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Long-Term Atmospheric Visibility Trends and Characteristics of 31 Provincial Capital Cities in China during 1957–2016

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Received: 11 June 2018; Accepted: 15 August 2018; Published: 17 August 2018

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Abstract: Millions of pulmonary diseases, respiratory diseases, and premature deaths are caused by poor ambient air quality in developing countries, especially in China. A proven indicator of ambient air quality, atmospheric visibility (AV), has displayed continuous decline in China's urban areas. A better understanding of the characteristics and the factors affecting AV can help the public and policy makers manage their life and work. In this study, long-term AV trends (from 1957–2016, excluding 1965–1972) and spatial characteristics of 31 provincial capital cities (PCCs) of China (excluding Taipei, Hong Kong, and Macau) were investigated. Seasonal and annual mean values of AV, percentage of 'good' (≥20 km) and 'bad' AV (<10 km), cumulative percentiles and the correlation between AV, socioeconomic factors, air pollutants and meteorological factors were analyzed in this study. Results showed that annual mean AV of the 31 PCCs in China were 14.30 km, with a declining rate of −1.07 km/decade. The AV of the 31 PCCs declined dramatically between 1973–1986, then plateaued between 1987–2006, and rebounded slightly after 2007. Correlation analysis showed that impact factors (e.g., urban size, industrial activities, residents' activities, urban greening, air quality, and meteorological factors) contributed to the variation of AV. We also reveal that residents' activities are the primary direct socioeconomic factors on AV. This study hopes to help the public fully understand the characteristics of AV and make recommendations about improving the air environment in China's urban areas.

Keywords: atmospheric visibility; provincial capital cities; characteristics; impact factors; China

1. Introduction

Atmospheric visibility is defined as the maximum horizon distance between a person's eye and the visible target against the background of the sky at certain weather conditions [1]. According to the Environmental Protection Agency, the natural AV of a non-polluted atmosphere varies from 145 km to 225 km in different areas [2]. AV is affected by meteorological factors (e.g., wind speed, relative humidity, temperature, etc.) and air pollutants (e.g., particulate matter, SO_2, NO_2, etc.). By eliminating specific weather conditions (e.g., fog, snow, and rain), the scattering and absorption of light by air pollutants occurs. When the concentration of air pollutants increases, AV declines effectively [3–7]. Therefore, AV is regarded as an applicable indicator for air quality [3–12]. Many studies have also shown that AV has a negative correlation with public health, especially in developing countries. Huang et al. (2009) demonstrated the association between AV, air quality and death rates. They suggested that AV is significantly associated with elevated death rates and cardiovascular disease in Shanghai, China [13]. Thach et al. (2010) revealed that AV provides a useful proxy for the assessment of environmental health risks from ambient air pollutants and is a valid approach for the assessment of the public health impacts of air pollution [14]. Ge et al. (2011) demonstrated that decreased AV influences hospital admission [15]. It can be concluded that changes in AV has a significant correlation with public health. The questions of how to increase air quality and AV have become matters that have attracted concerns from the public and researchers alike.

To understand the characteristics and factors affecting AV, studies have been carried out in highly developed regions all over the world [3–12,14–22]. Wang et al. (2009) revealed that since the mid-1980s, AV has increased in Europe and North America, but has decreased substantially over south and east Asia, South America, Australia, and Africa [14]. Sabetghadam et al. (2012) analyzed AV data collected during 1958–2008 from the historical airport AV database in Tehran, Iran, and found decreasing trends in AV from all of the database's monitoring stations [17]. In recent years, studies that have occurred in China (e.g., Shanghai [18,19], Beijing [20–22], and Guangzhou [22]) have shown increasing trends of AV. Overall, previous studies have revealed that developed countries display a general increasing trend of AV after the mid-1980s, whereas developing countries display substantially decreasing trends of AV due to rapid economic development—this is especially true in China [18–22]. These previous studies analyzed the characteristics of AV in their study areas, which provided valid suggestions for the public and environmental policy makers [3–12,16–25]. However, as there has been no long-term data, few studies have been able to analyze the relationship between AV and the factors affecting AV. The analysis of the factors affecting AV are mostly focused on the meteorological factors, with other factors affecting AV being rarely reported.

For China's centralized political system, environmental policies and regulations made at the national level have a strong mandate at the city level. National appeal also has a strong role in raising public awareness of environmental protection [17–25]. Studies of AV in typical urban areas can help the public and policy makers better understand how to improve AV in China. Provincial capital cities, the typical urban areas in China, have achieved abundant progress in the past decades and are expected to still undergo rapid urbanization. The explosive boosts in economy and urbanization have resulted in increasingly severe air pollution in these urban areas. Comprehensive understanding of AV trends and characteristics in the provincial capital cities (PCCs)of China are significantly helpful for environmental policy makers. Nevertheless, to date very few studies have analyzed the characteristics of AV and the factors affecting AV in the PCCs of China.

In this study, hourly AV data between 1957–2016 (excluding 1965–1972) were employed to investigate the long-term AV trends and characteristics of the 31 PCCs in China. A comprehensive understanding of the long-term AV features of typical urban areas in China were presented. We made attempted to meet three three objectives: (1) describe the characterization and the long-term trends of AV, (2) reveal the spatial variation of AV, and (3) examine the relationships between AV and the factors affecting AV (e.g., socioeconomic factors, air pollutants, and meteorological factors) in the 31 PCCs in China.

2. Experiments

2.1. Data

The geographical locations of PCCs are depicted in Figure 1, where the squares, triangles, and circles represent PCCs in northern, southeastern, and western China, respectively.

Figure 1. Locations of 31 provincial capital cities in China.

Well-trained operators measured AV using easily identifiable objects (e.g., tall buildings and mountain ridges) at predetermined distances. AV and meteorological hourly data was obtained through the official release by the National Oceanic and Atmospheric Administration of America (NOAA: https://www.climate.gov). Prior to 1987, the observation times for the meteorological hourly data were 1:00, 4:00, 7:00, 10:00, 13:00, 16:00, 19:00, and 22:00 (local time). This data also included wind speed, temperature, relative humidity, dew point temperature and air pressure. The NOAA is respected as an authority that develops the data sets on meteorological information all over the world. The monitoring sites in the PCCs of China are managed by the China Meteorological Administration. The hourly data of air pollutant concentration of PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and O_3 were obtained and downloaded from the official website of the China National Environmental Monitoring Center (CNEMC, http://www.cnemc.cn/).

