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RESEARCH ARTICLE

Urban 2D and 3D morphology and the pattern of ozone pollution: a 68-city study in China

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Abstract
Context Air pollution significantly impacts urban sustainable development and public health. Urban ozone pollution (UOP) is currently one of the most challenging tasks for urban air pollution control, and is possibly linked to urban morphology. However, the effect of urban two-dimensional (2D) (coverage or density, etc.) and three-dimensional (3D) (density + height, etc.) morphology on the UOP concentration remains unclear.
Objectives The objective of this study was to explore the influence of urban morphology on UOP concentration and provide useful information to control urban air pollutants.
Methods First, based on building height and remotely sensed UOP data from 68 Chinese cities, the general spatial pattern of urban 3D morphology and UOP was detected across different climate zones in China. Then, this study used variance decomposition to investigate the contribution of 2D and 3D urban morphology to UOP in China.
Results The study showed that China's urban morphology was dominated by Medium Rise & Medium Density (MRMD). Large cities had higher UOP levels in summer, especially for the urban morphology with Low Rise & High Density (LRHD). Further, UOP concentrations were substantially higher in

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the southern temperate zone than in other climatic zones. Anthropogenic factors (rather than natural factors) were always the dominant factors influencing UOP across different seasons; specifically, urban 2D and 3D morphology can explain 40% of UOP variation. The effects of urban 3D and 2D morphologies on UOP concentrations varied seasonally. Urban 2D morphology dominated in spring, whereas 3D morphology dominated in winter.

Conclusions Our study elucidates the effect of urban morphology on UOP and provides insights for sustainable urban development.

Keywords Ozone · Urban 3D morphology · Building height · Anthropogenic factor

Introduction

Urban air pollution is the most serious environmental problem faced by countries around the world, and has seriously impacted urban public health and sustainable social development (Ghasempour et al. 2021). Rapid urbanization has drastically exacerbated urban environmental problems such as air pollution (Strosnider et al. 2019; Hao et al. 2020). Urban ozone pollution (UOP) has become a serious environmental problem in many cities and poses a serious threat to the health of urban residents (Yazdi et al. 2019). The average surface UOP concentrations in the summer in major Chinese cities increased by approximately 20% in 2016–2017 compared to 2013–2014 (Xiao et al. 2018), and the percentage of days with ozone as the primary pollutant in some Chinese cities in 2017 was 43.1% (Ministry of Ecology and Environment of the People's Republic of China 2018). High UOP concentrations can cause asthma in children and hypertension in people who exercise in the open air (Gasana et al. 2012; Li et al. 2021a, b; Zhang et al. 2022b). An increase of 10 μg/m^3 in the average UOP concentration led to statistically significant increments of 0.42%, 0.44%, and 0.50% in nonaccidental, cardiovascular, and respiratory mortality, respectively (Yan et al. 2013). In the past five years, all air pollutants have sharply decreased in China, except for increasing UOP pollution (https://t.ynet.cn/baijia/33094433.html). Ozone has also become a challenging environmental problem because, in European and USA cities, O_3 is increasing more than at rural sites, while peak values are decreasing (Paoletti et al. 2014). Therefore, exploring the spatial patterns of UOP and its key drivers is crucial for understanding the formation of UOP, revisiting strategies for controlling air pollution and contributing to achieving urban sustainable development goals.

Many studies have focused on urban air pollutants, such as $PM_{2.5}$ and SO_2 (Lim et al. 2020; Ren and Ki 2020). Nevertheless, only a few studies have examined ozone, especially its formation mechanisms in cities (Guan et al. 2021). Some studies have attributed the increase in ozone concentrations to natural factors (such as temperature and humidity) (Ezimand and Kakroodi 2019; Chen et al. 2020; Guan et al. 2021). High temperatures accelerate ozone production, whereas precipitation and humidity reduce ozone concentration (Chen et al. 2022). High wind speeds accelerate ozone dispersion and are negatively correlated with ozone concentration, whereas low wind speeds cause ozone stagnation and sustained photochemistry and are positively correlated with ozone concentration (Wang et al. 2016). Therefore, natural factors may account for 89% of ozone concentration changes (Wang et al. 2011). However, anthropogenic factors can also impact ozone pollution (Wang et al. 2019), especially in cities (Paoletti 2009; Paoletti et al. 2014). Levels of urban electricity consumption, transportation, and secondary industries can also influence ozone concentrations by generating ozone precursors (Li et al. 2019; Liu et al. 2020; Xiang et al. 2020). Some studies have found that anthropogenic pollution can contribute 50% to severe ozone pollution events in eastern China (Li et al. 2017). Others highlight the risks of some plant-derived precursors, such as biogenic volatile organic compounds (BVOCs), possibly contributing to ozone pollution (Wang et al. 2022a). Therefore, the relative contributions of natural and human factors to ozone formation remain uncertain.

Urban areas are characterized by intense human activity (Zhao et al. 2018). Urban morphology including two-dimensional (2D) and three-dimensional (3D) building morphology, is a key anthropological factor (Zhu et al. 2019; Biljecki and Ito 2021; Wu et al. 2022). In fact, the 2D urban morphology form refers to the shape, size, and structure of urban areas in a flat surface (Millet et al. 2017; Yuan et al. 2017). For example, urban sprawl, land-use configuration, and fragmentary patterns were found to dramatically affect pollution concentrations, supported by evidence from the US, China, and Europe (Rodriguez et al. 2016; Tian et al. 2020; Li et al. 2021a, b).Urban sprawl and land-use type coverage or changes may affect ozone concentrations by influencing vehicle and industrial emissions (Ke et al. 2022). Changes in the density of the road network affect the lane layout, which in turn has an impact on ozone concentrations (Zhang et al. 2022a). Rapid urbanization also leads to the development of urban spatial morphology with obvious 3D characteristics, such as building height and volume, making the relationship between urban morphology and air quality more complex (Luan et al. 2019; Li et al. 2023). The 3D urban form can directly affect air circulation and urban pollutant dispersion. More compact cities may be affected by more severe air pollution (because of heat islands, sulfur dioxide, etc.) (Buccolieri et al. 2010; Hee-Sun and Mack 2014). However, compact cities have been shown to increase the use of urban public transport, which reduces vehicle emissions and thus affects ozone pollution (Ewing and Cervero 2010). Low-density and dispersed urban sprawl is thought to cause longer commutes, excessive automobile dependency, and traffic congestion (Zhao et al. 2010). In addition, urban compactness is linked to urban heat island effects, which may increase the demand for cooling energy, particularly in the summer, and promote the formation of ozone in many cases (Fallmann et al. 2016).There is also a close relationship between building height and ozone pollution, with taller buildings affecting the dispersion of ozone (Cai et al. 2022). Therefore, compared with 2D building morphology, urban 3D building morphology may better explain the changes in the levels of urban air pollutants (Ke et al. 2022). Through the current study, it was found that the influence of urban building factors on ozone mainly focuses on 2D morphology, and the influence of urban 3D morphology indicators on urban ozone concentration is still confusing, especially on a national scale and it is not clear whether seasonal changes affect the influence of building factors on urban ozone pollution.

Based on urban building height and remote-sensing UOP data from 68 major cities in China, we investigated the patterns and potential drivers of UOP. We assume that the UOP level depends on the urban 3D morphology of building height and density, irrespective of intercity differences. The specific objectives were to (1) detect the general spatial pattern of urban 3D morphology in China; (2) quantitatively investigate the spatiotemporal characteristics of UOP across different urban morphologies, different city sizes, and different climate zones; and (3) clarify the roles of natural and anthropogenic factors on ozone concentration change and further analyze in depth the contribution of urban 3D morphology to UOP variation. The current study will improve our understanding of the patterns and driving mechanisms of UOP and provide useful information for urban planners and designers to control urban air pollutants and enhance urban sustainability.

Methods

Study area

China has a vast territory, varied terrain, and a large range of latitudes with different types of temperate zones, including nine temperate zones: the highland climate zone, northern temperate zone, central temperate zone, southern temperate zone, northern subtropical zone, central subtropical zone and southern subtropical zone, northern tropics zone and central tropics zone (Zhou et al. 2022) (Fig. 1). In addition, during the process of rapid urbanization, notable changes in urban morphology during urban built-up area expansion can impact urban ozone concentrations. Urban ozone pollution causes losses of approximately 1.27% of the GDP in China, and some studies also predict that, if not controlled, the losses caused by ozone pollution will reach 2.27% of the GDP by 2030 (Xie et al. 2019). Therefore, it is necessary to explore the factors affecting the changes in ozone concentrations in urban areas.

In this study, 68 major cities were selected, including four municipalities directly under the central government, 25 capital cities of provincial or autonomous regions, and 39 prefecture-level cities (Fig. 1). These cities were selected by considering the uniformity in the distribution of cities in geographical space and different urbanization degrees and can comprehensively reflect the common conditions of Chinese cities.

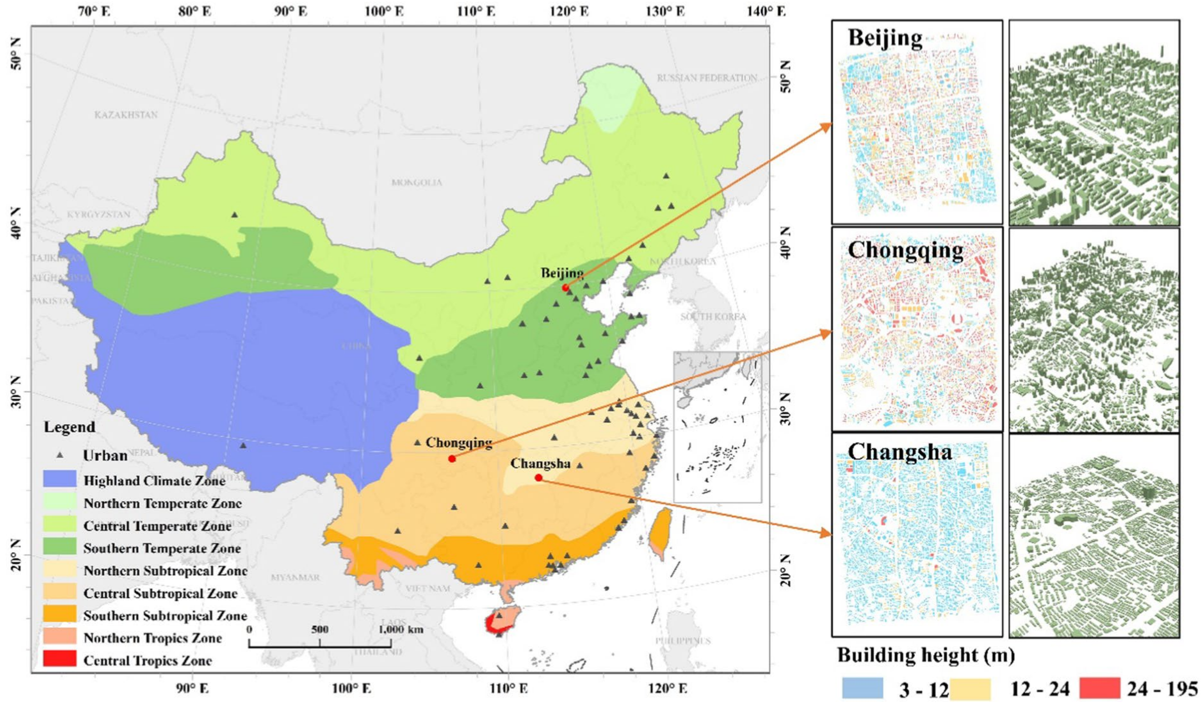


Fig. 1 Study area

Research framework

Our research framework consists of the following steps: (1) We obtained the urban impervious surface data to calculate the urban impervious surface BI intensity map, and then identified the urban boundary for the study area in each city. (2) Based on the building data provided by Amap, including building height and area, we estimated the urban form in the study area, and mapped the urban 3D morphology of the 68 cities. (3) Based on the urban ozone concentration data from 2017, we detected the changing patterns of urban ozone concentration across different climatic zones, different urban morphologies, and different seasons in China. (4) Based on the variance decomposition analysis and multiple linear regression models, we further explored the relationship between urban 3D and 2D morphology indicators and urban ozone concentration, and calculated the explanation rate of natural and anthropogenic factors on urban ozone concentration changes (Fig. 2).

