Visual Analysis Method of Air Pollution for High-dimensional and Spatial-temporal Data

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Abstract

In recent years, as one of the main problems of environmental pollution, air pollution has attracted the continuous attention of society. The existing analysis methods show the data characteristics in a single way, which is difficult to meet the needs of users' independent exploration and pollution pattern recognition. Therefore, an interactive visual analysis system of air pollution is proposed in this paper. Based on the 2013-2018 air pollution reanalysis dataset, high-dimensional and spatio-temporal pollution records are preprocessed by filling in missing values, inverse geocoding and pollution index aggregation technology. The Geographical Weighted Regression(GRW) and traceability algorithm are used to explore the climate correlation characteristics and the spatio-temporal evolution trend of pollution. The system consists of control panel and view display. The control panel helps users explore and choose dynamically. The view display part is composed of multiple views, supplemented by reasonable visual coding. At the same time, it supports flexible and intuitive interactive design to help users understand the pollution situation. In order to verify the effectiveness of the system, we conducted case studies from many aspects. To conduct user study, we compare the MeteoInfo software with the system and get good feedback according to the user experience. Therefore, the work is of great significance to the study of climate pollution and also provides technical support for decision-making of air pollution prevention and control.

Keywords

Visual Analysis; Air Pollution; Spatio-temporal Data; Geographical Weighted Regression.

1. Introduction

With the rapid economic development at the expense of the environment, serious air pollution has appeared in many cities and regions in China. Air pollution seriously endangers residents' health, and many experts and scholars have found that a large number of people around the world die from diseases related to air pollution every year. In 2017 alone, the number of people who died of diseases due to air pollution in the world reached nearly 5 million, while the number in China was still as high as 1.2 million. According to relevant data, air pollution will shorten the life expectancy by 20 months. Among all the risk factors, air pollution ranks among the top five. In addition, air pollution will do harm to the city and the natural environment. When the atmosphere is polluted and industrial waste gas is discharged, acid rain will be formed, which will corrode buildings and trees, resulting in the loss of nutrients in the soil and the change of soil structure, affecting the normal planting of crops and reducing agricultural output. In addition, air pollutants will also cause greenhouse effect, leading to sea level rise and other hazards.

China also spends a lot of money on the prevention and control of air pollution every year. Prevention and control of air pollution and protection of natural environment have become serious problems that China's current environmental construction has to face.

Although Chinese government has invested a lot of energy to control air pollution, it is still difficult to establish an air quality detection system, which makes it impossible to conduct a thorough study on air pollution. At present, most researchers believe that pollutants mainly come from two aspects. One is the discharge of local pollutants. The other is the spread of pollutants in other areas. To fundamentally solve the problems caused by air pollution, we need to systematically analyze the areas where the problems occurred, which requires the establishment of an air pollution analysis system to assist in relevant analysis.

In view of above situation, this paper analyzes the data of air pollutants through the open source dataset in China from 2013 to 2018, and processes the dataset accordingly. Data dimensionality reduction and correlation research of climate factors are used to further mine the data and obtain deeper information. On this basis, this paper establishes a national visual analysis system of air pollution. The system design and implementation of various views, interactive design of the whole process to help users analyze the evolution trend and spread of air pollution.

2. Related Work

2.1 Visual Analysis of Air Data

With the continuous development of air pollution detection technology, China has established a perfect air quality monitoring network. Monitoring points can continuously provide high-quality and high spatial-temporal resolution monitoring values of air pollutants, which makes it possible to visualize air pollutants. However, due to the high complexity of air pollution data, most traditional analysis methods focus on data abstraction. Visual analysis technology can retain the original information of data to provide users with certain visual feedback. Therefore, the visualization of air quality data has become a research hotspot in the field of visualization and visual analysis. Visual analysis based on air quality data is mainly divided into analyzing the temporal and spatial variation law of air quality, the influencing factors of air pollution and the transmission process of air pollution.