Socioeconomic data of the 31 PCCs was retrieved from the Chinese cities year book (the data collected in the administrative area of the city, which includes the urban, surrounding suburban and rural areas) (http://www.stats.gov.cn) and official municipal websites. According to previous studies, urban size, residents' activities, industrial activities and urban greening are the four socioeconomic factors which impacted the variation of AV [9–13,25–37]. For our study, we used the four variations previously mentioned and selected indicators for each socioeconomic variable by following two criteria. (1) The selected indicator must directly or indirectly affect AV, i.e., existing studies have shown the influence of these indicators on AV. (2) Data for these indicators must be available in all the PCCs (Table 1).

Table 1. Selected socioeconomic indicators and the source of citations.

Indicator	Effect	Sources
City size		
Areas of urban built-up	Negative	[11,26]
Resident populations	Negative	[10,11,13]
Area of city paved roads	Negative	[8,11,12,25,27]
Industrial activities		
Secondary industry GDP	Negative	[9,11,12]
Industrial dust Emission	Negative	[32,33]
Sulphur dioxide Emission	Negative	[32,33]
Industrial electricity consumption	Negative	[32,33]
Residents' activities		
Numbers of civilian vehicles	Negative	[8,11,12,25,27]
Total retail sales of consumer goods	Negative	[8,34]
Household electricity consumption	Negative	[34,35]
Urban greening		
Rate of forest cover	Positive	[28–30,35]
Green Covered Area	Positive	[28–30,35]
Area of park	Positive	[28–30,35]
Area of green land	Positive	[30,31,36,37]

2.2. Statistical Methods

The available AV data of the 31 PCCs was further classified into three categories: northern, southeastern, and western China. The average data of monitoring stations in northern, southeastern, and western China was found to have the mean values of 10, 11, and 10, respectively.

Five statistical approaches were utilized in this survey to investigate the trends of AV in PCCs of China during 1957–2016: (1) calculation of seasonal and annual change related to the trends of AV; (2) statistics of the occurrence rate of 'good' AV $\geq$ 20 km and 'bad' AV < 10 km [38,39]; (3) recapitulation of the cumulative percentiles; (4) extinction coefficient; and (5) correlation analysis between AV and the factors affecting AV (e.g., socioeconomic factor, air pollutants, and meteorological factors). Aforementioned investigation methods are explained in Sections 2.2.1–Section 2.2.5, respectively.

2.2.1. Annual and Seasonal Mean Value of Atmospheric Visibility

To make the presentation of temporal characteristic trends more concrete in this study, AV of the 31 PCCs in China were averaged annually and seasonal mean AV of the past 60 years in 31 PCCs were calculated.

2.2.2. Percentages of Atmospheric Visibility >20 Km and <10 Km Each Year

Rather than the mean AV, it was found that the public paid more attention to 'good' and 'bad' AV. As previous studies have mentioned that AV of 10 km is an important indicator of haze pollution in China [3,39] and AV of 20 km is an important indicator of high AV [5,6,18], 'good' and 'bad' AV were quantified as AV >20 km and <10 km respectively, in our study. Accordingly, the percentages of 'bad' AV can be regarded as a referential data of haze rate.

2.2.3. Lowest 20%, 50%, and Highest 20% Cumulative Percentiles of Atmospheric Visibility

Analyzing AV with cumulative percentiles for the PCCs is beneficial to get a better understanding of the data. The *i*th cumulative percentile is refers to the value of AV which equals or exceeds *i* percent (*i*%) of the AV data set during the study period [40]. According the Environmental Protection Agency, this study classifies the highest 20% (80%) percentile, 50% percentile, and lowest 20% (20%) percentiles of AV as 'relatively good', 'median', and 'relatively poor' AV, respectively [19].

2.2.4. Extinction Coefficient

Extinction coefficient β_{ext} (km^{-1}) is the light transmission properties of the atmosphere. A large extinction coefficient indicates that the light beam is quickly weakened as it passes through the atmosphere, whereas a small extinction coefficient indicates that the atmosphere is relatively transparent to the beam. In this study, β_{ext} was theoretically calculated via the Koschmieder relationship [41]

$$\beta_{ext} = 3.912/V \quad (1)$$

where V represents the visibility (km).

2.2.5. Correlation Analysis

To examine the relationship between AV and the factors affecting AV in the PCCs of China, we analyzed the correlation between AV and socioeconomic factors, air quality and meteorological factors. As long term socioeconomic data was limited in all the PCCs, we chose data that was collected in 2016 to analyze the spatial characteristics relationship between AV and the factors affecting AV.

3. Results

3.1. Long-Term Atmospheric Visibility Trends

3.1.1. Annual Mean Values

Table 2 summarizes the calculated mean AV during the periods of 1957–1964, 1973–1976, 1977–1986, 1987–1996, 1997–2006, 2007–2016, and 1957–2016, as well as the trends for each PCC during 1957–2016. As shown in Table 2, the mean value of AV in the 31 PCCs showed declining trends. The average AV of the 31 PCCs during the past 60 years of the study was 14.30 km, and the values for the PCCs in northern, southeastern, and western China were 12.92, 12.91, and 17.19 km, respectively. The annual mean AV in northern and southeastern China was found to be on the edge of bad AV (<10 km), whereas the AV of western China was higher than both north and southeast China, but did not reach good AV standards ($\geq$20 km). This indicated that AV in the PCCs of China were relatively poor. The decadal average AV of the PCCs in China during 1957–1964, 1973–1982, 1983–1992, 1993–2002, 2003–2012, and 2013–2016 were 17.97, 15.2, 14.36, 14.17, 13.08, 12.25, and 14.30 km, respectively. About 80% (24/31) of the PCCs have declined continuously over the past six decades. The average value of AV in PCCs have declined at a rate of -1.07 km/decade during the period of 1957–2016. The decadal average AV declined at the rate of -1.79 km/decade in Southeastern China, followed by the rate of -0.71 km/decade in northern China and the rate of -0.64 km/decade in western China. This meant that the air quality had degraded and became worse between 1957–2016.

Figure 2 depicts the trends of annual mean AV for the 31 PCCs in China during 1957–2016. In 1963, the average AV of the 31 PCCs reached the highest value at 18.89 km, while in 2014 it reached the lowest value at 10.56 km. During the 1973–1986 period, the AV degraded strikingly, with a declining rate of -1.72 km/decade. From 1986 to 2006, the AV decline was relatively steady, with a rate of -1.4 km/decade. Since 2006, the AV in 54.8% (17/31) of the PCCs showed an increasing trend ranging from 0.25 to 6.4 km/decade. The AV trends for northern (-0.71 km/decade), southern (-1.79 km/decade), and western China (-0.64 km/decade) have shown very similar fluctuations, while the trend of southeastern China has declined more distinctly overall.

