Estimated Acute Effects of Ambient Ozone and Nitrogen Dioxide on Mortality in the Pearl River Delta of Southern China

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BACKGROUND AND OBJECTIVES: Epidemiologic studies have attributed adverse health effects to air pollution; however, controversy remains regarding the relationship between ambient oxidants [ozone (O3) and nitrogen dioxide (NO2)] and mortality, especially in Asia. We conducted a four-city time-series study to investigate acute effects of O3 and NO2 in the Pearl River Delta (PRD) of southern China, using data from 2006 through 2008.

METHODS: We used generalized linear models with Poisson regression incorporating natural spline functions to analyze acute mortality in association with O3 and NO2, with PM10 (particulate matter ≤ 10 μm in diameter) included as a major confounder. Effect estimates were determined for individual cities and for the four cities as a whole. We stratified the analysis according to high- and low-exposure periods for O3.

RESULTS: We found consistent positive associations between ambient oxidants and daily mortality across the PRD cities. Overall, 10-μg/m3 increases in average O3 and NO2 concentrations over the previous 2 days were associated with 0.81% (95% confidence interval: 0.63%, 1.00%) and 1.95% (95% CI: 1.62%, 2.29%) increases in total mortality, respectively, with stronger estimated effects for cardiovascular and respiratory mortality. After adjusting for PM10, estimated effects of O3 on total and cardiovascular mortality were stronger for exposure during high-exposure months (September through November), whereas respiratory mortality was associated with O3 exposure during nonpeak exposure months only.

CONCLUSIONS: Our findings suggest significant acute mortality effects of O3 and NO2 in the PRD and strengthen the rationale for further limiting the ambient pollution levels in the area.

KEY WORDS: excess risk, mortality, nitrogen dioxide, ozone, PRD, time series. Environ Health Perspect 120:393–398 (2012). http://dx.doi.org/10.1289/ehp.1103715 [Online 8 December 2011]

Substantial evidence supports the association between ambient air pollution, including particulate matter (PM), ozone (O3), and nitrogen dioxide (NO2), and mortality and morbidity from cardiopulmonary diseases (Bell et al. 2004; Brook et al. 2010; Dockery et al. 1993; Pope and Dockery 2006; Samet et al. 2000). However, higher concentrations of air pollutants are often found in Asia, published Asian research is still limited, making region-specific results difficult to interpret and compare with findings for populations in the developed world (Cao et al. 2011; Chen et al. 2004; Wong et al. 2008; Zhou et al. 2010).

Chinese megacities are some of the most air-polluted cities in the world (Chan and Yao 2008). There has been growing concern about air-pollution–related health effects in the Pearl River Delta (PRD), which recently has undergone rapid economic development and urbanization. The PRD lies in the coastal part of southern China and comprises nine cities in Guangdong Province and the special administrative regions of Hong Kong and Macao. This region accounts for only 0.5% of the Chinese geographic area but holds 4% of the Chinese population and produces about one-fifth of the total gross domestic product. Remarkable problems of traffic and photochemical air pollution have emerged in the PRD, in large part due to vehicle emissions and high sun exposure year-round (Shao et al. 2009). Photochemical reactions involving nitrogen oxides, volatile organic compounds, and hydroxyl radicals produce O3, a secondary air pollutant, in the presence of sunlight [Hofzumahausa et al. 2009; World Health Organization (WHO) 2005]. The PRD was one of the first regions in China to experience serious photochemical smog pollution: up to 171 ppb O3 was measured in a suburb of Hong Kong, with sizable contributions likely from air mass transported from Guangdong cities in the PRD (So and Wang 2003). The PRD Regional Air Quality Monitoring Network, with 16 monitoring stations across the region, was established to facilitate research on pollution in the PRD (Hua et al. 2008; Zhang et al. 2008a).

