Spatial and temporal patterns of air quality in the three economic zones of China

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ABSTRACT
The air pollution problem in China continues to become more severe with dramatic economic development. The focus of this study was to create a map representing the spatial-temporal pattern of the air quality in the three major economic zones in China, including the Beijing–Tianjin–Hebei Economic Zone, the Yangtze River Delta Economic Zone, and the Pearl River Delta Economic Zone in 2014. A calendar view was used to visualize the daily condition of air quality and primary pollutant in each city in 2014, and geographic references were added to each visualization according to their spatial relationships. The map provides an efficient way to investigate and understand the current status of air quality and spatial-temporal patterns of air quality.

1. Introduction
China has experienced dramatic economic growth over the past three decades, which has been accompanied by serious air pollution problems. Although tremendous efforts have been made by China to limit air pollution, these problems remain severe. With the maintenance of economic growth in China, a priority which is largely achieved through the energy-intensive construction of infrastructure, protection of the environment is a low priority. Moreover, the lack of cooperation among various government agencies has been detrimental to the control of air pollution (Zhang, He, & Huo, 2012). Air pollution has grave effects on the environment, climate, and human health. Compelling results have shown strong associations between air pollution and various health effects (Chen et al., 2012; Kan, Chen, & Tong, 2012; Wang et al., 2013). Investigating and understanding both the current status of air quality and the spatial-temporal patterns of air quality are of significant importance to scientists, policy-makers, and the public, as these studies help to identify the major air pollution issues, raise public awareness of environmental protection, and inform an air pollution abatement policy.

Spatial-temporal patterns of air quality have previously been studied through statistical analysis (Carslaw & Ropkins, 2012), such as Spearman rank correlation analysis to evaluate relationships between monitoring stations (Li et al., 2014), seasonal-trend decomposition to analyze temporal variation, and trends of air quality (Bigi & Harrison, 2010; Cleveland, Cleveland, Mcrae, & Terpenning, 1990; Li et al., 2014), and regression models to predict air quality (Dionisio et al., 2010). However, a visualization of air quality offers several advantages over statistical analysis, as it can be intuitive, requires less understanding of complex mathematical or statistical algorithms and parameters, and can be easily understood, especially by the public. These advantages allow a visualization to reach more people, have a wider impact on humanity, and to raise public awareness of environmental protection. Visual methods can be used to analyze the temporal variation of air pollution in a city for time-oriented data (Aigner, Miksch, Muller, Schumann, & Tominski, 2008), and adding spatial reference to the cities allows for the spatial variation to be analyzed. This paper attempts to uncover the spatial-temporal patterns of air quality and the primary pollutant through the use of maps. The Beijing–Tianjin–Hebei Economic Zone, the Yangtze River Delta Economic Zone, and the Pearl River Delta Economic Zone are the three most important economic zones in China, and they have pioneered the nation in industrialization and urbanization processes. Thus, these regions attract the most attention regarding air pollution. This study focuses on analyzing the spatial-temporal variations and patterns among and within these zones.

2. Method
2.1. Study area and data
The Beijing–Tianjin–Hebei Economic Zone is located in northern China and includes two municipalities,
Beijing and Tianjin, and one province, Hebei. There are 13 cities, including Beijing and Tianjin, at the prefec-
tural level and above. The Yangtze River Delta Econ-
omic Zone is located in eastern coastal China and
includes one municipality, Shanghai, two provinces,
Jiangsu and Zhejiang, and various cities in Anhui pro-
vince, including Hefei, Maanshan, Wuhu, Chuzhou,
and Huainan. There are 30 cities, including Shanghai,
at the prefectural level and above. The Pearl River Delta Economic Zone is located in the southeastern
part of Guangdong Province in China. There are nine
cities at prefectoral level and above.

The Ministry of Environmental Protection of the
People’s Republic of China (http://datacenter.mep.
gov.cn/) provided daily data of the air quality index
(AQI), grade of AQI, and primary pollutant of cities
in China in 2014, according to Ambient Air Quality
Standards and Technical Regulation on Ambient Air
Quality Index (on trial) of China. AQI is defined as fol-
lows:

\[
AQI = \max\{IAQI_1, IAQI_2, IAQI, \ldots, IAQI_n\},
\]

where IAQI is the individual AQI, \(n\) is the pollutant
items. The pollutant with the highest IAQI is the pri-
mary pollutant of the day.