However, some PCCs have shown different trends. Harbin, Shenyang, and Lanzhou showed rising trends, whereas Jinan, Tianjin, Haikou, Changsha, Xining, and Lhasa showed no significant trends. That may due to the different socioeconomic, natural and geographical factors of these cities.

Table 2. Mean visibility (km) and change trends (km/decade) of the six decades of the 31 provincial capital cities in China.

	1957–1964	1973–1976	1977–1986	1987–1996	1997–2006	2007–2016	1957–2016	60-Year Trend
Northern China								
Beijing (BJ)	16.25	12.72	10.89	10.22	9.60	10.33	11.37	−1.26
Shijiazhuang (SJZ)	18.73	14.55	13.73	10.79	11.21	11.69	13.12	−1.36
Zhengzhou (ZZ)	21.07	12.72	11.27	10.36	8.77	5.87	11.00	−2.6
Harbin (HEB)	15.24	15.90	15.43	14.22	18.84	17.26	16.21	0.50
Changchun (CC)	15.47	15.64	14.84	17.73	13.86	9.19	14.28	−1.06
Shenyang (SY)	5.59	5.90	5.96	9.09	10.04	12.55	8.55	1.43
Hohhot (HHHT)	19.99	22.37	22.45	21.77	17.31	13.41	19.19	−1.62
Jinan (JN)	16.31	11.53	10.15	9.31	12.72	15.99	12.66	0.08
Taiyuan (TY)	14.75	14.87	13.90	10.36	8.96	8.13	11.37	−1.53
Tianjin (TJ)	11.91	8.85	10.74	11.48	12.63	11.81	11.49	0.19
Average	15.39	13.50	12.94	12.53	12.39	11.62	12.92	−0.71
Southeastern China								
Hefei (HF)	20.67	13.84	12.63	10.99	7.44	5.81	11.33	−2.81
Guangzhou (GZ)	23.00	15.36	11.45	9.35	8.66	8.81	12.08	−2.71
Nanning (NN)	21.34	19.86	18.52	16.78	11.30	9.67	15.63	−2.52
Haikou (HK)	20.44	16.44	17.20	18.36	20.07	19.66	18.89	0.07
Wuhan (WH)	16.16	11.60	8.78	13.60	11.35	8.36	11.47	−1.07
Changsha (CS)	13.07	11.62	11.71	12.31	11.37	12.66	12.15	−0.06
Nanjing (NJ)	19.71	14.43	12.80	10.63	6.64	5.99	11.08	−2.74
Nanchang (NC)	18.78	15.75	13.85	10.90	9.89	9.64	12.62	−1.99
Shanghai (SH)	11.65	8.69	9.24	8.26	7.09	7.87	8.70	−0.70
Hangzhou (HZ)	17.59	14.97	10.93	8.14	6.63	6.52	10.05	−2.31
Fuzhou (FZ)	26.67	22.75	19.42	15.67	15.93	12.03	17.98	−2.86
Average	19.01	15.03	13.32	12.27	10.58	9.73	12.91	−1.79
Western China								
Lanzhou (LZ)	14.81	13.94	15.23	18.51	20.82	22.78	18.29	1.71
Guiyang (GY)	14.23	19.14	19.32	17.62	13.61	10.80	15.46	−1.04
Yinchuan (YC)	33.73	23.98	20.96	23.04	21.73	19.28	23.18	−2.45
Xining (XN)	16.83	10.77	17.38	21.99	21.41	21.07	19.20	1.39
Xi'an (XA)	9.01	7.05	9.64	12.26	7.90	5.60	8.73	−0.50
Chengdu (CD)	11.41	10.02	8.21	9.13	7.13	6.02	8.39	−1.00
Lhasa (LS)	27.57	29.40	29.52	29.82	30.09	29.39	29.35	0.22
Urumqi (WLMQ)	33.04	31.79	22.97	23.51	24.57	24.21	25.85	−1.77
Kuming (KM)	22.16	22.44	18.99	17.87	12.38	11.34	16.79	−2.43
Chongqing (CQ)	9.92	9.16	7.02	5.28	5.52	5.88	6.79	−0.90
Average	19.16	17.77	16.92	17.90	16.52	15.64	17.19	−0.64
China								
Average	17.97	15.42	14.36	14.17	13.08	12.25	14.30	−1.07

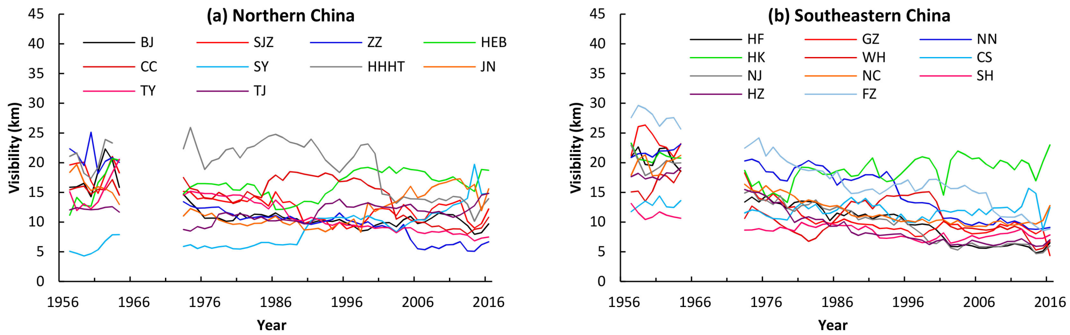

Figure 2. *Cont.*

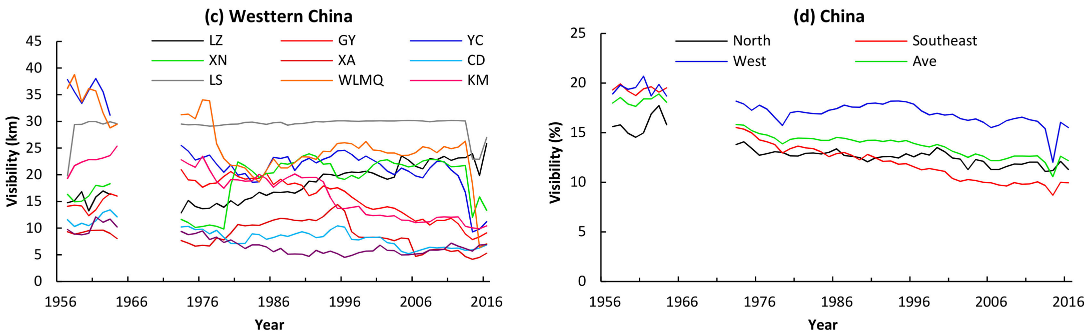

Figure 2. Variation of annual average visibility (km) of PCCs in (**a**) northern China, (**b**) southeastern China, and (**c**) western China in 1957–2016; (**d**) Variation of annual average visibility of northern China, southeastern China, western China and the whole 31 PCCs in China in 1957–2016.

