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Air quality and its response to satellite-derived urban form in the Yangtze River Delta, China

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ABSTRACT

Air pollution is one of the top environmental concerns and causes of deaths and various diseases worldwide. An important question for sustainable development is to what extent urban design can improve or degrade urban air quality. In this article, we explored the relationship between ground-based observations of air pollution and urban form in the Yangtze River Delta (YRD), the largest metropolitan region in China. We analyzed six criteria pollutants (SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, O_3) and summarized metric (air quality index, AQI) from 129 ambient air quality monitoring stations during 2015. Urban form was characterized using six spatial metrics, including the size, shape, regularity, fragmentation and traffic coupling factor of urban patches, based on satellite-derived land cover data. The results indicated that: (1) $PM_{2.5}$, PM_{10} and O_3 were three primary pollutants in the YRD. The annual average AQI was 79, and the air quality was "moderate" for human health, with the highest and lowest AQI appeared in winter (107) and summer (60). Moreover, the air quality of the southern areas (Zhejiang province, AQI: 68) was generally better than the northern parts (Jiangsu province, AQI: 86). (2) Through the size and shape of urban patches, urban form had a significant effect on urban air quality in the YRD. PARA_MN (Mean Perimeter-area ratio), ENN_MN (Mean Euclidean Nearest Neighbor Distance), CA (Total Urban Area) and NP (Number of urban patches) had the most significant impacts on air quality. PM_{10} and $PM_{2.5}$ were two important pollutants highly positively related to CA and NP, while negatively related to PARA_MN and ENN_MN. In addition, the polycentric urban form was associated with high air quality. (3) Land use configuration was an important indicator to describe the urban air quality. When buffer distance of spatial scale was 25 km, air quality showed the highest correlation with forest coverage. A high forest coverage rate contributed to the better air quality, increasing or preserving the forested areas would help mitigate the air pollution.

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1. Introduction

During 2014, 54% of the world's population resides in urban areas (United Nations, 2014). In recent decades, air pollution is one of the top environmental concerns and causes of death and disease. Worldwide, the number of premature deaths by air pollution increased from 0.22 million in 2010–3.7 million in 2012, highlighting a high health risk. In China, air pollution has become the fourth greatest risk factor in all deaths (Fang et al., 2015; Matus et al., 2012), thus poor urban air quality in China attracts great attention in recent years (Shobhakar, 2009; Yang et al., 2015).

Air quality can be influenced directly or indirectly by climate change, meteorological and socioeconomic factors, but the way in which cities grow and evolve spatially is a crucial component (Han et al., 2015; Lu and Liu, 2015). Most literatures in China currently focus on pollution sources and the meteorological condition of pollutants transformation (Zhang et al., 2009; Zhang and Zhang, 2014). Pursuant to those studies, the finding of spatial land use pattern and air quality has become more and more important, because the global change study gradually drives the research of land use (Tang and Liu, 2015). Urban form, the spatial land use configuration of the urban landscape, significantly affects how cities

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function and how much air pollution they produce (Borrego et al., 2006; EPA, 2010; Frank and Pivo, 1994). In detail, urban form can affect air quality by influencing population density, vehicle tailpipe emissions, configurations of streets influence pollutant dispersion, and local meteorology includes the energy efficiency of buildings (Bereitschaft and Debbage, 2013; Ewing and Rong, 2008; Weng, 2003; Zhou and Levy, 2008). Flow and pollutant dispersion around buildings is not only associated to the packing density of buildings, but originates also from building-height variability (Blocken, 2014), the increase of the building chimney height dramatically reduces the deposition rate of the chimney exhaust emission (Tominaga and Stathopoulos, 2013). The superposition and interaction of the flow patterns induced by the buildings and structures strongly affect the dispersion and govern the movement of pollutants (Lateb et al., 2016). The interaction of prevailing atmospheric conditions with buildings creates diverse air ventilation systems and complex flow structures (i.e. separation, circulation, and reattachment) in urban street canyons (Yazid et al., 2014). Computational fluid dynamics (CFD) models are common used to study the pollutant distributions and wind flow in street canyons (Li et al., 2006). Gaining a better understanding of the relationships between urban form and air quality is a critical component in the broader effort to identify effective urban land use configurations and develop healthier cities (John and Michael, 2014).

Landscape metrics are frequently used to characterize urban land use patterns and very useful for representing urban forms (Herold et al., 2005). There are several advantages of using landscape metrics for urban analysis, such as improving the representation of heterogeneous urban landscapes, bridging the gap between urban land use patterns and the governing processes, and facilitating the analysis of impacts of urban development on the surrounding environment (Chen et al., 2011). To our knowledge, better urban design has potential to enhance good air quality (Marshall, 2008; Madlener and Sunak, 2011). Existing literature revealed that low-density and car-oriented urban sprawl mainly increases air pollution and fragmentary urban form'is associated with low air quality (McCarty and Kaza, 2015). Metropolitan areas exhibiting higher levels of "sprawl-like" urban forms, generally had higher air pollution concentrations when controlling for climate, population, and land area. Furthermore, Bechle et al. (2011) used satellite-derived estimation of urban form and NO_2 air pollution for 83 global cities, and observed that more contiguous built-up areas tend to experience lower urban NO_2 concentrations. Clark et al. (2011) suggested that population centrality was associated with lower population weighted $PM_{2.5}$ and O_3 by investigating 111 U.S. urban areas.

