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



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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 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.

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1. Introduction

Abbreviations: APE, anthropogenic precursor emissions; CO, carbon monoxide; EC, eastern coastal area; GeoDetector, geographical detector model; MDA8, daily maximum 8-h average; MEIC, multi-resolution inventory of China; MUPR, middle and upper reaches of the Pearl River; MUVR, 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; O₃, 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.

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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 (O₃) (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 O₃ pollution is mainly concentrated, especially in summertime, in the North China Plain, Huanghuaihai Plain, Central Yangtze River Plain, Pearl River Delta, and Sichuan Basin in China (Cheng et al., 2018a, b). The ground-level ozone pollution is a serious threat to human health (Bonn et al., 2018; Moura et al., 2018; Yang et al., 2019b) 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). 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-h average (MDA8) ozone concentration. The limit for MDA8 ozone concentration is 100 μ g m⁻³ for Category I areas (e.g., natural protection zones, scenic resorts, and other areas needing special protection), and 160 μ g 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 O₃ 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,°C), 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 (Fig. 1b, c, and d). 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.

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). 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.



Fig. 1. Maps of 90th percentile of daily maximum 8-h average O_3 concentrations (a) and of CO emissions (b), NOx emissions (c), and VOCs emissions (d) with resolution of $0.25^{\circ} \times 0.25^{\circ} \times in$ China in 2016.

The spatial association between X (e.g. meteorological factors 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:

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

$$SSW = \sum_{h=1}^{L} N_h \sigma_h^2$$

$$SST - N \sigma^2$$
(1)

where h = 1, ..., 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. σ_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 O₃ concentrations, we also analyzed correlations between ground-level O₃ 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 O₃ 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 O₃ concentrations. The two dominant factors in summer were RH (q = 0.29) and PE (q = 0.21). The q



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.

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 O₃ generation in China. Similar to spring, in autumn, meteorological conditions were the major driving factors in the O₃ generation, and the primary impacting factor was temperature (q = 0.48). In winter, however, meteorological conditions and APE had comparable effects on O₃ 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 O₃ concentrations across all the four seasons, but RH and PE had negative effects on O₃ concentrations in both spring and summer (Fig. 1b). APE shows positive impacts on the ground-level O₃ 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 O₃ 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 O₃ generation in NE, followed by TE. TE was the dominant driving factor for the O₃ 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 O₃ 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. Fig. 4 shows the *a* 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 $q(NO\cap TE)$ (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). Fig. 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.

Fig. 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 \cap SD), NE (VO \cap TE) (VO denotes VOCs), and XJ (NO \cap TE). Generally, the interactions between APE and TE played a particularly important role in northern China, while APE \cap SD interaction played an important role in southern China. Figs. 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 O₃ generation.

4. Discussion

This study found that the effects of meteorological factors and anthropogenic precursors and their interactions on the groundlevel 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



Fig. 3. Annual and seasonal q values of driving factors in ten 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 X1 donates the first factor, X2 donates the second factor, and $X1 \cap X2$ is the interaction between the two factors. For example, in the pair of (TE, RH), X1 donates TE, X2 donates RH, and $X1 \cap X2$ is the interaction between TE and RH. NO denotes NOX; VO denotes VOCs.

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., 2019a).

We found that TE and SD were the main drivers of ozone concentrations with positive effects in most regions of northern (NC, NE, UYR, and MYR) and southern (MUPR, MUYR, 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



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

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 O₃ 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 can help government entities devise measures to manage ozone pollution.

Declaration of competing interest

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.

CRediT authorship contribution statement

Pengfei Liu: Software, Writing - original draft. **Hongquan Song:** Conceptualization, Supervision, Writing - review & 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.

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Appendix A. Supplementary data

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