3.1.2. Percentages of 'Good' and 'Bad' Atmospheric Visibility

The annual percentages of 'good' and 'bad' AV were calculated for the 31 PCCs in the western, southeastern, and northern China, respectively (Figure 3). During 1957–2016, 20 PCCs displayed declining trends in the percentage of 'good' AV, and 23 PCCs displayed rising trends in the percentage of 'bad' AV. Harbin, Shenyang, and Lanzhou showed both rising trends of 'good' AV and declining trends of 'bad' AV. Jinan, Tianjin, Haikou, Changsha, Xining, and Lhasa showed no significant trends of either 'good' or 'bad' AV.

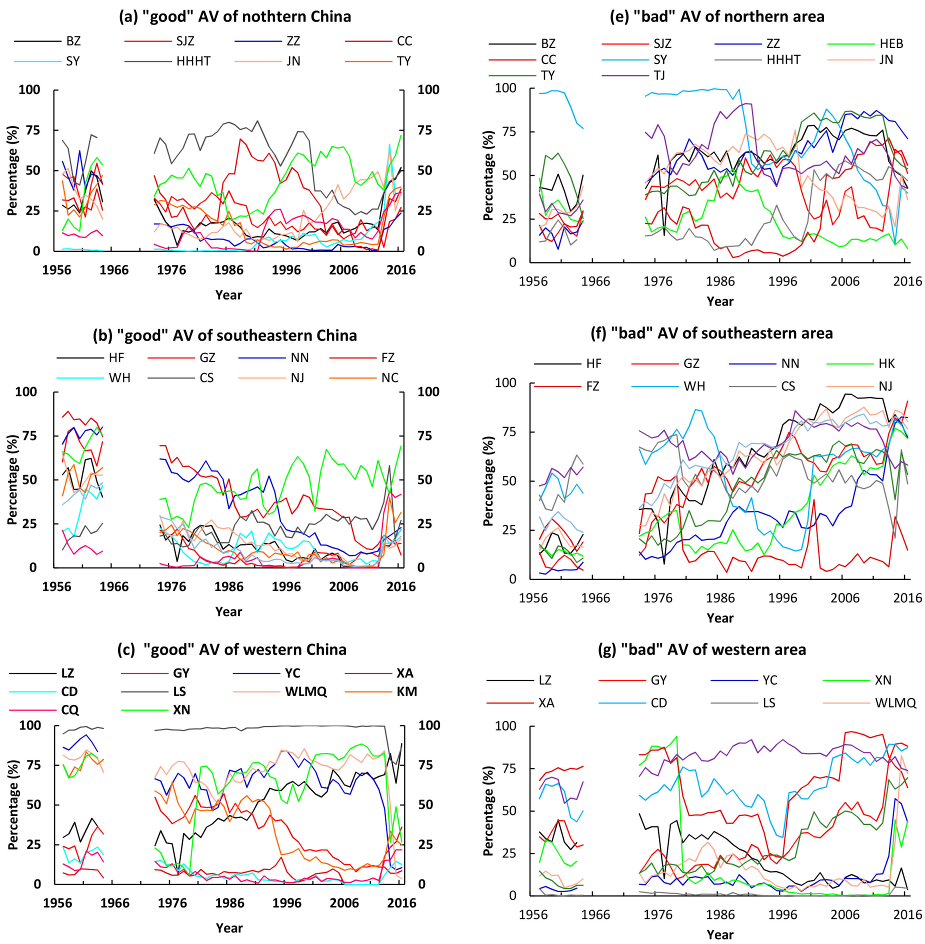

Figure 3. *Cont.*

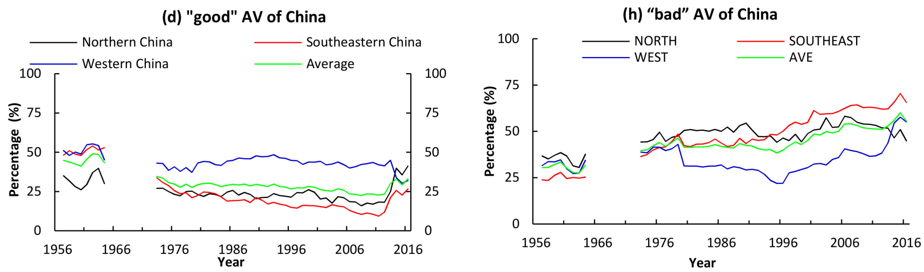

Figure 3. Annual percentages (%) of 'bad' visibility (<10 km, left column) and 'good' visibility (≥20 km, right column) in the PCCs of China during 1957–2016: (**a**) 'good' AV of northern China; (**b**) 'good' AV of southeastern China; (**c**) 'good' AV of western China; (**d**) the average percentage of 'good' AV of China; (**e**) 'bad' AV of northern China; (**f**) 'bad' AV of southeastern China; (**g**) 'bad' AV of western China; (**h**) the average percentage of 'bad' AV of China.

The average percentages of 'good' and 'bad' AV is presented in Figure 4. During the study period, it was found that there was a significant increasing trend of 'bad' AV for the PCCs in China, and an obvious declining trend in the percentage of 'good' AV. For the 31 PCCs, the mean value of 'bad' AV ranged from 27.49% to 60.05%, with an increasing rate of 4.0%/decade, while the 'good' AV percentage ranged from 22.45% to 48.99%, with a declining rate of −3.1%/decade. Since 2006, a percentage of 'good' AV was observed to be increasing at a rate of 10.6%/decade; however, the percentage of 'bad' AV was observed to be still increasing at a rate of 3.8%/decade.