Ambient O3 and NO2, two major oxidants involved in photochemical processes, have been associated with adverse health effects. A systematic review indicates that the reaction between O3 and biomolecules to form ozonides and free radicals triggers inflammatory responses and systemic oxidative stress in the cardiorespiratory system (Srebot et al. 2009). NO2 is a highly reactive and nitrogen-centered free radical that can induce airway inflammation (Kelly et al. 1996). Short-term exposure to ambient O3 and NO2 has adverse effects on pulmonary function, particularly in asthmatics, and may increase airway allergic inflammatory reactions, hospital admissions, and mortality (WHO 2004). Many epidemiologic studies suggested both short- and long-term effects of exposure to O3 (Bell et al. 2004; Gryparis et al. 2004; Jerrett et al. 2005) and NO2 (Hock et al. 2002; Samoli et al. 2006) on total and cause-specific mortality. A few studies focused on both oxidants as reactive components of the photochemical air pollution mixture and reported significant mortality effects of short-term oxidant exposure (Saez et al. 2002; Touloumi et al. 1997).

Air monitoring data collected through the PRD monitoring network have made it possible to assess the health effects of ambient air pollution on a regional scale. In this multicity study, we estimated associations between ambient O3 and NO2 and mortality in the PRD (2006–2008), using a time-series approach.

Materials and Methods

Study site description. Our study cities included Guangzhou, Foshan, Zhongshan, and Zuhai in the PRD (Figure 1). Guangzhou, the capital city of Guangdong Province, is a megacity that had 7.8 million urban residents in 2008; Foshan, Zhongshan, and Zuhai had 3.8, 1.5, and 1.0 million residents, respectively. These cities have a typical monsoon-influenced climate with wet, hot summers and dry,
cool to mild winters. The annual average precipitation is approximately 1,800 mm, the annual average temperature is 22–23°C, and the annual average relative humidity (RH) is 72–80%. The predominant southern or southeastern winds from the South China Sea during spring and summer bring relatively clean oceanic air, whereas northeastern winds carry air pollutants from close-vicinity northern cities in autumn and winter. These cities are typical of the PRD cities with respect to geographical, meteorological, and cultural conditions, although they vary in size and industrial structure.

**Mortality data.** We obtained daily mortality data for 2006 through 2008 on total (nonaccidental) deaths [International Classification of Diseases, 10th Revision (ICD-10; WHO 1994), codes A00–R99] and deaths attributed to cardiovascular diseases (codes I00–I99) and respiratory diseases (codes J00–J98) at all ages. The data also included subcategories of cardiovascular and respiratory mortality: coronary (codes I00–I09 and I20–I52), stroke (codes 160–169), and chronic obstructive pulmonary disease (COPD; codes J40–J47).

**Environmental data.** Air pollution data were measured at five monitoring stations in the area: two in Guangzhou (one regional monitoring station in Wangjingsha and one in the central city park Luhu), and one station each in Foshan, Zhongshan, and Zhuhai (Figure 1). All monitoring stations except the Luhu station are in urban areas with mixed residential and commercial activities. The monitors sample air about 10–20 m above ground level.

We obtained hourly concentrations of NO2, O3, sulfur dioxide (SO2), carbon monoxide (CO), and PM10 (PM with aerodynamic diameter ≤ 10 μm) from each station. NO2, SO2, O3, and CO were measured using chemiluminescence, fluorescence, ultraviolet, and infrared instruments, respectively; PM10 was measured by tapered element oscillating microbalance. We calculated 24-hr average concentrations for PM10, NO2, SO2, and CO for days that had measurements for at least 18 of 24 hr. We calculated 8-hr (from 1000 hours to 1800 hours) average concentrations for O3 for days with at least six of eight hourly measurements available. If monitor data for an individual pollutant were insufficient to calculate a daily average, all measurements from that day were excluded for that pollutant and monitor. Data from the two monitoring stations were averaged to derive concentrations for Guangzhou. Daily temperature and RH data for each city were obtained from the Chinese Academy of Meteorological Sciences. Missing data were not imputed.

