020

He, J., Ju, J., Wen, Z., Lü, J., & Jin, Q. (2007). A review of recent advances in research on Asian monsoon in China. *Advances in Atmospheric Sciences*, *24*(6), 972-992. https://doi.org/10.1007/s00376-007-0972-2

Ji, X. (2023). Ozone concentrations and meteorological factors in coastal areas of China in July of 2015-2022 [Data set]. Zenodo. https://doi.org/10.5281/zenodo.8210811

Ji, X., Hong, Y., Lin, Y., Xu, K., Chen, G., Liu, T., Xu, L., Li, M., Fan, X., Wang, H., Zhang, H., Chen, Y., Yang, C., Lin, Z., & Chen, J. (2023). Impacts of Synoptic Patterns and Meteorological Factors on Distribution Trends of Ozone in Southeast China During 2015–2020. *Journal of Geophysical Research: Atmospheres*, *128*(14), e2022JD037961. https://doi.org/https://doi.org/10.1029/2022JD037961

Li, C., Zhu, Q., Jin, X., & Cohen, R. C. (2022). Elucidating Contributions of Anthropogenic Volatile Organic Compounds and Particulate Matter to Ozone Trends over China. *Environ Sci Technol*, *56*(18), 12906-12916. https://doi.org/10.1021/acs.est.2c03315

Li, Y., Zhao, X., Deng, X., & Gao, J. (2022). The impact of peripheral circulation characteristics of typhoon on sustained ozone episodes over the Pearl River Delta region, China. *Atmospheric Chemistry and Physics*, *22*(6), 3861-3873. https://doi.org/10.5194/acp-22-3861-2022

Liu, J., Wang, L., Li, M., Liao, Z., Sun, Y., Song, T., Gao, W., Wang, Y., Li, Y., Ji, D., Hu, B., Kerminen, V.-M., Wang, Y., & Kulmala, M. (2019). Quantifying the impact of synoptic circulation patterns on ozone variability in northern China from April to October 2013–2017. *Atmospheric Chemistry and Physics*, *19*(23), 14477-14492. https://doi.org/10.5194/acp-19-14477-2019

Lu, R., Xu, K., Chen, R., Chen, W., Li, F., & Lv, C. (2023). Heat waves in summer 2022 and increasing concern regarding heat waves in general. *Atmospheric and Oceanic Science Letters*, *16*(1). https://doi.org/10.1016/j.aosl.2022.100290

Ma, F., & Yuan, X. (2023). When Will the Unprecedented 2022 Summer Heat Waves in Yangtze River Basin Become Normal in a Warming Climate? *Geophysical Research Letters*, *50*(4). https://doi.org/10.1029/2022gl101946

Ma, M., Gao, Y., Wang, Y., Zhang, S., Leung, L. R., Liu, C., Wang, S., Zhao, B., Chang, X., Su, H., Zhang, T., Sheng, L., Yao, X., & Gao, H. (2019). Substantial ozone enhancement over the North China Plain from increased biogenic emissions due to heat waves and land cover in summer 2017. *Atmos. Chem. Phys.*, *19*(19), 12195-12207. https://doi.org/10.5194/acp-19-12195-2019

Ma, Z., Xu, J., Quan, W., Zhang, Z., Lin, W., & Xu, X. (2016). Significant increase of surface ozone at a rural site, north of eastern China. *Atmospheric Chemistry and Physics*, *16*(6), 3969-3977. https://doi.org/10.5194/acp-16-3969-2016

Mao, J., Wang, L., Lu, C., Liu, J., Li, M., Tang, G., Ji, D., Zhang, N., & Wang, Y. (2020). Meteorological mechanism for a large-scale persistent severe ozone pollution event over eastern China in 2017. *J Environ Sci (China)*, *92*, 187-199. https://doi.org/10.1016/j.jes.2020.02.019

Pu, X., Wang, T. J., Huang, X., Melas, D., Zanis, P., Papanastasiou, D. K., & Poupkou, A. (2017). Enhanced surface ozone during the heat wave of 2013 in Yangtze River Delta region, China. *Sci Total Environ*, *603-604*, 807-816. https://doi.org/10.1016/j.scitotenv.2017.03.056

Qian, J., Liao, H., Yang, Y., Li, K., Chen, L., & Zhu, J. (2022). Meteorological influences on daily variation and trend of summertime surface ozone over years of 2015-2020: Quantification for cities in the Yangtze River Delta. *Sci Total Environ*, *834*, 155107. https://doi.org/10.1016/j.scitotenv.2022.155107

Vu, T. V., Shi, Z., Cheng, J., Zhang, Q., He, K., Wang, S., & Harrison, R. M. (2019). Assessing the impact of clean air action on air quality trends in Beijing using a machine learning technique. *Atmospheric Chemistry and Physics*, *19*(17), 11303-11314. https://doi.org/10.5194/acp-19-11303-2019

Wang, B., Wu, Z., Li, J., Liu, J., Chang, C.-P., Ding, Y., & Wu, G. (2008). How to Measure the Strength of the East Asian Summer Monsoon. *Journal of Climate*, *21*(17), 4449-4463. https://doi.org/https://doi.org/10.1175/2008JCLI2183.1