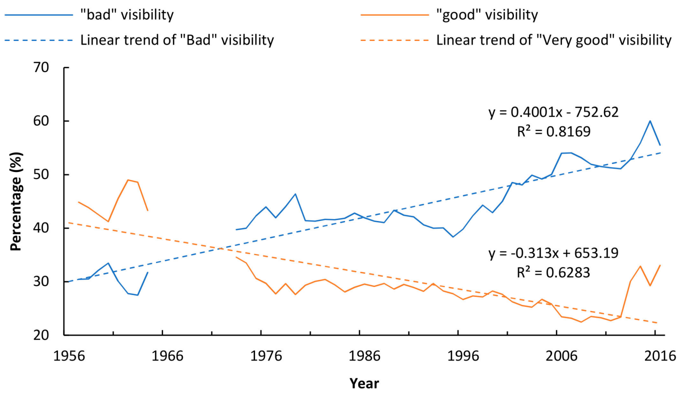

Figure 4. Annual mean 'bad' atmospheric visibility percentages (%) were less than 10 km (shown in left axis of y) from 1957 to 2016 in China's 31 PCCs. Dash lines refer to the curves of linear regression for the corresponding lines of trend.

3.1.3. Cumulative Percentiles

Table 3 summarizes the lowest 20% and 50%, and the highest 20% AV, as well as the corresponding changing trends over the past six decades for the 31 PCCs in China. The variations of the lowest 20% and 50%, and the highest 20% average region AV are depicted in Figure 6. In Table 3, the mean value of the lowest 20% and 50%, and the highest 20% AV for the PCCs in China were 8.64, 13.87, and 19.54 km, respectively. The declining rate of the highest 20% was found to be more obvious than those of the lowest 20% and 50% AV.

The lowest 20% and 50%, and the highest 20% AV in northern, southeastern and western China exhibited similar changes, but the magnitude of these trends was different. Southeastern China experienced the lowest AV and fastest declining rates for the lowest 20% and 50%, and the highest 20%, while western China showed the best AV and the lowest declining rates. Apart from Shenyang, Harbin, Tianjin, Lanzhou, and Nanning, the other cities all displayed declining trends for the lowest 20% and 50%, and the highest 20% of AV.

Table 3. Lowest 20% and 50%, and the highest 20% atmospheric visibility (km) as well as the changing trends (km/decade) of the PCCs in China.

Category	Stations	Worst 20%		50%		Highest 20%	
		Visibility	Trend	Visibility	Trend	Visibility	Trend
North	BeiJing (BJ)	4.96	−0.45	10.29	−0.74	15.48	−2.64
	ShiJiaZhuang (SJZ)	6.33	−0.82	11.69	−1.25	18.93	−1.83
	ZhengZhou (ZZ)	6.29	−1.58	10.08	−2.23	15.53	−3.55
	Harbin (HEB)	10.45	0.95	16.24	0.42	21.11	0.10
	ChangChun (CC)	9.95	−0.65	14.42	−1.04	17.71	−3.39
	ShenYang (SY)	5.68	0.93	8.65	1.44	11.80	2.38
	Hohhot (HHHT)	11.98	−1.00	19.26	−2.48	27.43	−1.37
	JiNan (JN)	5.75	−0.15	11.86	0.04	18.73	−0.46
	TaiYuan (TY)	6.72	−0.76	10.57	−0.87	14.93	−2.80
	TianJin (TJ)	8.28	0.19	10.60	−0.22	15.56	0.91
	Average	7.64	−0.32	12.37	−0.68	17.72	−0.99
Southeast	HeFei (HF)	6.06	−1.63	10.29	−2.51	16.23	−3.97
	GuangZhou (GZ)	7.34	−2.24	12.17	−2.84	15.96	−3.69
	NanNing (NN)	9.90	0.65	15.19	0.49	21.32	0.37
	HaiKou (HK)	12.82	0.65	18.30	0.49	25.97	0.36
	WuHan (WH)	6.37	−0.81	10.84	−0.41	15.96	−1.36
	ChangSha (CS)	4.49	−0.71	10.44	−0.11	19.01	0.74
	NanJing (NJ)	5.34	−1.54	9.77	−2.11	16.61	−3.39
	NanChang (NC)	7.97	−1.69	12.43	−1.93	17.21	−2.09
	ShangHai (SH)	4.44	−0.37	9.31	−0.24	12.08	−1.00
	HangZhou (HZ)	4.31	−1.13	8.88	−2.21	14.99	−3.21
	FuZhou (FZ)	10.43	−2.52	17.42	−3.57	25.16	−3.94
	Average	7.26	−1.30	12.28	−1.69	18.27	−2.35
West	LanZhou (LZ)	10.14	1.76	18.91	2.84	26.61	1.81
	GuiYang (GY)	8.94	−0.60	14.32	−0.97	22.40	−1.93
	YinChuan (YC)	14.74	−2.05	23.06	−2.62	31.76	−3.57
	XiNing (XN)	14.23	−1.43	18.77	−0.39	23.90	−1.38
	Xi'an (XA)	4.20	−0.33	8.41	−0.55	12.43	−0.38
	ChengDu (CD)	3.24	−0.25	7.75	−0.77	13.12	−1.39
	Lhasa (LS)	29.37	−0.01	29.83	−0.19	30.02	−0.19
	WuLuMuQi (WLMQ)	14.53	−0.27	29.45	−1.88	34.11	−4.47
	KuMing (KM)	11.01	−1.58	15.69	−2.24	22.91	−3.86
	ChongQing (CQ)	2.46	−0.26	5.26	−0.63	10.78	−1.07
	Average	11.29	−0.23	17.14	−0.63	22.80	−1.25
China	Average	8.67	−0.64	13.87	−1.02	19.54	−1.58

Figure 5 shows that the lowest 20% and 50%, and the highest 20% average AV have similar fluctuations during the study period. The lowest 20% and 50%, and the highest 20% average region AV declined at a rate of −0.64, −1.02 and −1.58 km per decade, respectively. The best 20% and 50%, and the worst 20% extinction coefficients were also presented, with annual increasing rates of 0.03, 0.02, and 0.001 km^{-1}, respectively (Figure 5).

