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Research Article

Net effect of air pollution controls on health risk in the Beijing–Tianjin–Hebei region during the 2022 winter Olympics and Paralympics

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ABSTRACT

Due to the non-linearity in ozone (O_3) formation, reducing the emission of nitrogen oxides (NO_x) may increase O_3 concentration. Given the counteractive O_3 response to NO_x reduction, overall impact of air pollution controls can be ambiguous when the assessments focus on the changes in pollutant concentrations. In this study, a risk-based method was used to gauge the net effect of air pollution controls on mortality risk in the Beijing–Tianjin–Hebei (BTH) region during the 2022 Winter Olympics and Paralympics (WOP). This mega-event presents a unique opportunity to investigate the efficacy of deep cuts in pollutant emissions. Results show that O_3 concentrations greatly increased as nitrogen dioxide (NO_2) concentrations decreased in the BTH. Due to the active photochemical formations, O_3 became the dominant pollutant that affected human health during the WOP. Despite the substantial O_3 increases, the health benefits of NO_2 reductions overwhelmed the adverse health effects of O_3 increases in most regions of the BTH (at 81 out of 112 stations). After considering the impacts of particulate matter, the integrated health risk of air pollution mixtures declined

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almost everywhere in the BTH. Our results underscore the great necessity of changing the assessment paradigm of pollution control from using concentration-based methods to using risk-based methods. Together with the carbon neutrality policy, stringent control of NO_x emission from combustion sources is a promising way to achieve synergistic control solutions for air pollution and climate change.

Introduction

In response to the increasingly severe global warming, China aims to reach the carbon emission peak by 2030 and achieve the carbon neutrality by 2060 (Chen and Lin, 2021). China is the largest energy consumer and carbon emitter in the world, producing one-third of global carbon emission (Liu et al., 2022). Policy drive in China to make a progressive reduction in carbon emission as part of global efforts to address the climate issues is clear. Climate change and air pollution are intricately linked. Many human activities (e.g., the combustion of fossil fuels) that produce greenhouse gases also emit air pollutants (Cheng et al., 2021; Shi et al., 2021). To achieve carbon neutrality target, clean energy transition shall be a key focus area in the long-term strategies (Hepburn et al., 2021). The emissions of air pollutants, such as nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particulate matter (PM), are expected to decline significantly.

Numerous air quality studies have reported worsening ozone (O_3) pollution since the implementation of the clean air plan in China (Tang et al., 2022; Ziemke et al., 2019). O_3 is a key gaseous pollutant and oxidant in the atmosphere (Lu et al., 2021). The mitigation of O_3 pollution remains difficult due to the non-linearity of O_3 formation with its precursors, such as NO_x and volatile organic compounds (VOCs) (de Foy et al., 2020; Zavala et al., 2020). When the O_3 formation regime is VOC-limited, reducing the NO_x emission may increase O_3 concentration. It is hypothesized that most urban areas in China are in VOC-limited regime because of their high NO_x emissions (Wang et al., 2021). As a result, reductions in the NO_x emissions in urban areas of China tend to increase O_3 concentrations (Zhao et al., 2020). Given the counteractive O_3 response to NO_x reduction, overall impact of air pollution controls can be ambiguous when the assessments focus on the changes in pollutant concentrations.

Exposure to air pollution is associated with a range of adverse health effects (Dominski et al., 2021; Hu and Guo, 2020). A global review of the association between the short-term exposure to air pollution and all-cause mortality concluded that the relative risks per 10 $\mu g/m^3$ increase in $PM_{2.5}$, NO_2, and O_3 concentrations were 1.0065, 1.0072, and 1.0043, respectively (Orellano et al., 2020). Two official Air Quality Health Index (AQHI) systems directly calculate the health risks of air pollutants and report them to the public. The AQHI in Canada calculates the risks of all-cause mortality for $PM_{2.5}$, NO_2, and O_3 (Stieb et al., 2008). The one in Hong Kong calculates the risks of hospital admissions for respiratory and cardiovascular diseases for different air pollutants (Wong et al., 2013). Because O_3 concentration may increase as NO_2 concentration decreases, it is unclear whether the emission controls effectively reduce the overall health risk. Therefore, understanding the net health effect of pollution variations is essential to guide the development of air pollution control strategies that aim to protect public health (Hossain et al., 2021).

Mega-events often present a unique opportunity for cities to combat air pollution (De La Cruz et al., 2019). In China, strict control measures are often implemented by the government to ensure good air quality during the mega-events (Chen et al., 2021; Pan et al., 2021). This is achieved through effective actions of the city leaders because air quality is linked to their political careers (Fang et al., 2022). During the 2008 Beijing Olympics, the Chinese government enforced a series of control measures to reduce the pollutant emissions from sources such as traffic, industry, and construction. As a result, the emissions of SO_2, NO_x, and PM_{10} in Beijing reduced by 41%, 47%, and 55%, respectively (Wang et al., 2010). Consequently, air quality improved significantly during the 2008 Beijing Olympics (Wang et al., 2014). These mega-events can be treated as ideal experiments to investigate the efficacy of deep cuts in pollutant emissions. In addition, they will provide clues to anticipate the impacts of carbon neutrality policy in the future.

In early 2022, Beijing hosted the Winter Olympics (February 4–20) and Paralympics (March 4–13). Air quality in the Beijing–Tianjin–Hebei (BTH) region during the 2022 Winter Olympics and Paralympics (WOP) attracted a considerable attention from the public. To help the government to enact pollution control measures, a number of studies were performed to evaluate the potential factors that could affect air quality during the WOP (Wang et al., 2022; Zhang et al., 2022). Due to the stringent controls of pollutant emissions, $PM_{2.5}$ concentration in Beijing decreased by 56.1% during the WOP, compared to the level during the same period in 2021 (MEE, 2022). Investigation of air pollution during the WOP can provide a new insight to the impacts of stringent controls of pollutant emissions. However, scientific studies on air pollution, particularly the gaseous pollutants, in the BTH during the WOP are limited.