In the visualization research of air pollution, Du Yi [1] et al. put forward a visual analysis system to reveal the lead/lag correlation between different areas in air pollution. This system can analyze the spatial and temporal dimensions and the correlation of air quality in different time and space scales, and use the ring mapping method to keep the contextual spatial information when the zoom level of the map is changed. Qu Humain [2] and others designed a visual analysis system for analyzing the correlation between different air pollutants and meteorological factors in Hong Kong. Li Jie et al. used multi-view combination to visually analyze the correlation between smog and meteorological conditions in China. J.Martorell-Marugan [3] et al. combined meteorological and air quality data with COVID-19 to design a visual analysis system DatAC, so as to explore and analyze the correlation between climate factors. The visual analysis system AirVis designed by Du [4] and others based on air quality monitoring data integrates three different views. ChenPengyu [5] visualizes the real-time monitoring data of 23 air quality monitoring points in Beijing. Analysts can obtain specific air quality data through interactive query. Sun Guoda [6] and others put forward a comprehensive visual analysis system to analyze the spatial-temporal model of urban agglomeration in the air quality data, and used the stacked graph with embedded lines to show the evolution and distribution of urban agglomeration. Zhu Zhiguang [7] and others used Voronoi diagram and hierarchical clustering algorithm to map the spatial division of air quality monitoring points to MDS diagram, thus assisting domain experts to determine the causes of air pollution.

2.2 Visualization of Spatial-temporal Multidimensional Data

In addition, the air pollution data is characterized by multi-dimensional space and time. Therefore, the visualization of high-dimensional spatial-temporal data is often involved in the design of air pollution visualization. In the research of high-dimensional spatial-temporal data visualization, Guo Hanqi [8] et al. designed the visualization form of traffic track lines for complex urban traffic track data, and showed the changes of traffic and flow direction of various moving objects in time dimension through river graphs with embedded glyphs. Liu Dongyu [9] and others modeled spatial-temporal multidimensional data as tensors, and compared and visually summarized them by partitioning the data. In visual design, icon mapping, ring mapping and other methods are commonly used, and the combination of different methods is often tried in practical application.

3. Tasks and Overview

After investigating background and reading related work, we summarize the system requirements and draw the following design scheme. The design goals are as follows:

Explore the temporal and spatial distribution mode of air pollution and analyze the evolution trend;

Consider meteorological factors comprehensively and analyze the impact of various meteorological factors on pollution transmission. Try to explore the mode of pollution transmission;

Provide effective decision-making of air pollution prevention and control.

In this paper, the visual analysis of air pollution aims to find the evolution trend of pollution, excavate the transmission path of pollution and analyze the correlation between pollution indicators and meteorological factors, which are the main factor concerned by experts. In order to help users achieve these goals, we propose a visual analysis framework, as shown in Figure 1. A visual analysis framework, which includes three main stages: data preprocessing, visual display and interaction design.