**Statistical analysis.** Because daily mortality counts typically follow a Poisson distribution, we used Poisson regression models to evaluate the association between mortality and air pollution controlling for temperature, RH, seasonal patterns, and long-term trends using natural spline smoothers (Burnett et al. 2004; Samet and Katsouyanni 2006; Wood 2006). Degrees of freedom of the natural spline smoothers were determined by Akaike’s information criterion (Hurvich et al. 1998) and generalized cross-validation. If there was overdispersion in the variance, we used the partial autocorrelation function (PACF) of the residuals to guide the selection of degrees of freedom until the absolute values of sum of PACF for lags up to 30 days reached minimum. Analyses were also adjusted for year, day of the week (DOW), and public holidays using categorical indicator variables. We adjusted for influenza epidemics by including an indicator variable that was assigned a value of 1 when the 7-day moving average of the respiratory mortality was greater than the 90th percentile of its city-specific distribution, and 0 otherwise (Samoli et al. 2006). Because the influenza variable was based on the distribution of respiratory mortality, and because previous studies (Braga et al. 2000; Touloumi et al. 2005) suggest that omitting control for influenza is unlikely to influence the association between air pollution and respiratory mortality, we adjusted for influenza only in models of total mortality and cardiovascular mortality (Touloumi et al. 2004). Residuals of each model were examined for discernible patterns and autocorrelation using residual plots and PACF plots, respectively [Health Effects Institute (HEI) 2010b].

Associations between mortality and average air pollutant concentrations on individual days (lag 0 to lag 6) and 2-day periods (lag 0–1 days and lag 1–2 days) were first examined in single-pollutant models. Preliminary analyses indicated that the largest pollutant effects were usually observed at lag 1–2 days (data not shown). Therefore, we report the excess risk (ER) of mortality and its 95% confidence interval (CI) associated with a 10-μg/m3 increase in the average concentration of each pollutant during the previous 1–2 days. Single-day temperature and RH (lag 0 or lag 1 day) were used in our analyses, and the reported results were from models with lag 1 day covariates.

After establishing the final model that controlled for time trend, temperature, RH, year, DOW, public holiday, and influenza epidemics, we calculated city-specific estimates by fitting Poisson regression models for each city separately. We calculated Q-statistics to test the homogeneity of effect estimates among the study cities (α = 0.05) (DeSimonian and Laird 1986). Because the cities are all located along the estuary of the Pearl River, in close proximity to each other (Figure 1), and are similar with regard to natural and social factors, and because measurements from the five monitoring stations were correlated (Pearson correlation coefficients ranged from 0.64 to 0.88 for O3 and from 0.43 to 0.83 for NO2), we also generated combined effect estimates by summing the mortality data across the four cities and averaging the environmental data from the five monitoring stations.

Figure 1. The PRD and locations of air pollution monitors in the four cities included in the study: Guangzhou, Foshan, Zhongshan, and Zhuhai.
In the city-merged analyses, both single- and two-pollutant models were applied to estimate the effects of O₃, NO₂, and PM₁₀ adjusted for confounding by other pollutants. Two-pollutant models were restricted to pollutants with Pearson correlation coefficients < 0.6 to avoid multicollinearity. Furthermore, we stratified O₃ exposure as exposure during peak (September through November) and nonpeak (December through August) exposure periods identified previously for the area (Zhang et al. 2008b; Zheng et al. 2010) by using 2-df splines to control for time trend during the peak period and 6-df splines for the nonpeak period (Zanobetti and Schwartz 2008). In the stratified analysis, we adjusted for PM₁₀, because stratum-specific effects of O₃ could be confounded by PM₁₀ (Bell et al. 2007).

Finally, we conducted a series of sensitivity analyses focused on O₃ to assess the impact of dropping model covariates, increasing or decreasing the degrees of freedom for time and meteorological spline variables by 25%, lagging temperature by 2–3 days or 4–6 days, and excluding days with daily concentrations of O₃ above the 95th or below the 5th percentile.

Analyses were performed using R (version 2.13.0; R Foundation for Statistical Computing, Vienna, Austria) with the mgcv package (version 1.5–5; Comprehensive R Archive Network, http://cran.r-project.org). Statistical significance was defined as p < 0.05.

