Journal Pre-proof

Effects of meteorological conditions and anthropogenic precursors on ground-level ozone concentrations in Chinese cities

Pengfei Liu, Hongquan Song, Tuanhui Wang, Feng Wang, Xiaoyang Li, Changhong Miao, Haipeng Zhao

PII: S0269-7491(20)30473-5

DOI: https://doi.org/10.1016/j.envpol.2020.114366

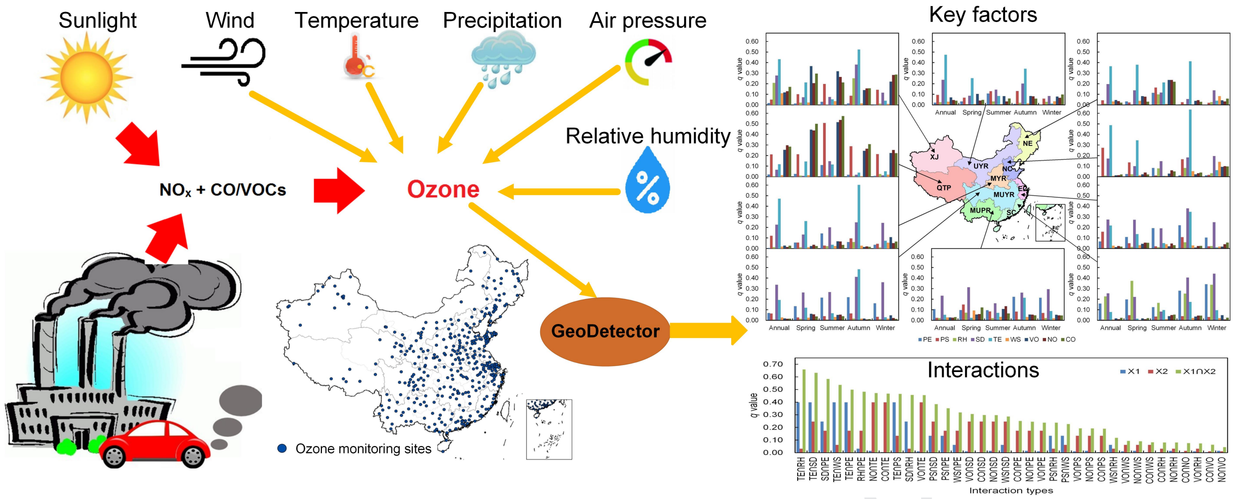
Reference: ENPO 114366

To appear in: *Environmental Pollution*

Received Date: 21 January 2020

Revised Date: 29 February 2020

Accepted Date: 10 March 2020


Sunlight
Wind
Temperature
Precipitation
Air pressure
Relative humidity
NOx + CO/VOCs
Ozone
GeoDetector
Ozone monitoring sites
Key factors
Interactions
Interaction types

Effects of meteorological conditions and anthropogenic precursors on ground-level ozone concentrations in Chinese cities

Pengfei Liu[1, 4†], Hongquan Song[2, 3, 4*†], Tuanhui Wang[2, 4], Feng Wang[2, 4], Xiaoyang Li[2, 4], Changhong Miao[1], Haipeng Zhao[2, 4]

[1] Key Research Institute of Yellow River Civilization and Sustainable Development & Collaborative Innovation Center on Yellow River Civilization of Henan Province, Henan University, Kaifeng, 475001, China

[2] Laboratory of Geospatial Technology for the Middle and Lower Yellow River Regions, Ministry of Education, Henan University, Kaifeng, Henan 475004, China

[3] Henan Key Laboratory of Integrated Air Pollution Control and Ecological Security, Henan University, Kaifeng, Henan 475004, China

[4] Institute of Urban Big Data, College of Environment and Planning, Henan University, Kaifeng, Henan 475004, China

† These authors contributed equally to this work and should be considered co-first authors.

* Corresponding author.

E-mail address: hqsong@henu.edu.cn (H. Song)

Address: College of Environment and Planning, Henan University, Kaifeng, Henan Province 475004, China

Abstract

Ground-level ozone pollution has negative impacts on human health and vegetation and has increased rapidly across China. Various factors are implicated in the formation of ozone (e.g., meteorological factors, anthropogenic emissions), but their relative individual impact and the impact of interactions between these factors remains unclear. This study quantified the influence of specific meteorological conditions and anthropogenic precursor emissions and their interactions on ozone concentrations in Chinese cities using the geographic detector model (GeoDetector). Results revealed that the impacts of meteorological and anthropogenic factors and their interactions on ozone concentrations varied significantly at different spatial and temporal scales. Temperature was the dominant driver at the annual time scale, explaining 40% (q = 0.4) of the ground-level ozone concentration. Anthropogenic precursors and meteorological conditions had comparable effects on ozone concentrations in summer and winter in northern China. Interactions between all the factors can enhance effects. The interaction between meteorological factors and anthropogenic precursors had the strongest impact in summer. The results can be used to enhance our understanding of ozone pollution, to improve ozone prediction models, and to formulate pollution control measures.

Keywords: air pollution, tropospheric ozone, interactive effects, GeoDetector model, China

Abbreviations: APE, anthropogenic precursor emissions; CO, carbon monoxide; EC, eastern coastal area; GeoDetector, geographical detector model; MDA8, daily maximum 8-hour average; MEIC, multi-resolution inventory of China; MUPR, middle and upper reaches of the Pearl River area; MUYR, middle and upper reaches of the Yangtze River; MYR, middle reaches of the Yellow River; NAAQS, National Ambient Air Quality Standard; NC, northern coastal area; NE, northeast area; NOx, nitrogen oxides; O_3, ozone; PE, accumulated precipitation; PS, surface air pressure; QTP, Qinghai-Tibetan Plateau; RH, relative humidity at 2-m above the ground; SC, southeast coastal area; SD, sunshine duration; TE, air temperature at 2-m above the ground; UYR, upper reaches of the Yellow River; VOCs, volatile organic compounds; WS, wind speed; XJ, Xinjiang.

1 Introduction

China has experienced rapid industrialization and urbanization in recent years, resulting in large emissions of air pollutants and high concentrations of ground-level or tropospheric ozone (O_3) (Liu et al., 2010; Wang et al., 2017a; Cheng et al., 2019; Chen et al., 2020). Several studies have reported the increasing ozone trends in Chinese cities over the past 20 years (Li et al., 2019a). Severe O_3 pollution is mainly concentrated, especially in summertime, in the North China Plain, Huanghuai Plain, Central Yangtze River Plain, Pearl River Delta, and Sichuan Basin in China (Cheng et al., 2018). The ground-level ozone pollution is a serious threat to human health (Goodman et al., 2015; Bonn et al., 2018; Moura et al., 2018; Yang et al., 2019) as well as vegetation (Tai et al., 2014; Feng et al., 2015; Gao et al., 2016; Mills et al., 2016). Therefore, the government has placed increasing emphasis on managing and monitoring this pollution (Wang et al., 2017a; Xu, 2018). Developing effective emission control strategies and predicting ozone concentrations depends on accurate and comprehensive understanding of the factors involved and their interactions.

