Air pollution characteristics and health risks in Henan Province, China

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ABSTRACT

Events of severe air pollution occurred frequently in China recently, thus understanding of the air pollution characteristics and its health risks is very important. In this work, we analyzed a two-year dataset (March 2014 – February 2016) including daily concentrations of six criteria pollutants (PM2.5, PM10, CO, SO2, NO2, and O3) from 18 cities in Henan province. Results reveal the serious air pollution status in Henan province, especially the northern part, and Zhengzhou is the city with the worst air quality. Annual average PM2.5 concentrations exceed the second grade of Chinese Ambient Air Quality Standard (75 μg/m³) at both 2014 and 2015. PM2.5 is typically the major pollutant, but ozone pollution can be significant during summer. Furthermore, as the commonly used air quality index (AQI) neglects the mutual health effects from multiple pollutants, we introduced the aggregate air quality index (AAQI) and health-risk based air quality index (HAQI) to evaluate the health risks. Results show that based on HAQI, the current AQI system likely significantly underestimate the health risks of air pollution, highlighting that the general public may need stricter health protection measures. The population-weighted two-year average HAQI data further demonstrates that all population in the studied cities in Henan province live with polluted air – 72% of the population is exposed to air that is unhealthy for sensitive people, while 28% of people is exposed to air that can be harmful to healthy people; and the health risks are much greater during winter than during other seasons. Future works should further improve the HAQI algorithm, and validate the links between the clinical/epidemiologic data and the HAQI values.

1. Introduction

A number of previous studies (e.g., Cao et al., 2012; Heal et al., 2012; Jin et al., 2017; Pope and Dockery, 2006; Pope and Dockery, 2013) have demonstrated clearly that the air pollutants could pose adverse effects on human health. Along with the rapid economic development and urbanization in China, air pollution has become particularly severe lately (Zhang and Cao, 2015), it is thus important to let the public know the air pollution status and its associated health risks. In 2012, the Chinese Ministry of Environmental Protection (CMEP) issued the Ambient Air Quality Index (AAQI) Technical Provisions (Trial) (HJ 633–2012) on the basis of the United States Environmental Protection Agency (US EPA) AQI, and it was implemented in the Chinese Ambient Air Quality Standard (CAAQS) (GB 3095-2012). The AQI level is determined by the concentrations of six criteria pollutants including SO2, NO2, CO, O3, PM2.5 and PM10. Basically the AQI acts as a guide for government to inform the public to take proper health protection measures. Thus studies on the spatiotemporal distributions of air pollutants and/or AQI is of central importance, and a number of prior works have investigated this issue and/or their relationships with meteorological conditions in various locations of China, for example Beijing (Guo et al., 2017; Yan et al., 2016), 31 provincial capital cities (Wang et al., 2014; Zhao et al., 2016), and many other areas (e.g., He et al., 2017; Hu et al., 2014; Wang et al., 2015; Xie et al., 2015; Zhang and Cao, 2015).

Nevertheless, the AQI system may have some issues in practice, because its calculation ignores the combined health effects of exposure to multiple air contaminants. Correspondingly, Kyrrkis et al. (2007) proposed an aggregate air quality index (AAQI) and demonstrated that it could estimate the exposure more effectively than the AQI; Wong et al. (2013) developed a risk-based air quality health index (HAQI), and showed its improvement over the existing AQI for Hong Kong. Since the atmospheric pollution in China is often characterized by high concentrations of multiple pollutants rather than a single pollutant, the current AQI system may be not accurate for health risk assessment. Indeed, Hu et al. (2015) compared the AQI, AAQI and HAQI for six megacities in China, and implied that AQI likely underestimated the health risks associated with exposure to multiple pollutants, especially...
when heavy pollutions occurred, although it needs to be validated by using real clinical data and epidemiological studies. Furthermore, considering the temporal and spatial heterogeneity of air pollutants under different atmospheric environments, it is worthwhile and important to conduct the health risk assessment using these novel indices for other areas. In this regard, Henan Province in China was chosen as a representative. Henan is an inland province, and is one of the most populated provinces with over 120 million people, and it is also an important economically developing region in China. On the other hand, the status of air pollution in Henan is also very serious. Public data showed that during the first half of 2015, Zhengzhou, the capital city of Henan Province, ranked as the third worst city in air quality among 74 major cities nationwide. Therefore, it is valuable to analyze and characterize the spatial and temporal distribution of air pollutants, and evaluate their health risks by comparing the three air quality indices (AQI, AAQI and HAQI) for Henan Province.

