Impacts of model resolution on predictions of air quality and associated health exposure in Nanjing, China

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HIGHLIGHTS

- Finer model resolution does not significantly improve predictions for PM2.5 and O3-8 h in Nanjing.
- The current sites well represent the exposure to PM2.5, but under-estimate the exposure to O3.
- Model resolution results in about 6% in the estimated premature mortality due to exposure to PM2.5.
- Model resolution results in more than 20% difference in premature mortality due to exposure to O3.

ARTICLE INFO

Article history:
Received 29 January 2020
Received in revised form 9 March 2020
Accepted 14 March 2020
Available online 19 March 2020

Handling Editor: Hongliang Zhang

Keywords:
Air quality models 
Grid resolution 
Spatial distribution 
Population exposure 
Premature mortality

ABSTRACT

Air quality models have been used in health studies to provide spatial and temporal information of various air pollutants. Model resolution is an important factor affecting the accuracy of exposure assessment using model predictions. In this study, the WRF/CMAQ model system was applied to quantitatively estimate the impacts of the model resolution on the predictions of air quality and associated health exposure in Nanjing, China in 2016. Air quality was simulated with a grid resolution of 1, 4, 12, and 36 km respectively. Predictions with 1 or 4 km resolution are slightly better for particulate matter with an aerodynamic diameter ≤ 2.5 μm (PM2.5) and its compositions and predictions with 12 km are slightly better for daily 8-h maximum ozone (O3-8 h). Model resolution does not significantly improve predictions for PM2.5 and O3-8 h in Nanjing, however, the spatial distributions of PM2.5 and O3-8 h are better captured with finer resolutions. Population weighted concentrations (PWCs) of PM2.5 with different model resolutions are similar to the average of observations, but PWCs of O3-8 h with all resolutions are obviously larger than the observations, indicating that the current sites may well represent the population exposure to PM2.5, but under-estimate the exposure to O3. Model resolution results in about 6% in the estimated premature mortality due to exposure to PM2.5 but more than 20% difference in premature mortality due to exposure to O3. Future studies are needed to evaluate the impacts of the resolution on the exposure of PM2.5 compositions in the city scale when PM2.5 composition measurements available at multiple sites.

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1. Introduction

In recent decades, due to the rapid economic development, the acceleration of urbanization, and the explosive growth of vehicles, substantial air pollutants have been emitted and air pollution issue has become an urgent problem in China (Yuan et al., 2012; Li et al., 2017). Air pollution causes adverse effects on public health. Long-term exposure to high concentrations of particulate matter with an aerodynamic diameter ≤ 2.5 μm (PM2.5) and ozone (O3) can cause damage to public health (Zhang et al., 2010; Billionnet et al., 2012; Han et al., 2014, 2015). Epidemiological studies have shown that fine particles are related to cancer, cardiovascular and
pulmonary diseases (Cao et al., 2011; Gao et al., 2015). Premature mortality due to air pollution in China was about 1.36 million in 2010 (Wang et al., 2014). Hu et al. (2017a) estimated that PM$_{2.5}$ caused 1.3 million premature mortality in China in 2013. Yin et al. (2019) estimated that 3964 premature mortalities were caused by ambient O$_3$ exposure in the Pearl River Delta region of China in 2010.

Air quality models have been used in the air pollution exposure assessment studies in recent years because of its capability of providing spatial and temporal information of various air pollutants (Arunachalam et al., 2006; Cohan et al., 2006; Henze et al., 2009; Flagg and Taylor, 2011; Lauwaet et al., 2013; Hu et al., 2014, 2015b, 2017b, 2019). Air quality models can predict air quality from global to local scales with different horizontal resolutions (Henze et al., 2009; Wong et al., 2012). For example, David et al. (2019) used the Goddard Earth Observing System (GEOS)-Chem global 3-D chemical-transport model to find that anthropogenic emissions led to 60% of 1.1 million premature deaths caused by PM$_{2.5}$ in India in 2012. The regional Weather Research and Forecasting model coupled with chemistry (WRF-Chem) was applied to find out that PM$_{2.5}$ and O$_3$ caused premature deaths in India of 570,000 and 12,000 in 2011, respectively (Shude et al., 2016). Hu et al. (2017a) found that industrial and residential sources were the two dominant sources of excess deaths in China in 2013 with the Community Multiscale Air Quality (CMAQ) model.

