Spatiotemporal Distribution of Various Air Pollutants and Orthogonality of Spatial and Temporal Patterns in mainland China

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Abstract

In this paper, data of monitoring stations over China and interpolation method are used to analyse the distribution of air pollutants and evaluate the air quality of China in 2015. Six main air pollutants $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3 and CO are discussed. Considering 7 geographic regions of China, the regularities of spatial distribution of different pollutants are summarized. The regularities of temporal distribution are studied respectively in the time range of one day, one week, and the whole year. Further, the orthogonality of spatial and temporal distribution is discussed. Finally, comparing our estimations and standards, it can be found that the main pollutants are $PM_{2.5}$ and PM_{10}, and the overall air quality of China in 2015 is not bad.

Introduction

In recent years, with the development of China, air pollution becomes a serious problem that government should deal with (2015). Under such condition, figuring out how air pollutants are distributed becomes an important task to the environmental management. In previous research, distributions of different air pollutants such as $PM_{2.5}$, PM_{10}, SO_2 and NO_2 over different locations and timescale has been studied in a partial manner (2016; 2017; 2018; 2015).

In this paper, six sorts of air pollutants $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, CO together with AQI has been included. Spatial and temporal distribution of these pollutants are estimated in different scales using radial base function interpolation method. Additionally, the orthogonality of spatial and temporal distribution is concluded.

Data

The amount of pollutants observed in each station in 2015 is provided by Yang Yu. The data covers each hour in each station in 2015. There are 1497 stations in total. After removing those without coordinate and duplicate stations, 1256 stations are left and taken into account. To compute the average value of a particular region, the shape file of Chinese administrative division, which can be found on GADM[1], is needed. With the shape file, we divide the map into 0.5 degree grid cell and aggregate the value of each cell in that region to obtain the average estimation.

[1]https://gadm.org/index.html

To make conclusions of different regions, we use the Chinese geographical division which divides China into seven geographical regions:

- Northeast: Heilongjiang, Jilin, Liaoning
- East: Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Taiwan
- North: Beijing, Tianjin, Shanxi, Hebei, Inner Mongolia
- Central: Henan, Hubei, Hunan
- South: Guangdong, Guangxi, Hainan, Hong Kong, Macao
- Southwest: Sichuan, Guizhou, Yunnan, Chongqing, Xizang
- Northwest: Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang

Interpolation

There are many multivariate interpolation methods for 2D interpolation, such as bilinear, bicubic methods (2018a). However, when applying these methods, there are always some empty parts in the map. It is because these methods are used to interpolate regular grid, but the position of stations does not form a regular grid. For this sort of scattered data, radial basis function(RBF) is used for interpolation in the paper (2018b). The function form is rather simple. For any point $\mathbf{x}$,

$$y(\mathbf{x}) = \sum_{i=1}^{N} w_i \phi\left(\|\mathbf{x} - \mathbf{x_i}\|\right). \tag{1}$$

$\mathbf{x_i}$ are those observation points and ϕ is a customized function. The estimation of w_i can be solved by linear least square.

Below several different functions are tested respectively.

In Figure 1, those interpolated by “quadratic” methods have a lot of empty parts caused by negative value. However, this does not happen in “linear” methods. When comparing “linear” methods $1/(1+r), e^{-r}, r$, the images in Xinjiang are quite different. In e^{-r}, concentration degrades so rapidly that only points close to observation station are not green. In contrast to e^{-r}, r-interpolation degrades much slower and most of Xinjiang is red. $1/(1+r)$ is the intermediate between e^{-r} and r. Due to lack of data, we cannot determine which function is the best. For simplicity, r-interpolation is used throughout the project.

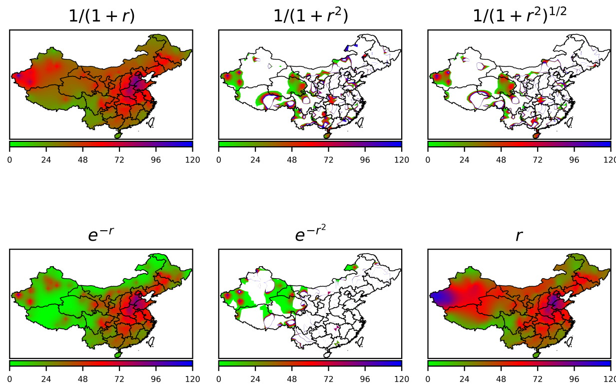

Figure 1: Interpolation of annually average concentration of PM2.5 using different $\phi(r)$

One of the advantage of RBF is that y is linear. Therefore, when it needs to compute the average value interpolation, calculating interpolation in each hour and then taking average for each point are not necessary. We can directly compute the average value for each station and then calculate the interpolation, which saves much of the time.