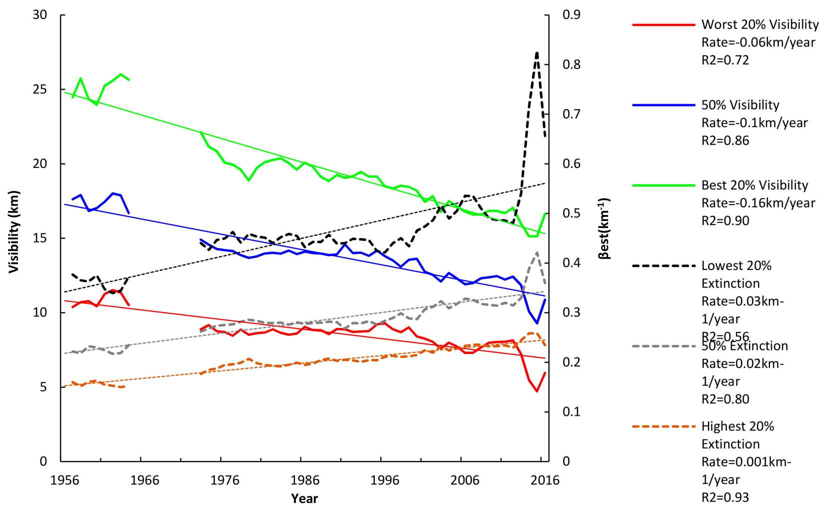

Figure 5. Lowest 20% and 50%, and the highest 20% average regional atmospheric visibility as well as extinction trends for the average of PCCs in China. Dashed lines refer to the curves of linear regression of the corresponding lines of trends.

3.2. Seasonal Variation

Figure 6 depicts the 60-year seasonal variation of AV in the 31 PCCs of China. The highest AV occur in the summer (June–August), followed by autumn (September–November), spring (March–May), and winter (December–February). Different parts of China showed different seasonal patterns. In northern and western China, the AV was highest in the summer, followed by spring, autumn and winter. In southeastern China, the highest AV occurred in the summer, followed by autumn, spring, and winter.

Some PCCs showed different characteristics e.g., Beijing, Shijiazhuang, Shenyang, Jinan, and Tianjin had similar variations of seasonal AV, where the highest AV occurred in the spring, followed by summer, autumn, and winter; Lhasa and Kunming showed no significant difference during the four seasons. Fuzhou had the highest AV in autumn, followed by summer, spring, and winter.

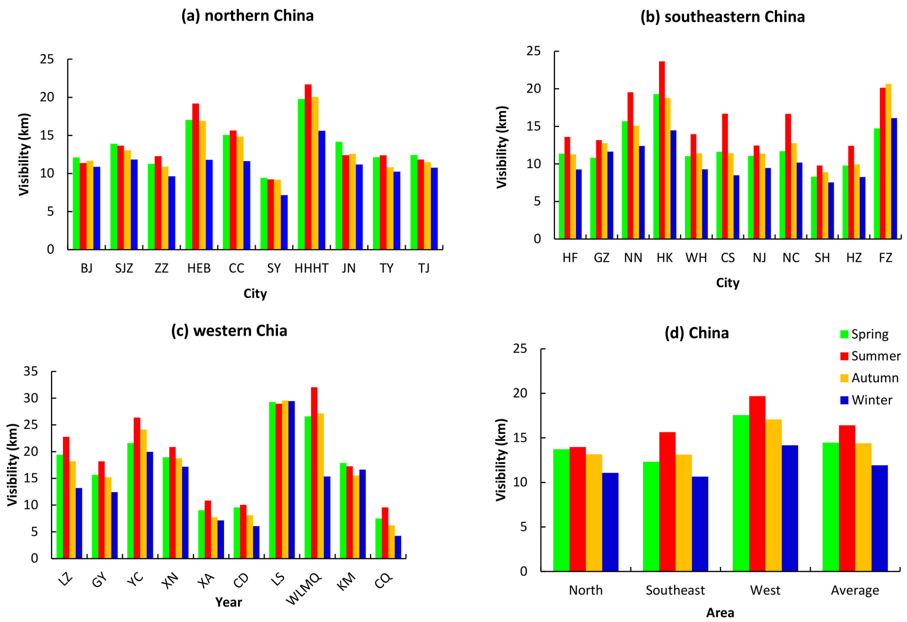

Figure 6. Trends of seasonal average visibilities in China's provincial capital cities. (**a**) Northern China; (**b**) southeastern China; (**c**) western China; (**d**) average value of China.

3.3. Impact Factors

Pearson correlation coefficients were calculated between AV and the factors affecting AV (e.g., socioeconomic factors, air pollutants, and meteorological factors) (Tables 4 and 5). Our result showed that AV was affected by urban size, residents' activities, and industrial activities, while urban green spaces showed no significant impact on AV. The indicators of urban size (e.g., population, built-up area, and the areas with paved road) had a negative impact on AV. Residents' activities, such as number of civilian vehicles, retail sales, household electricity consumption also had a negative impact on AV. Industrial activities, such as secondary industry GDP and industrial electricity consumption, were found to have a negative impact on AV. While industrial sulfur dioxide emissions and industrial dust emissions had no significant effect on AV.

Table 4. Correlation between atmospheric visibility and socioeconomic factors of 31 PCCs of China, 2016.

	Urban Size			Urban Greening			
	Resident Populations	Areas of Urban Built-Up	Area of City Paved Roads	Rate of Forest Cover	Area of Green Land	Areas of Park	Green Covered Area
Annual mean visibility	−0.379 *	−0.372 *	−0.464 **	0.010	0.094	0.144	−0.085
Bad visibility rate	0.432 *	0.436 *	0.511 **	−0.029	−0.014	−0.142	0.178
Good visibility rate	−0.32	−0.31	−0.411 *	0.022	0.101	0.118	−0.094
	Residents' activities			Industrial activities			
	Numbers of civilian vehicles	Total retail sales of consumer goods	Household electricity consumption	Secondary industry GDP	SO_2 emission of industry	Industrial dust Emission	Industrial electricity consumption
Annual mean visibility	−0.422 *	−0.375 *	−0.410 *	−0.444 *	−0.19	−0.08	−0.417 *
Bad visibility rate	0.502 **	0.422 *	0.469 **	0.508 **	0.21	0.11	0.469 **
Good visibility rate	−0.342 *	−0.31	−0.35	−0.395 *	−0.18	−0.07	−0.371 *

The relationship between the indicators of urban greening and atmospheric visibility was used partial correlation analysis and set area of urban built-up as reference factor. ** means $p < 0.01$, * means $p < 0.05$.

As revealed in Table 5, $PM_{2.5}$ and NO_2 have a negative impact on AV, while PM_{10}, SO_2, CO, and O_3 show no significant correlation with AV. Meteorological factors, such as average annual temperature and average annual air pressure, were found to have a negative impact on AV, whereas annual average wind speed had a positive impact on AV. However, the correlation between the annual average rainfall, hygrometer dew temperature point, and AV were not significant.

Table 5. Correlation between atmospheric visibility and air pollutants and meteorological factors of 31 PCCs of China, 2016.

