In recent years, with the rapid development of China’s economy, pollutant emissions have gradually increased and atmospheric environmental quality is declining [1]. Among them, the regional compound air pollution, which is mainly polluted by ozone and fine particles (PM$_{2.5}$), is especially significant [2-3]. PM$_{2.5}$ not only reduces visibility, but also serves as a carrier of heavy metal elements, organic matter, viruses and bacteria and other toxins that can invade the human respiratory and circulatory systems, endangering human health [4]. Researches have confirmed that the main sources of PM$_{2.5}$ in China are the combustion of coal and...
biomass, secondary nitrate or sulfate, soil, dust and so on [5]. The weekly trend of mass concentration is highly correlated with human activity [6], whereas the peak of the concentration value is mainly in the heating period, such as in January, February, March, November and December [7]. At present, there are some achievements in the study of PM$_{2.5}$ concentrations [8-9], source analysis [10], transmission and diffusion of pollutants [11] and so on. However, most of these studies have focused on inland cities, with relatively few studies of coastal cities. Recently, air pollution problems in coastal cities of China have become more and more serious, and air pollution problems occur more frequently [12-13]. Thus air pollution issues have gradually become hotspots of current research.

The Bohai Bay area occupies an important strategic position in China’s economic development. However, the heavy industry cities, represented by Tangshan, Tianjin and Dalian, have also brought serious environmental problems to the area. Therefore, this paper analyzes the pollution situation of PM$_{2.5}$ and related factors in the Bohai Bay area, studies the temporal and spatial characteristics, discusses its influencing factors, and provides the basis for pollution control in the area.

Material and Methods

Data Sources

The data of PM$_{10}$, SO$_2$, CO, NO$_2$, O$_3$ and PM$_{2.5}$, which is from January 2016 to December 2016, are from the China Environmental Monitoring Station “National Urban Air Quality Real-time Release Platform.”

Study Areas and Methods

This study chose 12 cities around China’s Bohai Bay area. According to the geographical distribution and urban distance from the sea, the 5 cities of Dongying, Jinzhou, Panjin, Tangshan and Tianjin are defined as non-coastal cities, and Dalian, Weihai, Yantai, Yingkou, Qinhuangdao and Huludao are defined as coastal cities (Fig. 1). The correlation analysis and independent-samples test of PM$_{10}$, SO$_2$, CO, NO$_2$, O$_3$ and PM$_{2.5}$ were carried out through SPSS, and the spatial characteristics of PM$_{2.5}$ and O$_3$ were studied by ArcGIS software.

Results and Discussion

Concentration Characteristics of Various Pollution Factors

The research results showed that the annual average concentration ranges of PM$_{2.5}$, PM$_{10}$, SO$_2$, CO, NO$_2$ and O$_3$ in coastal cities were 33.6~46.8 µg/m$^3$, 62.9~87.7 µg/m$^3$, 22.2~47.2 µg/m$^3$, 0.61~1.4 mg/m$^3$, 21.9~47.4 µg/m$^3$, and 94.3~126.1 µg/m$^3$; the annual average concentration ranges in non-coastal cities were 39.2~73.8 µg/m$^3$, 67.8~127.9 µg/m$^3$, 21.0~51.8 µg/m$^3$, 0.85~2.3 mg/m$^3$, 277~58.3 µg/m$^3$, and 96.8~131.1 µg/m$^3$. According to the annual average concentration of pollutants in different cities during the study period (Table 1), it can be found that the concentration of pollution factors in non-coastal cities is generally higher than that of coastal cities.

Excessive Situation of Pollution Factors

Table 2 shows that the noncompliance phenomenon of PM$_{2.5}$, PM$_{10}$ and O$_3$ in the Bohai area is serious, and PM$_{2.5}$ pollution is the most serious. At the same time, the noncompliance rates of the 3 pollution factors are all non-coastal cities higher than the coastal cities. If taking the concentration limit of PM$_{2.5}$ specified by WHO (10 µg/m$^3$) as the standard for calculation of the number of noncompliance days, the coastal and non-coastal cities are seriously exceeded, and exceeding the standard of 7.4 times, and some cities even could not meet the standard throughout the year, which implies that the PM$_{2.5}$ pollution problem in the Bohai Bay area is extremely serious.

The noncompliance rates of SO$_2$ and CO are both relatively small. Especially for SO$_2$, there is only one city in the coastal and non-coastal cities that has exceeded the standard. The reason may be that SO$_2$ is released mainly from coal-fired emissions, while NO$_2$ is mainly from coal-fired emissions, urban vehicle exhaust and industrial production processes [14-16]. In 1973, thermal power plant flue gas desulfurization began to be taken seriously when China’s environmental protection agencies were established. Afterward, China introduced the national 10$^{th}$ Five-Year Plan for Environmental Protection and the national 11$^{th}$ Five-Year Plan for Environmental Protection, which were given higher attention and required the installation of flue
Air Quality Characteristics of China’s...  