Ground-level ozone is mainly produced by complicated photochemical reactions among multiple precursors such as nitrogen oxides (NOx), volatile organic compounds (VOCs), carbon monoxide (CO), and methane (Fu et al., 2007; Li et al., 2018; Lu et al., 2018; Li et al., 2019b). In addition to the anthropogenic precursors, meteorological conditions have also been recognized as primary factors driving ground-level ozone production (Zhang et al., 2011; Li et al., 2016; Li et al., 2017; Lu et al., 2019). To understand how meteorological conditions and anthropogenic precursors influence ozone concentrations, previous studies have investigated the relationships between ozone concentrations and both meteorological conditions (Wang et al., 2017a; Chen et al., 2019) and anthropogenic precursors (Wei et al., 2014; Cheng et al., 2018a) across China (Wang et al., 2017a; Chen et al., 2019) and in some key regions such as Beijing-Tianjin-Hebei (Chen et al., 2019), the Yangtze River delta (Pu et al., 2017; Tong et al., 2017), and the Pearl River delta (Zhang et al., 2013). These studies revealed notable regional variations in the predominant meteorological factors affecting ground-level ozone.

Despite these studies, understanding of the various influences on ground-level ozone production is neither complete nor comprehensive. Most previous studies investigated the correlations between ozone concentrations and meteorological factors (Chen et al., 2020), without considering and interpreting the regional and seasonal influence of anthropogenic precursors. Therefore, the spatial and temporal variations of meteorological and anthropogenic effects on ground-level ozone concentrations across China remain unclear. In addition, the traditional correlation analysis may result in biased results because different meteorological factors and anthropogenic precursors interact closely with each other (Pearce et al., 2011; Chen et al., 2017). Therefore, advanced methods, such as Multiple Linear Regression (Zhao et al., 2016; Sharma et al., 2017), Quantile regression (Zhao et al., 2016), Principle Component Analysis (Sharma et al., 2017), Convergent Cross Mapping (Chen et al., 2020), and air quality models (Sanchez-Ccoyllo et al., 2006; Martins and de Fátima Andrade, 2008) were used to investigate meteorological and anthropogenic factors on ground-level ozone concentrations. However, even these methods have their shortcomings, in that they mainly describe the composite effects of multi-factors and have limitations in quantifying the effects of individual factors and their interactions. Consequently, it is essential to assess the impacts of individual anthropogenic precursors and meteorological factors and their interactions on ground ozone concentrations.

In this study, the geographical detector model (GeoDetector) (Wang et al., 2010; Wang et al., 2016), a spatial heterogeneity detector method, was adopted to quantify influences of specific anthropogenic precursors and meteorological factors and of their interactions on the ground-level ozone in urban areas of China. The results represent important specific information about the relative importance of the various factors involved in ground-level ozone concentrations, in both time and space. This information can be used by scientists to improve the performance of ozone prediction models, and by government entities to formulate emission control measures..

2 Materials and methods

2.1 Study area and datasets

This study focused on the influences of meteorological conditions and anthropogenic precursor emissions (APE) on ground-level ozone concentrations in 366 cities of mainland China. Mainland China was divided into ten regions based on economic development, climate, and topography (Fig. S1). These ten regions were: eastern coastal area (EC), middle and upper reaches of the Pearl River (MUPR), middle and upper reaches of the Yangtze River (MUYR), middle reaches of the

Yellow River (MYR), northern coastal area (NC), northeast area (NE), Qinghai-Tibetan Plateau (QTP), southeast coastal area (SC), upper reaches of the Yellow River (UYR), and Xinjiang (XJ) (Li et al., 2019c). Regions of MYR, NC, NE, and UYR were considered as northern China, while EC, MUPR, MUYR, and SC were considered as southern China.

The National Ambient Air Quality Standard (NAAQS) released by the China Ministry of Ecology and Environment in 2012 defined limits for the daily maximum 8-hour average (MDA8) ozone concentration. The limit for MDA8 ozone concentration is 100 μg m^{-3} for Category I areas (e.g., natural protection zones, scenic resorts, and other areas needing special protection), and 160 μg m^{-3} for Category II areas (e.g., residential areas, mixed commercial and transportation residential areas, cultural areas, industrial areas, and rural areas). Daily observations of ozone concentrations in 366 Chinese cities in 2016 (Fig. S2a) were obtained from the China National Environmental Monitoring Center. The assessment benchmark of annual ground-level ozone pollution is based on the 90th percentile of the MDA8 ozone concentration throughout the year. It can be seen that O_3 concentrations in most cities of China exceed the limits of NAAQS in 2016 (Fig. 1a).

Previous studies have shown that precipitation, air temperature, relative humidity, sunshine duration, surface air pressure, and wind speed are the main factors impacting the ground-level ozone concentrations (Tang et al., 2012). Therefore, the daily meteorological data at 839 meteorological stations (Fig. S2b) from January 1, 2016 to December 31, 2016 were acquired from China Meteorological Data Network (http://data.cma.cn), including the daily accumulated precipitation (PE, mm), the air temperature at 2-m above the ground (TE, ℃), the relative humidity at 2-m above the ground (RH, %), the sunshine duration (SD, h), the surface air pressure (PS, hPa), and the wind speed at 10-m above the ground (WS, m s^{-1}). The spatial distributions of meteorological factors in China are described in detail by Li et al. (2019c). The monthly anthropogenic emissions of NOx, VOCs, and CO in 2016, which were the precursors of the ground ozone, were from the multi-resolution inventory for China (MEIC, http://www.meicmodel.org/). The highest emissions of anthropogenic precursors concentrated in regions of NC, MYR, EC, MUYR, and SC (Figs. 1b, 1c, and 1d). The MEIC dataset provides gridded emissions, including sectors of residential, industry, transportation, and power, from 2008 to present (Zhang et al., 2009) and has been used in numerous air pollution studies (Jin and Holloway, 2015).

2.2 GeoDetector *q* statistic

This study adopted the GeoDetector *q* statistic to quantify the influences of meteorological and anthropogenic precursor emissions and their interactions on the ground-level ozone concentrations in China. GeoDetector *q* statistic is a spatial variance analysis model that can be used to assess non-linear associations between the potential factor and target geographic phenomena (Wang et al., 2010; Wang et al., 2016; Wang and Xu, 2017). The core of the underlying assumption of the model is that if an *X* (explanatory variable) causes *Y* (explained variable), then their spatial distribution is consistent. Compared to the commonly used traditional linear methods, GeoDetector *q* statistic can handle categorical explanatory variables, detect the dominant driving factor, and investigate the interactive effect between two *X* variables on *Y* without the restriction of linearity assumption and with immunity to the collinearity.

The spatial association between *X* (e.g. meteorological and anthropogenic precursor emissions in this study) and *Y* (e.g. the ground-level ozone concentrations in this study) can be measured by the *q* statistic, which can be defined as:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h {\sigma_h}^2}{N\sigma^2} = 1 - \frac{SSW}{SST}$$
$$SSW = \sum_{h=1}^{L} N_h {\sigma_h}^2 \qquad (1)$$
$$SST = N\sigma^2$$

where $h = 1, \ldots, L$ is the categories of factor *X*. N_h and N are the number of samples in category *h* and across the entire study region, respectively. *SSW* and *SST* are the sum of variance and global variance in category *h* and over the whole study region, respectively. ${\sigma_h}^2$ and σ^2 are the variance of samples in *h* and the global variance of *Y*, respectively, in the whole study region. The interval of *q* is [0, 1], which means that factor *X* explains $q \times 100\%$ of the ground-level ozone concentrations. The larger the *q* value, the stronger the non-linear association with regard to ozone concentrations. If the spatial distribution of ozone concentrations is completely determined by a factor *X*, the *q* value is 1, and if ozone concentrations and a factor *X* have no spatial association with each other, the *q* value is 0.