2. Methods

2.1. Monitoring sites and data sources

The locations of Henan province and the 18 cities included in this study are illustrated in Fig. 1. The 18 cities include Anyang (AY, population of 5.79 million), Hebi (HB, 5.79 million), Jiyuan (JY, 0.69 million), Jiaozuo (JZ, 3.69 million), Kaifeng (KF, 5.14 million), Luoyang (LY, 6.69 million), Luohe (LH, 2.77 million), Nanyang (NY, 11.77 million), Pingdingshan (PDS, 5.41 million), Puyang (PY, 3.9 million), Sanmenxia (SMX, 2.28 million), Shangqiu (SH, 5.67 million), Xinxiang (XX, 6.04 million), Xinyang (XY, 8.65 million), Xuchang (XC, 4.87 million), Zhengzhou (ZZ, 7.6 million), Zhoukou (ZK, 11.36 million), and Zhumadian (ZMD, 9.01 million), covering all urban areas of the province. Total population of the 18 cities occupies ~90% population of Henan province. Monitoring data of the six criteria pollutants – daily PM$_{2.5,}$ PM$_{10},$ SO$_2,$ NO$_x,$ CO, and 8 h-averaged O$_3$ concentrations, for each city were obtained from the National Environmental Monitoring (NEM) sites established in that city. The data used for each city was the average of all NEM sites in that city, and the data ranged from March 1, 2014 to February 29, 2016. The population data for each city was the average of all NEM sites in that city, and the data used for each city was the average of all NEM sites in that city, and the data ranged from March 1, 2014 to February 29, 2016. The population data of the 18 cities used for exposure assessment were referred to the 2015 Statistical Yearbook of Henan province (http://www.ha.stats.gov.cn/hntj/lib/tjnj/2015/indexce.htm).

2.2. Calculation of air quality indices

2.2.1. Air quality index (AQI)

Calculation of the AQI can refer to the Ambient Air Quality Index (AQI) technical Provisions (Trial) issued by CMEP. The AQI for each pollutant (AQI$_i$) is first calculated by using Eq. (1), and the maximum AQI$_i$ of all pollutants is chosen as the overall AQI according to Eq. (2).

\[
AQI_i = \frac{AQI_{i,1} - AQI_{i,1-1}}{(m_{i,j} - m_{i,j-1})} \times (m_i - m_{i,j-1}) + AQI_{i,j-1}, \quad j > 1.
\]

\[
AQI = \frac{\sum_{i=1}^{n} m_i \cdot \rho}{\sum_{i=1}^{n} m_{i,j} \cdot \rho}, \quad j = 1
\]

\[
AQI = \max(AQI_1, AQI_2, ..., AQI_n), \quad n = 1, 2, ..., 6.
\]

where $i$ represents the pollutant; $m_i$ is the measured concentration of $i$; $j$ is the health category index; $m_{ij}$ is the reference concentration for pollution $i$ corresponding to the $j$th health category. The reference concentrations for the pollutants in different health categories are provided by CMEP, and are presented in Table S1 of the Supporting information. Within this system, the air quality is classified into six classes according to the ranges of AQI values (<50: excellent, satisfactory; 51–100: good, acceptable; 101–150: light pollution, unhealthy for sensitive people; 151–200: moderate pollution, unhealthy; 201–300: serious pollution, very unhealthy - healthy people commonly have symptoms; >300: very severe pollution, hazardous - healthy people have significant symptoms, and should avoid outdoor activities).

2.2.2. Aggregate AQI (AAQI)

The AAQI considers influences of all six pollutants, which can be calculated simply by using the following Eq. (3) (Kyrkilis et al., 2007; Swamee and Tyagi, 1999):

\[
AAQI = \left( \sum_{i=1}^{n} (AQI_i)^\rho \right)^{1/\rho}
\]

where $\rho$ is an empirical constant, however the optimal $\rho$ value is still an open question, and some previous studies (Khanna, 2000; Swamee and Tyagi, 1999) suggested a range between 2 and 3 for $\rho$. Hu et al. (2015) tested the mean and standard deviations of AAQI/AQI ratios using four different $\rho$ values (i.e., 1.5, 2.0, 2.5, 3.0), and found the ratios were not very sensitive to the variations of $\rho$, and they used 2.0 for $\rho$. This value was also chosen in this study.