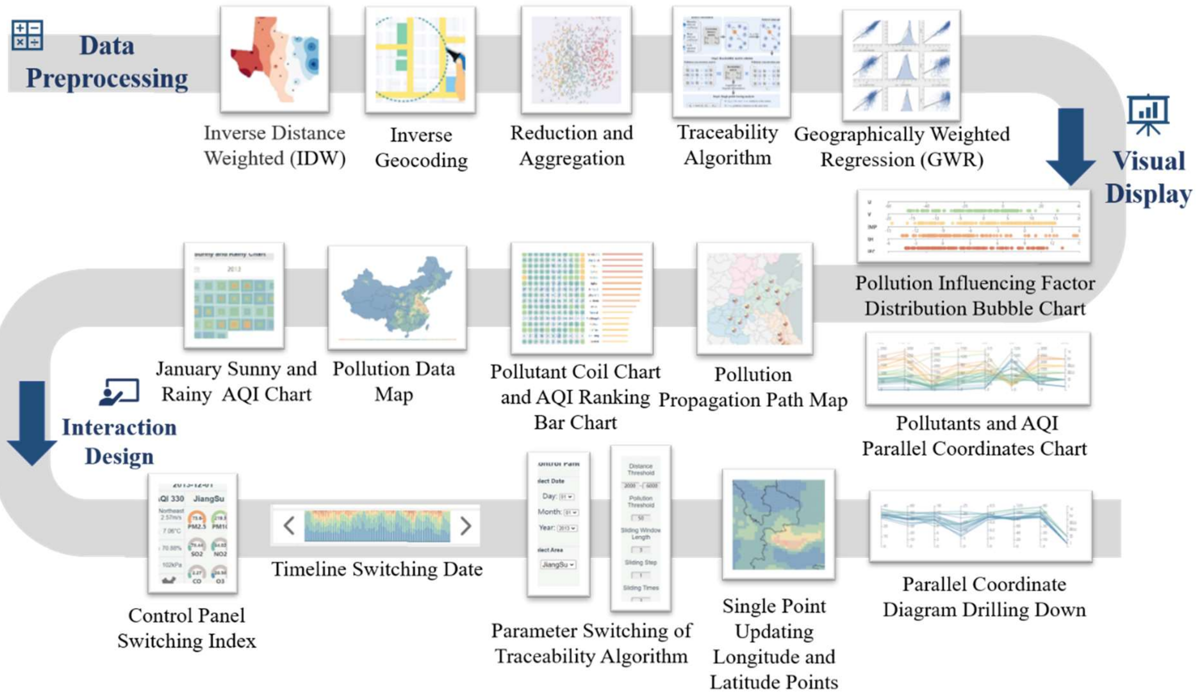


Figure 1. A visual analysis framework

We use Inverse Distance Weighted (IDW) [10] to fill in missing values to match the spatial resolution of datasets. Inverse Geocoding is used to convert the initial latitude and longitude data into city names that can be understood and used. The air quality index (AQI) is used to aggregate the concentration of pollutants into a single conceptual index. The meteorological factors were analyzed by Geographical Regression Weighted (GWR) [11] model. On the basis of these works, we innovate and realize multiple visual views to help users understand data and mine information. In addition, the interaction design of visualization system is also considered and implemented in the whole process.

4. Data Preprocessing

4.1 Dataset Introduction

The dataset used in this paper comes from China's high-resolution air pollution reanalysis data set released by the Institute of Atmospheric Physics, Chinese Academy of Sciences and other units, which contains the grid data of six conventional pollutants in China's ambient air quality standards. The dataset covers 375 provincial and municipal cities in China and the time range of air pollutants is from 2013 to 2018. The air pollutant concentration indexes are $\mathrm{PM}_{2.5}$, PM_{10}, NO_2, SO2, O3 and CO2. In addition to air pollutant indicators, the dataset also contains common meteorological data, such as wind direction, wind speed, temperature and common geographic data, such as longitude and latitude. The dataset has corresponding paper support and corresponding download links (https://doi.org/10.11922/sciencedb.00053).

In addition, because the conversion of geographic coordinates requires the use of geographic data, this paper also uses the geographic data set of Gaode platform (http://datav.aliyun.com/tools/atlas).

4.2 Inverse Geocoding

The Inverse Distance Weighted (IDW) is used to fill in the missing values in time and space dimensions. Clean the data with obvious logical errors, avoid data duplication and abnormalities, correct contradictory data and unify data units. In order to improve the interpretability of the data, this paper uses Inverse Geocoding to convert the longitude and latitude data into understandable city names. The work is realized by using the local geographic information database. Geohash code the longitude and latitude of cities above the county level in China, by inputting the target longitude and latitude, then converting the geohash to query the candidate cities and sorting according to the distance to find the nearest city.

4.3 Reduction and Aggregation

The air quality index (AQI) is adopted, which simplifies the monitored pollutant concentration into a single conceptual index value according to the proportion of various components in the air. According to relevant standards, this work uses the following formula for calculation:

$$IAQI_p = \frac{IAQI_{Hi} - IAQI_{Lo}}{BP_{Hi} - BP_{Lo}}\left(C_p - BP_{Lo}\right) + IAQI_{Lo} \tag{1}$$

Where, BP_{Hi} represents the upper limit of the minimum interval where a specific pollutant is located, BP_{Lo} represents the lower limit of the minimum interval where a specific pollutant is located. $IAQI_{Hi}$ represents the upper limit of the interval of the air quality sub index (IAQI) corresponding to the minimum interval of a specific pollutant, $IAQI_{Lo}$ represents the lower limit of the interval of the air quality sub index (IAQI) corresponding to the minimum interval of a specific pollutant. C_P represents the actual measured pollutant concentration. Each index is taken according to the corresponding time interval. And the maximum value of IAQI calculation results of all pollutants in the same time interval is taken as the AQI value of this time interval.