Wang, T., Xue, L., Feng, Z., Dai, J., Zhang, Y., & Tan, Y. (2022). Ground-level ozone pollution in China: a synthesis of recent findings on influencing factors and impacts. *Environmental Research Letters*, *17*(6), 063003. https://doi.org/10.1088/1748-9326/ac69fe

Wang, Y., Wen, Y., Wang, Y., Zhang, S., Zhang, K. M., Zheng, H., Xing, J., Wu, Y., & Hao, J. (2020). Four-Month Changes in Air Quality during and after the COVID-19 Lockdown in Six Megacities in China. *Environmental Science & Technology Letters*, *7*(11), 802-808. https://doi.org/10.1021/acs.estlett.0c00605

Weng, X., Forster, G. L., & Nowack, P. (2022). A machine learning approach to quantify meteorological drivers of ozone pollution in China from 2015 to 2019. *Atmospheric Chemistry and Physics*, *22*(12), 8385-8402. https://doi.org/10.5194/acp-22-8385-2022

Wu, G., Ding, Y., Chang, C.-P., Liu, J., Li, J., Wu, Z., & Wang, B. (2008). How to Measure the Strength of the East Asian Summer Monsoon. *Journal of Climate*, *21*(17), 4449-4463. https://doi.org/10.1175/2008jcli2183.1

Xie, X., Wang, H., Liu, X., Li, J., Wang, Z., & Liu, Y. (2016). Distinct effects of anthropogenic aerosols on the East Asian summer monsoon between multidecadal strong and weak monsoon stages. *Journal of Geophysical Research: Atmospheres*, *121*(12), 7026-7040. https://doi.org/10.1002/2015jd024228

Yan, Y., Wang, X., Huang, Z., Qu, K., Shi, W., Peng, Z., Zeng, L., Xie, S., & Zhang, Y. (2023). Impacts of synoptic circulation on surface ozone pollution in a coastal eco-city in Southeastern China during 2014-2019. *J Environ Sci (China)*, *127*, 143-157. https://doi.org/10.1016/j.jes.2022.01.026

Yang, Y., Li, M., Wang, H., Li, H., Wang, P., Li, K., Gao, M., & Liao, H. (2022a). ENSO modulation of summertime tropospheric ozone over China. *Environmental Research Letters*, *17*(3). https://doi.org/10.1088/1748-9326/ac54cd

Yang, Y., Li, M., Wang, H., Li, H., Wang, P., Li, K., Gao, M., & Liao, H. (2022b). ENSO modulation of summertime tropospheric ozone over China. *Environmental Research Letters*, *17*(3), 034020. https://doi.org/10.1088/1748-9326/ac54cd

Yin, C., Deng, X., Zou, Y., Solmon, F., Li, F., & Deng, T. (2019). Trend analysis of surface ozone at suburban Guangzhou, China. *Sci Total Environ*, *695*, 133880. https://doi.org/10.1016/j.scitotenv.2019.133880

Yu, Y., Wang, Z., He, T., Meng, X., Xie, S., & Yu, H. (2019). Driving factors of the significant increase in surface ozone in the Yangtze River Delta, China, during 2013–2017. *Atmospheric Pollution Research*, *10*(4), 1357-1364. https://doi.org/10.1016/j.apr.2019.03.010

Zhang, D., Chen, L., Yuan, Y., Zuo, J., & Ke, Z. (2023). Why was the heat wave in the Yangtze River valley abnormally intensified in late summer 2022? *Environmental Research Letters*, *18*(3). https://doi.org/10.1088/1748-9326/acba30

Zhang, J., Gao, Y., Luo, K., Leung, L. R., Zhang, Y., Wang, K., & Fan, J. (2018). Impacts of compound extreme weather events on ozone in the present and future. *Atmos. Chem. Phys.*, *18*(13), 9861-9877. https://doi.org/10.5194/acp-18-9861-2018

Zhao, Z., & Wang, Y. (2017). Influence of the West Pacific subtropical high on surface ozone daily variability in summertime over eastern China. *Atmospheric Environment*, *170*, 197-204. https://doi.org/10.1016/j.atmosenv.2017.09.024

Zheng, H., Kong, S., He, Y., Song, C., Cheng, Y., Yao, L., Chen, N., & Zhu, B. (2023). Enhanced ozone pollution in the summer of 2022 in China: The roles of meteorology and emission variations. *Atmospheric Environment*, *301*. https://doi.org/10.1016/j.atmosenv.2023.119701

Zhou, D., Ding, A., Mao, H., Fu, C., Wang, T., Chan, L. Y., Ding, K., Zhang, Y., Liu, J., Lu, A., & Hao, N. (2013). Impacts of the East Asian monsoon on lower tropospheric ozone over coastal South China. *Environmental Research Letters*, *8*(4), 044011. https://doi.org/10.1088/1748-9326/8/4/044011

Zhou, Y., Yang, Y., Wang, H., Wang, J., Li, M., Li, H., Wang, P., Zhu, J., Li, K., & Liao, H. (2022). Summer ozone pollution in China affected by the intensity of Asian monsoon systems. *Science of The Total Environment*, *849*, 157785. https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.157785