Some cities in the Yangtze River Delta Economic
Zone, including Chuzhou and Huainan in Anhui pro-
vince, are not represented on the map presented in this
study due to lack of data.

2.2. Visualizing time-oriented air quality of a
city

The daily data of air quality of a city is time-oriented.
A rectangle represents daily data, and the arrange-
ment of rectangles reflects the temporal structure of
a year. Quantitative and qualitative colors are used
to encode air quality grade and primary pollutant,
respectively.

2.2.1. Color legend design

A diverging color scheme is used to represent the grade
of air quality, which is based on the Technical Regulation
on Ambient Air Quality Index (on trial) (Table 1). The
color scheme accords with human cognition, in that
green indicates fresh and clean, warm colors, including
orange, red, and purple, indicate pollution, and brown
indicates more serious pollution.

Particles with an aerodynamic diameter less than
2.5 \(\mu\)m (PM2.5), particles with an aerodynamic diam-
eter less than 10 \(\mu\)m (PM10), sulfur dioxide (SO2),
nitrogen dioxide (NO2), carbon monoxide (CO), and
Ozone(O3) are defined as the six main pollutants
around the world in quantifying air pollution levels.
The qualitative color scheme representing the pollu-
tants is shown in Table 2, and is designed using
Color Brewer (Harrower & Brewer, 2003).

2.2.2. Arrangement of the daily data

To identify the temporal pattern of air quality over
multiple time scales, including day, week, and
month, rectangles that represent the daily data
should be arranged reasonably. The rectangles are
arranged to produce a calendar view to represent
the air quality of each city (Van Wijk & Van
Selow, 1999). The months can be easily detected in
the calendar view, as the aspect ratio of the polygon
representing each month is closer to 1. Moreover, the
calendar view can be used to detect the possible pat-
tern of a week.

The rectangles representing each day are arranged
according the calendar of 2014. As shown in Figure
1, rectangles representing Monday in May are in the
same row. The calendar view nests four temporal resol-
utions, including day, week, month, and year.

| Table 1. Corresponding information for AQI based on the Technical Regulation on Ambient Air Quality Index (on trial). |
|-----------------|----------------|-----------------|-----------------|-----------------|-----------------|
| AQI             | Grade of AQI   | Category of AQI | Color           | Health implications                                    |
| 0–50            | One            | Excellent       | Green           | No health implications                                  |
| 50–100          | Two            | Good            | Yellow          | Air quality is considered acceptable, and some pollutant may have a slight impact on the health of hypersensitive individuals |
| 100–150         | Three          | Lightly polluted| Orange          | Symptoms of susceptible population are aggravated slightly, healthy population have stimulating symptoms |
| 150–200         | Four           | Moderated polluted| Red            | Symptoms of susceptible population are aggravated more, and it may have impacts on the heart and respiratory system of healthy population |
| 200–300         | Five           | Heavily polluted| Purple          | Symptoms of population with heart disease and pulmonary disease are aggravated significantly, and his exercise tolerance is reduce. Healthy population have symptoms generally |
| >300            | Six            | Severely polluted| Brown          | The exercise tolerance of healthy population is reduce, some diseases appear in advance |

| Table 2. Pollutant. |
|---------------------|---------------------|
| Pollutant | color |
| SO2 | Green |
| NO2 | Yellow |
| CO | Orange |
| O3 | Red |
| PM10 | Pink |
| PM2.5 | Brown |
| None | Blue |
2.3. Adding spatial reference to the cities