In this study, we used observations from ground networks to explore the O_3 responses to the NO_x emission controls in the BTH of China during the WOP. Then, a health risk model is adopted to convert pollutant concentrations to the short-term mortality risks. We assessed the net health effect of the variations in air pollution mixtures (including NO_2, O_3, and $PM_{2.5}$) by the emission control measures. In particular, risk tradeoffs between NO_2 and O_3 are explored to understand the efficacy of deep cuts in NO_x emissions. Finally, we discussed the two assessment paradigms of pollution control (concentration-based vs risk-based) and the impacts of reducing NO_x emission under the context of the decarbonization.

1. Data and methodology

1.1. Study period

The 2022 Winter Olympics and Paralympics were multi-sport events held in Beijing and its surrounding areas during February 4–20 and March 4–13, respectively. To cover both Winter Olympics and Paralympics, the primary study period of our analyses is from February 4 to March 13, 2022. To investigate the impacts of emission reductions, this study also compared air pollution levels during February 4–March 13 between 2021 and 2022.

1.2. Study area

The BTH region of China, shown in Fig. S1, includes Hebei Province and two direct-administered municipalities: Beijing and Tianjin. These three regions are treated as “province” in this study. The BTH is the capital economic zone of China. With more than 110 million residents within an area of 217,156 km^2, the BTH is one of the biggest urbanized city clusters in China. This region involves heavy industries and large numbers of vehicles (Lang et al., 2021; Qi et al., 2017). With high pollutant emissions, air pollution issues in the BTH are prominent, imposing a significant threat to public health (Li et al., 2021).

1.3. Air quality data

Hourly NO_2, O_3, and $PM_{2.5}$ concentration data for the study period (i.e., February 4–March 13) in 2021 and 2022 were acquired from national ground monitoring network in China (http://www.cnemc.cn/). As shown in Figure S1, pollution data were available at 112 air quality stations in the BTH. In this study, the method for averaging pollution data followed the common epidemiological studies (Orellano et al., 2020). Specifically, the changes in the average concentrations of NO_2 and $PM_{2.5}$ during February 4–March 13 from 2021 to 2022 were evaluated and analyzed. For O_3, we focused on the changes in the average of daily maximum 8-h O_3 concentration during February 4–March 13 from 2021 to 2022.

1.4. Health risk model

The health risk model, which is currently used in the AQHI systems in Canada and Hong Kong, is adopted to estimate the short-term health risks of air pollutants (Stieb et al., 2008; Wong et al., 2013). The model quantifies the percentage of added health risk (%AR, or so-called excess risk) for different air pollutants. All-cause mortality, the most serious outcome of health problems, is used to represent the health risk. The %AR of all-cause mortality for specific pollutant i can be expressed as:

$$\%AR_i = \left(e^{\beta iCi} - 1\right) \times 100\% \tag{1}$$

where, C_i represents air pollutant concentration; and β_i is the coefficient representing the effect size caused by the air pollution for all-cause mortality. Table 1 summarizes the coefficients for all-cause mortality by NO_2, O_3, and $PM_{2.5}$ derived from the global review and the AQHI system in Canada. Our analyses mainly used the coefficients (β) derived from the global review. The difference and similarity between using the two sets of coefficients (β) for the risk estimation are presented in Section 2.3.

The risk conversion enables the assessment of the net health effect of the variations in multiple air pollutants (i.e., summation of %AR from different air pollutants). Based on the risk estimations, the efficacy of the deep cuts in pollutant emissions in the BTH during the WOP can be analyzed. In particular, the risk tradeoffs between NO_2 and O_3 (i.e., $\%AR_{NO2} + \%AR_{O3}$) can be evaluated to ascertain whether the NO_x emission controls effectively reduced the overall health risk in the BTH during the WOP.

2. Results

2.1. Pollution variations

Average pollutant concentrations during February 4–March 13 in 2021 and 2022 were compared. Panels (a), (b), and (c) in Fig. S2 display spatial distributions of the average NO_2, O_3, and $PM_{2.5}$ concentrations, respectively, over the BTH in 2021. Corresponding distributions in 2022 are shown in panels (d), (e), and (f). In terms of spatial variations, high NO_2 and $PM_{2.5}$ concentrations were found in central urban areas of the BTH with high pollutant emissions. By contrast, O_3 concentrations in central urban areas of the BTH were much lower than the outlying regions. The difference in the spatial patterns between O_3 and NO_2 mainly resulted from the NO titration effect in regions with high NO_x emissions (Tang et al., 2021). In terms of yearly variations, NO_2 and $PM_{2.5}$ concentrations reduced significantly due to the emission controls in the BTH during the WOP. The average NO_2 concentration over the BTH declined from 36.9 ± 8.9 $\mu g/m^3$ in 2021 to 31.6 ± 9.0 $\mu g/m^3$ in 2022 (i.e., by -5.3 ± 5.9 $\mu g/m^3$). The reductions in $PM_{2.5}$ concentrations were extremely substantial, with the average concentration over the BTH declined from 70.9 ± 11.9 $\mu g/m^3$ in 2021 to 42.3 ± 9.8 $\mu g/m^3$ in 2022 (i.e., by -28.6 ± 14.0 $\mu g/m^3$). By contrast, O_3 concentrations increased significantly, with the average concentration over the BTH increased from 80.2 ± 8.2 $\mu g/m^3$ in 2021 to 83.4 ± 5.6 $\mu g/m^3$ in 2022 (i.e., by 3.3 ± 5.2 $\mu g/m^3$).

The changes in pollutant concentrations from 2021 to 2022 were then explicitly assessed. The three panels in Fig. 1 display spatial distributions of the changes in (a) NO_2, (b) O_3, and (c) $PM_{2.5}$ concentrations from 2021 and 2022 in the BTH. Due to the controls of pollutant emissions, NO_2 and $PM_{2.5}$ concentrations declined at most stations (i.e., 88 and 110 out of 112 stations, respectively) in the BTH during the WOP. In particular, substantial reductions in NO_2 and $PM_{2.5}$ concentrations were found in Beijing. By contrast, increased O_3 concentrations were detected at most stations (i.e., 80 out of 112 stations) in the BTH. Similarly, Beijing experienced substantial increases in O_3 concentrations. The counteractive ozone responses to the NO_x reductions indicate that the dominant O_3 photochemical regime in the BTH is VOC-limited.