The interactive effect of two *X* factors on ground ozone concentrations also can be quantified by the *q* statistic. This index can be used to assess the interactive effect between two *X* variables by comparing the *q* values of two *X* variables with the *q* values of a single *X* variable. The interaction types between two *X* variables are described by Wang et al. (2016). To clarify the positive or negative effects of impacting factors on O_3 concentrations, we also analyzed correlations between ground-level O_3 concentrations and influencing factors at national and regional scales.

3 Results

3.1 Impacts on national ozone concentrations

There were large annual and seasonal variations in the impacts of driving factors on O_3 concentrations at the national scale (Fig. 2a). Meteorological conditions were the major driving factors in the generation of the ground-level O_3 throughout the whole year in urban areas of China (Fig. 2a). The temperature was the dominant factor (q = 0.40) and had positive effects on the O_3 concentration at the annual time scale (Fig. 2), followed by SD (q = 0.25) and the PE (q = 0.17) and show positive and negative impacts on O_3 concentrations, respectively.

The dominant factors impacting O_3 concentration in spring were meteorological factors, such as SD (q = 0.26), RH (q = 0.18), and TE (q = 0.15) (Fig. 2a). In summer, the meteorological conditions and APE showed similar impacts on O_3 concentrations. The two dominant factors in summer were RH (q = 0.29) and PE (q = 0.21). The q values of NOx, VOC, and CO in summer were 0.19, 0.13, and 0.12, respectively. This indicated that APE in summer played important roles in the O_3 generation in China. Similar to spring, in autumn, meteorological conditions were the major driving factors in the O_3 generation, and the primary impacting factor was temperature (q = 0.48). In winter, however, meteorological conditions and APE had comparable effects on O_3 concentrations. In that season, the dominant meteorological and anthropogenic factors were TE (q = 0.15) and CO (q = 0.12), respectively. SD and TE were positively correlated with O_3 concentrations across all the four seasons, but RH and PE had negative effects on O_3 concentrations in both spring and summer (Fig. 1b). APE shows positive impacts on the ground-level O_3 in spring, summer, and autumn, especially in summer, whereas it showed negative effects in winter.

3.2 Impacts on regional ozone concentrations

Regional and seasonal disparities were identified in the impacts of meteorological conditions and APE on ozone concentrations in China (Fig. 3). Generally, meteorological conditions were the primary influencing factors in all the ten regions. TE and SD were dominant driving factors in Northern and Southern China, respectively, throughout the whole year.

Similar to the annual time scale, meteorological conditions were also major factors impacting O_3 generation in spring (Fig. 3). The dominant meteorological factor was TE in northern China, and SD in regions of MUYR, MUPR, and EC. The dominant influencing factor in spring was RH (q = 0.37) in the SC region. In summer, SD was the dominant factor in most regions, including UYR, NC, MYR, MUYR, MUPR, and EC. However, the three precursor emissions were major drivers in the O_3 generation in NE, followed by TE. TE was the dominant driving factor for the O_3 concentration in autumn in regions of NC, NE, UYR, XJ, MYR, and MUYR, but the dominant factor was SD in regions of MUPR, SC, and EC. In winter, SD was the dominant influencing factor in most regions except for UYR, XJ, and QTP.

Figure S3 shows regional variations in correlations between the ground-level ozone concentrations and influencing factors. Both annual and seasonal TE and SD had positive impacts on O_3 concentrations in all regions, but PE and RH showed negative effects in most regions. APE can enhance O_3 generations in most regions, but it showed negative impacts on O_3 concentrations in XJ throughout the whole year and some regions in winter such as MUYR, MYR, NC, QTP, and UYR.

3.3 Interactive effects of driving factors

In total, 36 pairs of interactions between the nine factors were detected. Figure 4 shows the *q* value of any two influencing factors and the *q* value of the interaction between two factors. The interactions of SD∩TE, SD∩WS, PS∩TE, and PE∩TE are bivariate enhancements and the interactions between the remaining factors belong to the nonlinear enhancements (Fig. 4). The interaction between TE and RH (q = 0.66) was the strongest among all influencing factors. In the interaction between meteorological factors and precursor emission factors, the value of *q*(NO∩TE) (NO denotes NOx) was the largest (q = 0.47), indicating that the interaction between NOx and TE is the strongest. There were large seasonal variations in the interactive effects between the potential influencing factors (Fig. S4). Figure S4 shows that interactions between meteorological conditions played leading roles in ozone production in spring, autumn, and winter. The interaction *q* value between TE and SD was the largest among all the interactions. However, the largest interaction *q* value was between VOCs and RH in summer.

Figure 5 shows that there were large regional differences in interaction *q* values of impacting factors (the top 15 interaction *q* values are listed for each region). The interactive effects of meteorological factors were strongest among all the interactions in most regions, such as UYR, NC, MYR, MUYR, SC, and EC (Fig. 5). The leading interactive effects were between APE and meteorological conditions in regions of MUPR (NO ∩ SD), NE (VO ∩ TE) (VO denotes VOCs), and XJ (NO ∩ TE). Generally, the interactions between APE and TE played a particularly important role in northern China, while APE ∩ SD interaction played an important role in southern China. Figures S5-S8 show the seasonal interaction *q* values between potential impacting factors over the ten regions, demonstrating that there were large spatial and seasonal variations in the interactive effects on O_3 generation.

4 Discussion

This study found that the effects of meteorological factors and anthropogenic precursors and their interactions on the ground-level ozone concentrations significantly varied with seasons and regions across China. This is ascribed to the spatial and temporal disparities in precursors, meteorological conditions, and photochemical reactions. These should be the main reasons for the spatial and temporal differences in the ground-level ozone concentrations not only in China, but also throughout the world (Wang et al., 2017b; Wang et al., 2018b; Chen et al., 2019; Maji et al., 2019).

At the national scale, meteorological conditions were primary impacting factors throughout the whole year, which is consistent with numerous previous results that the meteorological factors play leading roles in the production of the ground-level ozone (Cheng et al., 2019; Ding et al., 2019; Chen et al., 2020; Han et al., 2020). However, the main drivers of ozone formation varied significantly across the four seasons. The influences of meteorological conditions on ground-level ozone were stronger during spring and autumn than in summer and winter. These findings could also confirm previous results that changes in aerosol chemistry and photolysis rates caused by the reduction of particulate matter has great impacts on hydroperoxyl radicals and thus significantly influences the ozone production (Li et al., 2019a). The higher emissions of biogenic NOx and VOCs may be the main drivers of the growing ozone pollution during summer under the high air temperature and long sunshine duration and generally stable anthropogenic emissions across seasons (Wang et al., 2008; Wang et al., 2018a; Chen et al., 2019). In winter, the precursors concentrations were highest, but the ozone concentration was lowest (Cheng et al., 2018b). The primary impacting factors were TE and CO in wintertime, because high CO concentrations can significantly change the oxidation capacity of the atmosphere and low temperature and radiation can reduce the photochemical reaction ability compared to other seasons (Wang et al., 2015;). Moreover, the titration of the nitric oxide is another mechanism of ozone destruction in wintertime (Yang et al., 2019).