Table 1. Concentration characteristics of pollution factors in coastal and non-coastal cities (mg/m³ for CO, µg/m³ for other pollution factors)\(^a\)

<table>
<thead>
<tr>
<th>City</th>
<th>PM(_{2.5})</th>
<th>PM(_{10})</th>
<th>SO(_2)</th>
<th>CO</th>
<th>NO(_2)</th>
<th>O(_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal Cities</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dalian</td>
<td>38.53±28.8</td>
<td>68.17±44</td>
<td>25.82±20.0</td>
<td>1.00±0.3</td>
<td>30.30±11</td>
<td>114.69±42.3</td>
</tr>
<tr>
<td>Dandong</td>
<td>42.15±24.3</td>
<td>70.67±44</td>
<td>29.63±25.6</td>
<td>1.35±0.4</td>
<td>25.10±10.9</td>
<td>96.66±39.7</td>
</tr>
<tr>
<td>Waibai</td>
<td>33.78±22.5</td>
<td>62.88±44</td>
<td>14.47±9.1</td>
<td>0.61±0.2</td>
<td>21.93±12.4</td>
<td>106.90±42.3</td>
</tr>
<tr>
<td>Yantai</td>
<td>39.64±29.0</td>
<td>75.55±45.8</td>
<td>22.22±11.0</td>
<td>0.79±0.4</td>
<td>34.67±15.1</td>
<td>102.67±36.3</td>
</tr>
<tr>
<td>Yantai</td>
<td>44.36±31.9</td>
<td>73.32±47.1</td>
<td>22.64±15.2</td>
<td>0.88±0.4</td>
<td>28.07±12.6</td>
<td>126.07±51.8</td>
</tr>
<tr>
<td>Qinhua</td>
<td>45.97±37.5</td>
<td>87.72±56.8</td>
<td>27.60±18.2</td>
<td>1.31±0.9</td>
<td>47.38±19.4</td>
<td>94.33±51.1</td>
</tr>
<tr>
<td>Huludao</td>
<td>46.76±35.8</td>
<td>87.57±58.7</td>
<td>47.17±35.3</td>
<td>1.34±0.6</td>
<td>35.79±16.2</td>
<td>116.15±51.3</td>
</tr>
<tr>
<td>Non-coastal Cities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dongying</td>
<td>64.07±42.5</td>
<td>120.00±65.5</td>
<td>47.55±25.0</td>
<td>1.17±0.5</td>
<td>39.52±19.1</td>
<td>131.10±61.2</td>
</tr>
<tr>
<td>Jinhzhou</td>
<td>54.80±40.2</td>
<td>83.28±54.5</td>
<td>51.81±36.4</td>
<td>1.02±0.5</td>
<td>36.77±14.9</td>
<td>118.74±51.8</td>
</tr>
<tr>
<td>Panjin</td>
<td>39.23±26.9</td>
<td>67.78±42.6</td>
<td>26.56±14.4</td>
<td>0.85±0.4</td>
<td>27.73±13.9</td>
<td>124.38±51.4</td>
</tr>
<tr>
<td>Tangshan</td>
<td>73.83±57.0</td>
<td>127.93±81.4</td>
<td>45.69±23.4</td>
<td>2.28±1.6</td>
<td>58.35±20.9</td>
<td>112.18±64.7</td>
</tr>
<tr>
<td>Tianjin</td>
<td>68.55±51.5</td>
<td>105.83±65.3</td>
<td>20.98±15.2</td>
<td>1.38±0.9</td>
<td>48.06±22.4</td>
<td>96.79±55.0</td>
</tr>
</tbody>
</table>

\(^a\) The ambient air quality standard (GB 3095-2012) prescribes the annual average concentration limit for PM\(_{2.5}\), PM\(_{10}\), SO\(_2\), CO, NO\(_2\) and O\(_3\).

gas desulfurization facilities when exceeding China’s regional sulfur dioxide emissions standards or total requirements of coal-fired power plants. Nitrogen oxide emissions of thermal power plants were gradually taken into account as the emission standard air pollutants thermal power plants (GB13223-2003) was made and promulgated in 2003, which is denitrification after desulfurization first, and thus SO\(_2\) removal effect is more significant. At present, the automobile exhaust and industrial sources produced a larger proportion of NO\(_2\) [17], even after the promotion of “shifting fuel from coal to gas” in China [18], the NO\(_2\) concentration value is still high.