To better understand the ozone response to the NO_x reduction, Fig. 2 shows the relationship between the changes in O_3 and NO_2 concentrations from 2021 to 2022 among all sta-

Table 1 – Coefficients (β) of the risk factors (NO2, O3, and PM2.5) for all-cause mortality.

Risk factors	Global review (Orellano et al., 2020)	AQHI in Canada (Stieb et al., 2008)
β_{NO2} (per μg/m^3)	0.000717	0.000871
β_{O3} (per μg/m^3)	0.000429	0.000537
$\beta_{PM2.5}$ (per μg/m^3)	0.000648	0.000487

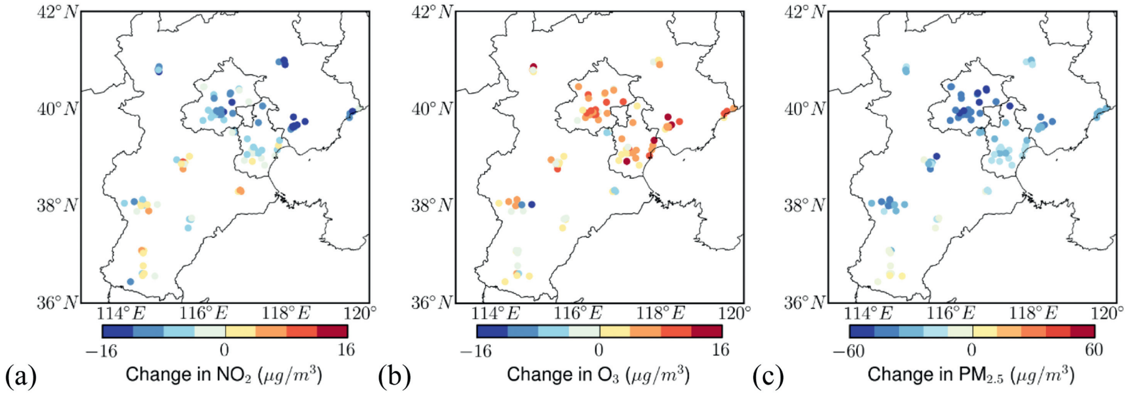

Fig. 1 – Spatial distributions of the changes in (a) NO_2, (b) O_3, and (c) $PM_{2.5}$ concentrations from 2021 to 2022 during February 4–March 13 in the BTH.

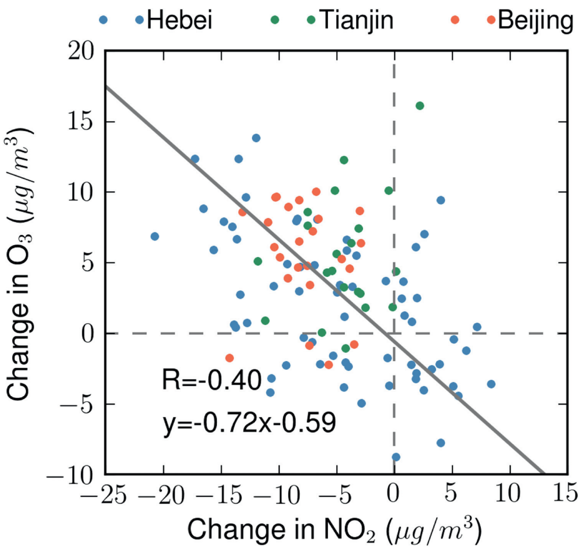

Fig. 2 – Relationship between the changes in O_3 and NO_2 concentrations from 2021 to 2022 during February 4–March 13 among all stations in the BTH. Blue, green, and red points represent the stations in Hebei, Tianjin, and Beijing, respectively.

tions in the BTH. Significant correlation is found between the changes in O_3 and NO_2 concentrations, with a negative correlation coefficient of -0.4 ($N = 112$). These results confirm the intrinsic association between the O_3 and NO_2 variations and the dominant VOC-limited photochemical regime in the BTH.

The changes in provincial averages of pollutant concentrations in the BTH are now assessed. Figure 3 shows the changes in provincial averages of NO_2 (blue bars), O_3 (green bars), and $PM_{2.5}$ (red bars) concentrations from 2021 to 2022 in the BTH. On the provincial average, the NO_2 concentrations reduced by -7.8 ± 3.0 μg/m^3 (25%), -4.4 ± 3.3 μg/m^3 (10%), and -4.7 ± 7.0 μg/m^3 (13%) in Beijing, Tianjin, and Hebei, respectively. By contrast, the provincial average O_3 concentrations increased by 5.6 ± 3.7 μg/m^3 (8%), 5.5 ± 4.2 μg/m^3 (7%), and 1.7 ± 5.4 μg/m^3 (2%) in the three provinces. Beijing experienced the most substantial NO_2 decreases and O_3 increases. The ratios of O_3 formation for NO_2 reduction are estimated to be 0.72 and 1.25 for Beijing and Tianjin, respectively. These results indicate that the NO_2 reduction in the BTH can produce a comparable amount of O_3 due to the high ozone reactivity to the NO_2 reduction. In terms of $PM_{2.5}$ concentration levels, sub-

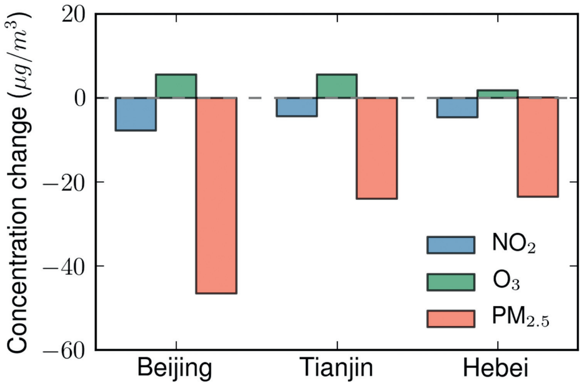

Fig. 3 – The changes in provincial averages of NO_2 (blue bars), O_3 (green bars), and $PM_{2.5}$ (red bars) concentrations from 2021 to 2022 during February 4–March 13 in the BTH.

Table 2 – Averages of the %AR of all-cause mortality for air pollutants during February 4–March 13 in 2021 and 2022 in the BTH and its provinces. The changes in the %AR of all-cause mortality from 2021 to 2022 are also presented.