We found that TE and SD were the main drivers of ozone concentrations with positive effects in most regions of northern (NC, NE, UYR, XJ, MYR, and MUYR) and southern (MUPR, SC, and EC) China in seasons of autumn and spring, respectively. In summer and winter, the main driving factor was SD in most regions. This is similar to previous studies which have found that TE and SD are the most important and positively driving factors affecting ozone concentrations (Camalier et al., 2007; Chen et al., 2020; Han, et al., 2020). This is due to the high temperature and low relative humidity in northern China (Li et al., 2019c), which provides ideal meteorological conditions for accelerating the photochemical reactions that produce ozone (Otero et al. 2016; Li et al., 2019a), thereby increasing the ozone concentration. In the SC region, the dominant impacting factor was RH in spring and summer. This is because RH in SC was higher than in other regions (Li et al., 2019c). As higher RH is frequently associated with greater atmospheric instability and cloud abundance, the photochemical reactions could be slowed and thus the ground ozone would be depleted (Camalier et al., 2007; Chen et al., 2020). Moreover, the increasing RH can greatly reduce the ozone concentration by possible precipitation scavenging, reduction of photochemical production efficiency, decrease in oxygen atoms, and increase in hydroxyl radicals (OH) (Jia and Xu, 2014; Gao et al., 2018; Yu, 2019).

Numerous studies have reported that APE is also important factors affecting ozone concentrations (Cheng et al., 2018b; Li et al., 2019a; Wang et al., 2019). This study found that the influence of precursor emissions on ozone concentrations in summertime is stronger than in other seasons at the national scale and in most regions of northern China. In summer, APE is the dominant impacting factor of ozone formation due to the high precursor emissions and meteorological conditions suitable for ozone generation. In cities of QTP, PS was the primary factor impacting ground ozone concentrations during summer, autumn, and winter. Given the QTP's high elevation, PS gradient might result in some exchanges between stratosphere and troposphere, which could contribute to tropospheric O_3 concentrations (Lin et al., 2015; Xu et al., 2016).

Interaction detectors reveal the effects of interactions between influencing factors on ozone concentrations. We found that most interactions between impacting factors belong to the nonlinear enhancement type, indicating that these interactions clearly enhance ozone concentrations. The interactions between meteorological factors and anthropogenic precursor emissions play a leading role in summer. This may be due to the higher temperature in summer, which is conducive to the accelerated photochemical reaction between the precursors, resulting in an increase in the ground-level ozone concentration. The dominated interaction between anthropogenic precursor emissions and meteorological factors was between APE and SD over most regions in summer. This is due to the longer sunshine duration in summertime, which can provide suitable conditions for photochemical reactions. In southern China, interactions between APE and factors of RH and SD are dominant in spring and winter. This dominance may be due to the high precipitation and relative humidity and shorter sunshine hours in Southern China (Li et al., 2019c).

While important results were identified in this study, there were some limitations need to be improved and addressed in the future research. First, our results still have some uncertainties due to the uncertainty of MEIC emission inventory. Second, we did not consider other unavailable meteorological factors that can affect ground-level O_3 concentrations such as planetary boundary layer height and total cloud area fraction. Third, the land use, socioeconomic factors, topography, and elevation were also not included to quantify their effects on ground-level ozone concentrations. In order to develop more accurate control measure for the abatement of the O_3 pollution, it is essential to quantify the contribution of each sector's APE to O_3 concentrations in the future. In addition, the results of this study need to be validated and applied in the development of ground-level ozone control strategies by using the atmospheric chemical transport model.

5 Conclusions

Results of this study showed large regional and seasonal variations in the effects of meteorological and anthropogenic factors and their interactions on ground-level ozone concentrations throughout China. At both the national and regional scales, meteorological conditions are the dominant drivers of ozone production. At the seasonal time scale, for all seasons, SD and RH are the main drivers of ground-level ozone concentrations in southern China while TE is the major driver in northern China. However, anthropogenic precursors are the dominant factors in NE during summer. Interactions between all influencing factors enhance ozone concentrations. The interaction between meteorological factors and anthropogenic precursors has a stronger impact in summer than in the other three seasons.

Due to the complicated formation mechanisms and interactions between various factors of meteorology and ozone precursors, it remains challenging to understand the relative importance of potential impacting factors and their interactions in the ground-level ozone generation. This study comprehensively quantifies the influences of meteorological conditions and anthropogenic precursors and their interactions on ground-level ozone concentrations. Considering the difficulty in understanding quantitatively the association and the interaction between ozone and its impacting factors, these findings could help us understand the mechanism of ozone pollution, can help scientists improve the performance of ozone prediction models, and help government entities devise measures to manage ozone pollution.

Acknowledgements

This study was financially supported by the Natural Science Foundation of China (41401107) and the Basic Frontier and Technology Research Project of Henan Province, China (162300410132).

References

Bonn, B., von Schneidemesser, E., Butler, T., Churkina, G., Ehlers, C., Grote, R., Klemp, D., Nothard, R., Schäfer, K., von Stülpnagel, A., Kerschbaumer, A., Yousefpour, R., Fountoukis, C., Lawrence, M., 2018. Impact of vegetative emissions on urban ozone and biogenic secondary organic aerosol: Box model study for Berlin, Germany. J. Clean. Prod., 176, 827-841. https://doi.org/10.1016/j.jclepro.2017.12.164

Camalier, L., Cox, W., Dolwick, P., 2007. The effects of meteorology on ozone in urban areas and their use in assessing ozone trends. Atmos. Environ. 41, 7127-7137. https://doi.org/10.1016/j.atmosenv.2007.04.061

Chen, Z., Li, R., Chen, D., Zhuang, Y., Gao, B., Yang, L., Li, M., 2020. Understanding the causal influence of major meteorological factors on ground ozone concentrations across China. J. Clean. Prod. 242, 118498. https://doi.org/10.1016/j.jclepro.2019.118498

Chen, Z., Cai, J., Gao, B., Xu, B., Dai, S., He, B., Xie, X., 2017. Detecting the causality influence of individual meteorological factors on local $PM_{2.5}$ concentration in the

Jing-Jin-Ji region. Sci. Rep.-UK 7, 40735. https://doi.org/10.1038/srep40735

Chen, Z., Zhuang, Y., Xie, X., Chen, D., Cheng, N., Yang, L., Li, R., 2019. Understanding long-term variations of meteorological influences on ground ozone concentrations in Beijing during 2006-2016. Environ. Pollut. 245, 29-37. https://doi.org/10.1016/j.envpol.2018.10.117

Cheng, L., Wang, S., Gong, Z., Li, H., Yang, Q., Wang, Y., 2018a. Regionalization based on spatial and seasonal variation in ground-level ozone concentrations across China. J. Environ. Sci.-China, 67, 179-190. https://doi.org/10.1016/j.jes.2017.08.011

Cheng, N., Li, R., Xu, C., Chen, Z., Chen, D., Meng, F., Cheng, B., Ma, Z., Zhuang, Y., He, B., Gao, B., 2019. Ground ozone variations at an urban and a rural station in Beijing from 2006 to 2017: Trend, meteorological influences and formation regimes. J. Clean. Prod. 235, 11-20. https://doi.org/10.1016/j.jclepro.2019.06.204

Cheng, N., Chen, Z., Sun, F., Sun, R., Dong, X., Xie, X., Xu, C., 2018b. Ground ozone concentrations over Beijing from 2004 to 2015: Variation patterns, indicative precursors and effects of emission-reduction. Environ. Pollut. 237, 262-274. https://doi.org/10.1016/j.envpol.2018.02.051