Spatial Distribution

The high-accuracy distributions in China of $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, and CO, which are the main air pollutants, are got by the data and interpolation method mentioned above. The regularities of space distributions of these air pollutants are summarized in this part.

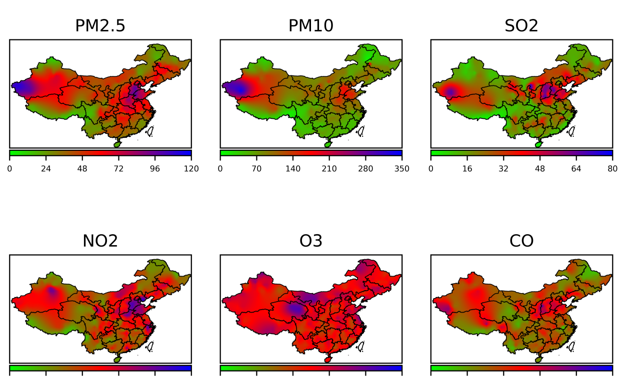

Figure 2: Distribution of annually average concentration of pollutants

By an overview of Figure 2, a general impression of the air quality over China can be got.

In the figures which represent $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO, two regions in the west of Xinjiang and around Hebei have the most serious pollution, which are the blue regions in the figures. The distribution of the red regions, which are the regions with pollution not so serious, is radial from the blue regions. In the south of China and the northeast of China, the pollution is slight in comparison.

It is special for the figure which represent O_3. It shows that the distribution is even and that the area with the maximum concentration of O_3 is around the northeast of Qinghai, the middle of Shaanxi and the west of Inner Mongolia.

In Table 1, the pollutants are considered in seven main regions of China, which are Central China, North China (includes the whole Inner Mongolia), South China, East China, Northeast, Northwest, and Southwest. The sheet shows the annual average concentrations of different pollutants in different regions, which is calculated by the result of interpolation method. In keeping with the overview, the annual average concentrations of all pollutants in Northwest, South China, and Southwest are obviously smaller than those in Central China, North China, East China, and Northwest.

As mentioned above, the two regions with the most serious pollution in China are in Xinjiang and around Hebei. However, the factors that make the high pollution are not the same for these two regions. The heavy industry with high emission in Hebei, such as iron and steel industry and cement industry, is one of the factors that make the poor air quality. However, the factors in Xinjiang are most natural factors but not man-made, such as climate and physiognomy. For example, the desert and sand storm will increase the concentration of particulate matter a lot.

There is something that should be explained. Because of the maldistribution of the observation points, the estimation by interpolation in some regions, such as in the west of China and Inner Mongolia, may be different with the fact. The whole Inner Mongolia is considered in the North China. As a result, it is not strange to see that the pollution in North China is not so serious, although the pollution in Beijing-Tianjin-Hebei Region is the most serious as we know.

Temporal Distribution

The data also shows some regularities of the time distribution of pollutants. In this part, the regularities will be analysed in one day, in a week, and in the whole year. That is because human activities, such as work and rest, changes in one day cycle, in one week cycle, and in one year cycle. In the whole year, the climatic conditions change with the seasons, which may be the factors that affect pollutants concentration. Thus, it is a reasonable guess that the concentration of pollutants will have the certain regularity in one day, in one week, and in the whole year.

Figure 3 shows the change curves of average concentration over 24 hours for different pollutants. The curves of $PM_{2.5}$, PM_{10}, CO, and NO_2 are similar, which have two peaks with similar height. one peak appears around 10h, and the other peak appears around 22h. The curve of SO_2 also has two peaks, but the peak appears around 22h is much lower than the other. The curve of O_3 is special, which only has one peaks that is around 15h.