Regions	Year	NO_2	O_3	$PM_{2.5}$
BTH	2021	2.68 ± 0.65	3.50 ± 0.36	4.71 ± 0.80
	2022	2.29 ± 0.66	3.64 ± 0.25	2.78 ± 0.65
	Change	-0.39 ± 0.43	0.14 ± 0.23	-1.93 ± 0.94
Beijing	2021	2.30 ± 0.59	3.20 ± 0.25	5.23 ± 0.26
	2022	1.73 ± 0.49	3.45 ± 0.18	2.09 ± 0.22
	Change	-0.57 ± 0.22	0.25 ± 0.16	-3.13 ± 0.22
Tianjin	2021	3.13 ± 0.30	3.33 ± 0.26	4.54 ± 0.34
	2022	2.81 ± 0.38	3.57 ± 0.17	2.92 ± 0.22
	Change	-0.32 ± 0.25	0.24 ± 0.18	-1.62 ± 0.44
Hebei	2021	2.68 ± 0.67	3.66 ± 0.34	4.57 ± 0.95
	2022	2.33 ± 0.63	3.74 ± 0.24	2.98 ± 0.68
	Change	-0.34 ± 0.51	0.08 ± 0.24	-1.59 ± 0.86

stantial reductions were found for all three provinces in the BTH, particularly for Beijing. The provincial averages of $PM_{2.5}$ concentrations declined by -46.7 ± 3.3 $\mu g/m^3$ (59%), -24.1 ± 6.6 $\mu g/m^3$ (35%), and -23.6 ± 12.7 $\mu g/m^3$ (34%) in Beijing, Tianjin, and Hebei, respectively.

2.2. *Net health effects of pollution variations*

The %AR of all-cause mortality was calculated to understand the short-term health risk of air pollution. Table 2 summarizes the averages of the %AR of all-cause mortality for air pollutants during February 4–March 13 in 2021 and 2022 in the BTH and its provinces. The changes in the %AR of all-cause mortality from 2021 to 2022 are also presented. Important results are summarized as follows. First, the %AR of mortality for NO_2 and $PM_{2.5}$ declined from 2021 to 2022 in the BTH and all three provinces (e.g., by -0.39 ± 0.43 and -1.93 ± 0.94 for NO_2 and $PM_{2.5}$, respectively, in the entire BTH). By contrast, the %AR of mortality for O_3 increased from 2021 to 2022 (e.g., by 0.14 ± 0.23 in the entire BTH). These risk variations were associated with the concentration variations. Second, O_3 became the dominant pollutant that affected human health in the BTH during the WOP (e.g., the %AR values were 2.29 ± 0.66, 3.64 ± 0.25, and 2.78 ± 0.65, for NO_2, O_3, and $PM_{2.5}$, respectively). By contrast, $PM_{2.5}$ rather than O_3 was generally the dominant pollutant in the BTH in the cold season if there was no strict emission control due to the mega-events. Third, despite the substantial O_3 increases, the beneficial effects of NO_2 reductions on health risk were strong enough to overwhelm the adverse effects of O_3 increases in the BTH and its provinces. As a result, the integrated health risk of NO_2 and O_3 (i,e., $\%AR_{NO2}+\%AR_{O3}$) declined in the BTH during the WOP. These results highlight the importance of the deep cut in NO_x emission to reduce the overall health risk, even though it may increase O_3 concentration.

We further focus on the risk tradeoffs between the NO_2 and O_3 variations. Panels (a) and (b) in Fig. 4 show the spatial distributions of the changes in the %AR of all-cause mortality from 2021 to 2022 for NO_2 and O_3, respectively. Due to the controls of NO_x emissions, the %AR of mortality for NO_2 declined in most regions of the BTH, particularly in Beijing (decreased by 0.4–1.0). By contrast, the %AR of mortality for O_3 extensively increased in the BTH, with the most substantial increases found in Beijing (increased by 0.4–0.6). Spatial distribution of the change in the integrated health risk (i.e., integrated %AR of mortality) of NO_2 and O_3 from 2021 to 2022 in the BTH is shown in panel (c). The integrated health risk of NO_2 and O_3 declined at most stations (81 out of 112 stations) in the BTH. On regional average, the integrated %AR of mortality for NO_2 and O_3 decreased by -0.25 ± 0.40. These results indicate that the controls of NO_x emissions during the WOP effectively reduced the overall health risk in the BTH, even though O_3 concentrations greatly increased. It is noted that the integrated health risk of NO_2 and O_3 increased at some stations in Hebei. These risk increases were associated with the steady or even increased NO_2 concentrations resulting from insignificant NO_x controls.

To better understand the net health effect of NO_2 and O_3 variation, Fig. 5 shows the frequency distributions of the changes in the integrated %AR of mortality for NO_2 and O_3 from 2021 to 2022 among all stations for each province in the BTH. The integrated %AR for NO_2 and O_3 decreased at 22 out of 24 stations, 13 out of 21 stations, and 46 out of 67 stations in Beijing, Tianjin, and Hebei, respectively. Corresponding provincial averages of the integrated %AR for NO_2 and O_3 decreased by -0.33 ± 0.26, -0.08 ± 0.35, and -0.27 ± 0.44 in three provinces. These results confirm that the NO_x emission controls greatly benefited the overall public health for all three provinces in the BTH, although the health risk for O_3 increased.

As shown in previous sections, $PM_{2.5}$ concentration levels experienced substantial declines in the BTH during the WOP. In this section, the effects of the $PM_{2.5}$ declines are taken into account to understand the variation in the overall health risk of air pollution mixtures. Fig. 6 shows spatial distribution of the change in the integrated %AR of mortality for NO_2, O_3, and $PM_{2.5}$ (i.e., $\%AR_{NO2} + \%AR_{O3} + \%AR_{PM2.5}$) from 2021 to 2022 at all stations in the BTH. After considering the impacts of $PM_{2.5}$ reduction, the integrated health risk of air pollution mixtures greatly declined almost everywhere (110 out of 112 stations) in the BTH. In particular, the integrated %AR of mortality for pollution mixtures drastically declined in Beijing (decreased by 3–4) due to the stringent emission controls during the WOP.