4.4 Geographically Weighted Regression (GWR)

The paper needs to analyze the impact of five meteorological factors on air pollution. Due to the spatial heterogeneity and spatial non stationarity in different provinces and cities, the correlation between dependent variables and independent variables (in this paper, the dependent variables are the five meteorological factors and the independent variables are the air quality indexes) will change with the different geographical location, while the general linear or nonlinear regression model cannot reflect the spatial non stationarity. Therefore, we use Geographic Weighted Regression (GWR) to deeply analyze the impact of various meteorological factors on air quality.

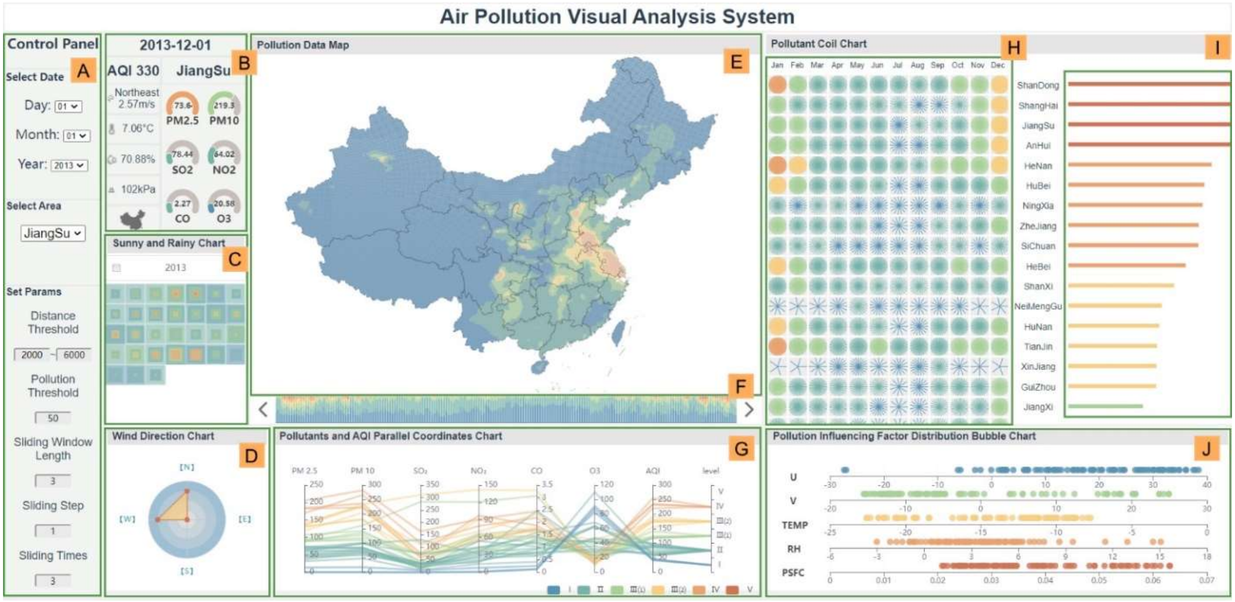
The Geographical Weighted Regression model introduces the geographical location of an attribute value into the model as the regression parameter and uses the attribute value of its adjacent area for local regression analysis. The parameters of the geographical weighted regression model are helpful to reveal the spatial relationship between the air quality index of a region and its meteorological factors. Meanwhile, the results will change with the change of spatial geographical location. The model structure is as follows:

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^{p} \beta_k(u_i, v_i) x_{ik} + \varepsilon_i \; (i = 1,2, \ldots, n) \tag{2}$$