The accuracy of exposure assessment using air quality models is affected by a few factors, and one of the factors is the model resolution. Many studies have been conducted in recent years to research the impact of the resolution (Pugh et al., 2013; Thompson et al., 2014; Schaap et al., 2015; Pepe et al., 2016; Jiang and Yoo, 2018; Korhonen et al., 2019). Korhonen et al. (2019) found that model resolution is a significant factor, which can affect the predicted health impacts by tens of percent or more. Some studies suggested that higher resolution could yield more accurate estimates. For instance, the Air Quality Modeling in Urban Regions Using an Optical Resolution Approach (AURORA) was used to find that exposure calculates at 1 km resolution in Brussels in 2005 is 38% higher than at 64 km resolution (Ridder et al., 2014). Tao et al. (2020) used Weather Research and Forecasting Model-Community Multiscale Air Quality Model found that high resolution with 1 km × 1 km could better reflect the temporal trends and magnitudes of meteorological conditions and air quality in the Beijing area. On the other hand, Liu and Zhang (2013) found that the use of higher resolution did not always lead to better results. Thompson and Selin (2012) observed that 12 km resolution may be more suitable than 36 km, 4 km or 2 km resolution for uncertainty analyses of health effects on account of ozone control scenarios. Tan et al. (2015) suggested that model performance has not improved significantly with higher resolution.

The impact of model resolution on air quality and associated health exposure depends on geographic characteristics, emissions, and population distribution in the studying areas. It is still unclear in China how the model resolution affects the health exposure assessment. This study, as a pilot study, aims to examine the impacts of model resolution on air quality predictions and health exposure assessment in Nanjing, a provincial capital city located in the eastern China which has been suffering high PM$_{2.5}$ and O$_3$ pollution (Che et al., 2008; Xie et al., 2016; Wu et al., 2017). We simulated air quality in Nanjing using the Weather Research and Forecasting Model (WRF) - CMAQ with a grid resolution of 1, 4, 12, and 36 km respectively, evaluated the predictions of PM$_{2.5}$ and O$_3$, and compared the exposure and premature mortality associated with PM$_{2.5}$ and O$_3$ estimated with different resolutions. The results will provide insights of how to improve air pollution exposure assessment using air quality models.

2. Methods

2.1. Model description

The CMAQ model used in this study is based on CMAQv5.0.2 (http://www.cmascenter.org/cmaq/). Modifications were made to improve the performance of the simulation of secondary inorganic and organic aerosol. SAPRC-11 was used as the photochemical mechanism to provide more detailed treatment of isoprene oxidation chemistry (Ying et al., 2015). In addition, pathways of secondary organic aerosol (SOA) formation from surface controlled reactive uptake of dicarboxyls, isoprene epoxidyld and methacrylic acid epoxide (Li et al., 2015; Ying et al., 2015). SOA yields were also corrected by vapor wall-loss (Zhang et al., 2014). Heterogeneous reactions of NO$_2$ and SO$_2$ on particle surface to form secondary nitrate and sulfate (Ying et al., 2014). The updated model has been applied to simulate air quality in entire China with a 36 km horizontal resolution (Hu et al., 2016, 2017c), and the predictions of PM$_{2.5}$ and O$_3$ in 2013 have been evaluated against ambient measurements. More details were discussed in Hu et al. (2016) and Hu et al. (2017c), and therefore not repeated here.