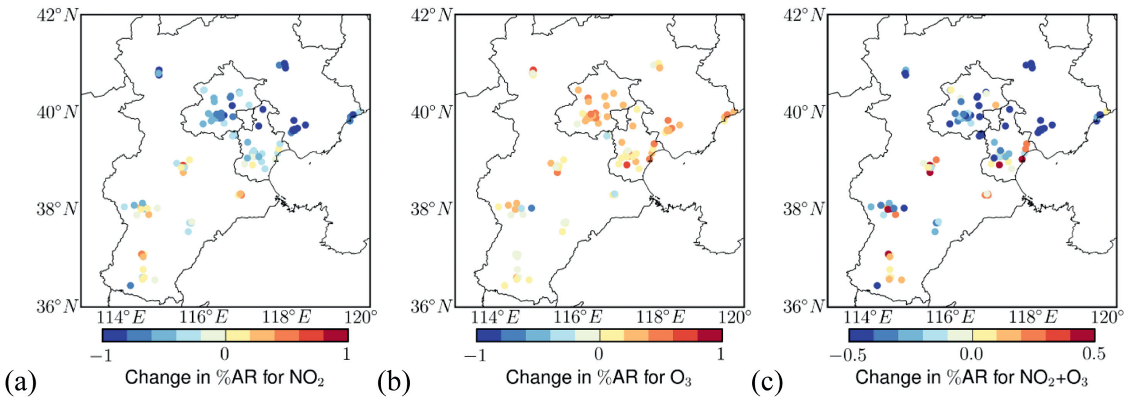

Fig. 4 – Spatial distributions of the changes in %AR of all-cause mortality from 2021 to 2022 for (a) NO_2 and (b) O_3 in the BTH. Panel (c) shows spatial distribution of the change in the integrated %AR of mortality for NO_2 and O_3 from 2021 to 2022 in the BTH.

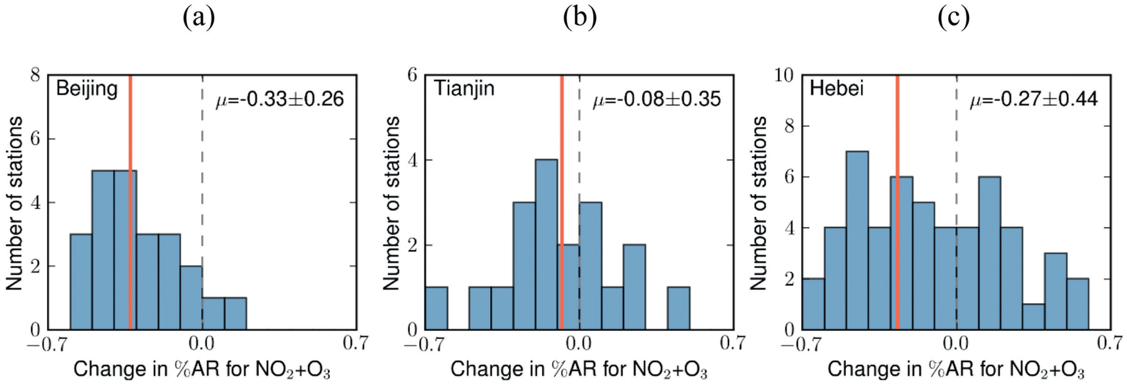

Fig. 5 – Frequency distributions of the changes in the integrated %AR of mortality for NO_2 and O_3 for three provinces in the BTH. Red lines mark the provincial averages of the declines in the integrated %AR of mortality for NO_2 and O_3.

2.3. *Using the coefficients (β) derived from the AQHI in Canada*

The overall health risk of pollution mixtures is determined by the air pollutants' concentrations and their effect size. To better understand the impacts of the β coefficients, we further evaluate the variations in %AR of all-cause mortality using the β coefficients derived from the AQHI in Canada. Panel (a) in Figure S3 displays spatial distribution of the change in the integrated %AR of mortality for NO_2 and O_3 from 2021 to 2022 in the BTH using the β coefficients from the AQHI in Canada. Results are similar to the Section 3.2, which used the β coefficients from the global review. Specifically, the health benefits of NO_2 reductions were strong enough to overwhelm the adverse effects of O_3 increases in most regions of the BTH. As a result, the controls of NO_x emissions reduced the integrated mortality risk at most stations (81 out of 112 stations) in the BTH. These results confirm the great necessity of stringent NO_x emission controls to protect public health in the BTH.

Panel (b) of Figure S3 shows the spatial distribution of the change in the integrated %AR of mortality for pollution mixtures (including NO_2, O_3, and $PM_{2.5}$) from 2021 to 2022 in the BTH using the β coefficients from the AQHI in Canada. Again, after considering the impacts of $PM_{2.5}$, the integrated health risk of air pollution mixtures greatly declined almost everywhere (108 out of 112 stations) in the BTH.

3. Discussion

In this study, a health risk tool was used to explore the net health effect of pollution variations in the BTH of China during the WOP. Due to the stringent NO_x emission controls, O_3 concentrations greatly increased in the BTH, particularly in Beijing. The counteractive ozone responses to the NO_x reductions indicate that the dominant ozone photochemical regime in this region is VOC-limited. Despite the substantial O_3 increases, the beneficial effects of NO_2 reductions on health risk were strong enough to overwhelm the adverse effects of O_3 increases in the BTH. As a result, the net health risk of NO_2 and O_3 declined in most regions (81 out of 112 stations) in the BTH. These results indicate the overall health benefit of a deep cut in NO_x emission in the BTH, even though O_3 concentrations may temporarily increase.