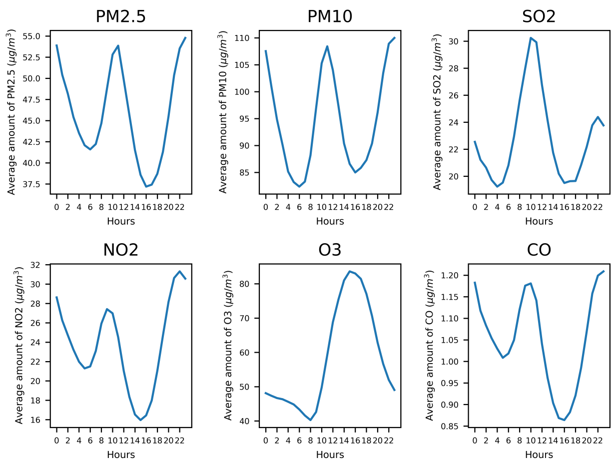

Figure 3: Daily average concentration of pollutants

According to some previous researches (2016), human daily activity is a factor of the regularity. The peak around 10h, which is time for commute, appears because of the traffic. The concentration increases at afternoon because of human activities after work, such as traffic and cooking. The concentration reaches another peak around 22h because the industrial production at night. The curve of O_3 seems strange, because being different with other pollutants, it is produced at high temperature from volatile organic compound and oxynitride. Thus its curve reaches the peak around 15h, when the temperature is highest.

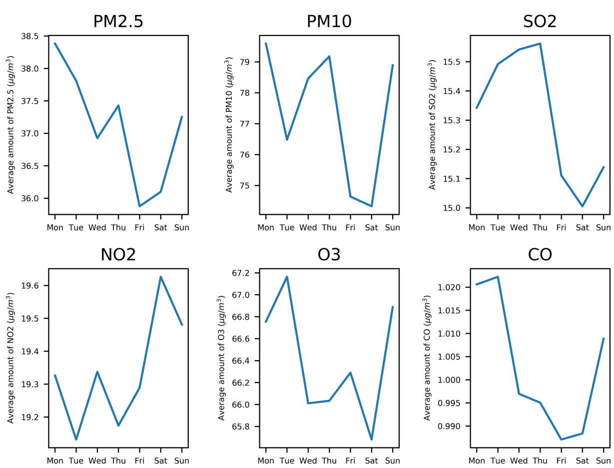

Figure 4: Weekly average concentration of pollutants

Figure 4 shows the change curves of average daily concentration from Monday to Sunday. However, the curves seem zigzag and irregular. Although some curves have similar peaks, it may just be a coincidence because there are only seven days in a week. Moreover, there is no obvious difference between weekdays and weekend, which can not reflect any regularities of weekly concentration changes. That means that the regularity of human weekly activities is not shown in the concentration changes.

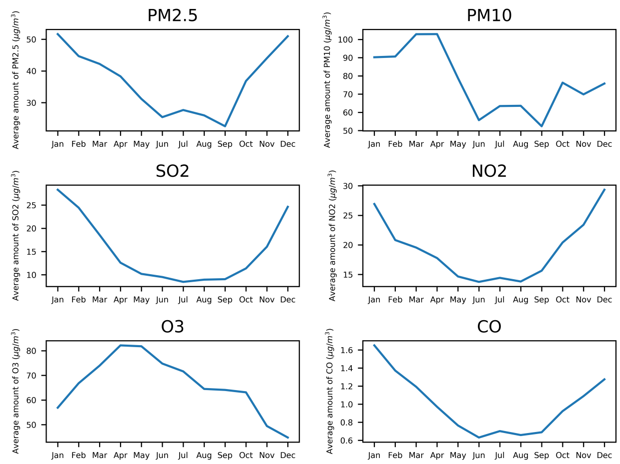

Figure 5: Monthly average concentration of pollutants

Figure 5 shows the change curves of average monthly concentration over the whole year. As it shows, the shape of concentration curves of $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO is like a letter U. The concentration decreases from January to June, keeps a low value from June to September, and increases from September to December. The curve of O_3 is special again. It is an inverted-U with a peak around April and May.

The exact reasons can not be given without further research, but some possible reasons can be given by the experience. The climate may be an important factor. Air motion and precipitation makes the diffusion of air pollutants easier in spring and summer, so the concentration decreases in spring and reaches a low level in summer. In contrast, air flows slowly in winter, which makes an opposite result. The heating in winter may be another reason, which increases the their use of coal and makes more polluting air. The curve of O_3 has a peak in summer because O_3 is produced at high temperature.

Orthogonality of Spatial Distribution and Temporal Distribution

The regularities of spatial distribution and temporal distribution of pollutants have been concluded above. Another valuable topic to discuss is the orthogonality of spatial distribution and temporal distribution. To simplify the analyse, AQI is used to represented the integrative concentration of six main air pollutants.