Spatial Distribution Characteristics of PM\(_{2.5}\) and O\(_3\)

Spatial distribution of PM\(_{2.5}\) and O\(_3\) concentrations in 2016 were obtained by spatial interpolation of the annual average concentration in the Bohai Bay area through

Table 2. Noncompliance rate of pollution factors during the study period (%)

<table>
<thead>
<tr>
<th>City</th>
<th>PM(_{2.5})</th>
<th>PM(_{10})</th>
<th>SO(_2)</th>
<th>CO</th>
<th>NO(_2)</th>
<th>O(_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal Cities</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dalian</td>
<td>8.47</td>
<td>6.28</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>13.39</td>
</tr>
<tr>
<td>Dandong</td>
<td>11.20</td>
<td>4.10</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>7.10</td>
</tr>
<tr>
<td>Waibai</td>
<td>5.19</td>
<td>3.28</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>27.21</td>
</tr>
<tr>
<td>Yantai</td>
<td>8.20</td>
<td>5.74</td>
<td>0.00</td>
<td>0.00</td>
<td>0.27</td>
<td>7.38</td>
</tr>
<tr>
<td>Yantai</td>
<td>12.57</td>
<td>6.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>23.50</td>
</tr>
<tr>
<td>Qinhua</td>
<td>16.39</td>
<td>12.84</td>
<td>0.00</td>
<td>1.91</td>
<td>7.10</td>
<td>11.20</td>
</tr>
<tr>
<td>Huludao</td>
<td>14.21</td>
<td>11.20</td>
<td>1.37</td>
<td>0.82</td>
<td>1.91</td>
<td>18.85</td>
</tr>
<tr>
<td>Non-coastal Cities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dongying</td>
<td>30.60</td>
<td>28.96</td>
<td>0.00</td>
<td>0.00</td>
<td>3.55</td>
<td>31.69</td>
</tr>
<tr>
<td>Jinhzhou</td>
<td>20.49</td>
<td>9.56</td>
<td>0.55</td>
<td>0.00</td>
<td>1.37</td>
<td>19.67</td>
</tr>
<tr>
<td>Panjin</td>
<td>7.92</td>
<td>5.46</td>
<td>0.00</td>
<td>0.00</td>
<td>0.27</td>
<td>22.40</td>
</tr>
<tr>
<td>Tangshan</td>
<td>34.15</td>
<td>28.96</td>
<td>5.46</td>
<td>0.00</td>
<td>16.12</td>
<td>22.40</td>
</tr>
<tr>
<td>Tianjin</td>
<td>31.42</td>
<td>18.31</td>
<td>1.37</td>
<td>8.74</td>
<td>15.30</td>
<td></td>
</tr>
</tbody>
</table>

Note: The noncompliance rate of each pollution factor is based on the Chinese Ambient Air Quality Standards Grade II limit for the calculation.
ArcGIS10.2 (Figs 2-3). From the spatial distribution point of view, PM$_{2.5}$ concentrations in non-coastal cities were higher than coastal cities. In the independent-samples test, the observed value of F statistic was 5.970 and the corresponding probability P value was 0.035, which was less than 0.05, and the variance of the two populations was significantly different. The observed value of T statistic is -2.924, and Sig(2-tailed) is 0.036, which is less than 0.05, and it can be concluded that there are significant differences between PM$_{2.5}$ in coastal and non-coastal cities.

From the spatial distribution of O$_3$ concentration, Panjin, Yingkou, Jinzhou, Huludao, and Dongying showed higher O$_3$ concentrations than other cities, and the pollution is rather serious. In the case of independent-samples test, we found that the concentration of O$_3$ in coastal and non-coastal cities was not significant. O$_3$ is mainly derived from industrial pollution combustion, VOCs generated during the production process, and emissions from airborne pollutants [19]. They all have similar sources of pollution in the Bohai Bay area, thus the concentration of O$_3$ in coastal and non-coastal cities did not show any significant difference.

According to the correlation analysis between the distance from the sea and the PM$_{2.5}$ pollution factors such as PM$_{10}$, we found that there are significant correlations between PM$_{2.5}$, PM$_{10}$ and NO$_2$, and the correlation coefficients are 0.786**, 0.635* and 0.584*, respectively. The main reason is that the coastal cities were influenced by clean air from the Bohai Bay area, which can help dilute the local pollutants [20]. However, non-coastal cities including Tangshan, Tianjin and other heavy industrial cities, were due to not only their own serious pollution problems [21-22]. At the same time, compared with coastal cities, the diffusion of pollutants is also slow. Under the combined influence, the difference of PM$_{2.5}$ concentration between the coastal cities and non-coastal cities is significant.