Data acquisition

Urban boundary: Built-up intensity (BI) maps were first generated using impervious surface data to extract the urban areas of each city. Areas with a BI value of 50% were selected as high intensity building sites and clustered together to form a compact urban area (Yu et al. 2021). Areas with no 3D building data or incomplete building data (e.g., the edges of the city) were excluded from the urban area because of limitations in the data sources.

Urban 2D and 3D morphology: Urban building data from 2017 were obtained using the online map service platform Amap (https://lbs.amap.com/), including the outline and total floor information of downtown buildings. The number of floors was multiplied by three to obtain the building height to analyze the urban 3D morphology (Cai et al. 2022). Urban 2D (building density or coverage, etc.) and 3D (height, volume, congestion, etc.) indicators were calculated based on the building-occupied area and building height; these indicators are commonly used in related studies and are representative (Table 1). To study urban morphology, we used high-resolution Google Earth images, as these data have been freely available. There are two indicators for urban morphological classification: average building height and building density, which reflect the intensity and pattern of buildings in 3D and 2D within the city. Building density is divided into three categories: low (0–0.15), medium (0.15–0.25), and high (> 0.25), and building heights are classified as low (3–12 m), medium (12–24 m), and high (> 24 m) (Cai et al. 2022). Based on the combination of these two factors, all cities in China can be divided into nine categories of urban morphology: High Rise & Low Density (HRLD), High Rise & Medium Density (HRMD), High Rise & High Density (HRHD), Medium Rise & Low Density (MRLD), Medium Rise & Medium Density (MRMD), Medium Rise & High Density (MRHD), Low Rise & Low Density (LRLD), Low Rise & Medium Density (LRMD), and Low Rise & High Density (LRHD) (Fig. 3).

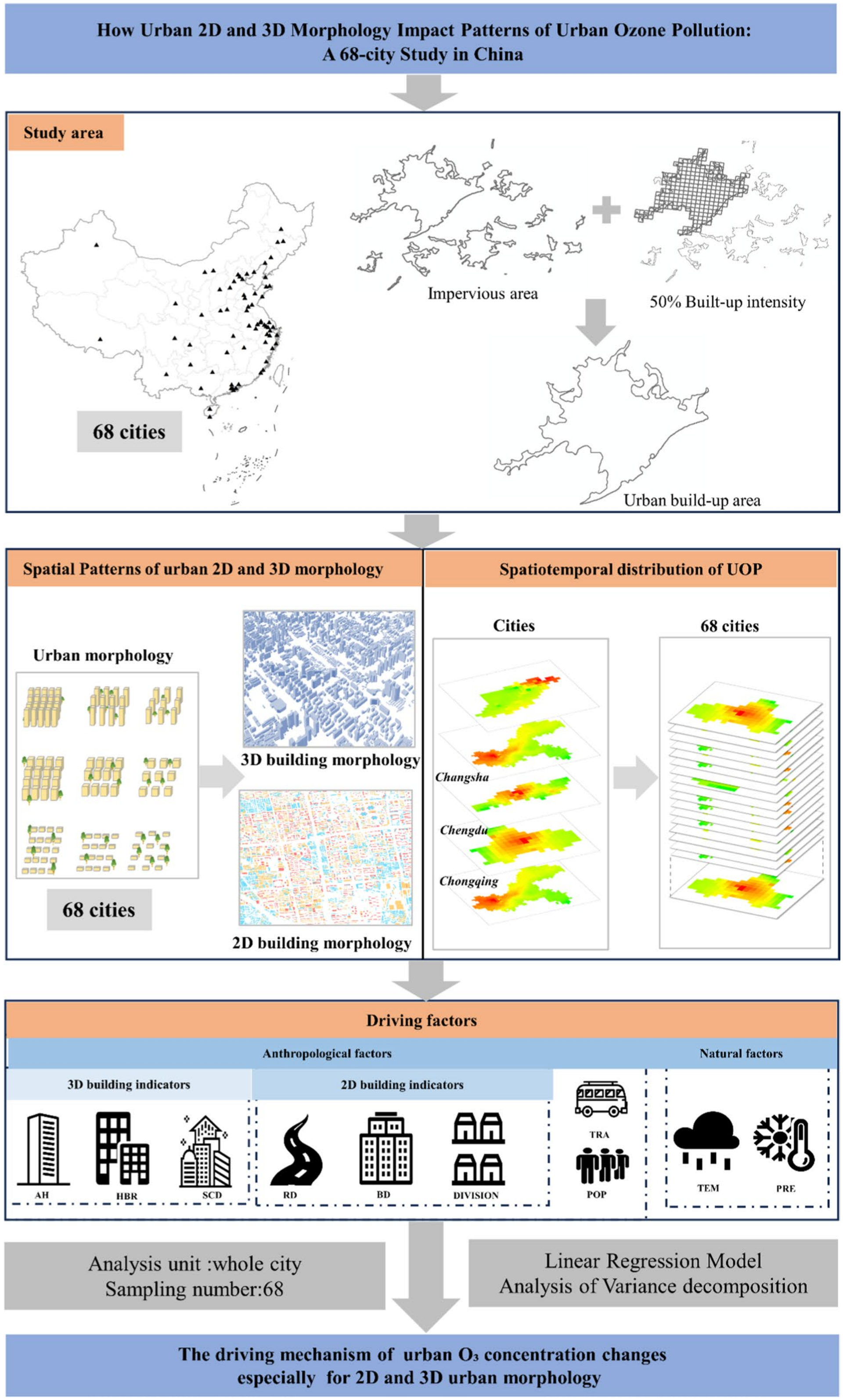
Urban ozone pollution: The surface maximum daily average 8-h (MDA8) O_3 product of 10×10 km was obtained from the China High Air Pollutants (CHAP) dataset. This was predicted from the solar radiation intensity and surface temperature, and other data, including observations, satellites, and models, by employing the space–time extremely randomized tree machine learning model. The MDA8 O_3 estimates had a relatively high accuracy with a high average out-of-sample (out-of-station) coefficient of determination (0.87), with a root mean square error of 17.10 μg/m^3 (Mircea et al. 2014; Fusaro et al. 2017; Wei et al. 2022). We used average ozone concentration data for the three years from 2016 to 2018. The National Ambient Air Quality Standards of China (NAAQS) and the WHO introduced concentration limits for the maximum daily 8-h average (MDA8) O_3 concentrations (Table 2).

Driving factors

To investigate the effects of natural and anthropogenic factors on urban atmospheric ozone concentrations, key indicators of these factors were selected in this study. Natural factors included temperature and precipitation, which have accelerated or slowed the effects on ozone concentrations, from the daily meteorological dataset of basic meteorological elements of the Chinese national ground-based meteorological stations (V3.0) (http://www.data.cma.cn/) (Table 3). Anthropogenic factors included urban morphology (Table 1), highway passenger traffic, and population density. Traffic exhaust is an important precursor to ozone production, and highway passenger traffic reflects the amount of urban traffic flow, which is from the Chinese Urban Statistical Yearbook 2018. (Zhang et al. 2022a). Urban population density was selected as a typical factor for urban air quality because it reflects the density of human activity. Urban population data were obtained from LandScan population datasets and used to calculate urban population density data for the study area (Table S1). According to the total permanent population, cities can also be divided into five sizes: super large city, very large city, large city, medium city and small city. (Table 4).

Data analysis

To explore the factors affecting urban ozone concentration, several methods have been used to quantify the contribution of natural and anthropogenic factors to urban ozone concentration. Pearson correlation analysis was first used to calculate the correlation and significance of natural and anthropogenic factors with urban ozone concentration. Analysis of variance decomposition was then used to calculate the relative contribution of natural and anthropogenic factors to the urban ozone concentration. Finally, factors that may affect urban ozone concentrations were analyzed using multiple linear regression models and correlation coefficients. Multicollinearity was evaluated using the variance inflation factor (VIF), where < 5 indicates no multicollinearity. In all statistical analyses, natural factors (Temperature (TEM) and Precipitation (PRE)) and anthropogenic factors (Average Height (AH), High Building Radio (HBR), Space Congestion Degree (SCD), Building Density (BD), Landscape Division Index (DIVISION), Road Density (RD), Population Density (POP), and Road Passenger Transport (TRA) were used as independent variables, and the urban ozone concentration was used as the dependent variable (Breiman 2001; Symonds and Moussalli 2011).


How Urban 2D and 3D Morphology Impact Patterns of Urban Ozone Pollution:
A 68-city Study in China
Study area
68 cities
Impervious area
50% Built-up intensity
Urban build-up area
Spatial Patterns of urban 2D and 3D morphology
Urban morphology
3D building morphology
68 cities
2D building morphology
Spatiotemporal distribution of UOP
Cities
68 cities
Changsha
Chengdu
Chongqing
Driving factors
Anthropological factors
Natural factors
3D building indicators
2D building indicators
AH
HBR
SCD
RD
BD
DIVISION
TRA
POP
TEM
PRE
Analysis unit :whole city
Sampling number:68
Linear Regression Model
Analysis of Variance decomposition
The driving mechanism of urban O3 concentration changes
especially for 2D and 3D urban morphology

◂**Fig. 2** The framework of our research

Results

Spatial patterns of urban 3D morphology in Chinese cities

In China, we found that the average building density (BD) was 0.18, ranging from 0.08 to 0.31 across different cities, and the AH of buildings in cities was 15.69 m, ranging from 5.21 to 27.31 m. The urban 3D urban morphology exhibited obvious spatial heterogeneity (Fig. 4). The average height (AH) and high building radio (HBR) were generally higher in southwestern cities, with some cities reaching the highest levels, while northern cities had lower AH and HBR. In contrast, the values of space congestion degree (SCD) and BD were high in large cities, such as Shanghai and Nanjing, and low in small cities, indicating that higher building densities characterize large cities. We also found that AH was positively correlated with GDP, elevation, and relief amplitude and negatively correlated with latitude (Fig. 5). Building density was positively correlated with GDP and negatively correlated with longitude (Fig. 5).

By combining urban building density and height, we analyzed China's urban morphology (Fig. 6). We found that China's urban morphology in cities is dominated by MRMD (28%) and MRHD (25%), followed by HRMD (12%), LRLD (3%), and MRHD (3%). The MRMD and MRHD morphologies were found in most Chinese cities, accounting for 53% of the total.