It is necessary to add a geographic reference to the visualization of air quality of each city to represent the spatial–temporal characteristics of air quality of the three economic regions. Diagram maps are commonly used, which can be achieved by placing each diagram in its geographic location on an underlying map. However, there are too many distracting graphic cues disturbing the diagram interpretation when a diagram is represented against an underlying map (Kraak & Ormeling, 2002). Furthermore, users concentrate on the diagram itself when comparing each diagram. Considering these two key issues with diagram maps, adding a precise geographic reference makes little sense. To solve these issues, each diagram is arranged according to its approximate geographic location (Zhou, Tian, Xiong, & Wang, 2016); a diagram representing a city and a diagram representing its neighboring city in geographic space are connected (the neighboring relationship is defined through a Euclidean minimal spanning tree (EMST), and the connected nodes in EMST are neighbors). The direction between two diagrams representing close neighboring cities in geographic space is expressed by a symbolic direction on the maps, and the specific system of direction is expressed as a set \(C_8=\{N, NE, E, SE, S, SW, W, NW\}\) (Frank, 1992). Thus, this method can represent the geographic relationships between the cities to some extent while offering a method to easily compare the air quality of each city. Figure 2 shows a comparison between the presented ‘grid’ method and a point diagram map. Diagrams in point diagram maps may overlap in

![Figure 1. Calendar view of AQI grade of Beijing in 2014.](image1)

![Figure 2. Comparison of the primary pollutant of the Yangtze River Delta Economic Zone represented by (a) the point diagram map and (b) the presented grid map.](image2)
some dense areas. Cities in each economic region are allocated a position according to the following steps:

(1) Construct an EMST of a group of cities according to their geographic locations.

It is necessary to extract a perceptually relevant structure of a set of points to preserve the spatial configuration of a group of cities. EMST is used as a structure of the group of cities, as it is of perceptual significance. The connected cities in EMST are neighboring cities.

(2) Transform the group of cities based on the MST.

The direction between the neighboring cities in a geographic space is described by a symbolic direction, and the specific system of direction is expressed as a set \( C_8=\{N, NE, E, SE, S, SW, W, NW\} \). Start from an arbitrary city, allocate an arbitrary position to the city, allocate a position to its neighboring city according to their directional relationship defined by the symbolic direction. As shown in Figure 3, the best position for \( p_2 \) is the darkest red grid cell, the second best position is the relatively dark red grid cell, and the third best position is the lightest red grid cell. Assignment is conducted in this manner until a position has been allocated to all diagrams. The results of the transformation of cities in the three economic zones are shown in Figure 4.

3. Results and discussion

3.1. Spatial variation

The air quality of the three economic zones was generally poor, and conditions gradually worsened from south to north at the national scale. Cities in the Beijing–Tianjin–Hebei Economic Zone were rendered red or even maroon, cities in the Yangtze River Delta Economic Zone were rendered yellow, and cities in the Pearl River Delta Economic Zone were rendered green and yellow (Maps 1(a), 2(a), and 3(a)). \( \text{SO}_2, \text{NO}_2, \text{CO}, \text{O}_3, \text{PM}_{2.5} \) and \( \text{PM}_{10} \), and \( \text{NO}_2 \) are regarded as the six indexes when evaluating air quality, and \( \text{CO}, \text{O}_3, \text{NO}_2 \) are considered as indicators of motor vehicle emission pollution source. \( \text{PM}_{2.5} \) (yellow), which causes the ‘gray sky’ phenomenon in recent years, and \( \text{O}_3 \) (orange), which is the main component of photochemical smog, are the primary pollutants in most of the cities for most of the time in the three economic zones, and they are the main factors influencing air quality (Maps 1(b), 2(b), 3(b)). With the rapid increase in the number of motor vehicles, the type of air pollution in the three economic zones is not the conventional coal combustion type with major pollutants total suspended particulate and \( \text{SO}_2 \).

At the scale of the economic zone, the air quality in Beijing–Tianjin–Hebei Economic Zone (Map 1(a)) allows the region to be divided into roughly three parts: (1) the southern part, including Baoding, Hengshui, Shijiazhuang, Xingtai, and Handan, which has the worst air quality; (2) the north-central part, including Beijing, Langfang, Tangshan, and Tianjin; and (3) the northern part including Zhangjiakou, Chengde, and Qinhuangdao, which has much better air quality than the other two parts. A Ward’s agglomeration hierarchical clustering method (Ward, 1963) based on squared Euclidean Distance was adopted to divide the cities into groups according to their AQIs to validate the division detected by the map. The result is shown in Figure 5(a), which is consistent with the findings from the map. We also adopt a between-groups linkage method and within-groups linkage method, and the three cluster results are very similar. The common primary pollutants in this zone were \( \text{PM}_{2.5}, \text{PM}_{10}, \text{and } \text{O}_3 \) (Map 1(b)). \( \text{PM}_{2.5} \) was not the common primary pollutant in the northern part, which makes this region quite different from the rest of the cities in this economic zone.