Where, y_i is the $nx1$ dimensional explanatory variable vector, which is the air quality index of all provinces and cities; x_{ik} is a $n \times k$ dimensional explanatory variable matrix; $\beta_k(u_i, v_i)$ represents the regression coefficient of the influencing factor k at the regression point i, and the weighted least square method is used to estimate the parameters; (u_i, v_i) represents the longitude and latitude coordinates of the observation point; ε_i follows the normal distribution with constant variance. At the same time, the Gaussian function is selected as the spatial weight function and the AIC criterion is used to select the bandwidth. Finally, the correlation coefficients of the five meteorological factors of each regression point are obtained.

5. Visualization System

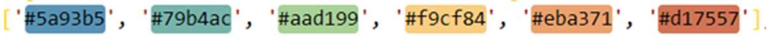
The system, as is shown in Figure 2, mainly includes control area and view area. Control area includes the Parameter Control Panel (Figure 2A) and Page Console (Figure 2B). The Parameter Control Panel, as the interface between the user and the algorithm, feeds back the user's satisfaction with the system in real time. The Page Console displays the basic information of other views. View area includes January Sunny and Rainy AQI Chart (Figure 2C), Wind Direction Chart (Figure 2D), Pollution Data Map (Figure 2E), National Annual Pollution Level Statistics Chart (Figure 2F), Pollutants and AQI Parallel Coordinates Chart (Figure 2G), Pollutant Coil Chart (Figure 2H), AQI Ranking Bar Chart (Figure 2I) and Pollution Influencing Factor Distribution Bubble Chart (Figure 2J).



Day: 01
Month: 01
Year: 2013
JiangSu
Distance Threshold 2000 ~ 6000
Pollution Threshold 50
Sliding Window Length 3
Sliding Step 1
Sliding Times 3

Figure 2. Air Pollution Visual Analysis System

The system applies the principle of consistency to the color channel. The basic idea of color matching is: red indicates serious pollution, blue indicates good air quality, and green and yellow are used as transition colors. Color matching and weather metaphor are consistent with the user's consistent thinking. The levels of color scheme used are shown in Figure 3.



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['#5a93b5', '#79b4ac', '#aad199', '#f9cf84', '#eba371', '#d17557']
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Figure 3. The levels of color scheme

5.1 Control Area

5.1.1 Parameter Control Panel

Parameter Control Panel displays the time, area, and effect-related parameter Settings performed by the current system. Depending on the input of the drawing view, these parameters are distance threshold, pollution threshold, sliding window length, sliding step size and sliding number. Adjust the parameters, and the results of the view will change accordingly. Users can switch to other views (such as maps) by selecting a date and region as required.

5.1.2 Page Console

Page Console displays the current date, the name of the region pointed to by the user on the map, the AQI index and the numerical information of the four meteorological factors in text. The values of six pollution indicators are displayed on the dashboard. The console data updates dynamically with the user’s mouse pointer over the pollution data map.

5.2 View Area

5.2.1 January Sunny and Rainy AQI Chart

January Sunny and Rainy AQI Chart is inspired by the visual epidemic barometer proposed by Visualization and Visual Analysis Laboratory of Peking University, and improved. We use different colors to map different pollutant levels, and use rectangular side length to map the number of provinces in the whole country with this pollution level. The user can use the drop-down box to select the corresponding year to update the view.

5.2.2 Wind Direction Chart

Wind Direction Diagram shows the wind direction and speed of the region at that time according to the region where the user mouse stays. The circular radar chart is presented in a basic way, and the same color channel is used for each layer, increasing layer by layer from inside to outside.

5.2.3 Pollution Data Map

Pollution Data Map adopts the form of scattered points to render the data of each coordinate point in the data and reflect the numerical size according to different color mapping. By clicking a province on the map, you can drill down the map to display the pollution propagation path map of the corresponding province.