2.2. Model application

In this study, the updated CMAQ model was applied to simulate the concentrations of PM$_{2.5}$ and its major components (i.e., sulfate (SO$_4^{2-}$), nitrate (NO$_3^-$), ammonium (NH$_4^+$), organic carbon (OC), elemental carbon (EC)), as well as gaseous pollutants including O$_3$, SO$_2$, NO$_2$, CO, etc. in Nanjing. Fig. 1 shows the nested domains in this study. Domain 1 covers the whole country of China with a grid resolution of 36 km × 36 km; Domain 2 covers the Yangtze River Delta region with a grid resolution of 12 km × 12 km; Domain 3 covers Nanjing and neighbor cities at a grid resolution of 4 km × 4 km; Domain 4 mostly covers Nanjing and surrounding areas at a grid resolution of 1 km × 1 km. The simulation periods are January, April, July, and October of 2016, which represents winter, spring, summer, and autumn, respectively. Initial and boundary conditions of the 36 km domain simulations were derived from the default vertical distribution of concentrations provided by the CMAQ model. The initial and boundary conditions of the 12, 4, and 1 km domains were generated from the nested simulations. A 3-day spin-up period was used to minimize the influence of initial conditions on the model predictions. The Meteorological inputs were generated using the WRF model version 3.8 based on the 6-hourly NCEP FNL (Final) Operational Model Global Tropospheric Analysis dataset. A more detailed description of the WRF model configuration have can be found in Hu et al. (2016). The anthropogenic air pollutant emission inventory of Nanjing (1 km × 1 km) estimated by Nanjing Municipal Academy of Ecology and Environment Protection Science was used in this study for the Nanjing region. For areas outside Nanjing, the Multi-resolution Emission Inventory of China (MEIC, 25 km × 25 km) of 2016 (http://www.meicmodel.org) was used. The Nanjing emission inventory and the MEIC emission inventory were re-gridded into the four nested domains. Biogenic emissions used in the simulation were estimated using the Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1) (Guenther et al., 2012). The Fire Inventory from NCAR (FINN) provided open burning emissions (Wiedinmyer et al., 2010). Emissions from windblown dust and sea salt were calculated inline, as described in Hu et al. (2015a).

2.3. Ambient air pollutants measurements

Observed concentrations of air pollutants (PM$_{2.5}$, 8 h-O$_3$, SO$_2$, NO$_2$, CO) were derived from 8 national ambient monitoring stations
in Nanjing, including Pukou, Shanxilu, Caochangmen, Xuanwuhu, Xianlin, Ruijinlu, Olympic_center, and Zhonghuamen (as shown in Fig. 1b). The observation data of PM$_{2.5}$ components, i.e., EC, OC, SO$_4^{2-}$, NO$_3^−$, NH$_4^+$ were measured at the Huankeyuan station (as shown in Fig. 1b).

2.4. Population-weighted concentration calculation

The average exposure concentrations of a region are calculated using the population-weighted concentration (PWC).

\[
PWC = \frac{\sum C_i \times P_i}{\sum P_i} \tag{1}
\]

where \( i \) is the grid cell within the region, \( C_i \) is the concentration of a certain component in grid \( i \), and \( P_i \) is the population density in grid \( i \) (Hu et al., 2010).

2.5. Health burden assessment

2.5.1. Calculation of premature mortality due to PM$_{2.5}$

The relative ratios (RRs) of premature mortality of chronic obstructive pulmonary disease (COPD), lung cancer (LC), adult ischemic heart disease (IHD), and cerebrovascular disease (CEV) due to long-term PM$_{2.5}$ exposure are calculated using the eq. (2) as used by Hu et al. (2017a).

\[
RR(C) = 1 + a \left( 1 - \exp \left( - \beta \left( X - X_{cf} \right)^\delta \right) \right) \tag{2}
\]

where \( a \), \( \beta \), and \( \delta \) are parameters fitted for different causes from exposure of cigarette smoke at high concentrations and of ambient air pollution at low concentrations. \( X \) is the annual average PM$_{2.5}$ concentration in units of \( \mu g \text{ m}^{-3} \) and in this study the average PM$_{2.5}$ in the four simulated months is used as the annual average concentration. \( X_{cf} \) is the counter-factual concentration below which is assumed that there is no additional risk. Premature mortality (M) can be calculated based on the calculation of RR using eq. (3).
where $y_0$ is the baseline mortality rate due to a particular disease category and $P$ is the population. The $y_0$ and $P$ in 2016 were obtained from the China Public Health and Family Planning Statistical Yearbook 2017 (CPHFPSY 2017).