2.2.3. Health-risk based AQI (HAQI)

To better reflect the health risks of air pollution, the AQI should
further take into account the known exposure-response relationships of various air contaminants established previously. For this purpose, Cairncross et al. (2007) proposed the concept of total excess risk (ER). First, the relative risk (RR) for pollutant i can be estimated using Eq. (4):

$$RR_i = \exp[\beta_i(m_i - m_{i,0})], \quad m_i > m_{i,0}$$  \hspace{1cm} (4)

where $\beta_i$ is the exposure-response coefficient, representing the additional health risk of per unit of pollutant i. The $\beta$ values for PM$_{2.5}$, PM$_{10}$, SO$_2$, NO$_2$ and O$_3$ are 0.038%, 0.032%, 0.081%, 0.13% and 0.048% for every 1 μg/m$^3$ increase, and for CO, it is 3.7% for every 1 mg/m$^3$ increase (Shang et al., 2013). $m_i$ is the measured concentration of pollutant i, and $m_{i,0}$ is the risk limit of pollutant i. In this study, the upper threshold values of CAAQS Grade II were used as $m_{i,0}$ values. This means that when the concentration of pollutant i is less than $m_{i,0}$, it is assumed to bring about no excess health effects (i.e., $RR_i = 1$).

The excess risk (ER) of the pollutant i can be calculated using Eq. (5):

$$ER_i = RR_i - 1$$  \hspace{1cm} (5)

The total ER of all pollutants (ER$_{total}$) is the sum of ER$_i$ of individual pollutants as shown in Eq. (6):

$$ER_{total} = \sum_{i=1}^{n} ER_i = \sum_{i=1}^{n} (RR_i - 1)$$  \hspace{1cm} (6)

Assuming the ER of a pollutant i is equal to ER$_{total}$, thus its equivalent relative risk ($RR^*_i$) can be defined as Eq. (7) (Hu et al., 2015):

$$RR^*_i = \frac{ER_{total} + 1}{\exp[\beta_i(m_i^* - m_{i,0})]}$$  \hspace{1cm} (7)

The equivalent concentration of i ($m_i^*$) can then be derived using Eq. (8):

$$m_i^* = \ln(ER^*_i) / \beta_i + m_{i,0}$$  \hspace{1cm} (8)

Then, by using the equivalent concentration ($m_i^*$) of pollutant i which in fact incorporates the health risks from all pollutants, instead of its measured concentration ($m_i$), HAQI can be calculated similarly as AQI by using Eqs. (9)–(11).

$$HAQI_i = \frac{(AQI_{ij} - AQI_{ij-1})}{(m^*_i - m_{ij-1})}, \quad j > 1$$  \hspace{1cm} (9)

$$HAQI_i = \frac{m^*_i - m_{i1}}{m_{i1}}, \quad j = 1,$$  \hspace{1cm} (10)

$$HAQI = \max\{HAQI_1, HAQI_2, ..., HAQI_6\}, \quad n = 1, 2, ..., 6$$  \hspace{1cm} (11)