	Air Pollutants					
	$PM_{2.5}$	PM_{10}	SO_2	CO	NO_2	O_3
Annual mean visibility	−0.464 **	−0.22	−0.10	−0.32	−0.429 *	0.10
Bad visibility rate	0.444*	0.22	−0.04	0.27	0.434 *	0.01
Good visibility rate	−0.436*	−0.21	−0.16	−0.32	−0.384 *	0.11
	Meteorological factors					
	Temperature	Air pressure	Humidity	Wind speed	Rain fall	Dew temperature point
Annual mean visibility	−0.30	−0.498**	−0.36	0.408 *	−0.21	−0.21
Bad visibility rate	0.376 *	0.456 *	0.35	−0.437 *	0.25	0.15
Good visibility rate	−0.28	−0.467 **	−0.33	0.406 *	−0.19	−0.13

Air pollutants e.g., $PM_{2.5}$ mean the concentration of $PM_{2.5}$.

4. Discussion

4.1. Long-Term Trends of the Atmospheric Visibility in 31 Pccs of China

Our results showed that AV in the urban areas of the 31 PCCs had declined between 1956–2006, then increased after 2006. These existing observations were confirmed in our findings [3–8,41–44]. Rapid development, industrialization, and urbanization in China were the main causes for the observed AV trends. This is especially true after 1979, when China carried out the 'Reform and Opening Up' policy. Since 1980, the economy of China developed rapidly, which were inevitably accompanied with environmental impact [8]. The mitigation of AV decline occurred after 2006, which may be due to the government's control of pollution. For China's centralized political system, pollution control policies, and regulations made at the national level have a strong mandate at the city level [23]. After the Chinese government became aware of the seriousness of environmental pollution, a series of laws, regulations, and standards have been formulated, adopted, and promulgated. For example, the Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution, the National Ambient Air Quality Standards (CNAAQS) (GB3095-1996) and the Emission Standards of Air Pollutants for Thermal Power Plants (APTPP) (GB13223-2003) and the Chinese Ambient Air Quality Standards (CAAQS) (GB3095-2012). After 2006, the AV in 54.8% of the PCCs have shown growing trends ranging from 0.25 to 6.4 km/decade, which may have been attributed to the effective policies of pollution control. Studies conducted in southeastern China have shown similar results [3]. It should be noted that when the policies mentioned above were implemented, the improvement in AV did not appear immediately. There was a grace period for the policies and regulations to fully take effect. For instance, the ATPTP was implemented in 2003, and was set up as two periodical indicators of dust emission from coal power generation outside the urban areas: 600 mg/m^3 for 2005 and 200 mg/m^3 for 2010.

4.2. Seasonal Variation of Atmospheric Visibility in 31 PCCs of China

The results showed that for most PCCs (with the exception of Beijing, Shijiazhuang, Shenyang, Jinan, Tianjin, Lhasa, Haikou, and Fuzhou) AV was higher in summer and autumn, and lower in winter and spring. Seasonal variations reflect most of the effects of meteorological conditions, such as those impacted by emissions from the global desert and residents' activities. During winter and spring, AV is relatively low due to two factors: stagnant meteorological conditions characterized by slow winds and shallow mixing layers occur more frequently, and there is a higher concentration of air pollutants due to the trapping of pollutants near the atmospheric surface [45–47]. Furthermore, emissions from the global desert are also a reason for low AV during spring and winter in northern and western China [48]. Air pollutants from fossil fuel combustion sources, such as residential coal combustion for heating during winter, were found to represent more than 90% of the total fuel consumption in northern China [48,49]. The sulfur content in the coal led to the release of SO_2, which further enhanced the sulfate formation of secondary aerosols, which is the main contributor to light extinction in northern China [50]. The degeneration of AV in spring and winter in China may also be attributed to the burning of biomass, which has been suggested as a cause in previous studies [51]. The relatively 'better' AV in summer and autumn can be attributed to the following reasons: the dilution conditions are better in this period: air convective mixing is strong, wind speed is high, and vertical exchange is fast; during this period air pollutants, especially particles, may be sharply reduced by wet removal from the strong effects of large precipitation; and strengthened pollutant dilution from large scale transport due to East Asian summer monsoons.

Many studies have shown the same seasonal variation of AV in different cities of China [5,6,42–44]. In our study, our results show a complete picture of the seasonal variations in the 31 PCCs and revealed that the seasonal variations of AV in different PCCs are slightly different. Compared with previous studies, which focus on a single city or single region, our results are broader, more comprehensive, and clearly present the seasonal variation characteristics of PCCs in different regions.

4.3. Special Characteristics of Atmospheric Visibility Trends in 31 PCCs of China

Our result reveal that not all the PCCs in China display the same AV trends. Due to different geographical, climatic, and socioeconomic factors, some PCCs showed different AV trends; specifically Harbin, Shenyang, Lanzhou, Jinan, Tianjin, Haikou, Changsha, Xining, and Lhasa. Shenyang, Harbin, Lanzhou, Jinan, Tianjin, and Changsha were regions that were industrialized relatively early and have suffered from air pollution prior to the 1950s [52]. Throughout the process of rapid urbanization and industrialization, the governments of these cities established environmental management policies earlier than other cities, thus the AV of these cities did not deteriorate significantly during the period of our study [46]. Shenyang and Harbin, as developed industrial cities, are the important industrial cities in northern China and have been centers for heavy industry in China since the 1930s. These two cities planned to diversify their industry and improve the environmental quality, during the 1960s [48]. Due to this plan, Harbin and Shenyang showed an increasing trend in AV during the study period.

Xining, Lhasa, and Haikou showed no significant trends and had relatively high AV. This may be due to these three PCCs having low industrial activities, low levels of urbanization, and less pollutants present. Moreover, the AV trends for these three PCCs did not show any significant change during the study period—the changing trends were almost 0. This could be contributed due to these cities being located in remote and unpolluted areas, where the economy is mainly based on agriculture and tourism.

4.4. Factors Affecting Atmospheric Visibility

Our results reveal that industrial activities, residents' activities and urban size expansion are the main sources of AV decline in PCCs. Urban greening can mitigate the declining trends, but the effects are not significant. Our findings were similar to those of previous studies [53–55], but different conclusions have been drawn.