**Results**

Table 1 summarizes the mortality data for the four PRD cities from 2006 through 2008. Average daily nonaccidental death counts were 83, 25, 21, and 9 for Guangzhou, Foshan, Zhongshan, and Zhuhai, respectively. About 56% of all nonaccidental deaths occurred in males, and 54–63% were attributed to cardiovascular or respiratory diseases.

Table 2 presents the air pollution levels of the four cities from 2006 through 2008. Foshan had the highest average concentrations of PM₁₀, NO₂, SO₂, and CO, and Zhongshan had the highest average concentration of O₃. Monthly O₃ concentrations were highest during the peak exposure period from September through November (Figure 2). Based on combined data for the four cities, O₃ was the least correlated with other pollutants (Pearson correlation coefficients, −0.06 to 0.17), whereas NO₂ was highly correlated with PM₁₀, SO₂, and CO (correlation coefficients, 0.72–0.82). Temperature was positively correlated with O₃ only, whereas RH was negatively correlated with all the pollutants (Table 3).

In the individual cities, adjusted ERs of total mortality in association with a 10-μg/m³ increase in exposure (1–2 day lag, single-pollutant models) ranged from 0.22% to 0.64% for O₃, 1.22% to 1.87% for NO₂, and 0.37% to 0.74% for PM₁₀ (Table 4). In general, we observed stronger associations of O₃, NO₂, and PM₁₀ with cardiovascular and respiratory mortality than with total mortality. Although there was heterogeneity for the associations between PM₁₀ and respiratory mortality and also some variation in Foshan and Zhuhai, no significant heterogeneity was found in the effect estimates of O₃ and NO₂ among the four cities, which supported our analyses with city-merged data.

In the city-merged analyses, effect estimates for O₃ were moderately reduced but still significant after adjustment for PM₁₀, NO₂, so₂, CO. Effect estimates for NO₂ and PM₁₀ were also attenuated but still significant after adjustment for O₃ (Table 5). The variation of effect estimates among pollutants became smaller when assessment was made per interquartile range (IQR) increase. For instance, the effect estimates of O₃ and NO₂ on total mortality were 0.81% and 1.95% per 10-μg/m³ increase for each pollutant (Table 5), whereas the estimates were 5.31% and 5.97% per IQR increase [see Supplemental Material, Table 1 (http://dx.doi.org/10.1289/ehp.1103715)]. Also observed significant increased risk in cardiorespiratory mortality per unit increase in air pollution: a 10-μg/m³ increase in O₃ exposure was associated with 0.79% (95% CI: 0.36, 1.22%), 1.17% (95% CI: 0.65, 1.70%), and 1.16% (95% CI: 0.56, 1.77%) increases in mortality from coronary, stroke, and COPD diseases, respectively (see Supplemental Material, Table 2).

Average concentrations of O₃ were 117.4 μg/m³ in the peak period (September through November) and 66.9 μg/m³ in the nonpeak period. O₃ exposure was significantly associated with total mortality and cardiovascular mortality in both periods (Table 6). After adjustment for PM₁₀, effect estimates for total and cardiovascular mortality increased in the peak period but decreased in the nonpeak period. Respiratory mortality was significantly associated with O₃ exposure during the nonpeak period only, and there was no evidence of an association during the peak period after adjusting for PM₁₀.

Our sensitivity analyses indicated that covariates did not introduce collinearity, and all were significant predictors (p < 0.05). Altering the degrees of freedom of time and meteorological smoothers and excluding days with extremely high or low O₃ concentrations did not alter total mortality effect estimates by > 20% [see Supplemental Material, Table 3 (http://dx.doi.org/10.1289/ehp.1103715)]. However, estimates for total mortality were somewhat sensitive to adjustment for temperature over different lag periods, resulting in ERs for a 10-μg/m³ increase in O₃ (1– to 2-day lag) of 0.70% (95% CI: 0.51%, 0.89%) and 0.63% (95% CI: 0.44%, 0.82%) when adjusted for temperature with a lag of 2–3 days or 4–6 days, respectively, with 0.81% (95% CI: 0.63%, 1.00%) when adjusted for temperature with a 1-day lag.