Pollution Propagation Path Map (Figure 4) is made up of multiple propagation paths. The line between the two places shows the route of contamination, the starting point of the arrow indicates the source of pollution, and the arrow points to the contaminated area. We also draw fan-shaped charts at the locations of each monitoring station, yellow, cinnamon and purple respectively represent the influence weight of wind direction, wind speed and humidity.

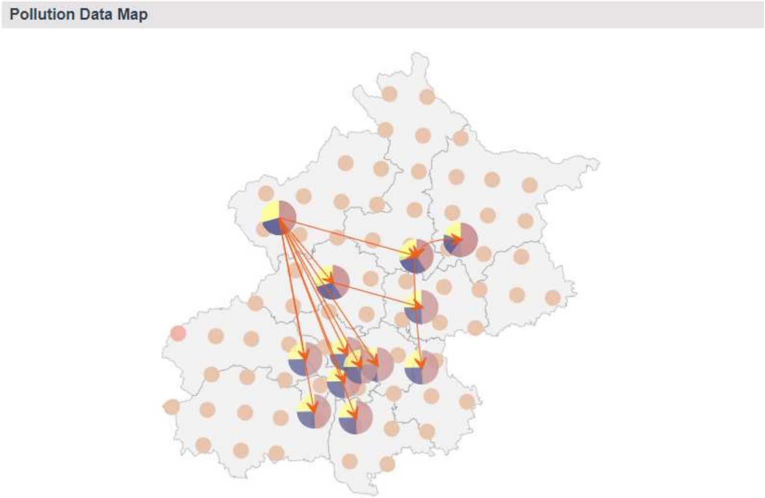

Figure 4. Pollution Propagation Path Map

5.2.4 National Annual Pollution Level Statistics Chart

National Annual Pollution Level Statistics Chart uses a stacked bar chart to show the number of provinces with six pollution levels in all dates in a given year. Different colors are used to map different pollution levels, so as to display the annual statistics of pollution levels in all provinces and the overall changes of the year. This chart is designed and implemented as one of the main entry points for time switching on the page. When users click on a bar chart, other views on the page request data and update the view based on the corresponding date.

5.2.5 Pollutants and AQI Parallel Coordinates Chart

Pollutants and AQI Parallel Coordinates Chart shows the pollution indicators, AQI and AQI grade of each province (or city of the province) in China. We use color mapping for different AQI levels.

5.2.6 Pollutant Coil Chart

Pollutant Coil Chart is used to show the monthly average value of a pollution index in a given year. Inspired by the characteristics of particulate matter measured by diameter in the atmosphere, we use the number of line segments to map the value of this pollution index, and use the color of line segments to map the pollution level corresponding to the monthly average AQI. The chart shows the changes of current pollution indicators in different months of the year in each province (or city of the province). The more lines in the coil, the higher the concentration of contamination.

5.2.7 AQI Ranking Bar Chart

AQI Ranking Bar Chart uses rectangular length to map the AQI of all provinces (or cities in the province) on the current date, and uses the corresponding AQI level of color mapping. This view shares the same vertical axis as the coil diagram and is presented in descending order of AQI values. It is updated in real time as the other views on the page are updated by year, region, or pollutant.

5.2.8 Pollution Influencing Factor Distribution Bubble Chart

Pollution Influencing Factor Distribution Bubble Chart visualizes the distribution of zonal wind speed, meridional wind speed, temperature, relative humidity, and surface pressure in all regions of each province. This view shows the values of five meteorological factors for each city in the current province for the day, plotted as a scatter plot on five single axes. The distribution of scattered points can effectively explain the overall distribution of meteorological factors in this province.

6. System Evaluation

6.1 Case Study

From 2013 to 2018, with the promulgation of the "ten articles on the atmosphere" and the public's attention to sustainable ecological development, the national pollution situation improved in many aspects. By comparing the pollution differences in the time dimension, we find that the concentration of various pollution indicators has been improved. According to Figure 5, the monthly average PM2.5 of all provinces in China decreases year by year (the coil becomes sparse). At the same time, the pollution situation in various provinces has also improved (green is gradually in the majority).