Our analyses underscore the great necessity of developing a risk-based guideline to gauge the effectiveness of air pollution control strategies that aim to protect public health. This is particularly useful for evaluating the effectiveness of the NO_x

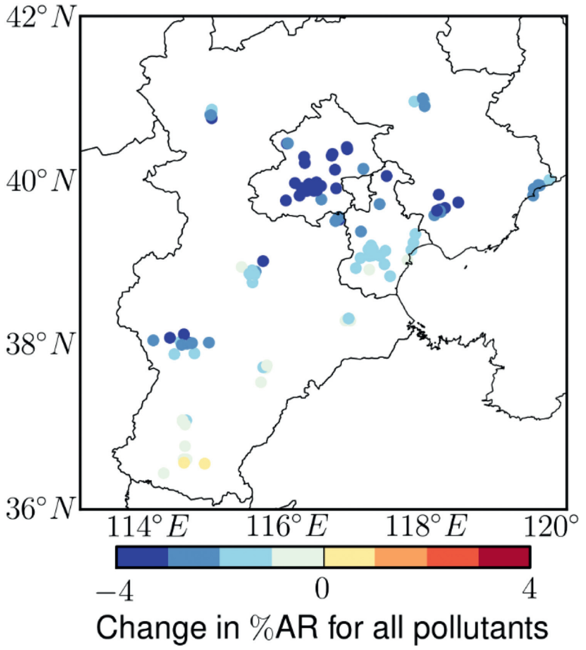

Fig. 6 – Spatial distribution of the change in the integrated %AR of mortality for NO_2, O_3, and $PM_{2.5}$ from 2021 to 2022 at all stations in the BTH.

emission controls, which may increase O_3 concentrations in some urban areas with the VOC-limited regime. The health risk tool used in this study estimates the short-term mortality risks of air pollutants, such as NO_2, O_3, and $PM_{2.5}$. The risk tradeoffs between different air pollutants can be done only when the pollutant concentrations are converted to the health risk. The risk conversion enables the assessment of the integrated health impacts of pollution mixtures.

Both AQHI systems in Hong Kong and Canada calculate the added health risk (or so-called excess risk) for different air pollutants. The added health risk (or excess risk) is a common parameter which identifies the excess rate of occurrence of a particular health effect associated with pollution exposure. The Hong Kong AQHI calculates the excess risk of hospital admission for respiratory and cardiovascular diseases, while the one in Canada calculates the excess mortality risk. Although different health outcomes are considered in the calculations, the ideas on calculating the excess risk are the same. The two AQHI systems then use different methods to normalize the excess risk and report the risk categories to the public.

In this study, the excess mortality risk associated with air pollution was calculated. The associations between air pollution exposure and the all-cause mortality have been documented in numerous epidemiological studies around the world (Khomenko et al., 2021). Death is the most serious outcome of a broad range of health problems. In addition, mortality is a variable that is easily defined and often well collected by governmental authorities. The Global Burden of Disease study estimated the global premature death that was attributable to air pollution to be around 7 million every year (Cohen et al., 2017). Therefore, the mortality risk was quantified to represent the health risk of air pollution in this study. Future analyses are suggested to take other health outcomes (e.g., hospital admissions) into account.

The overall health risk of NO_2 and O_3 is largely determined by the ratio between the β coefficients for NO_2 and O_3. In this study, two sets of β coefficients for all-cause mortality were obtained from global review and the official AQHI system in Canada. The ratios between the β coefficients for NO_2 and O_3 (i.e., β_{NO2}/β_{O3}) were estimated to be 1.67 and 1.62 from the two studies. The health risk of NO_2 is slightly higher than that of O_3. These results indicate that the NO_x emission controls often benefit the public health, unless the O_3 increase is much larger than the NO_2 decrease. The active O_3 responses to the NO_2 decreases tend to occur near the sources of high NO_x emissions, such as the roadside areas.

This study underscores the great health benefits from deep cuts in NO_x emissions. In a region deemed to be VOC-limited, conventional wisdom to rely on the VOCs emission control as a tool for O_3 management is experiencing great challenges due to the diversity and widespread nature of the VOCs species, and especially after the low-hanging fruit has been picked (Gao et al., 2021). In the long-term strategies, the deep cut in NO_x emission and a subsequent transition to a NO_x-limited regime are promising for the O_3 target attainment (Ou et al., 2016). In addition, as a common precursor of both O_3 and particulate matter, the reduction in NO_x emission would bring co-benefits on both pollutants.

NO_x emission controls align closely with the carbon neutrality policies. Many human activities (e.g., combustion of fossil fuels) that produce NO_x also emit greenhouse gases. Under the contexts of carbon neutrality policies and fast energy transitions, the combustion sources are expected to go through very stringent controls, which will bring substantial reductions in both carbon and NO_x emissions. Together with the carbon neutrality policy, stringent control of NO_x emission from combustion sources is a promising way to achieve synergistic control solutions for air pollution and climate change. The co-benefits of addressing climate and air pollution issues under stringent controls of combustion sources are likely to be the main drivers for the new development of effective control policies in the future.

In the initial phase of the decarbonization, O_3 concentration may increase as NO_x emission reduces. The “O_3 increase” is less of a problem if we take an overall health perspective. When everywhere is trying to push toward the carbon neutrality, it should not be blocked down by the question of “O_3 increase” as the increase is less related to overall health effects. There could still be areas with ozone increases but little NO_x reductions, particularly in downwind areas of major NO_x sources. A lot of these places, however, are rural areas. Therefore, their contributions to the overall public health risk are much less than the densely populated urban areas.

Various control measures were implemented by the Chinese government to ensure good air quality in Beijing during the WOP. The concentrations of air pollutants, especially particulate matter, declined drastically during the event. These pollution variations were well recorded by observations from ground networks. Therefore, these mega-events with strict emission controls afford a good opportunity for us to use real-time ground observations to evaluate the consequences of deep cuts in pollutant emissions. In addition, the comprehensive ground measurements allow a comprehensive evaluation of the health risk of pollutant mixtures and provide clues to foresee the impacts of decarbonization policy in the future.

This study has some limitations. First, this study is designed to evaluate the mortality risk of short-term air pollution exposure. It is recognized that exposure to ambient air pollution is not only associated with mortality but also associated with a range of diseases, such as respiratory and cardiovascular diseases (Holm and Balmes, 2022; Zheng et al., 2021). For instance, the AQHI system in Hong Kong calculates the %AR of hospital admission for respiratory and cardiovascular diseases for air pollutants (Wong et al., 2013). Therefore, future assessments are suggested to cover other health outcomes of air pollution exposure. Second, the ozone photochemical regime is complicated and may vary over time. The analyses in this study were performed only in the cold season (i.e., February 4–March 13). Compared to the warm season (e.g., July and August), O_3 concentrations during our study period were relatively low. A comprehensive investigation covering an extended period is of great necessity to understand the temporal variation in ozone formation and the overall impact of NO_x emission controls.