**Discussion**

We estimated significant acute mortality effects associated with exposure to ambient oxidants in the PRD. In general, associations between O₃ and NO₂ exposure and daily mortality were homogeneous among the study cities. The estimated effects of O₃ were robust to adjustment for other pollutants (PM₁₀, NO₂, so₂, CO), and effect estimates for NO₂ were robust to adjustment for O₃. Effect estimates for O₃ were larger for exposure during the peak period for total and cardiovascular mortality after adjustment for PM₁₀, whereas for respiratory mortality, the association appeared to be limited to exposure during the nonpeak period.

Table 1. Summary statistics of daily mortality counts in the PRD cities, 2006–2008 [mean ± SD (range)].

| Mortality     | Guangzhou | Foshan | Zhongshan | Zhuhai |
|---------------|-----------|--------|-----------|--------|
| Total         | 83.2 ± 16.5 (47–173) | 24.5 ± 8.2 (0–104) | 20.7 ± 6.1 (5–62) | 8.5 ± 3.2 (1–22) |
| Nonaccidental | 38.5 ± 9.2 (15–87)  | 10.9 ± 4.5 (0–45)  | 9.1 ± 3.6 (1–25)  | 3.7 ± 2.1 (0–12)  |
| Male          | 46.7 ± 9.8 (20–94)  | 13.6 ± 5.2 (0–59)  | 11.6 ± 4.0 (1–27) | 4.8 ± 2.3 (0–13)  |
| Coronary      | 30.1 ± 8.5 (11–74)  | 9.3 ± 4.4 (0–45)   | 9.4 ± 3.8 (0–26)  | 3.5 ± 2.2 (0–15)  |
| Respiratory   | 15.6 ± 5.2 (2–33)   | 5.0 ± 2.2 (0–25)   | 4.4 ± 2.3 (0–24)  | 1.3 ± 1.3 (0–8)   |
| COPD          | 7.7 ± 3.5 (0–27)    | 2.2 ± 1.6 (0–11)   | 2.3 ± 1.7 (0–11)  | 0.8 ± 0.9 (0–5)   |

Table 2. Summary statistics of ambient air pollutant concentrations in the PRD cities, 2006–2008 [mean (interquartile range)].

| Pollutant     | Guangzhou | Foshan | Zhongshan | Zhuhai |
|---------------|-----------|--------|-----------|--------|
| PM₁₀ (μg/m³) | 81.0 (82.0) | 121.3 (89.0) | 64.2 (58.2) | 43.5 (24.8) |
| NO₂ (μg/m³)  | 53.9 (33.1) | 70.4 (39.1) | 48.4 (34.2) | 38.1 (34.2) |
| O₃ (μg/m³)   | 78.2 (72.8) | 70.7 (77.3) | 85.7 (70.8) | 85.5 (76.5) |
| SO₂ (μg/m³)  | 55.2 (35.2) | 95.4 (73.2) | 57.3 (72.1) | 39.4 (40.0) |
| CO (ppm)     | 1.35 (0.61) | 1.65 (1.23) | 1.20 (0.87) | 1.29 (0.73) |

Data are 24-hr averages for PM₁₀, NO₂, SO₂, and CO and 8-hr (1000 hours to 1800 hours) averages for O₃.
We observed much higher concentrations of O₃ in the PRD cities (annual mean, 70–85 μg/m³) than those observed in North American cities (14–38 μg/m³) (Samet and Katsouyanni 2006). Our analysis indicated significant increases of 0.81% (95% CI: 0.63%, 1.00%) in total mortality, 1.01% (95% CI: 0.71%, 1.32%) in cardiovascular mortality, and 1.33% (95% CI: 0.89%, 1.76%) in respiratory mortality, per 10-μg/m³ increase in lag 1–2 day O₃ level in the PRD. Consistently, a multisite time-series study of 95 large U.S. urban communities estimated that a 10-ppb (≈ 20 μg/m³) increase in the previous week’s O₃ was associated with a 0.52% (95% CI: 0.27%, 0.77%) increase in daily mortality and a 0.64% (95% CI: 0.31%, 0.98%) increase in cardiovascular and respiratory mortality (Bell et al. 2004). A meta-analysis of 144 effect estimates from 39 time-series studies also provided strong evidence of a short-term association between O₃ exposure and mortality, with larger estimated effects on cardiovascular and respiratory mortality than on total mortality (Bell et al. 2005).