Ding, D., Xing, J., Wang, S., Chang, X., Hao, J., 2019. Impacts of emissions and meteorological changes on China’s ozone pollution in the warm seasons of 2013 and 2017. Front. Env. Sci. Eng. 13, 76. https://doi.org/ 10.1007/s11783-019-1160-1

Feng, Z., Hu, E., Wang, X., Jiang, L., Liu, X., 2015. Ground-level O_3 pollution and its impacts on food crops in China: A review. Environ. Pollut. 199, 42-48. https://doi.org/10.1016/j.envpol.2015.01.016

Fu, T.M., Jacob, D.J., Palmer, P.I., Chance, K., Wang, Y.X., Barletta, B., Pilling, M.J., 2007. Space-based formaldehyde measurements as constraints on volatile organic compound emissions in east and south Asia and implications for ozone. J. Geophys. Res. Atmos. 112, 1-15. https://doi.org/10.1029/2006jd007853

Gao, F., Calatayud, V., García-Breijo, F., Reig-Armiñana, J., Feng, Z., 2016. Effects of elevated ozone on physiological, anatomical and ultrastructural characteristics of four common urban tree species in China. Ecol. Indic. 67, 367-379. https://doi.org/10.1016/j.ecolind.2016.03.012

Gao, M., Yin, L., Ning, J., 2018. Artificial neural network model for ozone concentration estimation and Monte Carlo analysis. Atmos. Environ. 184, 129-139. https://doi.org/10.1016/j.atmosenv.2018.03.027

Han, H., Liu, J., Shu, L., Wang, T., Yuan, H., 2020. Local and synoptic meteorological influences on daily variability of summertime surface ozone in eastern China. Atmos. Chem. Phys. 20, 203-222. https://doi.org/10.5194/acp-20-203-2020

Jia, L., Xu, Y., 2014. Effects of relative humidity on ozone and secondary organic aerosol formation from the photooxidation of benzene and ethylbenzene. Aerosol Sci. Technol. 48, 1-12. https://doi.org/10.1080/02786826.2013.847269

Li, K., Chen, L., Ying, F., White, S. J., Jang, C., Wu, X., Cen, K., 2017. Meteorological and chemical impacts on ozone formation: A case study in Hangzhou, China. Atmos. Res. 196, 40-52. https://doi.org/10.1016/j.atmosres.2017.06.003

Li, K., Jacob, D.J., Liao, H., Shen, L., Zhang, Q., Bates, K.H., 2019a. Anthropogenic drivers of 2013-2017 trends in summer surface ozone in China. P. Natl. Acad. Sci. USA. 116, 422-427. https://doi.org/10.1073/pnas.1812168116

Li, M., Song, Y., Mao, Z., Liu, M., Huang, X., 2016. Impacts of thermal circulations induced by urbanization on ozone formation in the Pearl River Delta region, China. Atmos. Environ. 127, 382-392. https://doi.org/10.1016/j.atmosenv.2015.10.075

Li, M., Zhang, Q., Zheng, B., Tong, D., Lei, Y., Liu, F., Hong, C., Kang, S., Yan, L., Zhang, Y., Bo, Y., Su, H., Cheng, Y., He, K., 2019b. Persistent growth of anthropogenic non-methane volatile organic compound (NMVOC) emissions in China during 1990–2017: drivers, speciation and ozone formation potential. Atmos. Chem. Phys. 19, 8897-8913.

Li, P., De Marco, A., Feng, Z., Anav, A., Zhou, D., Paoletti, E., 2018b. Nationwide ground-level ozone measurements in China suggest serious risks to forests. Environ. Pollut. 237, 803-813. https://doi.org/10.1016/j.envpol.2017.11.002

Li, X., Song, H., Zhai, S., Lu, S., Kong, Y., Xia, H., Zhao, H., 2019c. Particulate matter pollution in Chinese cities: Areal-temporal variations and their relationships with meteorological conditions (2015–2017). Environ. Pollut. 246, 11-18. https://doi.org/10.1016/j.envpol.2018.11.103

Lin, W., Xu, X., Zheng, X., Dawa, J., Baima, C., Ma, J. 2015. Two-year measurements of surface ozone at Dangxiong, a remote highland site in the Tibetan Plateau. J. Environ. Sci. 31, 133-145. https://doi.org/10.1016/j.jes.2014.10.022

Liu, X.H., Zhang, Y., Xing, J., Zhang, Q., Wang, K., Streets, D.G., Jang, C., Wang W.X., Hao, J.M., 2010. Understanding of regional air pollution over China using CMAQ, part II. Process analysis and sensitivity of ozone and particulate matter to precursor emissions.

Atmos. Environ. 44, 3719-3727. https://doi.org/10.1016/j.atmosenv.2010.03.036

Lu, X., Hong, J., Zhang, L., Cooper, O.R., Schultz, M.G., Xu, X., Want, T., Gao, M., Zhao, Y., Zhang, Y., 2018. Severe surface ozone pollution in China: A global perspective. Environ. Sci. Tech. Let. 5, 487-494. https://doi.org/10.1021/acs.estlett.8b00366

Lu, X., Zhang, L., Chen, Y., Zhou, M., Zheng, B., Li, K., Liu, Y., Lin, J., Fu, T., Zhang, Q., 2019. Exploring 2016–2017 surface ozone pollution over China: source contributions and meteorological influences. Atmospheric Chemistry and Physics, 19(12), 8339-8361. https://doi.org/10.5194/acp-19-8339-2019

Maji, K.J., Ye, W.F., Arora, M., Nagendra, S.S., 2019. Ozone pollution in Chinese cities: Assessment of seasonal variation, health effects and economic burden. Environ. Pollut. 247, 792-801. https://doi.org/10.1016/j.envpol.2019.01.049

Martins, L.D., de Fátima Andrade, M., 2008. Ozone formation potentials of volatile organic compounds and ozone sensitivity to their emission in the megacity of São Paulo, Brazil. Water Air Soil Poll. 195, 201-213. https://doi.org/10.1007/s11270-008-9740-x

Mills, G., Harmens, H., Wagg, S., Sharps, K., Hayes, F., Fowler, D., Davies, B., 2016. Ozone impacts on vegetation in a nitrogen enriched and changing climate. Environ. Pollut. 208, 898-908. https://doi.org/10.1016/j.envpol.2015.09.038

Moura, B.B., Alves, E.S., Marabesi, M.A., De Souza, S.R., Schaub, M., Vollenweider, P., 2018. Ozone affects leaf physiology and causes injury to foliage of native tree species from the tropical Atlantic Forest of southern Brazil. Sci. Total. Environ. 610, 912-925. https://doi.org/10.1016/j.scitotenv.2017.08.130

Otero, N., Sillmann, J., Schnell, J.L., Rust, H.W., Butler, T., 2016. Synoptic and meteorological drivers of extreme ozone concentrations over Europe. Environ. Res. Lett. 11, 024005. https://doi.org/10.1088/1748-9326/11/2/024005

Pearce, J.L., Beringer, J., Nicholls, N., Hyndman, R.J., Tapper, N.J., 2011. Quantifying the influence of local meteorology on air quality using generalized additive models. Atmos. Environ. 45, 1328-1336. https://doi.org/10.1016/j.atmosenv.2010.11.051

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, 807-816. https://doi.org/10.1016/j.scitotenv.2017.03.056