3. Results and discussion

3.1. Overview of air pollution

Table 1 lists the annual average concentrations of PM$_{2.5}$, PM$_{10}$, CO, SO$_2$, NO$_2$ and O$_3$ for the 18 cities during 2014 and 2015, respectively. Note in this work, year 2014 refers to March 1, 2014 to February 28, 2015, and year 2015 refers to March 1, 2015 to February 29, 2016. Generally, based on the annual average values, the air quality has no obvious improvement during 2015 compared with that of 2014. Except that SO$_2$ concentration decreases 16.6% from 45.3 to 38.1 μg/m$^3$ and CO concentration remains at the same level, concentrations of PM$_{2.5}$, PM$_{10}$, NO$_2$ and O$_3$ even increase slightly – 0.8% for PM$_{2.5}$ from 79.4 to 80.0 μg/m$^3$, 0.5% for PM$_{10}$ from 135.2 to 135.9 μg/m$^3$, 1.5% for NO$_2$ from 40.7 to 41.3 μg/m$^3$, and 2.5% for O$_3$ from 87.2 to 89.4 μg/m$^3$. During 2015, only 7 out of 18 cities (HB, JY, KY, NY, SMX and XY) can meet the CAAQS Grade II standard for PM$_{2.5}$ (75 μg/m$^3$), and on average the annual PM$_{2.5}$ concentration is 6.7% higher than the Grade II standard. PM$_{10}$ concentration meets the CAAQS Grade II standard (150 μg/m$^3$), but is in the upper end, and is 2.7 times the Grade I standard. In particular, HY and ZZ were the two heavily polluted cities, with both the PM$_{2.5}$ and PM$_{10}$ annual concentrations significantly exceeding the Grade II standards. The pollution of gaseous species (CO, SO$_2$, NO$_2$ and O$_3$) is relatively moderate in Henan, except that NO$_2$ is slightly above the Grade I upper limit, CO, SO$_2$ and O$_3$ all meet the CAAQS Grade I standards. These results show that particulate matter (PM) pollution is more serious than the pollution from gaseous species in Henan Province.

The sources and formation mechanisms of PM$_{2.5}$ are complex, and recent findings showed that secondary aerosol components might
dominate the PM$_{2.5}$ mass (e.g., Huang et al., 2014; Zhang et al., 2007). CO can be regarded as a tracer for primary combustion source, and the PM$_{2.5}$/CO ratios can be used to qualitatively infer the contribution of secondary aerosols (He et al., 2017; Zhang and Cao, 2015). As shown in Fig. 2a, PM$_{2.5}$/CO ratios vary dramatically among different cities from 0.035 to 0.095 (mean values of 0.058 and 0.057 for 2014 and 2015, respectively), indicating the different primary/secondary contributions. Yet no significant variation is observed for the same city from 2014 to 2015, suggesting the sources/processes for PM$_{2.5}$ in the same city remain stable. Relative larger values (0.065–0.095) are found for LH, PDS, SQ, XY and ZMD, which are located in the middle and southern part of Henan province. These ratios are similar to cities in northeastern China, Yangtze River Delta and Pearl River Delta regions (He et al., 2017; Zhang and Cao, 2015), indicating the significant contribution of secondary species to the PM$_{2.5}$ mass in these areas. On the other hand, cities in the northern part, such as AY, HB, JY, LY and JZ, have small PM$_{2.5}$/CO ratios, similar to those in northwest China (He et al., 2017), indicating relatively large contributions from primary particles. It is worth to mention that, ZZ, one of the heaviest PM$_{2.5}$ pollution city, has a moderate PM$_{2.5}$/CO ratio (~0.05), indicating a complex source profile that both primary and secondary components are likely important. In addition, the primary source is likely a combination of industrial activities, transportation, biomass burning and re-suspended dust, etc.

On the other hand, PM$_{2.5}$/PM$_{10}$ ratios can act as an indicator to infer the contribution of coarse mode particles (dust) (Zhang and Cao, 2015). Overall, as shown in Fig. 2b, no significant variability of PM$_{2.5}$/PM$_{10}$ ratios is observed among different cities, reflecting the fact that the dust particles contribute similarly to the PM mass in Henan province. The average PM$_{2.5}$/PM$_{10}$ ratios in 2014 and 2015 are both 0.59, which is very close to 0.58 – the average ratio of 31 provincial cities during 2014–2015 (He et al., 2017). This ratio is remarkably higher than those found in west central and northwest of China (0.38–0.52), where local/regional dust particles contributed greatly (Zhang and Cao, 2015).

Fig. 3 presents the distributions of six AQI categories during 2014 and 2015. For 11 out of 18 cities, the number of days with excellent and good air quality increases, on average, from 182.3 days in 2014 to 199.3 days in 2015. In particular, AY, NY and XY are the three cities with the most significant improvement. However, days with serious and very severe pollution also increase from 26.2 days in 2014 to 34.8 days in 2015, especially in LY, PDS and XX. These results again emphasize the severe air pollution status in Henan province. Moreover, based on AQI values, ZZ, the capital city of Henan province, appears to be the city with the worst air quality: its number of days with excellent and good air is only 133 in 2015, while the number of days with moderate, serious and very severe pollution is the largest among all 18 cities during both 2014 and 2015. Geng et al. (2013) found that soil dust, secondary aerosol, coal combustion were the major sources of PM$_{2.5}$ in an industrial district of ZZ, while other sources including biomass burning, oil combustion and incineration also contributed. It can be expected that in urban area, traffic emissions can contribute to the heavy air pollution in ZZ as well.