Spatiotemporal distribution of UOP in Chinese cities across different climate zones

The annual average O_3 concentration in Chinese cities was 97.74 μg/m^3, ranging from 65.73 to 113.24 μg/m^3 (Fig. 7). Cities with UOP concentrations ranging from 0 to 100 μg/m^3 accounted for 54% of the total. The quarterly average O_3-8 h concentration had obvious seasonal characteristics, with the highest ozone concentration in summer (120.56 μg/m^3), and 11% of the cities had ozone concentrations above Grade II. In winter, the UOP concentration was the lowest (68.65 μg/m^3), 97% of the cities had ozone concentrations below Grade I standards (< 100 μg/m^3), and the air quality was excellent.

From the perspective of climatic zones, the quarterly average urban O_3 concentrations varied across different climatic zones (Figs. 7 and 8), particularly in summer. The highest ozone concentration was found in the southern temperate zone (105 μg/m^3), and 78% of cities had UOP concentrations of 100–160 μg/m^3, followed by the northern subtropical region (102 μg/m^3), central subtropical region (95 μg/m^3), and central temperate region (92.41 μg/m^3). The lowest ozone concentration was found in the southern subtropical region, with an average O_3 concentration of only 90.73 μg/m^3, and 98% of the cities had UOP concentrations ranging from 0 to 100 μg/m^3. In summer, the UOP concentrations differed more obviously among the different climate zones. The most serious UOP in summer was found in the southern temperate zone with the highest ozone concentration (152.39 μg/m^3), where 29% of the cities exceeded Grade II (> 160 μg/m^3). The average concentration in the southern subtropical zone was 75.99 μg/m^3, 100% of the cities did not exceed Grade I (0 ~ 100 μg/m^3), and the air quality was excellent. The differences in ozone concentrations between climatic zones were less pronounced in autumn and winter. In autumn, the highest concentration (90.37 μg/m^3) was found in the southern subtropical zone, and 67% of cities had ozone concentrations exceeding Grade I, forming a new center of ozone concentration in the Pearl River Delta region. In winter, urban ozone concentrations in all climatic zones were lowest in the cities.

The quarterly average urban O_3-8 h concentrations varied considerably across cities of different sizes (Fig. 9). In spring and summer, UOP concentrations increased with city size, with the highest ozone concentrations in supercities (120.42 μg/m^3 and 143.62 μg/m^3) and 50% of cities had UOP concentrations exceeding 160 μg/m^3 in summer. The lowest ozone concentrations were in small cities (114.12 μg/m^3 and 114.17 μg/m^3). In autumn and winter, the lower the urban size, the higher the UOP concentration. In autumn, small cities had the highest ozone concentrations (93.48 μg/m^3); in winter, UOP concentrations were highest in small cities (74.74 μg/m^3), while the lowest ozone concentrations were found in super large cities (66.48 μg/m^3) and all cities were Grade I.

Table 1 The main building morphology indicators in our study

Abbreviation (Metrics)	Expression	Description	Categories	Reference
AH (Average height)	$AH = \frac{1}{n}\sum_{i=1}^{n} H_i$	The average height of total buildings n is the number of buildings in the study area H_i is the height of the building i	3D BM	Berger et al. (2017)
HBR (High building radio)	$HBR = N_i/N$	Proportion of buildings over 24 m N_i is the number of buildings over 24 m N is the number of buildings in the study area	3D BM	Liu et al. (2020)
SCD (Space congestion degree)	$SCD = \sum_{i=1}^{n} (S_i \times H_i)/(A \times H_{max})$	The congestion degree of the building in three-dimension space S_i is the bottom area of the building i H_i is the height of the building i A is the study area $Hmax$ is the maximum height of the total buildings	3D BM	Zhang and hu (2013)
BD (Building density)	$BD = (\sum_{i=1}^{n} S_i)/A$	Degree of congestion in the study area S_i is the bottom area of the building i A is the study area n is the number of the buildings in the study area	2D BM	Ke et al (2022)
Division (Landscape Division Index)	$\text{DIVISION} = 1 - \sum_{i=1}^{m}\sum_{j=1}^{n}(\frac{a_{ij}}{A})^2$	Degree of connection between patches m is number of patch types present in the landscape, including the landscape border if present a_{ij} is area of building ij i is area of building type j is area of building number	2D BM	Ke et al (2022)
RD (Road Density)	$\text{RD} = l/A$	Road accessibility of the study area l is the total length of roads in the study area A is the study area	2D BM	Zhang et al (2022a)

We also found that the quarterly average urban O_3-8 h concentration varied across different urban morphologies (Fig. 10). The highest urban ozone concentration was found in cities with low rise and high urban building density, such as LRHD (105.44 μg/m^3), followed by LRMD (105.22 μg/m^3). The lower the building height and the higher the urban building density, the higher the UOP concentration.

Contribution of natural and anthropological factors to ozone concentrations

We found that natural (temperature and precipitation) and anthropogenic factors jointly influenced the urban ozone concentration during different seasons (Fig. 11). Natural and anthropogenic factors had the most notable influence on the urban ozone concentration in summer ($R^2 = 0.5$) and the least influence in

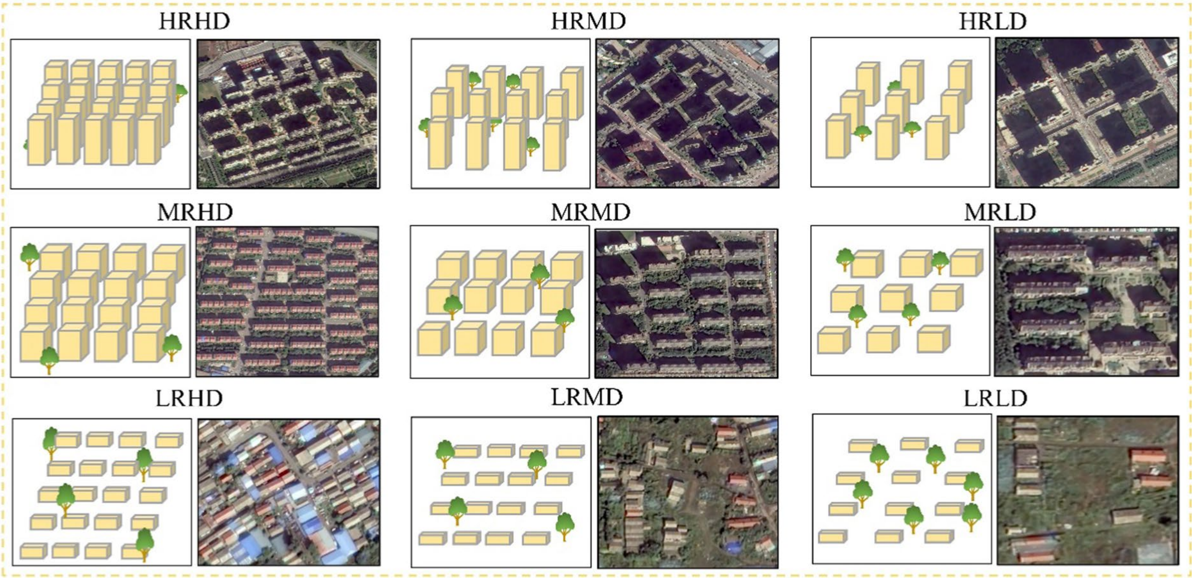


Fig. 3 The nine categories and the percentage of 3D urban morphology in China (HRHD (High Rise & High Density), HRMD (High Rise & Medium Density), HRLD (High Rise & Low Density), MRHD (Medium Rise & High Density), MRMD (Medium Rise & Medium Density), MRLD (Medium Rise & Low Density), LRHD (Low Rise & High Density), LRMD (Low Rise & Medium Density), LRLD (Low Rise & Low Density))

Table 2 The different O_3 pollution levels based on the NAAQS standard

Ozone pollution level	Grade I	Grade II	Grade III	Grade IV	Grade V
Ozone concentration index	0 ~ 100 μg/m^3	101 ~ 160 μg/m^3	161 ~ 215 μg/m^3	216 ~ 265 μg/m^3	265 ~ 800 μg/m^3
Category	excellent	good	Mild pollution	Moderate pollution	heavy pollution

Table 3 Information of all data

Data	Time	Type	Resolution(m)	Source
OSM road network	2017	Shapefile	–	https://wordpress.org/plugins/osm/
Global artificial impervious area	2017	Grid	30	https://www.x-mol.com/
Urban population	2017	Grid	1000	https://landscan.ornl.gov
Meteorological data	2017	Statistical	–	https://data.cma.cn/
Building data	2017	Shapefile	–	https://lbs.amap.com/
Highway passenger traffic (Built-up area)	2017	Statistical	–	http://www.stats.gov.cn/

Table 4 The different classifying cities in our study

City size	Small city	Medium city	Large city	Very large city	Super large city
Urban population	0 ~ 500,000 people	500,000 ~ 1,000,000 people	1,000,000 ~ 5,000,000 people	5,000,000 ~ 10,000,000 people	> 10,000,000 people

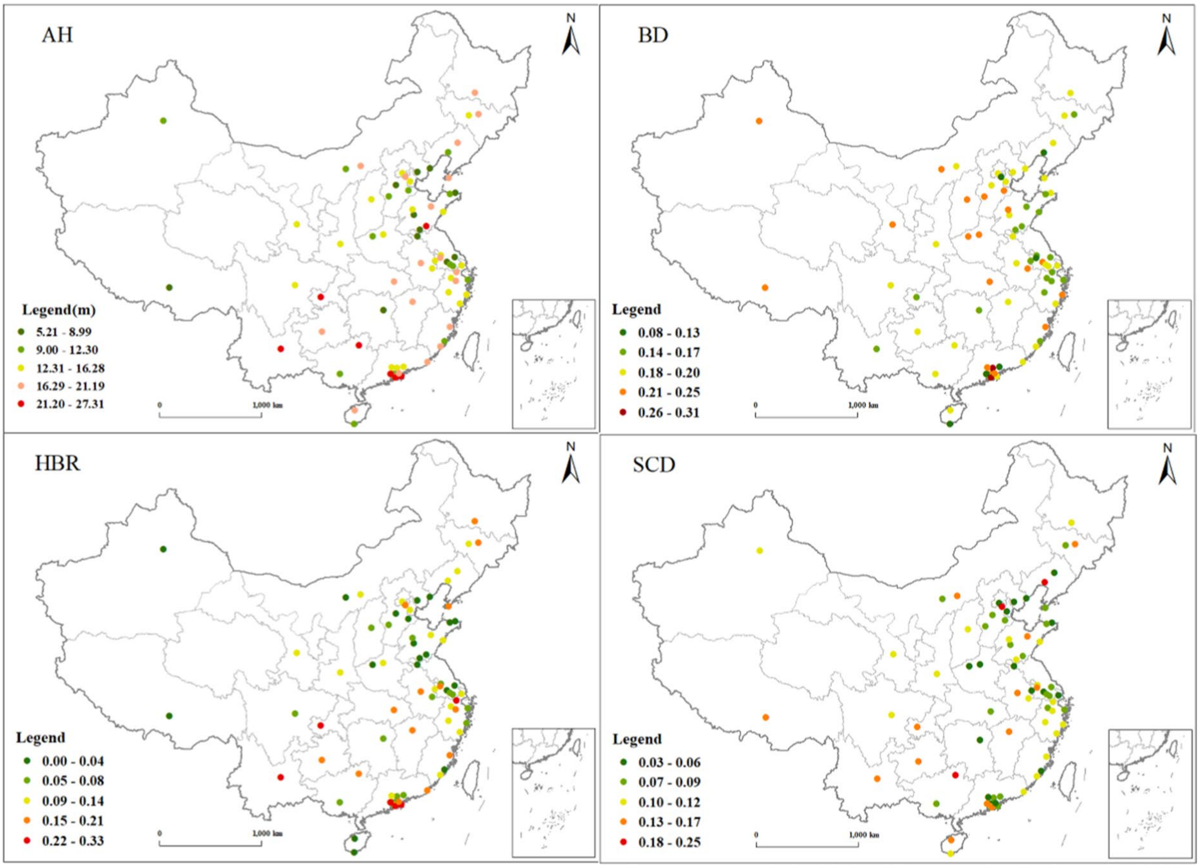


Fig. 4 The spatial distribution of 3D landscape metrics in 68 cities in China (AH: average height; BD: building density; HBR: high building ratio; SCD: space congestion degree)

autumn ($R^2 = 0.36$). Overall, anthropogenic factors are the main factors influencing urban ozone concentration, with an explanation rate above 20% in all seasons, which is two times higher than that of natural factors. Natural factors (16%) had a greater influence, and it was closest to the influence of anthropogenic factors (20%) only in autumn. Therefore, we can see that in cities, the urban ozone concentration is mainly affected by anthropogenic factors.