Sanchez-Ccoyllo, O.R., Ynoue, R.Y., Martins, L.D., de Fátima Andrade, M., 2006. Impacts of ozone precursor limitation and meteorological variables on ozone concentration in Sao Paulo, Brazil. Atmos. Environ. 40, 552-562. https://doi.org/10.1016/j.atmosenv.2006.04.069

Sharma, A., Mandal, T.K., Sharma, S.K., Shukla, D.K., Singh, S., 2017. Relationships of surface ozone with its precursors, particulate matter and meteorology over Delhi. J. Atmos. Chem. 74, 451-474. https://doi.org/10.1007/s10874-016-9351-7

Tai, A.P.K., Martin, M.V., Heald, C.L., 2014. Threat to future global food security from climate change and ozone air pollution. Nat. Clim. Change. 4, 817-821. https://doi.org/10.1038/nclimate2317

Tang, G., Wang, Y., Li, X., Ji, D., Hsu, S., Gao, X., 2012. Spatial-temporal variations in surface ozone in Northern China as observed during 2009 – 2010 and possible implications for future air quality control strategies. Atmos. Chem. Phys. 12, 2757-2776. https://doi.org/10.5194/acp-12-2757-2012

Tong, L., Zhang, H., Yu, J., He, M., Xu, N., Zhang, J., Qian, F., Feng, J., Xiao, H., 2017. Characteristics of surface ozone and nitrogen oxides at urban, suburban and rural sites in Ningbo, China. Atmos. Res. 187, 57-68. https://doi.org/10.1016/j.atmosres.2016.12.006

Xu, W., Lin, W., Xu, X., Tang, J., Huang, J., Wu, H., Zhang, X. 2016. Long-term trends of surface ozone and its influencing factors at the Mt Waliguan GAW station, China－Part 1: Overall trends and characteristics. Atmos. Chem. Phys, 16, 6191-6205. https://doi.org/10.5194/acp-16-6191-2016

Wang, H., Wu, Q., Liu, H., Wang, Y., Cheng, H., Wang, R., Wang, L., Xiao, H., Yang, X., 2018a. Sensitivity of biogenic volatile organic compound emissions to leaf area index and land cover in Beijing. Atmos. Chem. Phys. 18, 9583-9596. https://doi.org/10.5194/acp-18-9583-2018

Wang, J., Li, X., Christakos, G., Liao, Y., Zhang, T., Gu, X., Zheng, X., 2010. Geographical detectors-based health risk assessment and its application in the neural tube defects study of the Heshun region, China. Int. J. Geogr. Inf. Sci. 24, 107-127. https://doi.org/10.1080/13658810802443457

Wang, J.F., Zhang, T.L., Fu, B.J., 2016. A measure of spatial stratified heterogeneity. Ecol. Indic. 67, 250-256. https://doi.org/10.1016/j.ecolind.2016.02.052

Wang, P., Guo, H., Hu, J., Kota, S. H., Ying, Q., Zhang, H., 2019. Responses of $PM_{2.5}$ and O_3 concentrations to changes of meteorology and emissions in China. Sci. Total. Environ. 662, 297-306. https://doi.org/10.1016/j.scitotenv.2019.01.227

Wang, Q., Han, Z., Wang, T., Zhang, R., 2008. Impacts of biogenic emissions of VOC and NOx on tropospheric ozone during summertime in eastern China. Sci. Total Environ. 395, 41-49. https://doi.org/10.1016/j.scitotenv.2008.01.059

Wang, T., Xue, L., Brimblecombe, P., Lam, Y.F., Li, L., Zhang, L., 2017a. Ozone pollution in China: A review of concentrations, meteorological influences, chemical precursors, and effects. Sci. Total. Environ. 575, 1582-1596. https://doi.org/10.1016/j.scitotenv.2016.10.081

Wang, W., Ren, L., Zhang, Y., Chen, J., Liu, H., Bao, L., Tang, D., 2008. Aircraft measurements of gaseous pollutants and particulate matter over Pearl River Delta in China. Atmos. Environ. 42, 6187-6202. https://doi.org/10.1016/j.atmosenv.2008.06.001

Wang, W.N., Cheng, T.H., Gu, X.F., Chen, H., Guo, H., Wang, Y., Bao, F.W., Shi, S.Y., Xu, B.R., Zuo, X., Meng, C., Zhang, X.C., 2017b. Assessing spatial and temporal patterns of observed ground-level ozone in China. Sci. Rep-UK. 7, 3651. https://doi.org/10.1038/s41598-017-03929-w

Wang, Y., Du, H., Xu, Y., Lu, D., Wang, X., Guo, Z., 2018b. Temporal and spatial variation relationship and influence factors on surface urban heat island and ozone pollution in the Yangtze River Delta, China. Sci. Total Environ. 631, 921-933. https://doi.org/10.1016/j.scitotenv.2018.03.050

Wang, Z., Li, Y., Chen, T., Zhang, D., Sun, F., Wei, Q., Dong, X., Sun, R., Huan, N., Pan, L. 2015. Ground-level ozone in urban Beijing over a 1-year period: Temporal variations and relationship to atmospheric oxidation. Atmos. Res. 164, 110-117. https://doi.org/10.1016/j.atmosres.2015.05.005

Wei, W., Cheng, S., Li, G., Wang, G., Wang, H., 2014. Characteristics of ozone and ozone precursors (VOCs and NOx) around a petroleum refinery in Beijing, China. J. Environ.

Sci.-China 26, 332-342. https://doi.org/10.1016/S1001-0742(13)60412-X

Yang, J., Liu, J., Han, S., Yao, Q., Cai, Z., 2019. Study of the meteorological influence on ozone in urban areas and their use in assessing ozone trends in all seasons from 2009 to 2015 in Tianjin, China. Meteorol. Atmos. Phys. 131, 1661-1675. https://doi.org/ 10.1007/s00703-019-00664-x

Yang, P., Zhang, Y., Wang, K., Doraiswamy, P., Cho, S.H., 2019. Health impacts and cost-benefit analyses of surface O_3 and $PM_{2.5}$ over the US under future climate and emission scenarios. Environ. Res. 178, 108687. https://doi.org/10.1016/j.envres.2019.108687

Yu, S., 2019. Fog geoengineering to abate local ozone pollution at ground level by enhancing air moisture. Environ. Chem. Lett. 17, 565-580. https://doi.org/10.1007/s10311-018-0809-5

Zhang, Q., Streets, D.G., Carmichael, G.R., He, K.B., Huo, H., Kannari, A., Klimont, Z., Park, I.S., Reddy, S., Fu, J.S., Chen, D., Duan L., Lei, Y., Wang, L.T., Yao, Z.L, 2009. Asian emissions in 2006 for the NASA INTEX-B mission. Atmos. Chem. Phys. 9, 5131-5153. https://doi.org/10.5194/acp-9-5131-2009

Zhang, R., Sarwar, G., Fung, J.C., Lau, A.K., 2013. Role of photoexcited nitrogen dioxide chemistry on ozone formation and emission control strategy over the Pearl River Delta, China. Atmos. Res. 132, 332-344. https://doi.org/10.1016/j.atmosres.2013.06.001

Zhang, Y.N., Xiang, Y.R., Chan, L.Y., Chan, C.Y., Sang, X.F., Wang, R., Fu, H.X., 2011. Procuring the regional urbanization and industrialization effect on ozone pollution in Pearl River Delta of Guangdong, China. Atmos. Environ. 45, 4898-4906.