However, several other studies reported acute O₃ exposure effects on cardiovascular mortality but not respiratory mortality, including an analysis of seven Spanish cities in the EMECAM (Spanish Multicenter Study on the Relationship between Air Pollution and Mortality) project (Saez et al. 2002) and studies in Asia (HEI 2010b; Zhang et al. 2006). Wong et al. (2008) reported that effect estimates of O₃ were significant for total and cardiovascular mortality but only marginally significant for respiratory mortality in four Asian cities. In addition, a recent review of Asian studies reported positive but much smaller and inconsistent effect estimates for O₃ and mortality across cities (HEI 2010a). Considering the limited number of estimates available for meta-analysis, future studies should be conducted in more Asian cities in order to address the inconsistency.

Consistent with previous studies (Burnett et al. 2004; Michelozzi et al. 1998; Touloumi et al. 1997), our analysis indicated significant associations between short-term change in NO₂ and mortality in the PRD, with estimated increases of 1.95% (95% CI: 1.62%, 2.29%) in total mortality, 2.12% (95% CI: 1.58%, 2.65%) in cardiovascular mortality, and 3.48% (95% CI: 2.73%, 4.23%) in respiratory mortality, per 10-μg/m³ increase in lag 1–2 day NO₂ concentrations. However, the magnitude of NO₂ effect estimates in our study was much greater than comparable estimates reported for Western populations (pooled estimates, 0.30–0.50% increases in total, cardiovascular, and respiratory mortality per 10-μg/m³ increase in lag 0–1 day NO₂ concentrations) (Samoli et al. 2006). Our estimates were also larger than comparable
Ambient oxidants of O₃ and NO₂ are major air pollutants in the PRD. Estimated effects of O₃ were moderately reduced but still significant after adjustment for PM₁₀, SO₂, and CO in two-pollutant models. This is probably because O₃, as a secondary pollutant, has formation paths in the environment different from those of PM₁₀, SO₂, and CO, and thus does not typically covary with these pollutants. With weak correlations observed between O₃ and other pollutants, the mortality effects of O₃ were stronger in cold seasons with lower O₃ levels (Wong et al. 1999, 2001). People with respiratory diseases may be more sensitive to high O₃ exposure than are people with other diseases; thus, with very high mean level of 117.4 μg/m³ measured in the peak period, the risks of respiratory mortality could be reduced because vulnerable subjects may have died before the O₃ concentration reached higher levels (Wong et al. 2001).

Limitations should be noted in interpreting the results of our study. First, exposure data were obtained from only one or two air pollution monitoring stations in each city. Air pollution exposure may be spatially autocorrelated across our study cities, which may violate the assumption of independent exposures among cities for the merged regression analyses. The limited number of air pollution monitoring stations and exposure data to assess spatial structure of air pollution between cities may yield biased variance of parameter estimates and inefficient significance tests in our study (Jerrett et al. 2005). Second, no PM₂.₅ and component data were available for the study period. Compared with PM₁₀, PM₂.₅ is a better index of combustion source air pollution and has better accuracy.