2.5.2. Calculation of premature mortality due to O

The RR of O3 exposure was calculated with eq. (4) as defined in Jerrett et al. (2009).

$$RR = \exp(\beta(X - X_c))$$

where $\beta$ is the estimated slope of the log-linear relationship between the concentration and COPD related mortality, $X$ is the average concentration of O3 in the four months and $X_c$ is the theoretical minimum concentration, set to 37.6 ppb (Lim et al., 2012). Premature mortality ($M$) for COPD attributable to ambient O3 was estimated with the following two formulas.

$$M = y_0P \frac{RR - 1}{RR}$$

Table 1

<table>
<thead>
<tr>
<th>PM2.5</th>
<th>EC</th>
<th>OC</th>
<th>SO2^-</th>
<th>NO3^-</th>
<th>NH4^+</th>
<th>O3-8 h</th>
<th>SO2</th>
<th>NO2</th>
<th>CO</th>
</tr>
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<tbody>
<tr>
<td>1 km</td>
<td>NMB</td>
<td>0.03</td>
<td>0.10</td>
<td>0.05</td>
<td>0.54</td>
<td>0.30</td>
<td>0.49</td>
<td>0.09</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>NME</td>
<td>0.30</td>
<td>0.40</td>
<td>0.32</td>
<td>0.57</td>
<td>0.42</td>
<td>0.51</td>
<td>0.22</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>0.72</td>
<td>0.76</td>
<td>0.67</td>
<td>0.65</td>
<td>0.64</td>
<td>0.79</td>
<td>0.81</td>
<td>0.68</td>
</tr>
<tr>
<td>4 km</td>
<td>NMB</td>
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<td>0.07</td>
<td>0.12</td>
<td>0.54</td>
<td>0.34</td>
<td>0.48</td>
<td>0.06</td>
<td>0.46</td>
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<tr>
<td></td>
<td>NME</td>
<td>0.31</td>
<td>0.40</td>
<td>0.32</td>
<td>0.57</td>
<td>0.44</td>
<td>0.49</td>
<td>0.24</td>
<td>0.51</td>
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<tr>
<td></td>
<td>R</td>
<td>0.74</td>
<td>0.74</td>
<td>0.67</td>
<td>0.62</td>
<td>0.66</td>
<td>0.80</td>
<td>0.62</td>
<td>0.58</td>
</tr>
<tr>
<td>12 km</td>
<td>NMB</td>
<td>0.17</td>
<td>0.02</td>
<td>0.22</td>
<td>0.58</td>
<td>0.33</td>
<td>0.48</td>
<td>0.02</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>NME</td>
<td>0.33</td>
<td>0.39</td>
<td>0.36</td>
<td>0.60</td>
<td>0.43</td>
<td>0.50</td>
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<tr>
<td></td>
<td>R</td>
<td>0.72</td>
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<td>0.66</td>
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<td>0.64</td>
<td>0.80</td>
<td>0.85</td>
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<tr>
<td>36 km</td>
<td>NMB</td>
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<td>0.34</td>
<td>0.26</td>
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<td>0.08</td>
<td>0.17</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>NME</td>
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<td>0.45</td>
<td>0.5</td>
<td>0.41</td>
<td>0.33</td>
<td>0.26</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>0.74</td>
<td>0.76</td>
<td>0.63</td>
<td>0.72</td>
<td>0.67</td>
<td>0.82</td>
<td>0.80</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Fig. 2. Model results of PM2.5 and its compositions with different resolutions compared to observations.
\[
RR = \frac{\sum_{i=1}^{N} P_i \times RR}{\sum_{i=1}^{N} P_i}
\]

where \(y_0\) is the baseline mortality rate due to COPD; \(P\) is the population; \(RR\) represents the average population-weighted relative risk; \(i\) is the grid cell within the region; \(N\) is the number of grid cells of Nanjing and \(P_i\) is the population of grid cell \(i\).