In Fig. 4, we further illustrate the average AQI values at different seasons for the 18 cities during 2014 and 2015, respectively (Spring: March – May, Summer: June – August, Autumn: September – November, Winter: December – February). In most cases, the AQI values are in an order of winter > spring > autumn > summer. This result is generally consistent with that of Wang et al. (2014) for the 31 capital cities.
in China. The AQI values for many cities during spring, summer and autumn of 2015 are lower than during those of 2014, but the air quality becomes much worse during 2015 winter than during 2014 winter. Although local authorities had taken some measures, the effectiveness appeared to be not significant. This is likely due to the increased energy consumption (coal and vehicles) and deterioration of meteorological conditions that were not favorable for pollutant dispersion. Anyway, our results underscore that more efforts are needed to effectively improve the air quality especially during wintertime.

### 3.2. Major air pollutant

In Figs. 5a and b, the proportions of major pollutants for all cities during 2014 and 2015 are presented. Each pie chart shows the number fractions of days with one of the six criteria pollutants as the major or primary pollutant (defined as the pollutant with the largest AQI calculated by Eq. (1) when AQI $> 50$) for that city. On an annual basis, PM$_{2.5}$ is the most frequent major pollutant, and occupies over half of the year for most cities (except for SMX, LY, JY and NY in 2014, and for
NO2 and CO, occasionally act as the major pollutants (on average, less than 10% together). During both 2014 and 2015, SO2 pollution is serious in JY, and NO2 pollution is critical in JZ, XX, HB and PY. Generally speaking, NO2 and SO2 pollutions are more severe in northwest Henan. Interestingly, for ZK during 2014, CO pollution is significant, even more serious than O3, representing the specific air pollution characteristics of this city.

Correspondingly, we further show the proportions of major pollutants during four seasons of 2014 and 2015, respectively, in Figs. 5c–j. During winter of both 2014 and 2015, PM10 is the dominant pollutant in all cities, following by PM2.5. O3 rarely becomes the major pollutant, while SO2 pollution in JY, LY, JZ and SMX during 2014 winter, and in JY and JZ during 2015 winter, NO2 pollution in PY, HB and XX during 2014 winter, and in HB during 2015 winter, CO pollution in AY and HB during 2015 winter, can be serious. PM2.5 and PM10 are still the two main pollutants during spring; but SO2, NO2 and CO pollutions in the aforementioned cities become much less severe than those during winter (except CO pollution in ZK), and instead, O3 pollution increase evidently. The air pollution during summer behaves very differently - O3 pollution is very serious, which dominates over PM2.5 and PM10, and appears to be the most important air contaminant in many cities (particularly in LH, XC and NY during 2014 summer). The increase of O3 concentrations might be attributed to the enhanced photochemical production facilitated by the stronger solar radiation and the enhanced VOCs emissions during summer than during other seasons (e.g., Atkinson and Arey, 2003; He et al., 2017; Li et al., 2012; Zhang and Ying, 2011). This result also highlights that appropriate measures should be taken to lessen O3 pollution in addition to PM pollution during summer. During autumn, the pollution is relatively complicated, as the fractions of major pollutants vary greatly among different cities, and for some cities, the proportions change significantly from 2014 to 2015. In particular, NO2 pollution seems to be worse during 2015 autumn in a number of cities (AY, HB, JZ, XX, ZZ, KF, SQ, SMX, LY, PDS and XC) than it during 2014 autumn. SO2 pollution is very serious for JY during 2015 autumn. In JZ, SO2 pollution is reduced, but CO and NO2 pollutions on the other hand are enhanced during 2015 autumn compared with those of 2014 autumn. In summary, air pollution in Henan has clear seasonal differences and spatial variability, suggesting that different measures are probably required to effectively reduce the air pollution in different seasons and different cities.