Figure 6 analyses the change curves of average AQI over 24 hours for every province in China. The shape of curves in the figure are all similar, which shows that the regularity of daily distribution is general in all province in China. It is interesting that some provinces with low pollution have curves with little fluctuation. For example, the curve that represents Hainan, which is at the bottom of the figure, is nearly a hor-

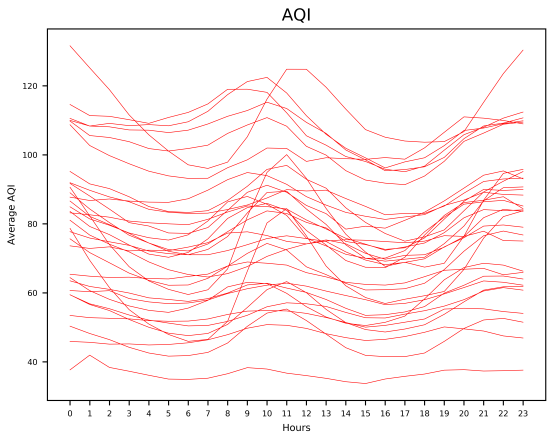

Figure 6: Daily average concentration of AQI for all provinces except Taiwan, Hong Kong and Macao (lack of data)

izontal line. This educes a reasonable educt that the regions with good air quailty have less changes of AQI.

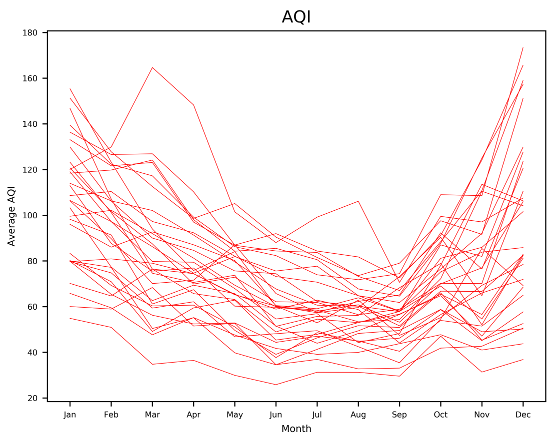

Figure 7: Monthly average concentration of AQI for all provinces except Taiwan, Hong Kong and Macao (lack of data)

Figure 7 shows the change curves of monthly average AQI over the whole year for every province in China. It can be seen that all curves are roughly U-shaped, which conforms with the regularity summarized above and shows that the regularity is general in space. Similar to the daily distribution, the conclusion that lower AQI is with less changes is also applied in this figure.

It can be found that the curve of Xinjiang, which is at the top of the figure, is the most special. A possible reason is the unique natural and geographical conditions in Xinjiang. Another interesting phenomenon is that the AQI increases quickly between September and October in many province, which means that this is a general phenomenon in China. Similar to the analyses for 2014 in former research (2016), the reason may be some special pollution processes in October, which leads to the decline in air quality across China. However, it can not be proved by the data.

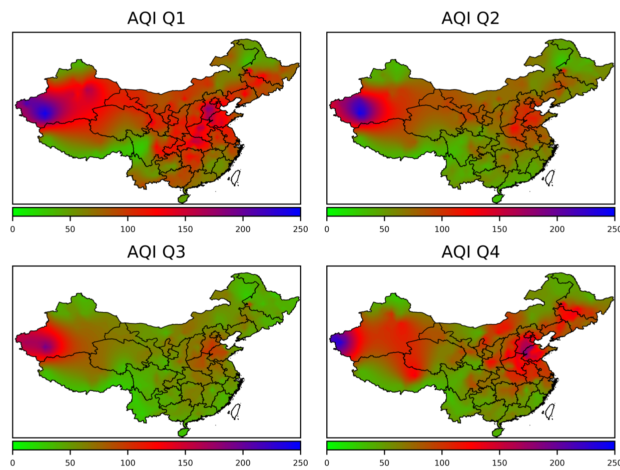

Figure 8: Average AQI in 4 seasons

Figure 8 is the spatial distribution of AQI in China in spring, summer, autumn, and winter. It can be found that the distribution does not change a lot in four seasons, which means that the spatial distribution is general in the whole year. The visible difference is the integral level of AQI, and the regularity has been discussed above. As the figure shows, the AQI in spring and winter is higher than that in summer and autumn, which matches the conclusion above.