We further investigated the factors affecting urban ozone concentrations and found that building factors contributed substantially to UOP concentrations (Fig. 12). The building factor had a relative explanatory power of more than 40% in all seasons and was the main influencing factor. In spring, the 2D building factor had the highest relative explanatory power for ozone concentrations (39%) and was the main influencing factor, three times more than the 3D building factor (13%). Urban ozone concentrations showed a positive correlation with BD (18%, $P < 0.005$) and a negative correlation with DIVISION (19%, $P < 0.005$). In summer, the relative explanatory power of the 2D building factor was 23%, comparable to the 3D building factor (19%), where the urban ozone concentration showed a positive correlation with HBR (5%, $P < 0.01$) and a negative correlation with DIVISION (15%, $P < 0.05$). In spring and summer, DIVISION was the most influential building factor. In autumn and winter, the relative explanatory power of the 3D building factors (30% and 31%, respectively) was significantly higher than that of the 2D building factors (13% and 23%, respectively). HBR (16%, $P < 0.05$) showed a significant negative correlation with ozone concentration in winter and was the most influential building factor in autumn and winter; SCD and BD had a higher relative explanatory power

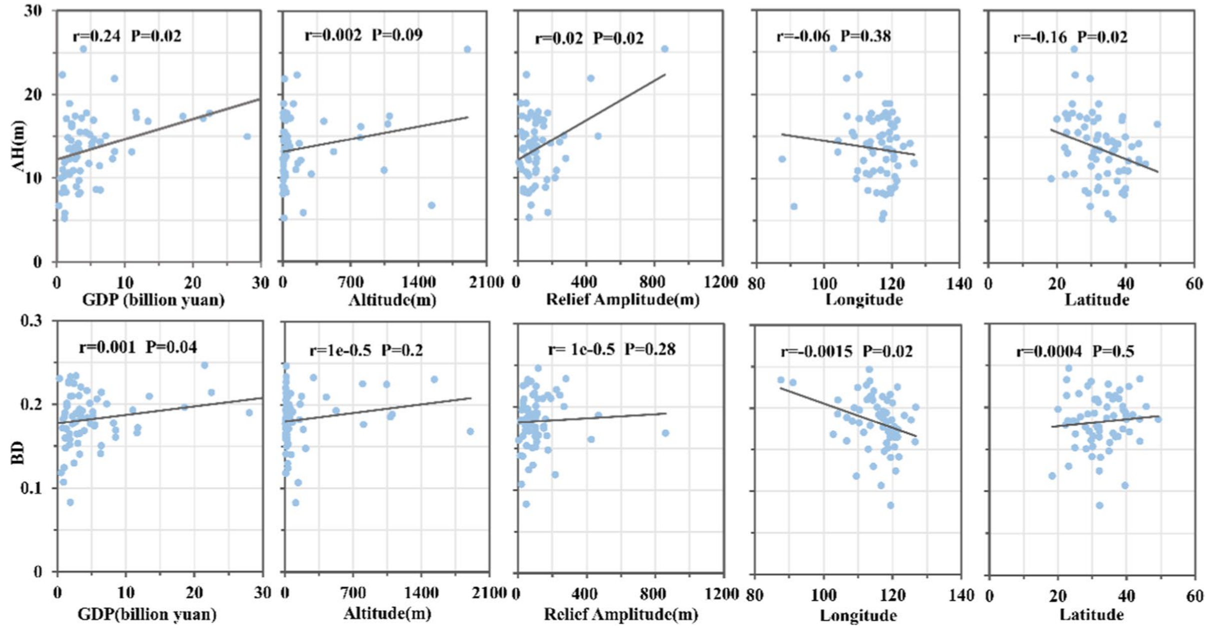


Fig. 5 The relationship between AH (BD) and GDP, altitude, relief amplitude, longitude, latitude in China

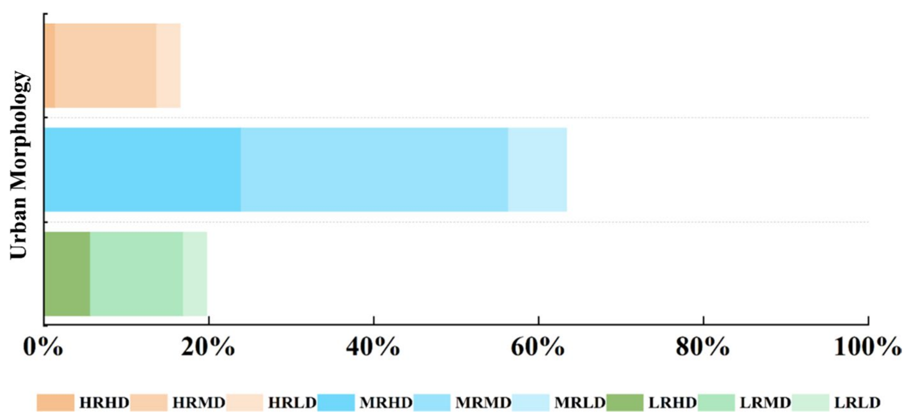


Fig. 6 Percentage of the number of cities in nine different urban morphologies in China

in winter (15%, $P<0.05$ and 16%, $P<0.05$) than in autumn (8%, $P<0.01$ and 9%, $P<0.01$), and both were positively correlated with UOP concentration.

Discussion

Urban 2D and 3D morphology in China and its impacts on ozone concentration

Our study found that the average building height in China is 15.69 m. In contrast, the average global building height is 6.16 m, with taller buildings being present in high-income countries such as the United States and Oceania. Cities with high buildings and densities are mainly located in the United States, Europe, China, and the Middle East, mainly related to the region's affluence and different individual contributions to global competition for land (Li et al. 2022). In this study, we found that AH and HBR show a trend to be high in Southwest China and low in Northeast China. Building height is positively correlated with topographic relief and altitude, indicating that building height also increases as mountain

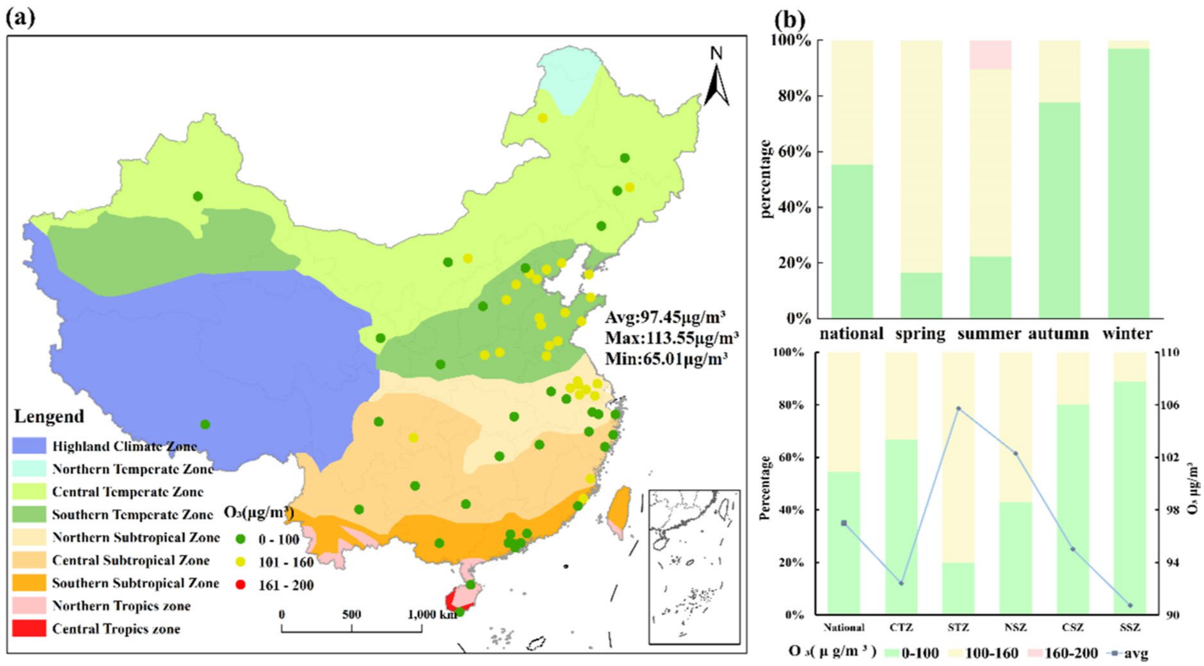


Fig. 7 Spatial distribution of O_3-8 h annual mean concentration in China (**a**) and the percentage of cites with different O_3-8 h concentration across different seasons and climate zones (**b**). (CTZ: Central Temperate Zone; STZ: South Temperate Zone; NSZ: Northern Subtropical Zone; CSZ: Central Subtropical Zone; SSZ: Southern Subtropical Zone)

undulation and altitude increase. This is due to the many mountains and few plains in Southwest China, limiting the horizontal expansion of the city, which can only develop vertically. North China is dominated by plains or low hills, with open terrain, and is also influenced by precipitation and mostly has low-rise bungalows (Zhou et al. 2019; Huang et al. 2022). On the other hand, urban building height and density are closely related to a city's economic development. The average height and BD increase with GDP; the higher the level of urbanization is, the larger the proportion of building land, and the taller the buildings. Wealthy cities continue to build upward and outward to gain more space for growth (Huang et al. 2022). As many people move into better-developed cities, land prices rise, and buildings can only increase upward. We also find that AH is negatively correlated with latitude and BD is negatively correlated with longitude (Fig. 5). China's topography is high in the west and low in the east, showing a 3-step ladder (Ren et al. 2022), with rolling hills in the west and a more extensive plain terrain in the east, with an overall slope toward the sea. At the same time, the south has more mountainous terrain, while the north is flatter, and the flat and open terrain allows more space for cities to expand horizontally. China's urban morphology is dominated by medium-rise and medium-density buildings and dominates all urban centers (Taubenböck et al. 2020). Notably, dense and highly built-up cities are increasing, whereas Low Rise & Low Density (LRLD) cities are decreasing. This is mainly due to urbanization and the influx of population into urban centers, where urban sprawl does not increase as rapidly as population growth, driving cities to higher and denser levels (Kuang 2020; Huang et al. 2022).