3.3. Health risks: comparison of three indices

Fig. 6 presents the scatter plots which compare the HAQI, AAQI and AQI values for all cities. Note, when concentrations of air pollutants are less than the CAAQS Grade II upper limits, they are assumed to pose no excess health risks. In this case, the HAQI values are equal to AQI and such data are not included here. For those unhealthy days (when AQI > 100), as shown in Figs. 6a and b, HAQI and AAQI values are all larger than the corresponding AQI values, indicating that the health risks by considering multi-pollutants are higher than those considering only one major pollutant. The calculated HAQI correlate well with AQI ($r^2 = 0.81$), yet the correlation between AAQI and AQI is much better ($r^2 = 0.92$), and on average, AAQI value is larger than HAQI - AAQI is 46% higher than AQI, and HAQI is 32% higher than AQI. The scatter plots including days with AQI≤100 are presented in Fig. 51, and the slopes are 1.25 and 1.48 for HAQI vs. AQI and AAQI vs. AQI, respectively. Furthermore, we divide the data into four health categories according to AQI values in Figs. 6c and d. It can be seen that, for days with light pollution (AQI: 101–150) and very severe pollution (AQI > 300), the estimated excess AAQI values (AAQI-AQI) are much larger than the excess HAQI values (HAQI-AQI) – the mean values are 65.5 versus 23.2 for light pollution, and 177.4 versus 115.6 for severe pollution. Excess AAQI is a bit higher than the HAQI for moderate pollution days (AQI: 151–200) (71.7 versus 63.6), yet is on average less than the HAQI in case of serious pollution (AQI: 201–300) (91.0 versus
The results reflect that different approaches used to consider the pollutants’ health risks can lead to different effects. Our results are also different from Hu et al. (2015), which shows that AAQI is typically less than HAQI for days with very severe pollution, but is larger than HAQI in other cases. This difference reveals that the different air pollution characteristics can cause different behaviors of HAQI and AAQI.

In Fig. 7, we illustrate the number of days (two-year average of all 18 cities) in five health risk categories based on AQI values, and each category is further classified by the different levels of HAQI and AAQI values. Obviously, distribution of data is different based on different types of classifications. For the AQI-based healthy days (AQI < 100), as HAQI is equal to AQI, so there is no misclassification, but 58%, 19% and 0.8% of the days would be with light, moderate and serious pollutions if based on AAQI. For AQI-based light pollution days (100 < AQI < 150), 21% and 11% of days would be moderate and serious pollutions based on HAQI values; misclassification is more obvious based on AAQI – 66% and 28% of days would be with moderate and serious pollutions. For AQI-based moderate pollution days (150 < AQI < 200), HAQI groups 67% and 11% of them into days of serious and very severe pollutions, and the percentages are 94% and 2.4% if based on AAQI. For AQI-based
serious pollution days (200 < AQI < 300), 63% and 66% of days would be with very severe pollution if based on HAQI and AAQI, respectively. Individual HAQI and AAQI classifications for each city during 2014 and 2015 are presented in Fig. S2. Overall, our results show clearly that the health risks are in many cases were underestimated by one or two risk categories based on the AQI system, indicating that people should take stricter health protection measures than those recommended by the AQI system.

Fig. 8 depicts the spatial distribution of average HAQI and AAQI values for Henan province during 2014 and 2015, respectively. It appears that the air pollution is more serious in the northern part of Henan except HB. Annually, based on HAQI, all cities are under light pollution (100 < HAQI < 150) and a few cities (AY, ZZ and JZ during 2014, XX, JZ and ZZ during 2015) are even with moderate pollution (150 < HAQI < 200). While based on AAQI, almost all cities would be under moderately polluted air (150 < AAQI < 200) during both 2014 and 2015.

The excess risk ($ER_{\text{total}}$) calculated by Eqs. (5) and (6) can reflect the additional health risks due to the six criteria pollutants when their concentrations are higher than the corresponding CAAQS Grade II upper limits. We show the average $ER_{\text{total}}$ values for all cities in Fig. 9. The $ER_{\text{total}}$ values fluctuate greatly among different cities, ranging from 1.1% (XY) to 3.0% (AY) with a mean value of 1.7%. Among the six pollutants, PM$_{2.5}$ and PM$_{10}$ are still the two major species that contributed the majority of $ER_{\text{total}}$ in all cities (on average 84%, as shown in the pie chart of Fig. 9); O$_3$ typically ranks the third, but CO in AY, NO$_2$ in HB, XX and ZZ can bring about more health risks than O$_3$. SO$_2$ overall contributes insignificantly to the $ER_{\text{total}}$ although its pollution can be serious for some cities (Fig. 5).