Figure 5. The comparison between Pollutant Coil Charts

From Figure 6, the air quality is generally in a good trend and more provinces are at the excellent level of air quality. The columnar statistical chart of AQI grade also confirms this finding. Although January is a month with serious air pollution, AQI values in most cities have decreased significantly during this period, and pollution control has achieved good results.

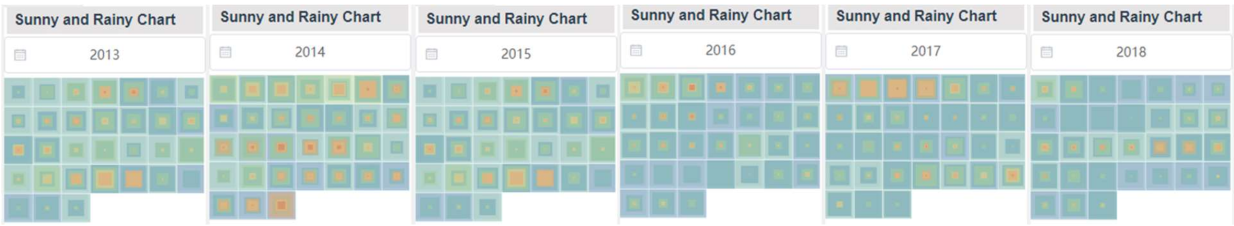

Figure 6. The comparison between Sunny and Rainy Charts

On this basis, the temporal and spatial distribution characteristics of air pollution are further analyzed. We found that there is a strong correlation between the change of air pollution and seasonal change. The air pollution of all provinces in China is relatively serious at the beginning and end of each year. There are a large number of provinces with serious pollution, severe pollution and moderate pollution. The pollution situation in the middle of each year (from June to October) is relatively good and most provinces are at an excellent level. For a single pollution index, this characteristic still exists. It can be seen from the pollutant coil diagram that for a single province, the average value of pollutants in December, January and February is high (coils are dense), and the pollution level corresponding to IAQI is serious (orange and red); In the middle of the year, for example, from June to October, the average value of pollutants decreases (the coils are sparse) and the pollution level also decreases (the color appears green). We consider that the frequent use of heating in winter and the setting off of fireworks and firecrackers lead to PM2.5, SO2 and other pollutants are obviously discharged.

At the same time, pollution indicators are related to meteorological factors and regional differences. From February 19 to 23 in 2014, Beijing's air pollution index was good and AQI remained at a good level. The AQI value increased significantly from 24th to 26th, and its PM2.5 and PM10 pollutants increased significantly. However, after 26th, the air pollution level in Beijing has been greatly improved and the AQI index is lower than 50. This paper explores the influencing factors of the change of pollution in Beijing during this period. According to the distribution Bubble Diagram of Pollution Influencing Factors, we find that the changes of wind direction, wind speed and humidity played an important role in this period. The overall transmission trend is from the northwest to the south of Beijing. From the perspective of wind direction and speed, Figure 7 shows that Beijing is mainly westerly at this stage and there is a trend of transition to the northwest. After the pollution reached severe pollution in some areas, the pollution situation gradually improved. We found that the change of humidity reduced the pollution. With the decrease of temperature, the possibility of rainfall is great, which greatly promotes the settlement of pollutants.

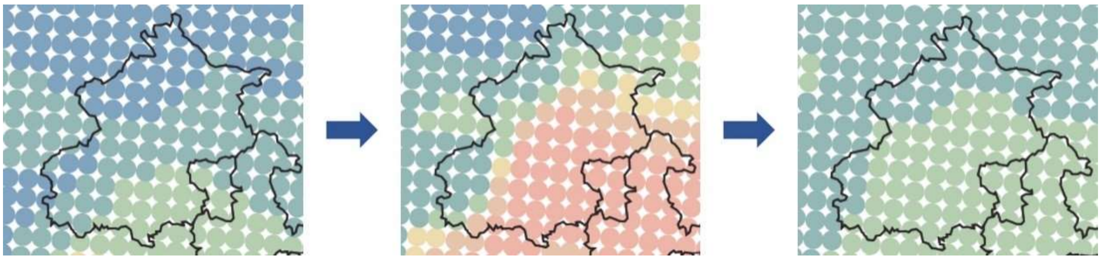

Figure 7. The pollution trend in Beijing

6.2 User Study

After investigation, we find that MeteoInfo [12] is widely used in case studies of atmospheric transmission. The software well simulates the results of Hysplit4 and Concentration Weighted Trajectory (CWT) algorithm. However, the software has a single output result, which can only provide users with trajectory map and contribution heat map. Meanwhile, the software lacks the evaluation of influence factors in the propagation process.