Buildings are the main bodies of a city. Urban 2D building morphology refers to urban structures with a planar, 2D character in terms of size, shape and structure. Among the 2D building morphology indicators, BD was significantly and positively correlated with ozone concentration, whereas; DIVISION was negatively correlated, as in previous studies (Ke et al. 2022). The building density represents the density of building coverage and DIVISION is the degree of fragmentation of the city's building sites. The density and fragmentation of building sites are closely related to the industrial layout and traffic planning (Cao et al. 2021). Dense building sites are suitable for industrial layout and urban construction for traffic lane planning, while fragmented building sites are the opposite. Industrial and traffic emissions are direct sources of ozone production, so building sites indirectly affect ozone concentrations (Zhang et al. 2022a). In addition, the relative importance of the same building factors in explaining the effects of UOP varies considerably from season to season. For example, BD has the greatest relative importance among building factors for spring ozone concentrations, which can be attributed to two factors. First, the increase in building density increases the demand for transport routes (Lu and Liu 2016), which indirectly increases traffic flow, thus increasing the emission of ozone precursors and the generation of ozone pollution. Second, in spring, temperature factors are the most important factor influencing the relative importance of ozone concentrations. BD affects airflow, and the higher the BD is, the higher the temperature (Lee 2019), which accelerates the rate of reaction of ozone precursors, and the higher the UOP.

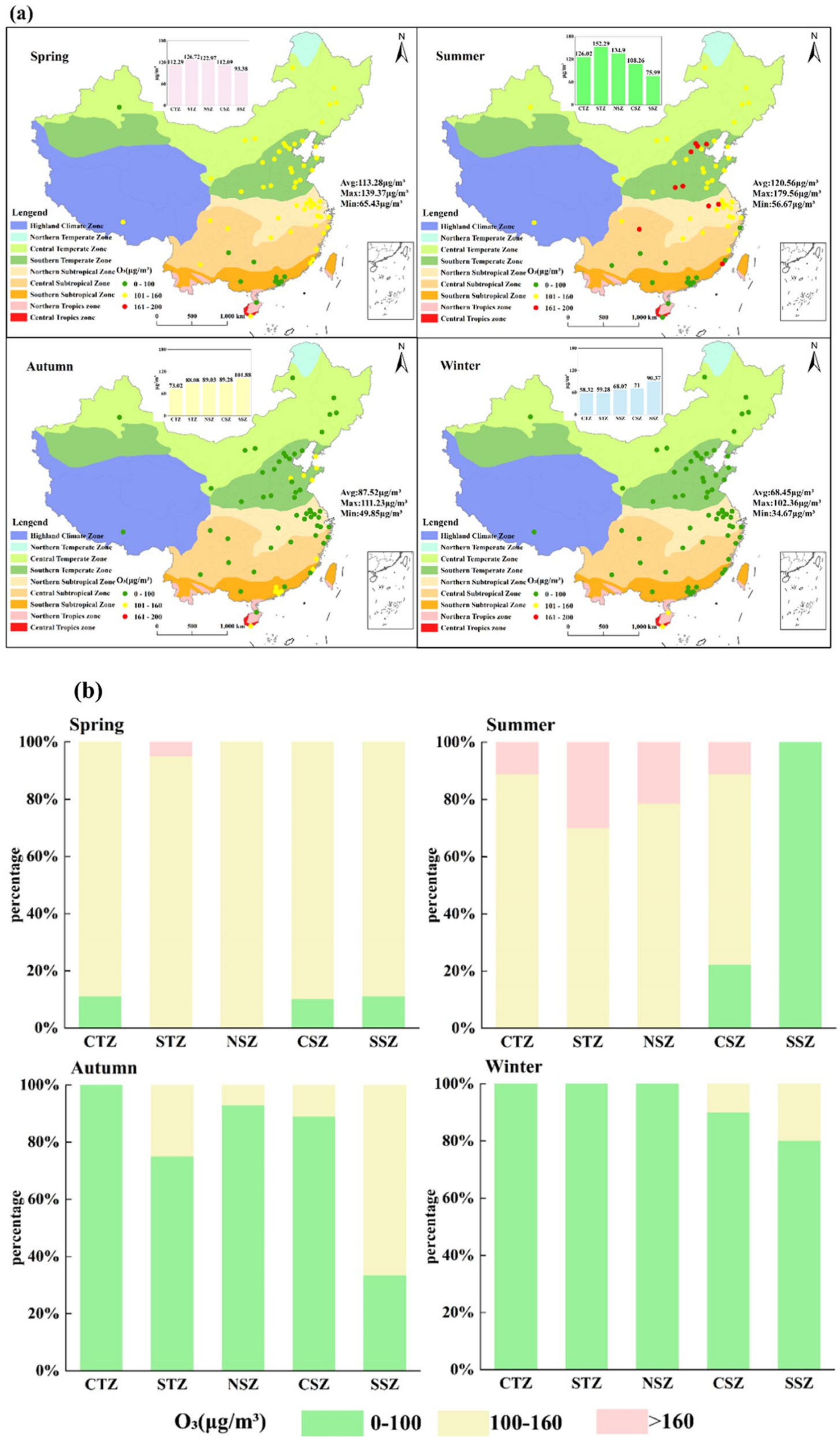
The density, height, and form of buildings affect the ventilation and heat dissipation of the city, and the layout of buildings affects the planning of urban industries and transportation. The clustering of buildings is a manifestation of urbanization, resulting in a large population concentration, all of which substantially the impact urban ozone concentration (Li et al. 2019; Zhang et al. 2020; Jedwab et al. 2021). Our study found that the AH and BHR of 3D building morphology indicators were negatively correlated with ozone concentrations, with taller buildings resulting in lower ozone concentrations, most significantly in autumn and winter. Within a specific height range near the ground, the higher the floor is, the higher the wind speed, accelerates the dispersion and weakens the ozone concentration. The shading effect of the higher floors weakens the solar radiation in the city, therefore weakening the average temperature in parts of the city and slowing ozone production. On the other hand, tall buildings in cities are mainly located in urban centers, and the main sources of ozone production are the industrial areas of cities. In contrast, industrial emissions from cities generally do not spread to urban centers; therefore, ozone concentrations in high-floor locations are low. However, the results of our study differ from those of previous studies; for example, taller floors increase wind-blocking and thus inhibit the dispersion of urban ozone concentrations (Taseiko et al. 2009), and the effect of average building height on air pollutants is quite ambiguous (Yang et al. 2020). Therefore, the analysis of the distribution and dispersion of ozone concentrations must be combined with the height and density of buildings, which requires a comprehensive analysis.

The space congestion degree and ozone concentration show an obvious positive correlation—the more crowded the urban building space, the higher the ozone concentration in the city; on the one hand, buildings can function as wind barriers—the narrower the area, the less wind speed and wind force, and hence the ozone diffusion is weakened (Hoek et al. 2008; Weber et al. 2014; Peng et al. 2018); on the other hand, confined buildings make interactions between single buildings; solar radiation is repeatedly reflected and absorbed, and the accumulation of solar radiation leads to a higher temperature, which accelerates ozone generation (Xu and Chen H 2021).

Our study showed that anthropogenic factors are the dominant factors affecting ozone in urban areas. Studies have shown that the main sources of ozone are small amounts of natural sources and large amounts of anthropogenic sources, including nitrogen oxides and volatile organic compounds (Lu et al. 2019; Wang et al. 2020). Anthropogenic factors provide a large number of precursors for ozone production, while natural factors accelerate or diminish ozone production or dispersion (Wang et al. 2020). Anthropogenic factors are the main source of ozone production and play a major role in influencing ozone concentrations, whereas natural factors play a minor role. Building factors are an important part of anthropogenic factors, urban 2D building morphology influences the industrial layout and transportation planning of the city, increasing or decreasing the production of ozone precursors (Cao et al. 2021), and 3D urban building form influences the ventilation and heat dissipation of the city, accelerating or slowing down the ozone reaction rate (Li et al. 2019). Building factors have a significant impact on urban ozone pollution.

Factors influencing the seasonal and regional variation in ozone concentration

Our study found that the UOP concentrations changed substantially across different seasons (Zhou


(a)
Spring
Avg:113.28μg/m³
Max:139.37μg/m³
Min:65.43μg/m³
Summer
Avg:120.56μg/m³
Max:179.56μg/m³
Min:56.67μg/m³
Autumn
Avg:87.52μg/m³
Max:111.23μg/m³
Min:49.85μg/m³
Winter
Avg:68.45μg/m³
Max:102.36μg/m³
Min:34.67μg/m³
Lengend
Highland Climate Zone
Northern Temperate Zone
Central Temperate Zone
Southern Temperate Zone
Northern Subtropical Zone
Central Subtropical Zone
Southern Subtropical Zone
Northern Tropics zone
Central Tropics zone
O3(μg/m³)
0 - 100
101 - 160
161 - 200
0 500 1,000 km
N
(b)
Spring
Summer
Autumn
Winter
percentage
0% 20% 40% 60% 80% 100%
CTZ STZ NSZ CSZ SSZ
O3(μg/m³) 0-100 100-160 >160

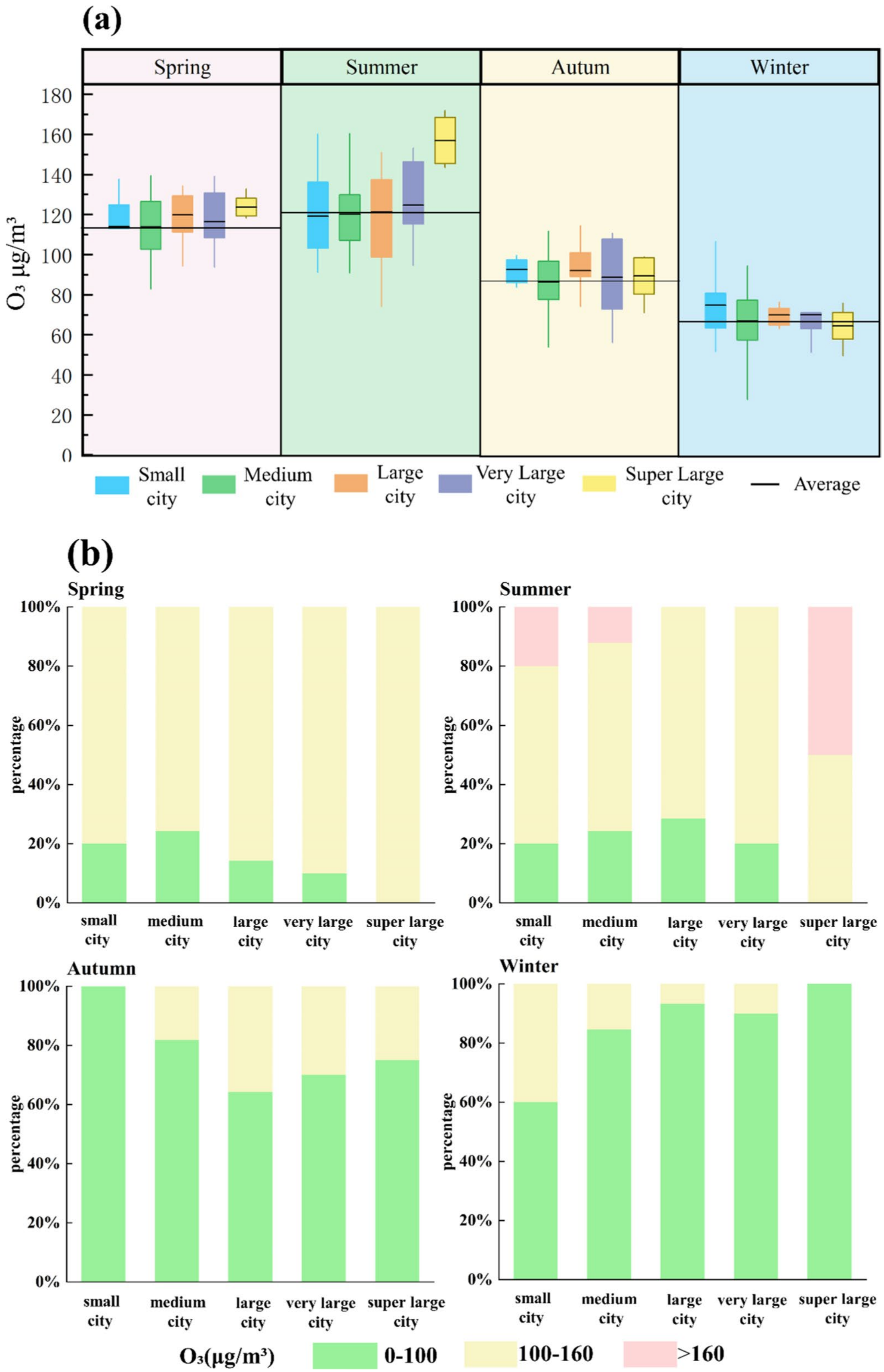
◂**Fig. 8** Seasonal spatial distribution of O_3-8 h concentration in different climate zones in China (**a**) and the percentage of cities with different urban O_3-8 h concentration across five different climate zones, China (**b**) (CTZ: Central Temperate Zone; STZ: South Temperate Zone; NSZ: Northern Subtropical Zone; CSZ: Central Subtropical Zone; SSZ: Southern Subtropical Zone)