In our study, we found that industrial SO_2 emission and industrial dust emissions showed no significant correlation with the change of AV in the 31 PCCs that were observed, which is inconsistent with other study results. Kuo et al. (2013) suggested that NO_x and SO_x are the main sources of secondary aerosols, and also promote the formation of secondary aerosols, which significantly impact AV negatively [54]. Zhang et al. (2015) also found that during haze time where AV < 10 km, the conversions between SO_2 and SO_4^{2-} accounted for about 20% concentration of $PM_{2.5}$ [10]. Different from their findings, our results meant that industrial activities are not the primary factors that affect AV. This indicates that the Chinese environmental policies have had an efficient impact on the industrial pollution in recent years. On the other hand, exhaust emission indicators of residents' activities, such as the number of vehicles and retail sales, were significantly related to the decline of AV. This indicates that residents' activities have become a significant factor affecting changes in AV.

Energy consumption was also a major cause of reduced AV [27]. Our results showed that the electricity consumption of residents' activities and industrial activities were all negatively correlated with the change of AV. As thermal power is still the main source of electricity in China, the power generation process produces $PM_{2.5}$ emissions. Relevant data showed that thermal power accounted for 75.56% and 73.44% in 2005 and 2010, respectively. Mo et al. (2013) revealed that the firepower electricity industry discharged 36.1% of total $PM_{2.5}$ emissions in 2010, which indicated that electric consumption was positively correlated with air pollutant emissions [56].

City size also had significant effects on AV. City sizes correspond to population and built-up areas. Built-up areas are associated with construction activities and residents' activities. Larger city size corresponds more traffic and more energy consumption. All these contribute to a discharge of air pollutants. These are the reasons of AV decline in urban areas.

Our result showed that urban greening can mitigate the declining trends, but the effects are not significant. In our study, some PCCs with similar socioeconomic conditions (e.g., population, urban area, and secondary GDP, due to different forest coverage and urban afforestation areas) were obviously different in terms of AV. These PCCs also had different indicators of urban greening, as shown in Table 2 with comparisons such as: Nanjing vs. Wuhan, Changsha vs. Zhengzhou, Jinan vs. Hangzhou. However, correlation between the indicators of urban greening and AV were positive, but not statistically significant, which indicates that an obvious effect of urban greening on AV does not exist. This shows that urban greening has a weak effect on visibility improvement and the effect is not significant for the PCCs of China in recent years. This may be related to complex influences by other factors. Previous studies have provided the reasons for this result [30,31,57]. Irga et al. (2015) concluded that urban areas with proportionally higher concentrations of urban forest may experience better air quality with regards to reduced ambient particulate matter; however, conclusions about other air pollutants have yet to be explained [30]. Grundström et al. (2014) indicated that the effect of urban vegetation on air pollution concentrations was small [57]. Other results suggest that for anthropogenic pollutants measured in northern climates, the role of urban greenery, mostly deciduous vegetation, is negligible in improving local air quality.

4.5. Application: Policy Recommendation

The Chinese government has made many efforts to improve environmental pollution. Since 2006, the total emission of SO_2 and chemical oxygen demand (COD), an indicative measure of the amount of oxygen that can be consumed by reactions and a water quality metric that can determine the effect an effluent will have on the receiving body, were set as the major environmental assessment indicators for the "National 11th Five-Year Plan for National Economic and Social Development". After 2013, the Action Plan for Prevention and Control of Atmospheric Pollution (http://www.zhb.gov.cn) was implemented, and more attention has been paid on industrial emission reduction. As mentioned in Section 4.1, many air quality evaluation systems have been formulated. They have all played important roles on increasing AV. As mentioned in Section 4.1, studies taken in Beijing, southeast China, and western China showed that AV have increased since 2006, which indicates that the policies enacted by the central government have been effective.

According to our results, as mentioned in Section 4.4, policymakers should pay more attention to increasing clean energy, limiting urban expansion, urban population control, pollution emissions from civic activities, and urban greening.

4.6. Limitation

This paper builds a platform for a comprehensive understanding of the long-term AV trend of 31 PCCs in China. However, it should be noted that there are limitations in our study. The analysis of impact factors conducted in this study only included the data of the 31 PCCs, as data was unavailable for the surrounding cities and rural areas. Further research needs to be focused on the impacts of the surrounding cities and rural area.

5. Conclusions

Long-term trends and characteristics of AV in urban areas of the 31 PCCs of China during 1957–2016 were analyzed based on the hourly records obtained through the official release by NOAA. Since these monitoring stations are located across all 31 provinces, the whole country's urban areas AV trends were well recorded. We characterized the spatial and temporal variations of the AV and built a platform for a comprehensive understanding of the trends in 31 PCCs of China. The results revealed that the AV of China's urban areas was in decline from 1957–2006 and showed an increasing trend between 2006 and 2016. AV in the PCCs of north, southeast, and west China all showed declining trends, but due to different socioeconomic, natural, and geographical factors, the range of AV was different. In developed industrial cities such as Harbin, Shenyang, and Lanzhou, an increasing trend in AV was observed. We concluded that this increasing AV trend in developed industrial cities was due to the efforts of early environmental protection legislation and industrial transformation. Remote cities—such as Haikou, Xining, and Lhasa—that are farther from China's major urban agglomerations and have relatively low industrial activities were found to have non-significant AV trends. For seasonal variation, the highest AV occurs in summer (June–August), followed by autumn (September–November), spring (March–May), and winter (December–February). It was observed that different parts of China showed different seasonal patterns. In northern and western China, the AV was highest in summer, followed by spring, autumn, and winter, and in southeastern China the highest AV occurred in summer, then autumn, spring, and winter. Some PCCs also showed different seasonal characteristics and this was attributed to different socioeconomic, natural and geographical factors.

AV variation in China is caused by multiple factors, including city area expansion, industrial activities, population, residents' activities, air pollutants, meteorological factors, policies, and urban forest. Our results showed that in recent years, residents' activities were the primary direct impact on AV in the urban areas of PCCs in China. Based on our study results, we make the recommendation for policymakers to pay more attention to residents' activities. This study also calls for future studies to investigate the associations between air quality, meteorological conditions, and AV in different areas, and to further improve the understanding of the physical and chemical processes which affect air quality in China.

Author Contributions: W.F. conceived and designed the study; W.F., J.D., and Z.C. analyzed the data anddiscussed the results; Z.Z., Q.L., and M.W. discussed the results; and W.F. and E.D. wrote the paper.

Funding: This research was funded by Public Interest Program of Chinese Ministry of State Forestry (nos. 201404301 and 201404315), and Public Program of National Engineering Research Center for the Forest Park (nos. PTJH1500207 and PTJH1500218).

Acknowledgments: We thank the National Oceanic and Atmospheric Administration of America (NOAA) for the dataset.

Conflicts of Interest: The authors declare no conflict of interest.

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