In order to better assess the human exposure to air pollution, we incorporate the population data of each city, and present the cumulative population (in % of total population of the 18 cities) against the two-year average HAQI values. Results for different seasons are also displayed. This figure highlights the high health risks due to air pollution in Henan province. On average, all people in the 18 cities live with “polluted” air (HAQI > 100), and 28% of population is exposed to “unhealthy” air (150 < HAQI < 200). The air quality is relatively better during summer with 20% of people living in “good” air (HAQI < 100) and the remaining population living in lightly polluted air that is unhealthy for sensitive people (100 < HAQI < 150). Pollution is heavier during spring and autumn than during summer, as 8% and 16% of population are exposed to “unhealthy” air (150 < HAQI < 200). The health risks are very serious during winter as all population is exposed to “unhealthy” air (HAQI > 150), and ~31% of people is even exposed to “very unhealthy” air (HAQI > 200) that healthy people would commonly have symptoms. Similar plots for 2014 and 2015 are depicted in Fig. S3. Generally, compared with results from 2014, less people is exposed to “unhealthy” air during 2015 spring, summer and autumn, yet the population exposure becomes much worse during 2015 winter—over half of people (61%) are exposed to “very unhealthy” air, while the fraction is only 20% during 2014 winter. This finding highlights again that even the air quality is
improved during spring, summer and autumn; more effective measures and research are still strongly needed to abate the wintertime air pollution (Fig. 10).

4. Conclusions and remarks

This work analyzed the air pollution characteristics and associated health risks in Henan province, China, by using daily data of PM$_{2.5}$, PM$_{10}$, CO, SO$_2$, NO$_2$ and 8-h-average O$_3$ data in 18 cities acquired during March 2014 – February 2016. We found that PM pollution was more serious than the gas pollution in Henan: annual PM$_{2.5}$ concentration was higher than the CAAQS Grade II standard during both 2014 and 2015; annual PM$_{10}$ concentration met the Grade II standard, but was ~2.7 times the Grade I standard. The air quality was overall not improved from 2014 to 2015 based on either pollutants’ concentrations or AQI values. The air pollution was more serious in northern Henan, and Zhengzhou, the capital city of Henan province, appeared to be the city with the worst air quality. PM$_{2.5}$ was typically the major pollutant following by PM$_{10}$ and O$_3$ for most cities. During summer, air quality was relatively better but ozone pollution became much more serious than it during other seasons. HAQI (and AAQI) that considered the combined health effects of multiple pollutants was introduced to assess the health risks of air pollution. Results showed that for 40% of polluted days (AQI > 100), current AQI system underestimated the health risks by at least one risk category if based on HAQI. Population-weighted HAQI data showed that all people in the 18 studies cities of Henan province lived with polluted air (HAQI > 100), with 28% of them exposing to “unhealthy” air (150 < HAQI < 200). Health risks were particularly high during winter, as 31% of population could be exposed to “very unhealthy” air (HAQI > 200).

Results presented in this work imply that the health risks due to air pollution on a specific day can be more serious than those suggested by the current AQI system, thus stricter protection measures should be taken by the public. However, it should be noted that, real-world epidemiologic studies and clinical data are still required to validate whether or not the HAQI/AAQI values can better represent the health risk of the air pollution. Regarding the HAQI calculation, further efforts should also be paid to improve the algorithm by choosing more proper $m_a$ and $\beta$ values. Especially, as the excess risks of PM$_{2.5}$ and PM$_{10}$ associate not only with the mass loadings but also closely with the chemical compositions, more studies should be conducted to improve the $\beta$ value by considering dynamic variations of aerosol compositions. Simultaneously measured aerosol composition data, such as those obtained from real-time instruments (Canagaratna et al., 2007; Ge et al., 2017; Ng et al., 2011; Wang et al., 2016a, 2016b), can be integrated into the HAQI calculation.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.envres.2017.04.026.

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