et al. 2022). The UOP was most severe in China during spring and summer, and ozone was mainly concentrated in the southern temperate zone and the northern subtropical zone (Chen et al. 2020). In spring and summer, the temperatures rebound, and the temperature difference between north and south is small, while precipitation is less in the north than in the south, and experiences longer daylight hours, making UOP concentrated in this region. Precipitation has purified ozone concentrations, whereas high temperatures and intense illumination are sufficient to accelerate ozone production (Mao et al. 2020). Meanwhile, there are many industrial production bases in the southern temperate zone and northern subtropical zone, among which the Beijing-Tianjin-Tangshan industrial zone and the Yangtze River Delta urban agglomeration are industrial agglomerations(Yang et al. 2022). Industrial emissions produce many ozone precursors, which generate ozone under photochemical action and cause severe ozone pollution (Wang et al. 2022b). During autumn and winter, UOP concentrations changed nationwide owing to temperature effects. Ozone concentrations in temperate regions fall to the lowest point of the year (Shen et al. 2022), while UOP concentrations in the southern subtropical region and in the south increase, and the urban agglomeration of the Pearl River Delta becomes an ozone center in winter. Urbanization has led to industrialization and transportation development. The influx of large industrial aggregations and populations has caused an increase in industrial emissions and vehicle emissions. Ozone pollution is the most severe in this region, as such emissions provide many precursors for the formation of ozone pollutants (Symonds and Moussalli 2011; Zhou et al. 2022).

The relationship between ozone concentration and city class also varied with season. In spring and summer, ozone concentrations increase with urban size. However, the ozone concentration decreased in autumn and winter, with increasing urban size. On the one hand, urbanization has attracted large amounts of industry and population, leading to ozone pollution from industrial and vehicle emissions (Zhang et al. 2022a). On the other hand, in autumn and winter, straw burning in rural and suburban areas causes ozone pollution in urban centers. In contrast, urban areas in small cities are closer to rural areas and are more vulnerable than larger cities (Zhang et al. 2019).

The relative importance of building factors varied significantly between seasons; For example, building factors had the most significant effect on ozone concentrations, with 2D building factors being the dominant factor in the spring and 3D building factors being the dominant factor in the winter, but the factors that had the greatest effect in each season were temperature, precipitation, or population density. HBR was positively correlated with ozone concentrations during the summer months and negatively correlated with ozone concentrations during the other seasons. These results indicate that both 3D urban characteristics and climatic conditions cannot be ignored when conducting urban planning. The relative contribution of architectural factors to ozone concentration is influenced by both natural and anthropological factors, and the climatic and anthropological factors of the city should be taken into full consideration when urban planning is carried out. In summer, the effect of HBR on ozone concentration shows a clear positive correlation different from other seasons. Because HBR represents the ratio of high-rise buildings in a city and represents the level of urban economic development, the larger the HBR is, the more high-rise buildings there are in a city, and the higher the level of urban economic development (Huang et al. 2022). In summer, ozone concentration is most significantly affected by natural factors, traffic and population, and building factors have the lowest relative influence on ozone concentration. Most Chinese cities have the highest ozone concentrations in summer, and the more economically developed the city is, the more serious the ozone pollution. At the same time, most cities in China have the smallest shaded area of the year in the summer, weakening the shading effect and adding to the ozone response.

In general, although the explanatory power of the building factor is influenced by other factors that change with the seasons, the explanatory power of ozone concentration has been dominant among many factors and has an important influence on ozone concentration. Building height and building density reflect the 3D building form of the city, whereas


(a)
Spring
Summer
Autum
Winter
O3 μg/m3
180
160
140
120
100
80
60
40
20
0
Small city
Medium city
Large city
Very Large city
Super Large city
Average
(b)
Spring
Summer
Autumn
Winter
percentage
100%
80%
60%
40%
20%
0%
small city
medium city
large city
very large city
super large city
O3(μg/m3)
0-100
100-160
>160

◂**Fig. 9** Seasonal variation of O_3-8 h concentration at different city sizes in China (**a**) and percentage of cities with different urban O_3-8 h concentration for different city sizes in China (**b**). The boxes represent the 25th and 75th percentiles, and the horizontal black lines inside the boxes represent the average (small-size: pop < 500,000; medium-size: 500,000 < pop < 1,000,000; large-size:1,000,000 < pop < 5,000,000; very large-size: 5,000,000 < pop < 10,000,000; super large-size: pop > 10,000,000 pop(people)), $p < 0.05$

the 2D building form is more represented by urban building coverage (Yuan et al. 2019; Hu et al. 2020). Although studies have compared the effects of 3D and 2D building indicators on air pollutants (Lu et al. 2016; Li et al. 2019), from the perspective of seasonal changes, the explanatory power of 3D and 2D indicators on ozone concentration also shows different explanatory power depending on the season because the natural factors and human factors on the generation, diffusion, and weakening effects of ozone concentration vary with season. Therefore, cities must plan their urban layout according to their geographical location and climatic conditions.

Limitations and prospects

This study has some limitations. The resolution of the ozone data in our study was 10 × 10 km, which may not be an accurate representation of urban ozone. There is an error in the actual ozone concentration in the urban study area, which may affect the correlation between the building morphology metrics and the UOP concentration. Due to the limited sample of cities selected for the preliminary study, we analyzed the effects of building factors on UOP by focusing on the effects of seasonal variations and simplifying the effects of regional variations on UOP.

The influence of building metrics on ozone concentrations is not only the relationship between density and height, as described in our study, but is also influenced by a range of factors, such as building shape and spatial building pattern. Building 3D indicators only provides a new perspective for studying urban buildings, and many more complex factors govern ozone dispersion, transport, and transformation. Urban green spaces and tree species could also contribute to O_3 pollution via BVOCs efflux and direct leaf absorption (Paoletti 2009; Sicard et al. 2018). A new criteria and method has been developed for selecting urban trees to reduce increasing ozone levels in cities (Sicard et al. 2018).

Therefore, in future studies, the precision of ozone data should be improved to reduce the error between building data and actual buildings, and to reflect the influence of building indicators on air quality more accurately. Including green space will improve urban forest-based natural solution development (Wang et al. 2022a). The height and density of buildings can reflect the 3D shape of a city, and the impact of building factors on ozone concentration can be affected by different seasons and spatial locations. Therefore, in future studies, it is important to pay attention not only to seasonal variations but also to the influence of regional factors on UOP. Urban planners should tailor urban planning to reduce the levels of air pollutants in cities.

Conclusions

This study examined the spatial and temporal variation in ozone concentrations from the perspective of urban building morphology and investigated the effects of natural and anthropogenic factors on ozone concentrations. The main findings are as follows.

(1) The average building density and height were 0.18 and 15.69 m, respectively, in China. Taller buildings and high densities were mostly found in Southwestern China, particularly in larger cities. In addition, we found that China's urban morphology in most (53%) cities was dominated by MRMD (28%) and MRHD (25%).
(2) Urban ozone pollution was the most severe in summer, especially in the southern temperate zone. However, in winter, higher UOP concentrations were observed in the southern subtropical zone. Urban ozone concentrations vary considerably across cities of different sizes. In spring and summer, UOP concentrations increased with city size; in winter, UOP concentrations were the highest in small cities. We also found that UOP concentrations varied across different urban morphologies, and the highest urban ozone concentration was found in cities with LRHD.
(3) Anthropogenic factors were the main factors influencing ozone concentration, and their influence was more than 55%, with urban morphology

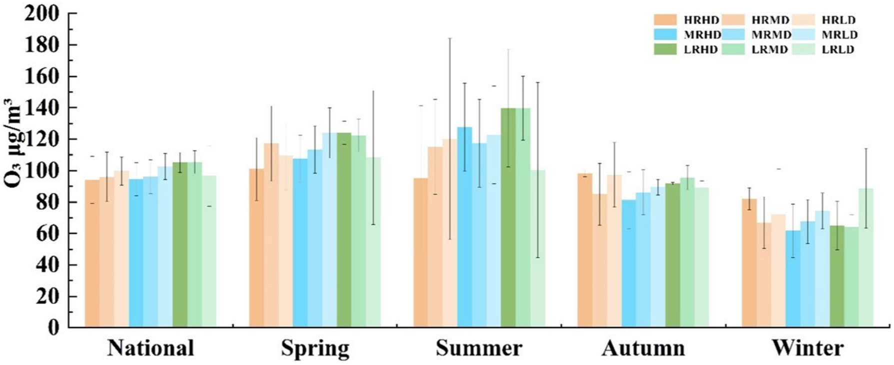


Fig. 10 Seasonal variation in O_3-8 h concentration in different urban forms. The vertical black line on the graph represents the standard deviation (High Rise & Low Density (HRLD), High Rise & Medium Density (HRMD), High Rise & High Density (HRHD), Medium Rise & Low Density (MRLD), Medium Rise & Medium Density (MRMD), Medium Rise & High Density (MRHD), Low Rise & Low Density (LRLD), Low Rise & Medium Density (LRMD), and Low Rise & High Density (LRHD)), $p < 0.05$