3. Results and discussion

3.1. Impacts on \(\text{PM}_{2.5}\) and \(O_3\) predictions

Table 1 summarizes the statistical results of model performance in simulating \(\text{PM}_{2.5}\) and its compositions as well as four gaseous pollutants including daily 8-h maximum \(O_3\) (\(O_3\)-8 h), \(\text{SO}_2\), \(\text{NO}_2\), and \(\text{CO}\). Normalized mean bias (NMB), normalized mean error (NME) and correlation coefficient (R) was calculated according to Emery et al. (2017). For \(\text{PM}_{2.5}\), \(\text{NO}_3\), \(\text{EC}\), and \(\text{OC}\), predictions at all resolutions meet the criteria for air pollutants proposed by Emery et al. (2017) (NMB within \(\pm 30\%\), \(\pm 40\%\), \(\pm 50\%\), NME no greater than 50%, 75%, 65% respectively, and R greater than 0.4). Moreover, predictions for \(\text{PM}_{2.5}\) with all resolutions reach the performance goal of NMB within \(\pm 10\%\), NME less than 35%, and R greater than 0.7. The results with different resolutions are not very different, but the \(\text{PM}_{2.5}\) results at 1 km are slightly better than the coarser resolutions. Predictions for \(\text{EC}\) at the grid resolution of 36 km do not meet the goal that the NMB and the NME are not exceeding \(\pm 20\%\) and \(\pm 50\%\) respectively. Predictions for \(\text{OC}\) at the grid resolution of 1 km and 4 km meet the goal that the NMB and the NME are not exceeding \(\pm 15\%\) and 45% respectively. Predictions for \(\text{SO}_4^{2-}\), \(\text{NO}_3\), and \(\text{NH}_4^+\), the model performance at the grid resolution of 36 km was slightly better than that of finer resolutions. Predictions for \(O_3\)-8 h at all resolutions except 36 km meet the criteria, which is NMB within \(\pm 15\%\), NME less than 25%, and R should larger than 0.5. 8 h-\(O_3\) predictions at the resolution of 12 km have the best performance.

Fig. 2 shows the comparison of predicted \(\text{PM}_{2.5}\) and its compositions with the different resolutions and observed concentrations at the Huankeyuan site, and Fig. 3 shows the time series of the...
predictions and observations of PM\textsubscript{2.5} and its compositions. The CMAQ model well captures the daily variation trend of PM\textsubscript{2.5} and most components. OC predictions at high resolutions (1, 4, and 12 km) are better than that of coarse resolution (36 km). Fig. 4 and Fig. 5 show the results of the gaseous pollutants with different resolutions. Observed and simulated values of the gaseous pollutants are the average of eight national stations. The model well captures the temporal variability of observations. General agreement is found between the predicted and observed O\textsubscript{3}-8 h, SO\textsubscript{2}, and NO\textsubscript{2} concentrations, and the model tends to under-predict CO.

Fig. 6 shows the spatial distributions of PM\textsubscript{2.5} with 1, 4, 12, and 36 km resolution, respectively, in the four months. The model well simulates the seasonal variation of PM\textsubscript{2.5} concentrations, which is the highest in winter and the lowest in summer. Predictions at high resolutions, especially at 1 km and 4 km present the more detailed variations on the spatial scale. On the contrary, the concentrations of 36 km have more uniform spatial distribution due to the coarse resolution that cannot present detailed spatial changes. The high concentration of PM\textsubscript{2.5} is mainly concentrated in main urban areas and chemical industrial parks as domestic, transportation, and industrial activities. In these areas, PM\textsubscript{2.5} concentrations are significantly higher than in other areas. The model captures the temporal and spatial variations of PM\textsubscript{2.5} concentrations well, indicating its capability to predict PM\textsubscript{2.5} pollution in different regions.
Fig. 7 shows the spatial distributions of O₃-8 h with 1, 4, 12, and 36 km resolution, respectively. Similarly to the predictions of PM₂.₅, predictions of O₃-8 h at the higher resolutions yield more detailed spatial variations. Seasonal variations in the concentration of O₃-8 h are well reflected, i.e., the highest in summer and the lowest in winter. The distribution of O₃-8 h is more dispersed than that of PM₂.₅. Low concentrations of O₃-8 h are observed in scattered areas in the domain due to titration effect of large NOₓ emissions in those areas.