According to the discussion above, the orthogonality of spatial distribution and temporal distribution of air pollutants has been verified preliminarily.

Comparison with Standard

The spatial distribution and temporal distribution of air pollutants is discussed in detail above. However, the perniciousness of air pollutants can not be easily expressed by the concentration only without considering the standards.

The standards are different in different countries. In China, the latest ambient air quality standards is **GB 3095-2012**. In this part, the standards will be used to measure the effect of air pollutants on people.

Table 2 shows the annual average concentration of $PM_{2.5}$, PM_{10}, SO_2, and NO_2 for every province. CO and O_3 are not considered because there are no annual average concentration standards for CO and O_3 in **GB 3095-2012**. It is not difficult to find that the concentrations of SO_2 and NO_2 satisfy secondary standards nearly in every province. However, there are only 7 and 10 provinces with concentration that satisfies secondary standard of $PM_{2.5}$ and PM_{10} respectively. which is much worse than the situation of SO_2 and NO_2. That means the main pollutants that effect people are $PM_{2.5}$ and PM_{10}.

An important value to measure the air quality is AQI. According to the computing method of AQI, AQI depends on the concentration of a pollutant that makes the most serious pollution. AQI is between 0 and 50 when all kinds of pollutants reach primary standard and is between 0 and 100 when all kinds of pollutants reach secondary standard.

Table 3 counts the number of days with AQI falling in six intervals, which represent different air quality level, for every province. It also shows the total number of days for all province together. It can be found that the number of days with AQI at level 1 and level 2 is more than eighty percent, and that the number of days with AQI at level 1 is slightly more than quarter. Thirteen provinces had more than ninety percent of days with AQI no more than 100. It shows that the overall air quality in 2015 was not bad. However, days with AQI at level 5 and level 6 exist, which means that there is some days with very serious pollution in some regions, such as Beijing-Tianjin-Hebei Region.

Conclusion

The distribution of the main air pollutants in China in 2015 is estimated by data and interpolation method. After comparing different $\phi(r)$, $\phi(r) = r$ is chosen. Because of the lack of data, the distribution in Xinjiang can not be estimated accurately.

The regularities of distribution are considered in both space dimension and time dimension.

About spatial distribution, the west of Xinjiang and Beijing-Tianjin-Hebei Region are two regions with the highest concentration of most of pollutants. O_3 is special, which concentrates around the northeast of Qinghai, the middle of Shaanxi and the west of Inner Mongolia. The distribution of other regions is radial from these regions.

About temporal distribution, regularities are considered in time range of one day, one week, and the whole year. It can be found that concentration changes regularly in one day and the whole year. The reason may be human activities and natural conditions. There may be regularity in time range of one week. However, it is not obvious and it seems that there is no relation with human cycle activities in a week.

It is interesting to analyse the orthogonality of distribution in space dimension and time dimension. It can be discovered that, in principle, spatial distribution is general in time and temporal distribution is general in space.

Comparing the estimations with standards, it can be found that the main pollutants that affect air quality are $PM_{2.5}$ and PM_{10}, and that the air quality is not bad in many provinces, except some regions with some days seriously polluted.

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Region	PM2.5	PM10	SO2	NO2	O3	CO
Northeast	42.13	70.99	20.88	22.53	58.06	0.86
East	51.32	84.23	24.16	28.49	56.18	1.00
North	43.33	84.73	28.48	25.69	63.58	1.08
Central	61.08	97.41	24.57	27.23	54.96	1.16
South	36.28	55.87	15.45	20.07	52.06	0.95
Southwest	33.46	69.44	17.64	19.15	55.06	0.93
Northwest	54.36	131.96	24.10	24.96	59.49	1.19