Although existed studies explored the spatial pattern and focused on little impact factors of air quality, few studies deeply analyzed quantitatively the impacts of different urban land use patterns on air quality (Zhang and Zhang, 2014). Besides, some researches provided evidence for linkages between urban form and air quality just based on 1–2 air pollutants (i.e. tropospheric O_3 or NO_2) as the air quality measure, or the single (though multivariate) urban sprawl index to characterize urban form (Bereitschaft, 2011; Ewing et al., 2003; Stone, 2008), instead of multiple indicators. In addition, most empirical studies on urban areas concentrated on metropolitan areas in developed countries (Lu and Liu, 2015), but with limited observational evidence linking urban form and urban air quality at a multi-urban scale (not individual sectors) in developing countries such as China (Clark et al., 2011). Apparently, urban air quality has improved for many pollutants in developed countries in recent decades, but declined in most developing countries for reasons including rapid urban growth, increased congestion and automobile ownership, strained transportation infrastructure, and lack of effective emission control policies (EPA, 2010; WHO, 2010). As a result, measuring and characterizing how and to what degree particular aspects of urban form affects air quality in developing countries is an important step for planners and policy analysis. Before 2012, air pollution index (API), with three criteria air pollutants (PM_{10}, SO_2, NO_2), was the criterion for monitoring and evaluating air pollution in China. However, API was not comprehensive to describe the air pollution level in China, especially compared to standards in World Health Organization (WHO) (Sun et al., 2012). In 2012, Chinese Ministry of Environmental Protection (MEP) has published the third revision of the "*Ambient air quality standards*" (GB3095-2012). Following this standard, a relatively comprehensive indicator-air quality index (AQI), with six criteria air pollutants (SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, O_3), was proposed and implemented in 74 cities since 2012, in 113 cities from 2013, in all prefecture-level cities from 2015.

Therefore, based on those previous studies and accumulate experiences above, the present study explores the correlation between urban form and urban air quality in China, specific for the Yangtze River Delta (YRD), which suffers from intensive human disturbance and rapid urbanization. We analyzed the newly proposed air quality index (AQI) in addition to its six criteria pollutants (SO_2, NO_2, PM_{10}, $PM_{2.5}$, CO, O_3), and the hourly observation for air pollution from 129 ambient air quality monitoring stations during 2015. Urban form was characterized using spatial metrics including the size, shape, regularity, fragmentation and traffic coupling factor of urban patches, applied to satellite-derived land cover data. The objectives of this research work were 1) to examine the spatial and temporal variation of air quality for different types of land cover in the YRD during 2015, and 2) to link urban forms to different levels of air pollution. This research will provide the essential information and better understanding of urban form and air quality as an empirical case, and identify the instant challenges to improve the air quality in the densely populated area.

2. Data and methods

2.1. Study area

Yangtze River Delta (116°29′–123°45′ E, 27°14′–35°33′ N) is located at the junction of the Yangtze River and the East China Sea (Fig. 1), belongs to marine subtropical monsoon climate with four distinct seaosns, has an annual mean temperature of 16.7 °C, and receives 1536 mm of annual precipitation (2015, data from China Meteorological Data Network). It covers an area of 210,700 km^2, encompasses Jiangsu province, Zhejiang province, and Shanghai municipality, with 25 cities in total. In addition, it contains 2.1% of the national land areas, 11% of the population and contributes 21.7% of the Chinese national economy (Jiangsu Statistics Bureau, 2014; Shanghai Statistics Bureau, 2014; Zhejiang Statistics Bureau, 2014). The YRD is one of the most developed, densely populated, and economically vibrant regions in China. It is strong in finance and export processing as well as heavy industries with major companies, its rapid economic growth and high degree of urbanization have resulted in a remarkable incensement of air pollutant emissions (National Development and Reform Commission, 2014).

In recent 10–20 years, the urban built-up areas in the YRD ranged from 1.6 million km^2 in 1990–2.8 million km^2 in 2013, increased by 74.68%, which suggested significant variation within the urban form in the YRD. Similarly, the total energy consumption in 2013 was about four times more than that in 1985 (Zhai et al., 2012). Since 2005, the total electric consumption in the YRD increased by more than 5% annually, reached 994.14 billion kilowatt-hour (KWH) in 2014. The number of vehicles increased to 23.63 million, accounting for 16.2% of the national average rate, which accelerated the annual average NO_2 concentration, and the annual NO_2 emissions in the YRD exhibited an increasing trend by

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