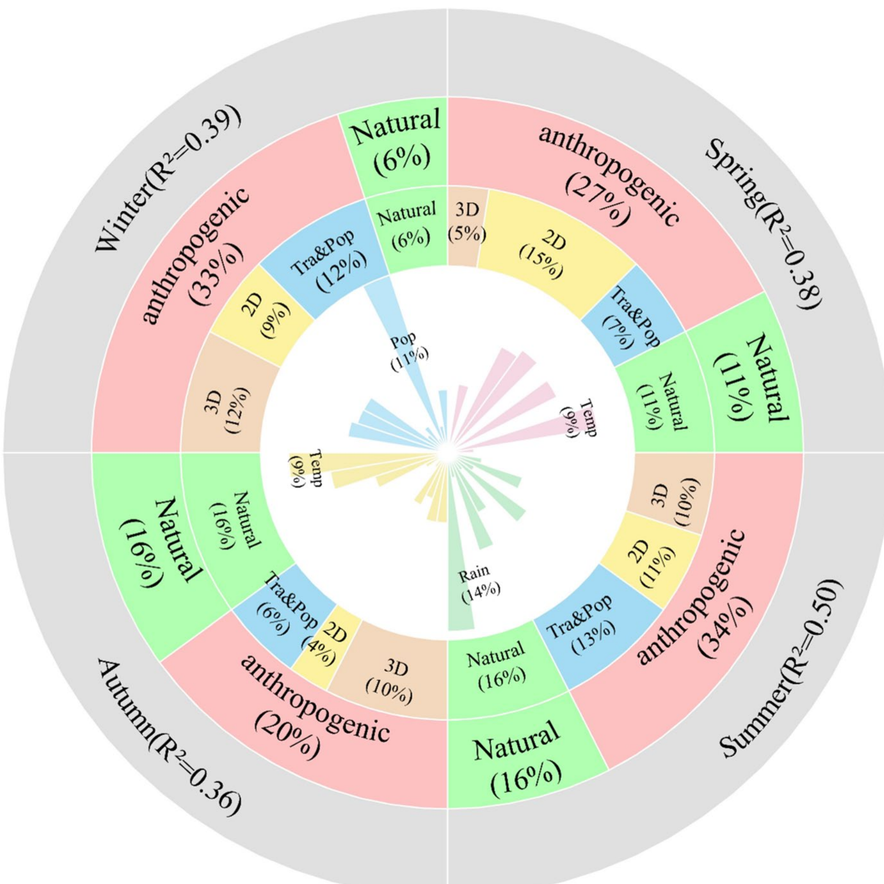


Fig. 11 Variance explained rates of natural and anthropological factors on O_3 concentration in different seasons

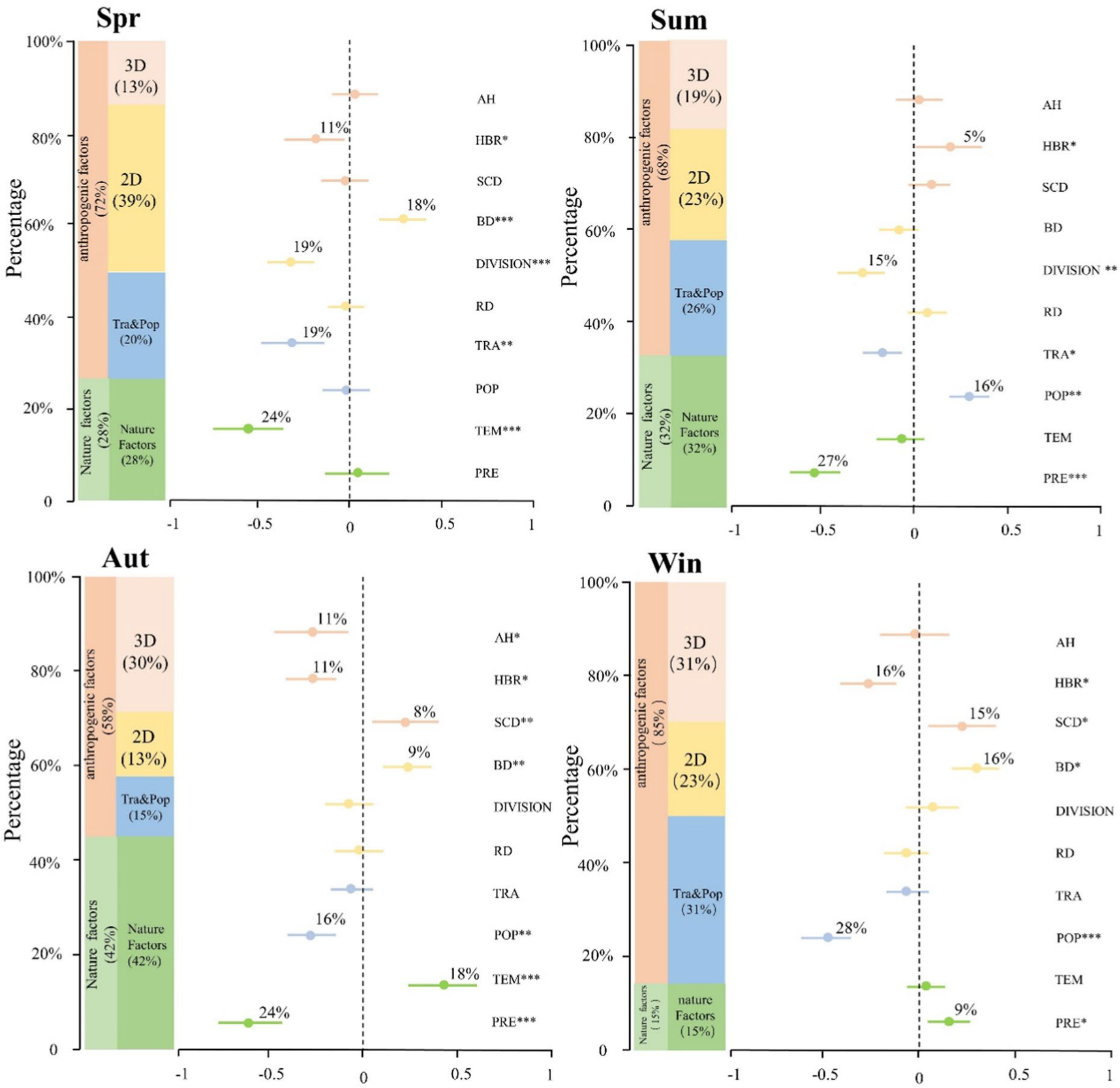


Fig. 12 Relative explanatory power of natural and human factors on ozone concentration in different seasons (AH (Average Height), HBR (High Building Radio), SCD (Space Congestion Degree), BD (Building Density), DIVISION (Landscape Division Index), RD (Road Density), POP (Population Density), TRA (Road Passenger Transport), TEM (Temperature), PRE (Precipitation)). The P value of each predictor is given as: *P < 0.05, **P < 0.01, ***P < 0.001

accounting for 42%. 2D building factors were the main factors in spring and summer, while 3D building factors were the main factors in autumn and winter.

With rapid urbanization, the number of urban buildings will continue to increase, and urban ozone pollution will become more severe. Our study deepens the understanding of the influence of urban buildings on ozone concentrations and provides guidance to governments and policy-makers for urban planning to ameliorate urban ozone pollution.

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Declarations

Competing interests The authors declare no competing interests.

References

Biljecki F, Ito K (2021) Street view imagery in urban analytics and GIS: a review. Landsc Urban Plan 215:104217

Breiman (2001) Random forests. Mach Learn 45(1):5–32

Buccolieri R, Sandberg M, Sabatino SD (2010) City breathability and its link to pollutant concentration distribution within urban-like geometries. Atmos Environ 44(15):1894–1903

Cai Z, Demuzere M, Tang Y, Wan Y (2022) The characteristic and transformation of 3D urban morphology in three Chinese mega-cities. Cities 131:103988

Cao Q, Luan Q, Liu Y, Wang R (2021) The effects of 2D and 3D building morphology on urban environments: a multi-scale analysis in the Beijing metropolitan region. Build Environ 192:107635

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

Chen Y, Li H, Karimian H, Li M, Fan Q, Xu Z (2022) Spatio-temporal variation of ozone pollution risk and its influencing factors in China based on Geodetector and Geospatial models. Chemosphere 302:134843

Ewing R, Cervero R (2010) Travel and the built environment. J Am Plan Assoc 76(3):265–294

Ezimand K, Kakroodi AA (2019) Prediction and spatio—temporal analysis of ozone concentration in a metropolitan area. Ecol Indic 103:589–598

Fallmann J, Forkel R, Emeis S (2016) Secondary effects of urban heat island mitigation measures on air quality. Atmos Environ 125:199–211

Fusaro L, Marando F, Sebastiani A, Capotorti G, Blasi C, Copiz R, Congedo L, Munafò M, Ciancarella L, Manes F (2017) Mapping and assessment of PM10 and O3 removal by woody vegetation at urban and regional level. Remote Sens-Basel 9(8):791

Gasana J, Dillikar D, Mendy A, Forno E, Vieira ER (2012) Motor vehicle air pollution and asthma in children: a meta-analysis. Environ Res 117:36–45

Ghasempour F, Sekertekin A, Kutoglu SH (2021) Google Earth Engine based spatio-temporal analysis of air pollutants before and during the first wave COVID-19 outbreak over Turkey via remote sensing. J Clean Prod 319:128599

Guan Y, Xiao Y, Rong B, Zhang N, Chu C (2021) Long-term health impacts attributable to PM2.5 and ozone pollution in China's most polluted region during 2015–2020. J Clean Prod 321:128970

Hao Y, Zheng S, Zhao M, Wu H, Guo Y, Li Y (2020) Reexamining the relationships among urbanization, industrial structure, and environmental pollution in China—new evidence using the dynamic threshold panel model. Energy Rep 6:28–39

Hee-Sun C, Mack C (2014) Effects of compact urban development on air pollution: empirical evidence from Korea. Sustainability 6(9):5968

Hoek G, Beelen R, de Hoogh K, Vienneau D, Gulliver J, Fischer P, Briggs D (2008) A review of land-use regression models to assess spatial variation of outdoor air pollution. Atmos Environ 42(33):7561–7578

Hu Y, Dai Z, Guldmann JM (2020) Modeling the impact of 2D/3D urban indicators on the urban heat island over different seasons: a boosted regression tree approach. J Environ Manage 266:110424

Huang H, Chen P, Xu X, Liu C, Wang J, Liu C, Clinton N, Gong P (2022) Estimating building height in China from ALOS AW3D30. ISPRS J Photogramm 185:146–157

Jedwab R, Loungani P, Yezer A (2021) Comparing cities in developed and developing countries: population, land area, building height and crowding. Reg Sci Urban Econ 86:103609

Ke B, Hu W, Huang D, Zhang J, Lin X, Li C, Jin X, Chen J (2022) Three-dimensional building morphology impacts on PM(2.5) distribution in urban landscape settings in Zhejiang China. Sci Total Environ 826:154094

Kuang W (2020) 70 years of urban expansion across China: trajectory, pattern, and national policies. Sci Bull 65(23):1970–1974