Table 1: Annually average concentration of pollutants in seven regions

Province	PM2.5	PM10	SO2	NO2
Beijing	70.51308802	100.1617561	15.69307259	36.2073822
Tianjin	75.16322175	128.4537827	26.92155884	42.98020641
Hebei	67.35036424	123.1808715	39.39586357	39.9945006
Shanxi	56.21650114	99.30525174	53.81069063	31.94108043
Nei Mongol	37.49787515	76.59064191	23.82445556	22.48185671
Liaoning	50.80173434	87.611652	33.38005027	29.13407639
Jilin	50.27951294	83.81746311	21.6044234	26.42300482
Heilongjiang	36.52764963	61.32465019	17.05627233	19.14884565
Shanghai	51.14810192	72.90263763	16.83197326	40.85212477
Jiangsu	58.16811528	98.88260298	24.07545027	32.55658451
Zhejiang	43.89526363	67.40405847	15.45635238	33.31930729
Anhui	55.44005666	84.23593303	19.10924299	27.26592293
Fujian	29.17094423	49.06345727	14.37900319	19.33976122
Jiangxi	39.59844787	61.54895497	22.23653577	18.93781658
Shandong	74.59378978	131.493584	42.39241131	39.20292155
Henan	74.09757407	124.4836962	33.2383935	36.02382312
Hubei	61.01289374	93.11669022	19.10004292	25.30297584
Hunan	50.37569971	78.98630498	22.4420848	21.74426111
Guangdong	34.6144499	54.24113364	14.81466903	22.91539461
Guangxi	39.96932602	60.11461343	17.7078215	19.12229484
Hainan	19.79935933	35.50667863	3.404903436	11.94024435
Chongqing	49.69723221	78.23787255	13.38684677	25.88657136
Sichuan	32.45184668	57.47349398	14.94073652	22.06504369
Guizhou	34.15395244	58.32728935	21.22234978	19.10651242
Yunnan	26.9201299	47.47235899	15.50908288	16.92572661
Xizang	34.78992586	82.78311141	19.23845079	18.14213253
Shaanxi	48.75999762	91.71276999	25.38937716	30.59412452
Gansu	45.73832054	94.88665084	23.96203423	25.46584685
Qinghai	44.58985947	95.20179575	23.03655442	19.74931456
Ningxia Hui	45.04476669	105.4878819	36.61054955	24.03396459
Xinjiang Uygur	61.20591549	160.7079112	24.07643494	26.36122524
Secondary Standard	35	70	60	40
Passing Provinces	7	10	31	29

Table 2: Annually average concentration of pollutants in all provinces except Taiwan, Hong Kong and Macao (lack of data)

Province	0-50	51-100	101-150	151-200	201-300	301-500	Passing Rate(≤ 50)	Passing Rate(≤ 100)
Fujian	299	135	0	0	0	0	62.91%	100.00%
Hainan	317	46	1	0	0	0	87.09%	99.73%
Yunnan	232	130	2	0	0	0	63.74%	99.45%
Xizang	67	295	2	0	0	0	18.41%	99.45%
Sichuan	187	172	5	0	0	0	51.37%	98.63%
Guizhou	173	180	11	0	0	0	47.53%	96.98%
Jiangxi	143	209	12	0	0	0	39.29%	96.70%
Guangdong	196	155	13	0	0	0	53.85%	96.43%
Guangxi	170	166	22	6	0	0	46.70%	92.31%
Heilongjiang	181	154	25	3	1	0	49.73%	92.03%
Zhejiang	109	222	29	3	1	0	29.95%	90.93%
Nei Mongol	107	223	32	2	0	0	29.40%	90.66%
Qinghai	18	311	31	3	1	0	4.95%	90.38%
Chongqing	94	215	33	16	6	0	25.82%	84.89%
Hunan	81	223	54	6	0	0	22.25%	83.52%
Anhui	45	254	53	11	1	0	12.36%	82.14%
Shaanxi	50	247	52	14	1	0	13.74%	81.59%
Shanghai	113	182	57	7	5	0	31.04%	81.04%
Gansu	26	268	65	4	1	0	7.14%	80.77%
Jilin	93	198	52	17	4	0	25.55%	79.95%
Liaoning	64	222	61	14	3	0	17.58%	78.57%
Ningxia Hui	26	253	61	19	5	0	7.14%	76.65%
Shanxi	23	252	69	19	1	0	6.32%	75.55%
Hubei	40	223	72	24	5	0	10.99%	72.25%
Jiangsu	38	225	76	15	10	0	10.44%	72.25%
Beijing	90	134	71	36	30	3	24.73%	61.54%
Shandong	12	210	96	26	19	1	3.30%	60.99%
Hebei	25	182	97	43	17	0	6.87%	56.87%
Tianjin	43	151	101	42	22	5	11.81%	53.30%
Henan	9	178	136	27	14	0	2.47%	51.37%
Xinjiang Uygur	2	168	148	36	10	0	0.55%	46.70%
Total	3003	6183	1539	393	157	9	26.61%	81.41%

Table 3: Days of AQI on different level in all provinces except Taiwan, Hong Kong and Macao (lack of data)