**Monthly Change Characteristics of PM$_{2.5}$**

As shown in Fig. 4, the concentration of PM$_{2.5}$ in coastal cities is lower than that in non-coastal cities, and the trend is consistent. In the period of January, March, November and December, during these four months, PM$_{2.5}$ pollution was the most serious, whereas in July, August and September, the pollution was relatively light. The lowest concentration shown by season was in the summer, followed by autumn, while winter and spring showed the highest concentration. There is more rainfall in summer and it is calculated that there is a significant negative correlation between rainfall and PM$_{2.5}$ and the correlation is up to -0.692*. At the same time, there is a strong wind in the rain, and it has a good settlement and dilution to the air pollutants. In addition, the solar radiation in summer and autumn is strong, and the convective conditions are better than other seasons, which can help accelerate the spread of air pollutants [23-24]. However, there is little precipitation in the winter and spring, and the atmosphere is stable, and
reverse temperature is prone to occur in the morning and at night, causing the accumulation of contaminants in the near strata. Moreover, in winter and spring the pollutants may be transported from the inland to the coastal cities, and this also may result in a higher concentration of pollutants in winter and spring [25-26].

**PM$_{2.5}$ Week Change**

It is generally acknowledged that industrial enterprises stopped production and the number of people going out was reduced on weekends. The PM$_{2.5}$ concentration showed the phenomenon that the weekend was lower than the working day, which was the “weekend effect” [27]. Our study found that the PM$_{2.5}$ changes on the working days and weekends in coastal cities and non-coastal cities were relatively stable, and did not show a significant “weekend effect” (Fig. 5). This may be because the economically developed population in the bay area frequented on weekends and working days and the use of motor vehicles is large.

**Correlation Analysis**

Fig. 6 shows that the correlation coefficients of PM$_{10}$, SO$_2$, CO, NO$_2$ and PM$_{2.5}$ in coastal cities are lower than those in non-coastal cities, but they show strong positive correlation. These correlation coefficients are 0.889, 0.862, 0.608, 0.581, 0.821, 0.795, 0.749, and 0.678 respectively, which indicates that the pollutants in the bay area are still mainly from anthropogenic sources [28].

As can be seen from Table 3, the correlation between O$_3$ and PM$_{2.5}$ is weak, mostly showing the negative correlation. When the amount of pollutant emissions is relatively large, and in addition of the adverse weather conditions, PM$_{2.5}$ easily becomes the main pollutant. However, O$_3$ is easily formed in high temperature and high light conditions, and it is partially lost by catalytic reaction with NOx, HOx, and ClOx [26]. The formation conditions between these two are contradictory to a certain extent, which leads to its negative correlation [29].

Our study has shown that the population, car ownership, gross regional product and energy consumption are significantly related to PM$_{2.5}$ [30-31], but it is very interesting that no similar results were found in this study. We think that this may be caused by two reasons. The first is that the city is close to the sea, the non-coastal cities, which is the farthest distance from the sea, is only 50 km from the sea. Therefore, it is still under the clean effect of the ocean air mass, which leads to deviation from previous research. Second, this study only selected 1 year and 12 cities, and the data were relatively small and need to be studied further.
Conclusions

Based on the analysis of the long-term monitoring data, its spatiotemporal distribution characteristics of pollution factors of the urban agglomeration in the Bohai Bay area of China in 2016 have been investigated in detail.

1. The concentrations of $PM_{2.5}$, $PM_{10}$, and $O_{3}$ in the Bohai Bay area and the noncompliance rates are all higher in non-coastal cities than in coastal cities.

2. Based the analysis of the spatial distribution of $PM_{2.5}$ and $O_{3}$ in 2016 and the identification of independent samples, the $PM_{2.5}$ concentration in coastal cities and non-coastal cities was significantly different, but there was no significant difference in $O_{3}$.

3. From the monthly concentration change of $PM_{2.5}$ in coastal and non-coastal cities, in January, March, November, and December, $PM_{2.5}$ pollution is the most serious, whereas the period of July, August, and September is the lightest pollution. That is, the concentration value is the lowest in summer, followed by autumn, and the highest concentrations are in winter and spring. No significant “weekend effect” was found in weekly changes.

4. $PM_{2.5}$ is significantly related to $PM_{10}$ but its correlation is lower than non-coastal cities. The correlation between $O_{3}$ and various pollution factors is not obvious, and the relationship is more complicated.

In view of the differences in pollution between the coastal cities and non-coastal cities in the Bohai Bay area of China, it is suggested that the bay area formulate pollution control measures according to different regions. This study not only provides a basis for pollution control in the area, but also has important significance for air pollution control in China.

Acknowledgements

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Conflict of Interest

The authors declare no conflict of interest.

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