In this study, we obtained all available data from national air quality monitoring network in the BTH. Beijing, Tianjin, and Hebei had 24, 21, and 67 stations, respectively. Since most people live in urban areas, the majority of air quality stations are located in urban areas to monitor the pollution exposure levels. Due to the current setting of monitoring network, conclusions made in this study only represent the situations in residential areas of the BTH. Future study can be performed to focus on the remote areas if more data are available.

The major focus of this study is the risk tradeoffs between the variations of NO_2 and O_3. The lockdowns during the Olympics and Paralympics affected the concentrations of other air pollutants, including sulfur dioxide (SO_2) and carbon monoxide (CO). However, the health risks of SO_2 and CO are generally lower than those of NO_2, O_3, and $PM_{2.5}$. As a result, SO_2 and CO were dropped from the Canada's AQHI because they were not associated with additional health risk once the effects of NO_2, O_3, and $PM_{2.5}$ were taken into account. Therefore, the excess risks for three major pollutants, including NO_2, O_3, and $PM_{2.5}$, were calculated in this study.

Air pollution level in Beijing experienced a drastic decline during the past decade. A great air quality achievement was reported by the Beijing government in early 2022, showing that the air pollution level over Beijing in 2021 was below the national ambient air quality standard. Given the large variation in the historical air pollution level, this study compared the pollutant concentrations in 2022 with the levels in 2021, rather than the years before 2021. In addition, to minimize the impacts of meteorological variations, we compared the pollutant concentrations during the same period (i.e., February 4–March 13) in 2021 and 2022. This comparison design is consistent with the one used by the government to report the $PM_{2.5}$ variations during the WOP. Future studies are warranted to assess the detailed impacts of meteorological factors on air pollution levels in the BTH during the WOP.

4. Conclusions

This study used observations from ground networks to investigate the spatial variation in the ozone reactivity to NO_2 reduction in the BTH of China during the WOP. Then, a health risk model was applied to gauge the net health benefits of pollution controls. The risk tradeoffs between different air pollutants (including NO_2, O_3, and $PM_{2.5}$) were then evaluated. Results show that the O_3 concentrations greatly increased as NO_2 concentrations decreased in the BTH. Due to the active O_3 responses to NO_x controls, the ratios of O_3 formation for NO_2 reduction were estimated to be 0.72 and 1.25 in Beijing and Tianjin, respectively. Risk analyses showed that O_3 became the dominant pollutant that affected human health during the WOP. Despite the substantial O_3 increases, the beneficial effects of NO_2 reductions on health risk were strong enough to overwhelm the adverse effects of O_3 increases in most regions of the BTH. As a result, the combined health risk of NO_2 and O_3 extensively declined in the BTH. Our results underscore the importance of using a health risk tool to gauge the effectiveness of air pollution control strategies and the overall health benefit from stringent controls of NO_x emissions in the BTH. These results are of global relevant in the context of carbon neutrality. When everywhere is trying to act toward the carbon neutrality, it should not be blocked down by the question of "O_3 increase" as the increase is less related to overall health effects.

Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A Supplementary data

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jes.2022.10.008.

REFERENCES

Chen, K., Metcalfe, S.E., Yu, H., Xu, J., Xu, H., Ji, D., et al., 2021. Characteristics and source attribution of PM2.5 during 2016 G20 summit in Hangzhou: efficacy of radical measures to reduce source emissions. J. Environ. Sci. 106, 47–65.

Chen, X., Lin, B., 2021. Towards carbon neutrality by implementing carbon emissions trading scheme: policy evaluation in China. Ener. Pol. 157, 112510.

Cheng, J., Tong, D., Zhang, Q., Liu, Y., Lei, Y., Yan, G., et al., 2021. Pathways of China's PM2.5 air quality 2015–2060 in the context of carbon neutrality. Nat. Sci. Rev. 8 (12) nwab078.

Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., et al., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. The Lanc 389, 1907–1918.

de Foy, B., Brune, W.H., Schauer, J.J., 2020. Changes in ozone photochemical regime in Fresno, California from 1994 to 2018 deduced from changes in the weekend effect. Environ. Poll. 263, 114380.

De La Cruz, A.R.H., Dionisio Calderon, E.R., França, B.B., Réquia, W.J., Gioda, A., 2019. Evaluation of the impact of the Rio 2016 Olympic Games on air quality in the city of Rio de Janeiro, Brazil. Atmos. Environ. 203, 206–215.

Dominski, F.H., Lorenzetti Branco, J.H., Buonanno, G., Stabile, L., Gameiro da Silva, M., Andrade, A., 2021. Effects of air pollution on health: a mapping review of systematic reviews and meta-analyses. Environ. Res. 201, 111487.

Fang, L., He, P., Tian, C., Yao, Y., Chen, H., 2022. Beyond the ceremony: mega-event, air quality and political career. PL. ONE 17, e0262470.

Gao, M., Teng, W., Du, Z., Nie, L., An, X., Liu, W., et al., 2021. Source profiles and emission factors of VOCs from solvent-based architectural coatings and their contributions to ozone and secondary organic aerosol formation in China. Chemos 275, 129815.

Hepburn, C., Qi, Y., Stern, N., Ward, B., Xie, C., Zenghelis, D., 2021. Towards carbon neutrality and China's 14th Five-Year Plan: Clean energy transition, sustainable urban development, and investment priorities. Environ. Sci. and Ecotech. 8, 100130.

Holm, S.M., Balmes, J.R., 2022. Systematic review of ozone effects on human lung function, 2013 through 2020. Chest 161, 190–201.

Hossain, Md.S., Frey, H.C., Louie, P.K.K., Lau, A.K.H., 2021. Combined effects of increased O3 and reduced NO2 concentrations on short-term air pollution health risks in Hong Kong. Environ. Poll. 270, 116280.

Hu, F., Guo, Y., 2020. Health impacts of air pollution in China. Front. Environ. Sci. Eng. 15, 74.