### 3.2. Impacts on population exposure

Fig. 8 shows the PWCs of PM₂.₅ and O₃-8 h with different resolutions, compared to the average of observations at the 8 national monitoring stations and average concentrations of all Nanjing grids. For PM₂.₅, PWCs are larger than the average value of all Nanjing grids, which means a large fraction of the population in Nanjing reside near the high PM₂.₅ locations (the distribution of population can be seen from Fig. 1c). Compared to the average of observations, the difference of PWCs is relatively small with a resolution of 1 km (1.11%), 4 km (4.32%), and 12 km (−0.09%), but relatively large with 36 km (−10.03%). The national observation sites are designed to represent the air quality of PM₂.₅ of a city, and most of the sites are located in urban centers. Therefore, the current sites in Nanjing seem to be capable of well representing the overall population exposure of PM₂.₅. On the contrary, PWCs of O₃-8 h are similar to the average concentrations of all Nanjing grids with all resolutions but obviously larger than the observations. PWCs of O₃-8 h are higher than the average of observations by 20.7% with 36 km predictions, 15.8% with 12 km, 18.6% with 4 km, and 20.1% with 1 km. Since the sites are mostly located in urban centers, it is likely the observed O₃ concentrations under-estimate the population exposure to O₃ in the current monitoring network.
Fig. 9 shows the comparison of the seasonal PWCs of PM$_{2.5}$ compositions to observations at the Huankeyuan site and the average of all Nanjing grids at the resolution of 1 km. The difference between PWCs and observations is substantially large. The large difference is partly due to the under-predictions of the components by the CMAQ model, as shown by the negative NMB values in Table 1. In addition, currently, only one site is available for PM$_{2.5}$ components measurements. Using one single site is not enough to well represent the exposure of PM$_{2.5}$ compositions in Nanjing, even though the seasonal variation in the exposure can be captured.

Fig. 10 compares PWCs of the PM$_{2.5}$ compositions to observations at Huankeyuan and the average of all Nanjing grids with different resolutions. The resolution affects little on the difference between the PWCs and the observations (and the difference between the average of predictions in all Nanjing grids and the observations). To fully evaluate the impacts of the resolution on the exposure of PM$_{2.5}$ compositions in a city, PM$_{2.5}$ composition measurements should be made at multiple sites in the future.

Fig. 8. PWCs of PM$_{2.5}$ and O$_3$-8 h with different resolutions, compared to the average of site observations and the average of all simulated Nanjing grids.

Fig. 9. PWCs of PM$_{2.5}$ compositions with a resolution of 1 km, compared to the observations and the average of all simulated Nanjing grids.
3.3. Impacts on health burden assessment

Fig. 11 shows estimated premature mortality due to exposure to PM$_{2.5}$ and O$_3$, respectively, in Nanjing with different resolutions. It is estimated that more than 7000 premature deaths caused by PM$_{2.5}$ in 2016 with all resolutions. The per-capita mortality is about 11.4–12.0 deaths per 10,000 people, which is consistent with the Jiangsu provincial average of 10.5 per 10,000 people in 2013 estimated in Hu et al. (2017a). Premature mortality with the resolution of 36 km is 7,139, which is the lowest of the four resolutions and the premature mortality with the resolution of 4 km is 7,547, which is the highest. No sequential change in the mortality with the resolution from low to high is due to the concentration change is not sequential as shown in the Section 3.1. In addition, the spatial distribution also changes, which affect the population exposure. As indicated in Section 3.2, PWC change with the resolution is also not sequential. The resolution results in about a 6% difference in premature mortality estimation. The impact of resolution on the premature mortality estimation of total PM$_{2.5}$ mass is small in Nanjing.