For the problem driven visualization system, it is not feasible to use qualitative indicators to prove the effectiveness of the system. Therefore, based on the above discussion, we recruited 20 volunteers, including 10 environmental students who have used MeteoInfo software and have some knowledge of air pollution and 10 students majoring in computer science without professional knowledge of this direction.

After learning about our visualization system, volunteers began to explore MeteoInfo software and our system for some tasks. We summarize the feedback and draw the following conclusions:

(1) All volunteers can clearly find the most polluted areas through pollution contribution map or basic information display. However, 11 volunteers said that when the pollution in multiple areas produced extreme conditions in a certain period of time, the color of the heat map in MeteoInfo became complex and the heavily polluted areas would interfere with the research in other cities. In the same time, the way of using pollution data map for visual analysis is clearer and more intuitive.

(2) We found that the MeteoInfo software cannot understand the basic information of the city specified by the user. Therefore, volunteers cannot complete the comparison and further exploration of urban information through MeteoInfo software. However, through our system, when users are curious about the information of a city or try to explore the overall level of the city in that period, the basic information control panel and coil diagram provide main view help.

(3) The black box technology adopted by MeteoInfo software cannot reasonably analyze the pollution influencing factors. Therefore, all volunteers said that the software could not satisfy the exploration of pollution reasons. The visualization system comprehensively considers the meteorological data and reasonably uses the Geographical Weighted Regression model to describe the distribution of meteorological influencing factors in this period. The pie distribution beside the station in the pollution transmission path can also enable users to clearly understand the distribution of pollution influencing factors in each path. Volunteers said that this function provides them with more exploration space and imagination.

Based on above research, our visualization system has obvious effectiveness in analyzing the comparison between pollution transmission path and urban pollution level. Nevertheless, MeteorInfo is a mature and classic analysis platform, which can still solve many backward trajectory problems. Our system aims to become an auxiliary tool for controlling the overall situation of air pollution and subsequent policy-making.

7. Conclusion

The system uses the open dataset of China's high-resolution air pollution reanalysis from 2013 to 2018, focusing on the analysis tasks such as analyzing the temporal and spatial distribution mode and temporal and spatial evolution trend of air pollution, identifying major pollution sources, comparing pollution differences and evaluating the state of atmospheric environment. We processed the data in many ways and finally designed and implemented the national air pollution visual analysis system, and evaluated the system through cases.

First of all, we preprocess the data, including reverse geocoding, data cleaning, data statistics, IAQI and AQI level calculation. The correlation between pollution index and atmospheric factors was calculated by geographical weighted regression model. Under the guidance of the analysis task, we design the system into view area and control area. For the view area, we design a variety of views, such as Pollution Data Map, Pollutant Coil Chart, AQI Ranking Bar Chart, etc. These views provide an analysis of the spatial and temporal distribution patterns and evolution trends of pollution. Among them, the innovative design and implementation of Pollutant Coil Chart and Pollution Propagation Path Map are put forward. For control area, we design flexible and rich interactions, which can be used by users for interest analysis.

In the process of case analysis using the system, some areas with obvious pollution characteristics can be analyzed through the view, and the causes of pollution changes can be analyzed based on the actual situation. The system can detect or reflect specific events related to air pollution, such as enterprises' leakage of exhaust gas, sudden large-scale pollution, artificial rainfall, and pollution events caused by meteorological changes. Based on the completion of visual analysis tasks, our work makes a more accurate implementation and detailed design of visual coding, view innovation and interaction.

Acknowledgments

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