### Table 4. ER of mortality associated with a 10-μg/m³ increase in lag 1–2 day O₃, NO₂, and PM₁₀ concentrations under single- and two-pollutant models* based on combined data for four cities in the PRD [percent (95% CI)].

| Mortality        | Pollutant | Method               | Total       | Cardiovascular | Respiratory |
|------------------|-----------|----------------------|-------------|----------------|-------------|
| Total (nonaccidental) | O₃       | Single-pollutant model | 0.81 (0.63, 1.00) | 1.01 (0.71, 1.32) | 1.33 (0.89, 1.76) |
|                  | Adjusted for PM₁₀ | 0.54 (0.34, 0.75) | 0.71 (0.37, 1.05) | 0.87 (0.39, 1.36) |
|                  | Adjusted for NO₂ | 0.43 (0.23, 0.64) | 0.62 (0.29, 0.96) | 0.58 (0.10, 1.06) |
|                  | Adjusted for SO₂ | 0.70 (0.51, 0.90) | 0.92 (0.60, 1.23) | 1.16 (0.71, 1.61) |
|                  | Adjusted for CO  | 0.72 (0.53, 0.91) | 0.89 (0.58, 1.20) | 1.17 (0.72, 1.61) |
|                  |                          |                        |                          |                          |
| Cardiovascular   | NO₂       | Single-pollutant model | 1.95 (1.62, 2.29) | 2.12 (1.58, 2.65) | 3.48 (2.73, 4.23) |
|                  | Adjusted for O₃     | 1.63 (1.27, 2.00) | 1.67 (1.08, 2.25) | 3.07 (2.25, 3.89) |
|                  | Adjusted for PM₁₀   | 0.79 (0.62, 0.96) | 0.91 (0.64, 1.19) | 1.26 (0.80, 1.65) |
|                  | Adjusted for NO₂    | 0.58 (0.39, 0.76) | 0.64 (0.34, 0.95) | 0.93 (0.51, 1.36) |

*Two-pollutant models were limited to pollutants with Pearson correlation coefficients < 0.6; other covariates controlled for were the same as those in Table 4.

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### Table 5. ER of nonaccidental mortality associated with a 10-μg/m³ increase in lag 1–2 day O₃, NO₂, and PM₁₀ concentrations under single- and two-pollutant models† based on combined data for four cities in the PRD [percent (95% CI)].

| Pollutant | Method               | Total       | Cardiovascular | Respiratory |
|-----------|----------------------|-------------|----------------|-------------|
| O₃        | Single-pollutant model | 0.81 (0.63, 1.00) | 1.01 (0.71, 1.32) | 1.33 (0.89, 1.76) |
| Adjusted for PM₁₀ | 0.54 (0.34, 0.75) | 0.71 (0.37, 1.05) | 0.87 (0.39, 1.36) |
| Adjusted for NO₂ | 0.43 (0.23, 0.64) | 0.62 (0.29, 0.96) | 0.58 (0.10, 1.06) |
| Adjusted for SO₂ | 0.70 (0.51, 0.90) | 0.92 (0.60, 1.23) | 1.16 (0.71, 1.61) |
| Adjusted for CO  | 0.72 (0.53, 0.91) | 0.89 (0.58, 1.20) | 1.17 (0.72, 1.61) |
| NO₂        | Single-pollutant model | 1.95 (1.62, 2.29) | 2.12 (1.58, 2.65) | 3.48 (2.73, 4.23) |
| Adjusted for O₃     | 1.63 (1.27, 2.00) | 1.67 (1.08, 2.25) | 3.07 (2.25, 3.89) |
| Adjusted for PM₁₀   | 0.79 (0.62, 0.96) | 0.91 (0.64, 1.19) | 1.26 (0.80, 1.65) |
| Adjusted for NO₂    | 0.58 (0.39, 0.76) | 0.64 (0.34, 0.95) | 0.93 (0.51, 1.36) |

†Poisson regression model controlled for time trend, temperature, RH, year, DOY, public holiday, and influenza epidemics.
a larger proportion of secondary particles. Franklin and Schwartz (2008) suggested that some secondary particle, such as particulate sulfate, may be partly responsible for observed O₃ effects. Therefore, adjusting for PM₁₀, instead of PM₂.₅, or its components, may overestimate the effect of O₃.

Conclusion

We estimated significant increases in mortality associated with O₃ and NO₂ exposures in the PRD. The evidence of differential effects of O₃ on mortality from different diseases supports the need for further investigation of the pathophysiological mechanisms of O₃-associated cardiovascular and respiratory effects. Our findings strengthen the rationale for further limiting ambient oxidant pollution in the PRD.

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