About 300 premature deaths due to exposure to O$_3$ throughout the year are estimated. The per-capita mortality is about 0.42–0.51 deaths per 10,000 people, which is similar to the result in Pearl River Delta (0.61 per 10,000 people) in Yim et al. (2019). The premature deaths attributed to O$_3$ are 318, 290, 260, and 281 with the resolution of 1, 4, 12, and 36 km, respectively. The difference in O$_3$ premature mortality estimation can be more than 20% when using different resolutions. Therefore, the choice of model resolution is important for the health impact assessment of O$_3$ in Nanjing. As discussed previously, the spatial distribution of PM$_{2.5}$ is relatively smooth while the spatial distribution of O$_3$ is more dispersed, a finer grid resolution of 4 km and below is suggested for O$_3$ modeling in the city level.

4. Conclusions

In this study, the WRF/CMAQ model was applied to quantify the impacts of model resolution on the prediction of PM$_{2.5}$ and O$_3$ and associated health exposure in Nanjing, China with the resolution of 1, 4, 12 and 36 km. A few conclusions can be drawn from the study:

(1) Higher resolutions generally have better performance of simulating PM$_{2.5}$ and its compositions in Nanjing. 1 km resolution yields the lowest NMB and NME for PM$_{2.5}$ and OC. Predictions with 12 km yield the lowest NMB and NME for O$_3$-8 h.

(2) Accurate spatial distribution is a vital factor for health exposure assessments. Predictions with higher resolution, especially with the resolution of 1 km, can better capture the detailed spatial variations of PM$_{2.5}$ and O$_3$-8 h. PWCs of PM$_{2.5}$ are of small difference with the average of observations, indicating the current national monitoring sites in Nanjing can well represent the overall population exposure of PM$_{2.5}$. However, the PWCs of O$_3$-8 h are obviously larger than the observations with all resolutions, suggesting that the current sites may under-estimate the population exposure to O$_3$. As currently, only one single site is available for PM$_{2.5}$ composition measurements, it is difficult to evaluate the impacts of the resolution on the exposure to different PM$_{2.5}$ compositions, and how well the site can represent the population exposure to PM$_{2.5}$ compositions in Nanjing. To fully evaluate the impacts of the resolution on the exposure of PM$_{2.5}$ compositions in a city, PM$_{2.5}$ composition measurements should be made in multiple sites in future.

(3) By calculating premature mortality related to PM$_{2.5}$ and O$_3$, the results suggest that the resolution results in about 6% difference in premature mortality estimation due to PM$_{2.5}$ exposure in Nanjing, while the difference could more than 20% in premature mortality estimation due to O$_3$. Therefore, the choice of grid resolution is important for health analyses of PM$_{2.5}$ and even more important for health analyses of O$_3$. 

Fig. 10. PWCs of PM$_{2.5}$ compositions with different resolutions, compared to the observations and the average of all simulated Nanjing grids.

Fig. 11. Premature mortality due to exposure to the PM$_{2.5}$ and O$_3$ respectively, in Nanjing in 2016.
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Ting Liu: Conceptualization, Data curation, Formal analysis, Writing - original draft. Chunlu Wang: Data curation, Formal analysis, Writing - review & editing. Yyi Wang: Data curation, Formal analysis, Writing - review & editing. Lin Huang: Formal analysis, Writing - review & editing. Jingyi Li: Formal analysis, Writing - review & editing. Fangjian Xie: Methodology, Writing - review & editing. Jie Zhang: Methodology, Writing - review & editing. Jianlin Hu: Conceptualization, Funding acquisition, Methodology, Writing - review & editing.

Acknowledgment

This work was supported by the National Key R&D Program of China (2018YFC0213800), the National Natural Science Foundation of China (41975162, 41675125 and 41705102), and Jiangsu Environmental Protection Research Project (2016015).
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