At the scale of economic zone, the Yangtze River Economic Zone was faced with light air pollution. This zone can be divided according to air quality (Map 2(a)) into roughly two parts, the first being the southern part, including Zhoushan, Lishui, Ningbo, Taizhou, and Wenzhou, which has a much better air quality than the rest of the cities in this zone. A Ward’s agglomeration hierarchical clustering method
based on squared Euclidean Distance was also used here, and the result is shown in Figure 5(b), which is consistent to some extent with the findings from the map. We also adopt the between-groups linkage method and within-groups linkage method, and the three cluster results are basically the same. The common primary pollutants in this zone were PM2.5 and O3, but there were some differences throughout the zone (Map 2(b)). The primary pollutant in cities of Anhui province, including Hefei, Ma’anshan, and Wuhu, was almost always PM$_{2.5}$, and it was rare that O$_3$ was the primary pollutant. PM$_{10}$ was sometimes the primary pollutant, especially in northern Jiangsu province, including Xuzhou and Lianyungang, and NO$_2$ was the primary pollutant distributed sporadically in cities of Zhejiang province.

At the scale of economic zone, the Pearl River Delta Economic Zone can be divided into roughly two parts according to air quality (Map 3(a)); (1) the north-western part, including Foshan, Guangzhou, Dongguan,
and Zhaoqing, which has relatively worse air quality and (2) the southern and north-eastern parts, which have better air quality. The result from the Ward’s agglomeration hierarchical clustering method based on squared Euclidean Distance for this zone is shown in Figure 5(c), which is consistent with the findings from the map. We also adopt between-groups linkage method and within-groups linkage method, and the three cluster results are the same. The common primary pollutants in this zone were O₃, PM₂.₅, and NO₂ (Map 3(b)), with NO₂ being the primary pollutant mainly in the north-western part.

3.2. Temporal variation

There was an obvious seasonal pattern in both the Beijing–Tianjin–Hebei Economic Zone and the Pearl River Delta Economic Zone; summer had the best air quality, then autumn and spring, and winter had the worst air quality (Maps 1(a), 2(a) and 3(a)). Coal heating and unfavorable meteorological factors may cause serious air pollution during winter. This seasonal pattern was not obvious in the Yangtze River Delta Economic Zone.

At the scale of economic zone, the primary pollutant in the Beijing–Tianjin–Hebei Economic Zone altered throughout the year between PM₂.₅, PM₁₀, or O₃, with PM₂.₅ for most of the year and O₃ mainly during May through August in some cities (Map 1(b)). In the Yangtze River Delta Economic Zone, PM₂.₅ was the primary pollutant for most of the year, with O₃ the primary pollutant concentrated in the middle of the year in most cities (Map 2(b)). The Pearl River Delta Economic Zone has a coarser spatial resolution of variation,
with the temporal distribution of different primary pollutants more concentrated: O₃ in the middle of the year and PM₂.₅ at the beginning and the end of the year (Map 3(b)). In some cities, including Foshan, Guangzhou, and Dongguan, NO₂ was sometimes the primary pollutant, especially during the months of spring.

4. Conclusions

The air quality map shows the spatial–temporal patterns of the air quality of the three economic zones in China. The calendar view was used to visualize both the daily condition of air quality and the primary pollutant of each city in 2014, and the geographic references were added to the visualization according to their spatial relationships. This method is helpful for identifying major air pollution issues, raising public awareness of environmental protection, and making an air pollution abatement policy. Future work will focus on combining the visualization method (qualitative analysis) with quantitative analysis to make the result not only intuitive, but also more accurate and persuasive, and it will use precise data rather than the classified data. Some statistical models may be used to analyze the air quality in China, such as the principal component analysis and also localized models (Gollini, Lu, Charlton, Brunsdon, & Harris, 2013).

Software

Several software packages were used in the development of the map. A script was developed in Python to color a calendar view to visualize the air quality of each city. ESRI ArcGIS 10.1 was used to arrange the diagram of each city according to their locations. CorelDRAW X6 was used for cartographic enhancement.

Disclosure statement

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