Khomenko, S., Cirach, M., Pereira-Barboza, E., Mueller, N., Barrera-Gómez, J., Rojas-Rueda, D., et al., 2021. Premature mortality due to air pollution in European cities: a health impact assessment. Lanc. Plan. Heal. 5, e121–e134.

Lang, J., Liang, X., Li, S., Zhou, Y., Chen, D., Zhang, Y., et al., 2021. Understanding the impact of vehicular emissions on air pollution from the perspective of regional transport: a case study of the Beijing-Tianjin-Hebei region in China. Sci. Tot. Environ. 785, 147304.

Li, C., Ma, X., Fu, T., Guan, S., 2021. Does public concern over haze pollution matter? Evidence from Beijing-Tianjin-Hebei region. China. Sci. Tot. Environ. 755, 142397.

Liu, Z., Deng, Z., He, G., Wang, H., Zhang, X., Lin, J., Qi, Y., Liang, X., 2022. Challenges and opportunities for carbon neutrality in China. Nat. Rev. Earth Environ. 3, 141–155.

Lu, C., Mao, J., Wang, L., Guan, Z., Zhao, G., Li, M., 2021. An unusual high ozone event over the North and Northeast China during the record-breaking summer in 2018. J. Environ. Sci. 104, 264–276.

MEE, 2022. Air quality during Beijing Winter Olympics and Paralympics. https://www.mee.gov.cn/ywdt/hjywnews/202203/t20220315_971533.shtml

Orellano, P., Reynoso, J., Quaranta, N., Bardach, A., Ciapponi, A., 2020. Short-term exposure to particulate matter (PM10 and PM2.5), nitrogen dioxide (NO2), and ozone (O3) and all-cause and cause-specific mortality: systematic review and meta-analysis. Environ. Int. 142, 105876.

Ou, J., Yuan, Z., Zheng, J., Huang, Z., Shao, M., Li, Z., et al., 2016. Ambient ozone control in a photochemically active region: short-term Despiking or long-term attainment? Environ. Sci. Technol. 50, 5720–5728.

Pan, X., Zhao, Y., Wang, M., 2021. Impact of COVID-19 on extremely polluted air quality and trend forecast in seven provinces and three cities of China. Front. Environ. Sci. 9, 770900.

Qi, J., Zheng, B., Li, M., Yu, F., Chen, C., Liu, F., et al., 2017. A high-resolution air pollutants emission inventory in 2013 for the Beijing-Tianjin-Hebei region. China. Atmos. Environ. 170, 156–168.

Shi, X., Zheng, Y., Lei, Y., Xue, W., Yan, G., Liu, X., et al., 2021. Air quality benefits of achieving carbon neutrality in China. Sci. Total Environ. 795, 148784.

Stieb, D.M., Burnett, R.T., Smith-Doiron, M., Brion, O., Shin, H.H., Economou, V., 2008. A new multipollutant, no-threshold air quality health index based on short-term associations observed in daily time-series analyses. J. Air Wast. Manag. Assoc. 58, 435–450.

Tang, G., Liu, Y., Zhang, J., Liu, B., Li, Q., Sun, J., et al., 2021. Bypassing the NOx titration trap in ozone pollution control in Beijing. Atmos. Res. 249, 105333.

Tang, K., Zhang, H., Feng, W., Liao, H., Hu, J., Li, N., 2022. Increasing but variable trend of surface ozone in the Yangtze river delta region of China. Front. Environ. Sci. 10, 836191.

Wang, M., Zhao, Wenhui, Li, L., Liu, T., Wang, L., Shen, N., et al., 2022. Air quality assessment and Gray model prediction for the 2022 winter Olympics in Zhangjiakou. China. Air Qual. Atmos. Health. 15, 1303–1315.

Wang, S., Gao, J., Zhang, Y., Zhang, J., Cha, F., Wang, T., et al., 2014. Impact of emission control on regional air quality: an observational study of air pollutants before, during and after the Beijing Olympic Games. J. Environ. Sci. 26, 175–180.

Wang, S., Zhao, M., Xing, J., Wu, Y., Zhou, Y., Lei, Y., et al., 2010. Quantifying the air pollutants emission reduction during the 2008 olympic games in Beijing. Environ. Sci. Technol. 44, 2490–2496.

Wang, W., van der A, R., Ding, J., van Weele, M., Cheng, T., 2021. Spatial and temporal changes of the ozone sensitivity in China based on satellite and ground-based observations. Atmos. Chem. Phy. 21, 7253–7269.

Wong, T.W., Tam, W.W.S., Yu, I.T.S., Lau, A.K.H., Pang, S.W., Wong, A.H.S., 2013. Developing a risk-based air quality health index. Atmos. Environ. 76, 52–58.

Zavala, M., Brune, W.H., Velasco, E., Retama, A., Cruz-Alavez, L.A., Molina, L.T., 2020. Changes in ozone production and VOC reactivity in the atmosphere of the Mexico City Metropolitan Area. Atmos. Environ. 238, 117747.

Zhang, Y., Pan, X., Tian, Yu, Liu, H., Chen, X., Ge, B., et al., 2022. Transport patterns and potential sources of atmospheric pollution during the XXIV olympic winter games period. Adv. Atmos. Sci. 39, 1608–1622.

Zhao, S., Yin, D., Yu, Y., Kang, S., Qin, D., Dong, L., 2020. $PM_{2.5}$ and O_3 pollution during 2015–2019 over 367 Chinese cities: Spatiotemporal variations, meteorological and topographical impacts. Environ. Poll 264, 114694.

Zheng, X., Orellano, P., Lin, H., Jiang, M., Guan, W., 2021. Short-term exposure to ozone, nitrogen dioxide, and sulphur dioxide and emergency department visits and hospital admissions due to asthma: a systematic review and meta-analysis. Environ. Int. 150, 106435.

Ziemke, J.R., Oman, L.D., Strode, S.A., Douglass, A.R., Olsen, M.A., McPeters, R.D., et al., 2019. Trends in global tropospheric ozone inferred from a composite record of TOMS/OMI/MLS/OMPS satellite measurements and the MERRA-2 GMI simulation. Atmos. Chem. Phy. 19, 3257–3269.