Lee C (2019) Impacts of urban form on air quality: emissions on the road and concentrations in the US metropolitan areas. J Environ Manage 246:192–202
Li M, Zhang Q, Kurokawa JI, Woo JH, He K, Lu Z, Ohara T, Song Y, Streets DG, Carmichael GR (2017) MIX: a mosaic Asian anthropogenic emission inventory under the international collaboration framework of the MICS-Asia and HTAP. Atmo Chem Phys 17(2):935–963
Li C, Wang Z, Li B, Peng Z-R, Fu Q (2019) Investigating the relationship between air pollution variation and urban form. Build Environ 147:559–568
Li A, Zhou Q, Xu Q (2021a) Prospects for ozone pollution control in China: an epidemiological perspective. Environ Pollut 285:117670
Li F, Zhou T, Lan F (2021b) Relationships between urban form and air quality at different spatial scales: a case study from northern China. Ecol Indic 121:107029
Li M, Wang Y, Rosier JF, Verburg PH, van Vliet J (2022) Global maps of 3D built-up patterns for urban morphological analysis. Int J Appl Earth Obs 114:103048
Li JX, Han LJ, Zhou WQ, Li WF, Qian YG, Zhang ZM (2023) Uncertainties in research between urban landscape and air quality: summary, demonstration, and expectation. Landscape Ecol 38:2475–2485
Lim CH, Ryu J, Choi Y, Jeon SW, Lee W-K (2020) Understanding global PM2.5 concentrations and their drivers in recent decades (1998–2016). Environ Int 144:106011
Liu Y, Song M, Liu X, Zhang Y, Hui L, Kong L, Zhang Y, Zhang C, Qu Y, An J, Ma D, Tan Q, Feng M (2020) Characterization and sources of volatile organic compounds (VOCs) and their related changes during ozone pollution days in 2016 in Beijing. China Environ Pollut 257:113599
Lu C, Liu Y (2016) Effects of China's urban form on urban air quality. Urban Stud 53(12):2607–2623
Lu X, Zhang L, Chen Y, Zhou M, Zheng B, Li K, Liu Y, Lin J, Fu T-M, Zhang Q (2019) Exploring 2016–2017 surface ozone pollution over China: source contributions and meteorological influences. Atmos Chem Phys 19(12):8339–8361
Luan Q, Bo LI, Caihua YE, Zhang X, Zhang Y (2019) Preliminary analysis about impacts of urban 3D landscape pattern on regional meteorological condition in Beijng. Ecol Environ Sci 28(3):514–522
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 92:187–199
Millet, Dylan B, Bechle, Matthew J, Marshall, Julian D (2017) Does Urban Form Affect Urban NO2? Satellite-Based Evidence for More than 1200 Cities. Environ Sci Technol 51(21):12707–12716
Ministry of Ecology and Environment of the People's Republic of China (2018) Report on the State of the Ecology and Environment in China 2017. https://www.gov.cn/. Accessed 22 May 2018
Mircea M, Ciancarella L, Briganti G, Calori G, Cappelletti A, Cionni I, Costa M, Cremona G, D'Isidoro M, Finardi S, Pace G, Piersanti A, Righini G, Silibello C, Vitali L, Zanini G (2014) Assessment of the AMS-MINNI system capabilities to simulate air quality over Italy for the calendar year 2005. Atmos Environ 84:178–188
Paoletti E (2009) Ozone and urban forests in Italy. Environ Pollut 157(5):1506–1512
Paoletti E, De Marco A, Beddows DCS, Harrison RM, Manning WJ (2014) Ozone levels in European and USA cities are increasing more than at rural sites, while peak values are decreasing. Environ Pollut 192:295–299
Peng J, Jia J, Liu Y, Li H, Wu J (2018) Seasonal contrast of the dominant factors for spatial distribution of land surface temperature in urban areas. Remote Sens Environ 215:255–267
Ren Z, Fu Y, Dong Y, Zhang P, He X (2022) Rapid urbanization and climate change significantly contribute to worsening urban human thermal comfort: a national 183-city, 26-year study in China. Urban Clim 43:101154
Ren L, Ki M (2020) Effects of socioeconomic and natural factors on air pollution in China: a spatial panel data analysis. Sci Total Environ 740:140155
Rodriguez MC, Dupont-Courtade L, Oueslati W (2016) Air pollution and urban structure linkages: evidence from European cities. Renew Sust Energy Rev 53:1–9
Shen L, Liu J, Zhao T, Xu X, Han H, Wang H, Shu Z (2022) Atmospheric transport drives regional interactions of ozone pollution in China. Sci Total Environ 830:154634
Sicard P, Agathokleous E, Araminiene V, Carrari E, Hoshika Y, De Marco A, Paoletti E (2018) Should we see urban trees as effective solutions to reduce increasing ozone levels in cities? Environ Pollut 243:163–176
Strosnider HM, Chang HH, Darrow LA, Liu Y, Vaidyanathan A, Strickland MJ (2019) Age-specific associations of ozone and fine particulate matter with respiratory emergency department visits in the United States. Am J Respir Crit Care Med 199(7):882–890
Symonds MRE, Moussalli, A (2011) A brief guide to model selection, multimodel inference and model averaging in behavioural ecology using Akaike's information criterion. Behav Ecol Sociobiol 65(1):13–21
Taseiko OV, Mikhailuta SV, Pitt A, Lezhenin AA, Zakharov YV (2009) Air pollution dispersion within urban street canyons. Atmos Environ 43(2):245–252
Taubenböck H, Debray H, Qiu C, Schmitt M, Wang Y, Zhu XX (2020) Seven city types representing morphologic configurations of cities across the globe. Cities 105:102814
Tian Y, Yao XBA, Mu L, Fan QJ, Liu YJ (2020) Integrating meteorological factors for better understanding of the urban form-air quality relationship. Landscape Ecol 35(10):2357–2373
Wang P, Chen Y, Hu J, Zhang H, Ying Q (2019) Source apportionment of summertime ozone in China using a source-oriented chemical transport model. Atmos Environ 211:79–90
Wang ZB, Li JX, Liang LW (2020) Spatio-temporal evolution of ozone pollution and its influencing factors in the Beijing-Tianjin-Hebei Urban Agglomeration. Environ Pollut 256(113419):1–11
Wang R, Bei N, Hu B, Wu J, Liu S, Li X, Jiang Q, Tie X, Li G (2022a) The relationship between the intensified heat waves and deteriorated summertime ozone pollution in the Beijing–Tianjin–Hebei region, China, during 2013–2017. Environ Pollut 314:120256
Wang WJ, Tian PL, Zhang J, Agathokleous E, Xiao L, Koike T, Wang H, He X (2022b) Big data-based urban greenness

in Chinese megalopolises and possible contribution to air quality control. Sci Total Environ 824:153834

Wang T, Xue L, Brimblecombe P, Lam YF, Li L, Zhang L (2016) Ozone pollution in China: a review of concentrations, meteorological influences, chemical precursors, and effects. Sci Total Environ 575:1582–1596

Wang Y, Zhang Y, Hao J, Luo M (2011) Seasonal and spatial variability of surface ozone over China: contributions from background and domestic pollution. Atmos Chem Phys 11(7):3511–3525

Weber N, Haase D, Franck U (2014) Assessing modelled outdoor traffic-induced noise and air pollution around urban structures using the concept of landscape metrics. Landscape Urban Plan 125:105–116

Wei J, Li Z, Li K, Dickerson RR, Pinker RT, Wang J, Liu X, Sun L, Xue W, Cribb M (2022) Full-coverage mapping and spatiotemporal variations of ground-level ozone (O3) pollution from 2013 to 2020 across China. Remote Sens Environ 270:112775

Wu WB, Yu ZW, Ma J, Zhao B (2022) Quantifying the influence of 2D and 3D urban morphology on the thermal environment across climatic zones. Landscape Urban Plan 226:104499

Xiang S, Liu J, Tao W, Yi K, Tao S (2020) Control of both PM2.5 and O3 in Beijing-Tianjin-Hebei and the surrounding areas. Atmos Environ 224:117259

Xiao L, Hong J, Lin Z, Cooper OR, Schultz MG, Xu X, Tao W, Gao M, Zhao Y, Zhang Y (2018) Severe surface ozone pollution in china: a global perspective. Environ Sci Technol 5:487–494

Xie Y, Dai H, Zhang Y, Wu Y, Hanaoka T, Masui T (2019) Comparison of health and economic impacts of PM(2.5) and ozone pollution in China. Environ Int 130:104881

Xu H, Chen H (2021) Impact of urban morphology on the spatial and temporal distribution of PM2.5concentration: a numerical simulation with WRF/CMAQ model in Wuhan China. J environ manage 290:112427

Yan M, Liu Z, Liu X, Duan H, Li T (2013) Meta-analysis of the Chinese studies of the association between ambient ozone and mortality. Chemosphere 93(6):899–905

Yang J, Shi B, Shi Y, Marvin S, Zheng Y, Xia G (2020) Air pollution dispersal in high density urban areas: research on the triadic relation of wind, air pollution, and urban form. Sustain Cities Soc 54:101941

Yang X, Zeng G, Iyakaremye V, Zhu B (2022) Effects of different types of heat wave days on ozone pollution over Beijing-Tianjin-Hebei and its future projection. Sci Total Environ 837:155762

Yazdi MD, Wang Y, Di Q, Zanobetti A, Schwartz J (2019) Long-term exposure to PM25 and ozone and hospital admissions of Medicare participants in the Southeast USA. Environ Int 130:104879

Yu X, Liu Y, Zhang Z, Xiao R (2021) Influences of buildings on urban heat island based on 3D landscape metrics: an investigation of China's 30 megacities at micro grid-cell scale and macro city scale. Landscape Ecol 36(9):2743–2762

Yuan M, Song Y, Huang Y, Hong S, Huang L (2017) Exploring the association between urban form and air quality in China. J Plan Educ Res 38(4):413–426

Yuan M, Song Y, Huang Y, Shen H, Li T (2019) Exploring the association between the built environment and remotely sensed PM25 concentrations in urban areas. J Clean Prod 220:1014–1023

Zhang X, Lu Y, Qg W, Qian X (2019) A high-resolution inventory of air pollutant emissions from crop residue burning in China. Atmos Environ 213:207–214

Zhang Y, Ou C, Chen L, Wu L, Liu J, Wang X, Lin H, Gao P, Hang J (2020) Numerical studies of passive and reactive pollutant dispersion in high-density urban models with various building densities and height variations. Build Environ 177:106916

Zhang A, Xia C, Li W (2022a) Exploring the effects of 3D urban form on urban air quality: evidence from fifteen megacities in China. Sustain Cities Soc 78:103649

Zhang X, Osei F, Stein A, Cheng C, Maji KJ (2022b) Temporal and spatial evolution of short-term exposure to ozone pollution: its health impacts in China based on a meta-analysis. J Clea Prod 373:133938

Zhao PJ, Lu B, de Roo G (2010) Urban expansion and transportation: the impact of urban form on commuting patterns on the city fringe of Beijing. Environ Plan 42(10):2467–2486

Zhao D, Chen H, Li X, Ma X (2018) Air pollution and its influential factors in China's hot spots. J Clea Prod 185:619–627

Zhou W, Jiao M, Yu W, Wang J (2019) Urban sprawl in a megaregion: a multiple spatial and temporal perspective. Ecol Indic 96:54–66

Zhou Y, Zhao H, Mao S, Zhang G, Jin Y, Luo Y, Huo W, Pan Z, An P, Lun F (2022) Exploring surface urban heat island (SUHI) intensity and its implications based on urban 3D neighborhood metrics: an investigation of 57 Chinese cities. Sci Total Environ 847:157662

Zhu Z, Zhou Y, Seto KC, Stokes EC, Deng C, Pickett STA, Taubenböck H (2019) Understanding an urbanizing planet: Strategic directions for remote sensing. Remote Sens Environ 228:164–182