https://doi.org/10.1016/j.atmosenv.2011.06.013

Zhao, W., Fan, S., Guo, H., Gao, B., Sun, J., Chen, L., 2016. Assessing the impact of local meteorological variables on surface ozone in Hong Kong during 2000–2015 using quantile and multiple line regression models. Atmos. Environ. 144, 182-193. https://doi.org/10.1016/j.atmosenv.2016.08.077

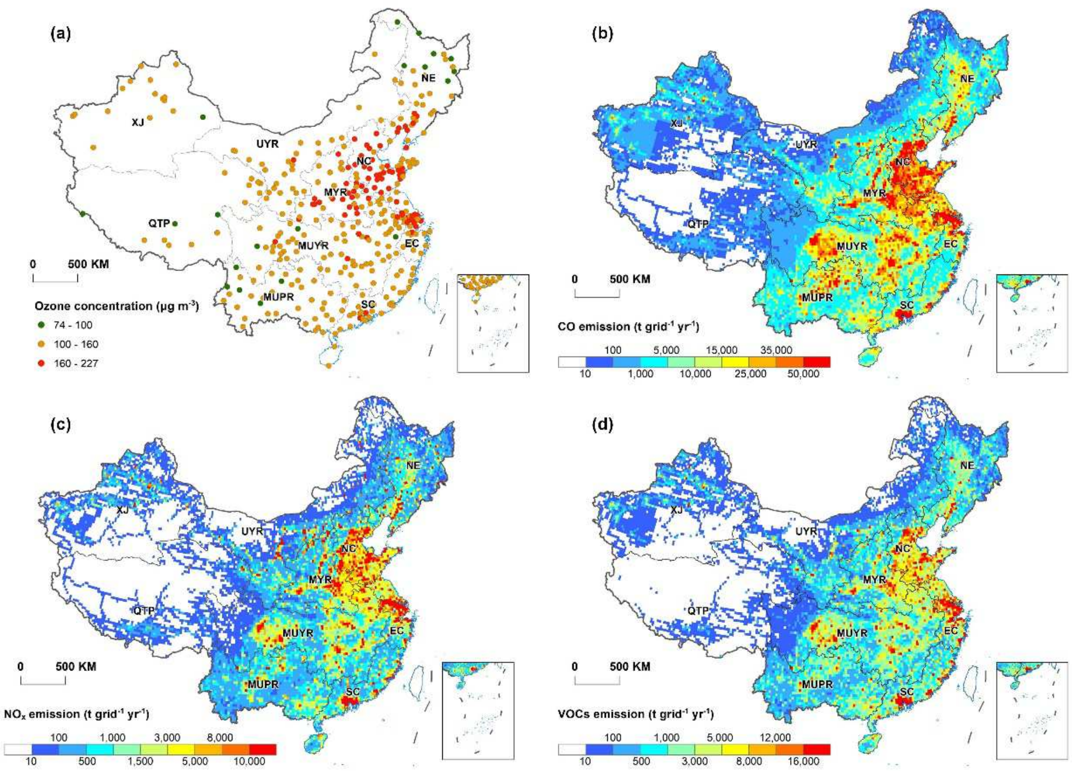


Fig. 1. Maps of 90th percentile of daily maximum 8-hour average O_3 concentrations (a), CO emissions (b), NOx emissions (c), and VOCs emissions (d) in China in 2016 with resolution of 0.25° × 0.25°.

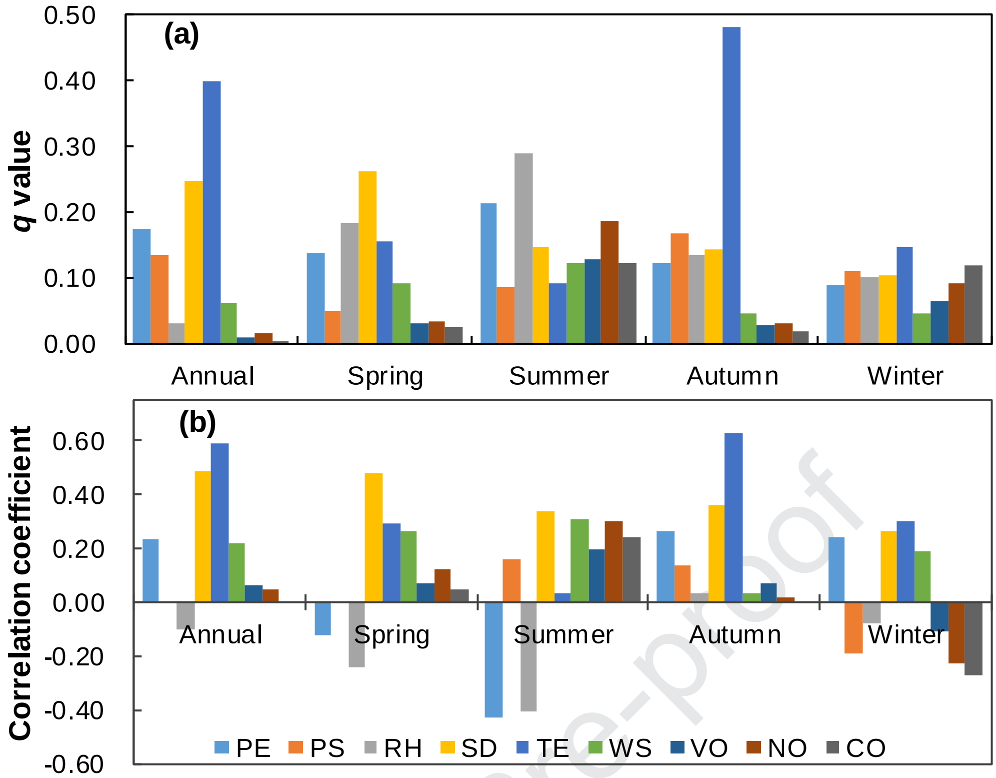


Fig. 2. Annual and seasonal *q* values (a) of driving factors for ozone concentrations and correlations (b) between ozone concentrations and impacting factors at the national scale (China). NO denotes NOx; VO denotes VOCs.

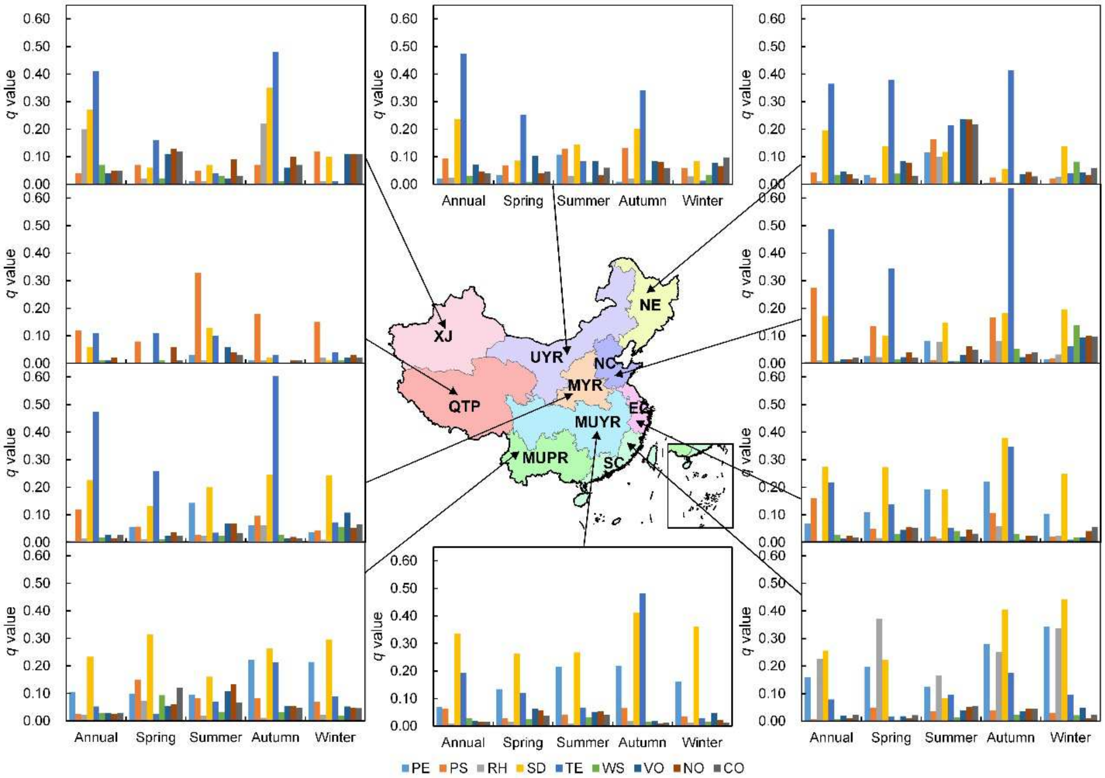


Fig. 3. Annual and seasonal *q* values of driving factors in 10 regions of China. NO denotes NOx; VO denotes VOCs.

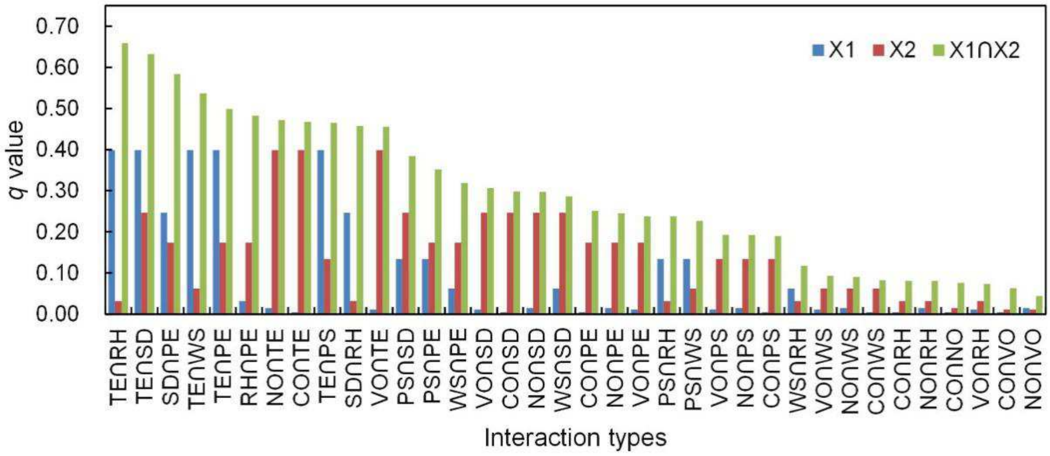


Fig. 4. Annual interactive *q* values and original *q* value of each pair of factors. Note that *X*1 donates the first factor, *X*2 donates the second factor, and *X*1∩*X*2 is the interaction between the two factors. For example, in the pair of (TE, RH), *X*1 donates TE, *X*2 donates RH, and *X*1∩*X*2 is the interaction between TE and RH. NO denotes NOx; VO denotes VOCs.

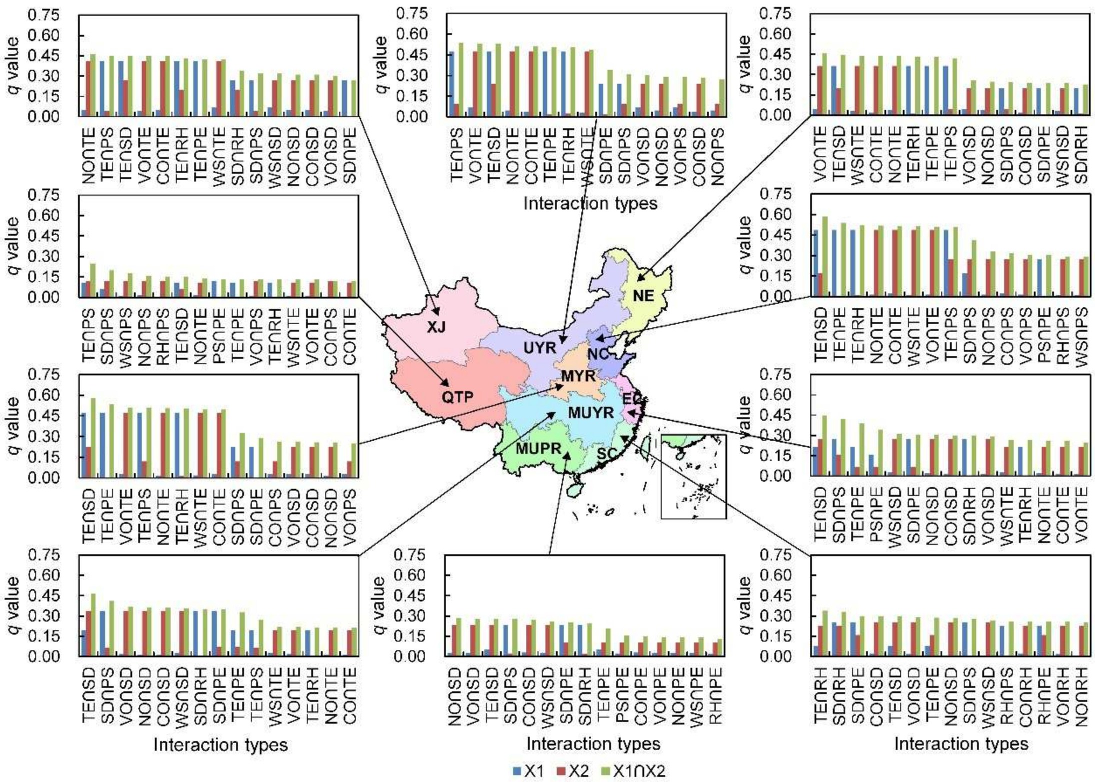


Fig. 5. Annual interaction *q* values between influencing factors over the 10 regions of China. NO denotes NOx; VO denotes VOCs.

Highlights

- Effects of meteorology and precursors on ozone had spatial-temporal variations.
- Meteorological conditions were dominant drivers of the ground ozone concentrations.
- Impacts of precursors on ozone were comparable to meteorology in summer and winter.
- Interactions between impacting factors had enhanced effects on ozone concentrations.

Author Statement

Pengfei Liu: Software, Writing-Original draft preparation; **Hongquan Song:** Conceptualization, Supervision, Writing-Review and Editing, Funding acquisition; **Tuanhui Wang:** Software, Visualization, Data Curation; **Feng Wang:** Data Curation, Investigation; **Xiaoyang Li:** Data Curation, Investigation; **Changhong Miao:** Investigation; **Haipeng Zhao:** Validation, Visualization.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: