# Health Effects of Air Pollution Involving Multiple Pollutants: The Impact of Co-Exposure to $PM_{2.5}$ and $O_3$ on Mortality in China

Heqing Huang
National School of Development, Peking University

Fan Xia
School of the Environment, Nanjing University

Jintao Xu
National School of Development, Peking University

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# 1. Introduction

- **There have been many studies on the health costs of air pollution**
  - But most of them focus on particulate matter (including TSP, $PM_{10}$ , $PM_{2.5}$ )
    - e.g. Ebenstein et al. (2017 PNAS), Barwick et al. (2018 WP), Deryugina et al. (2019 AER), Xia et al. (2022 JEEM).
  - **Few studies that simultaneously identify the effects of co-exposure to multiple pollutants**
    - Godzinski and Castillo (2021 JEEM) simultaneously studied the health hazards of five pollutants PM, $O_3$, $NO_2$, $SO_2$ and CO by means of IV-Lasso , and found that the results were quite different from those when pollutants were studied separately. They launched the question of " Air pollution or Pollutants? " .
- **Besides particulate matter, why ozone?**

# 1. Introduction

## ☐ Besides particulate matter, why ozone?

1. Harmful effects of ozone

| $O_3$ concentration (ug/m$^3$) | Exposure time (hour) | Health effects |
|---|---|---|
| 30 | / | Olfactory threshold |
| 50 | / | Background concentration |
| 200 | 1 | Cause eye irritation |
| 200 | 1 | Affect children's lung function |
| 300 | 1 | **Increased incidence of asthma** |
| 400 | 1 | **Exacerbation in patients with chronic lung disease** |
| 600 | / | Causes nose and throat irritation |
| 700 | 2 | Increased respiratory resistance |
| 1,000 | 1 - 2 | **Changes in lung function** |
| 2,000 | 1.5 | Cough, tiredness |
| 3,200 | 2 | Muscle dyskinesia, inability to express thoughts,chest pain,cough |
| 6,400 | 1 | sleepy |
| 8,600 | 0.5 | **headache, wheezing, increased pulse** |
| 10,700 | / | **Dangerous to life** |

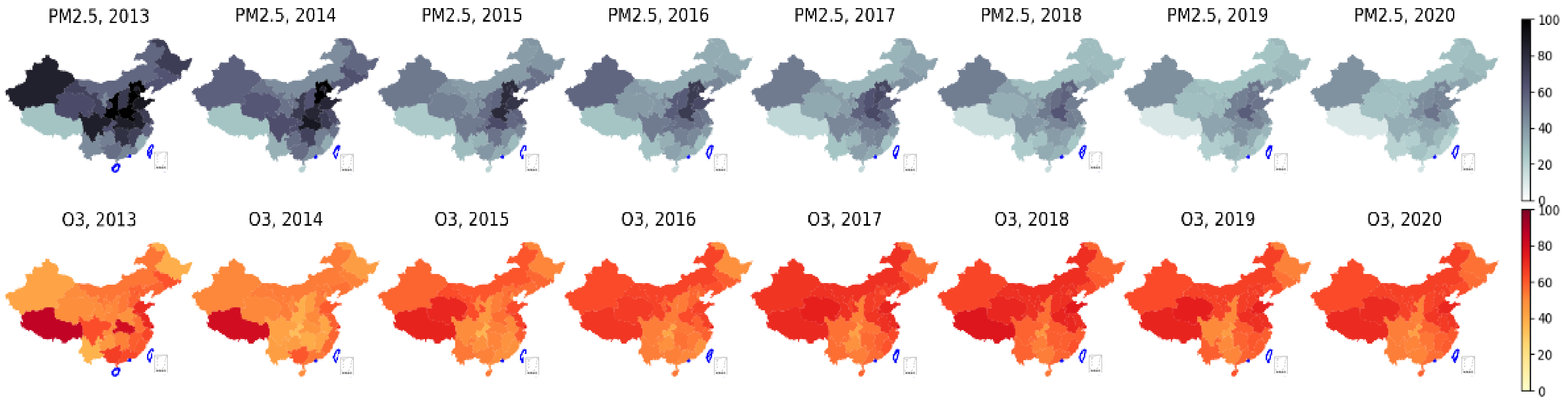
( Kong et. al., 1993 )

# 1. Introduction

## ☐ Besides particulate matter, why ozone?

2. The concentration of $PM_{2.5}$ decreased significantly in China, but the $O_3$ concentration increased significantly.

- Falling PM2.5 may be one of the reasons for $O_3$ rise.
- Li K. et al. (2019 Nature Geoscience ) and Li K. et al. (2019 PNAS ) found that $PM_{2.5}$ can inhibit the generation of $O_3$ by absorbing hydrogen peroxide (HO2) and nitrogen oxide (NOx) radicals.



# 1. Introduction

## Besides particulate matter, why ozone?

3. The concentrations of ozone and other pollutants are usually negatively correlated

Correlation between major pollutant concentrations and AQI

| | aqi | pm25 | pm10 | o3 | no2 | so2 | co |
|---|---|---|---|---|---|---|---|
| aqi | 1.00 | 0.95 | 0.93 | -0.08 | 0.70 | 0.54 | 0.06 |
| pm25 | 0.95 | 1.00 | 0.86 | -0.17 | 0.73 | 0.56 | 0.06 |
| pm10 | 0.93 | 0.86 | 1.00 | -0.08 | 0.62 | 0.53 | 0.06 |
| o3 | -0.08 | -0.17 | -0.08 | 1.00 | -0.28 | -0.22 | -0.01 |
| no2 | 0.70 | 0.73 | 0.62 | -0.28 | 1.00 | 0.54 | 0.05 |
| so2 | 0.54 | 0.56 | 0.53 | -0.22 | 0.54 | 1.00 | 0.06 |
| co | 0.06 | 0.06 | 0.06 | -0.01 | 0.05 | 0.06 | 1.00 |

4. The co-control of multiple pollutants, especially of $PM_{2.5}$ and $O_3$, is the policy emphasis of air pollution prevention and control program during the 14th Five-Year Plan

- Premier Li Keqiang demanded at the executive meeting of the State Council that "during the 14th Five-Year Plan period, we will deepen the battle against pollution and strengthen the co-control of $PM_{2.5}$ and $O_3$ ".

# Research Contents

1. To identify simultaneously the effects of both ozone and fine particulate matter exposure on mortality
2. To explore the interactive health effects of ozone and fine particulate matter exposure
3. To study spatial and seasonal heterogeneity in the health effects of ozone and fine particulate matter pollution

# 2. Data

## ☐ Cause-specific death data (Disease Surveillance Points, DSP )

- From CDC, 605 county-level surveillance points nationwide;
- Recoding death cases, from 2013 to the present.

- The current study uses daily death counts from 106 surveillance points, 2013-2018
- six types of death causes:

  (1) total non-accidental deaths (total)

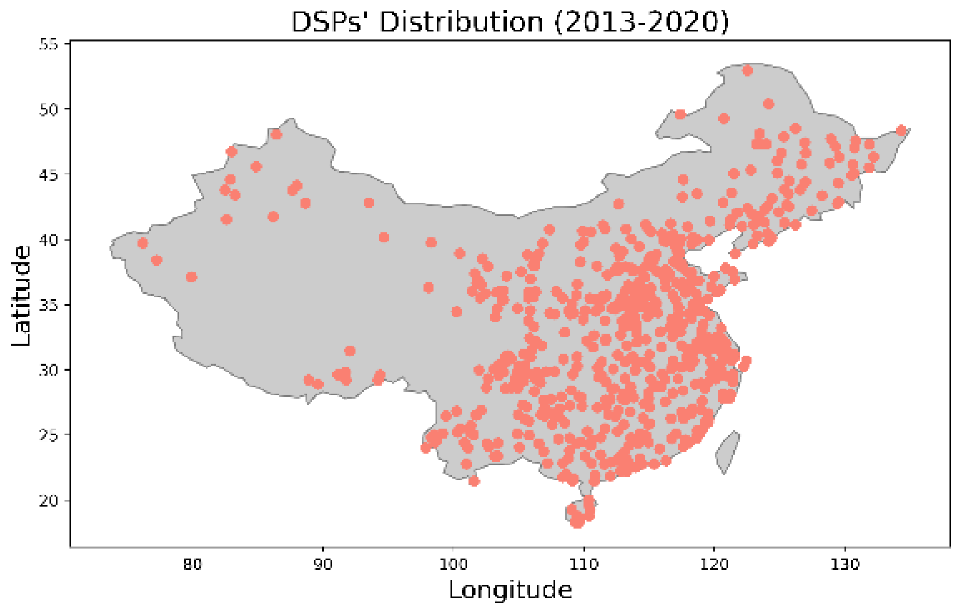
  (2) Deaths from cardiovascular and cerebrovascular diseases (cir)

  (3) Deaths from ischemic heart disease (ihd)

  (4) Deaths from cerebrovascular diseases (cer)

  (5) Deaths from chronic obstructive pulmonary disease (copd)

  (6) Deaths from lung cancer (lc)



# 2. Data

## ◻ Air quality data

- From China National Environmental Monitoring Centre, more than 1,600 monitoring stations across the country;
- Hourly concentration of pollutants, from 2013 to present.

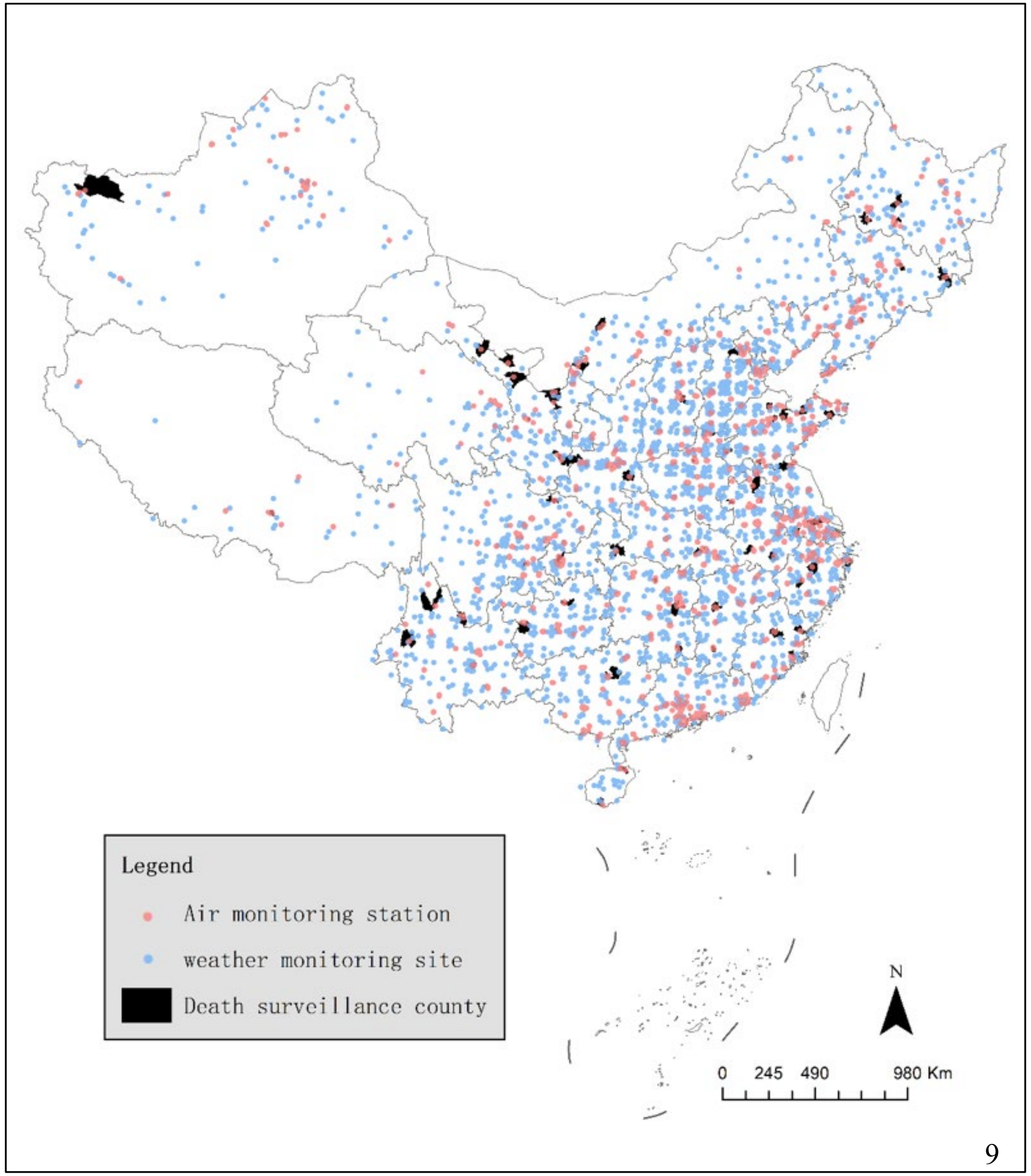
## ◻ Meteorological data

- From China Meteorological Administration, more than 2,000 suface weather stations across the country;
- Near-surface meteorological data such as hourly temperature, pressure, wind direction and speed.

## ◻ Thermal Inversion data

- NASA MERRA-2 satellite data
- 42 layers of atmospheric temperature, 0.5° × 0.625°

Distribution of death cause monitoring points, air quality monitoring points, and weather stations



# 2. Data matching and description

- For each DSP county, we average data from air quality/meteorological stations within the county.
- If there is no station in this county, then the weighted averages of air quality/meteorological stations within the prefecture-level city will be obtained using inversed distance as the weight.

| Variables | Unit | Mean | Std. dev. | Min | Max | Obs. |
|---|---|---|---|---|---|---|
| **A. Death surveillance data** | | | | | | |
| Total non-accidental deaths (total) | # | 9.7 | 6.9 | 0.0 | 221.0 | 220,044 |
| Cardiovascular and cerebrovascular disease deaths (cir) | # | 4.6 | 3.9 | 0.0 | 166.0 | 220,044 |
| ischemic heart disease deaths (ihd) | # | 1.9 | 2.1 | 0.0 | 69.0 | 220,044 |
| Cerebrovascular disease deaths (cer) | # | 2.2 | 2.1 | 0.0 | 70.0 | 220,044 |
| Lung cancer deaths (lc) | # | 0.8 | 1.1 | 0.0 | 13.0 | 220,044 |
| Chronic Obstructive Pulmonary Disease deaths (copd) | # | 0.7 | 1.1 | 0.0 | 20.0 | 220,044 |

| Variables | Unit | Mean | Std. dev. | Min | Max | Obs. |
|---|---|---|---|---|---|---|
| **B. Air pollution data** | | | | | | |
| $PM_{2.5}$ concentration | ug/m$^3$ | 53.4 | 46.3 | 1.7 | 2668.0 | 185,943 |
| $O_3$ concentration _ | ug/m$^3$ | 58.2 | 32.1 | 1.0 | 757.5 | 185,819 |
| **C. Meteorological data** | | | | | | |
| Pressure | kPa | 96.2 | 8.5 | 57.4 | 104.4 | 219,995 |
| Temperature | °C | 14.3 | 11.0 | -30.3 | 36.2 | 219,994 |
| Relative humidity | % | 65.6 | 19.1 | 4.6 | 100.0 | 219,995 |
| Precipitation | mm | 2.6 | 9.1 | 0.0 | 264.7 | 219,998 |
| Wind speed | m/s | 4.8 | 2.0 | 0.0 | 29.6 | 219,998 |
| Wind direction | / | 8.4 | 4.4 | 1.0 | 17.0 | 219,998 |
| Sunshine duration | Hour | 5.8 | 4.1 | 0.0 | 14.3 | 219,998 |

## 3.1 Empirical Strategies - Instrumental Variables

### Thermal inversion

- Affects the transmission and diffusion conditions of pollutants, and therefore traps pollution.
- Commonly used: Deschenes et al. (2020 JDE), Xia et al. (2022 JEEM), Chen et al. (2022 JDE) etc.

### Wind direction

- Affects the transport and diffusion of pollutants: Deryugina et al. (2019 AER) , Lai et al. (2022 AJAE) .
- Upwind pollution level/ transmissions are also used as IV: Barwick et al. (2018 WP) , Chen et al. (2021 JAERE)
- Inspired by Deryugina et al. (2019 AER), we **interact wind direction and thermal inversion with indicators of seven geographic regions (North China, East China, South China, etc.) , allowing the effect of wind direction or thermal inversion on endogenous variables ($PM_{2.5}$ and $O_3$ concentration) to vary by geographic location.** Meanwhile, more instrumental variables can be obtained.

### Sunshine duration

- Sunlight is necessary for ozone generation, so sunshine duration is highly related to ozone level. Bae et al. (*2020 Environmental Research*) used sunshine duration as one of the IVs for ozone.

## 3.2 Regression model

$$ihs(Y_{ct}) = \beta_0 + \beta_1 MA(O_{3\,ct}, \boldsymbol{w}) + \beta_2 MA(PM_{2.5\,ct}, \boldsymbol{w}) + MA(Weather_{ct}, \boldsymbol{w})'\theta + FE_{cym} + \epsilon_{ct}$$

- $ihs(Y_{ct})$ : the number of deaths in county c on date t ;
- $O_{3\,ct}$: Daily maximal 8-hour $O_3$ concentration in county c on date t;
- $PM_{2.5\,ct}$: Daily average concentration of $PM_{2.5}$ in county c on date t;
- $Weather'_{ct}$: Temperature, air pressure, relative humidity, precipitation and wind speed. The temperature is divided into ten decile bins;
- $FE_{cym}$: Interactive fixed effects of county (c), year (y), month (m) (district × year ×month) ;
- $\epsilon_{ct}$: Clustered by county.
- $MA(x, w)$: Take the moving average of the variable x over the window of the past w days and the current day, where *w* is the window length .

## 3.3 Varying instrumental variable combinations (set $w = 0$)

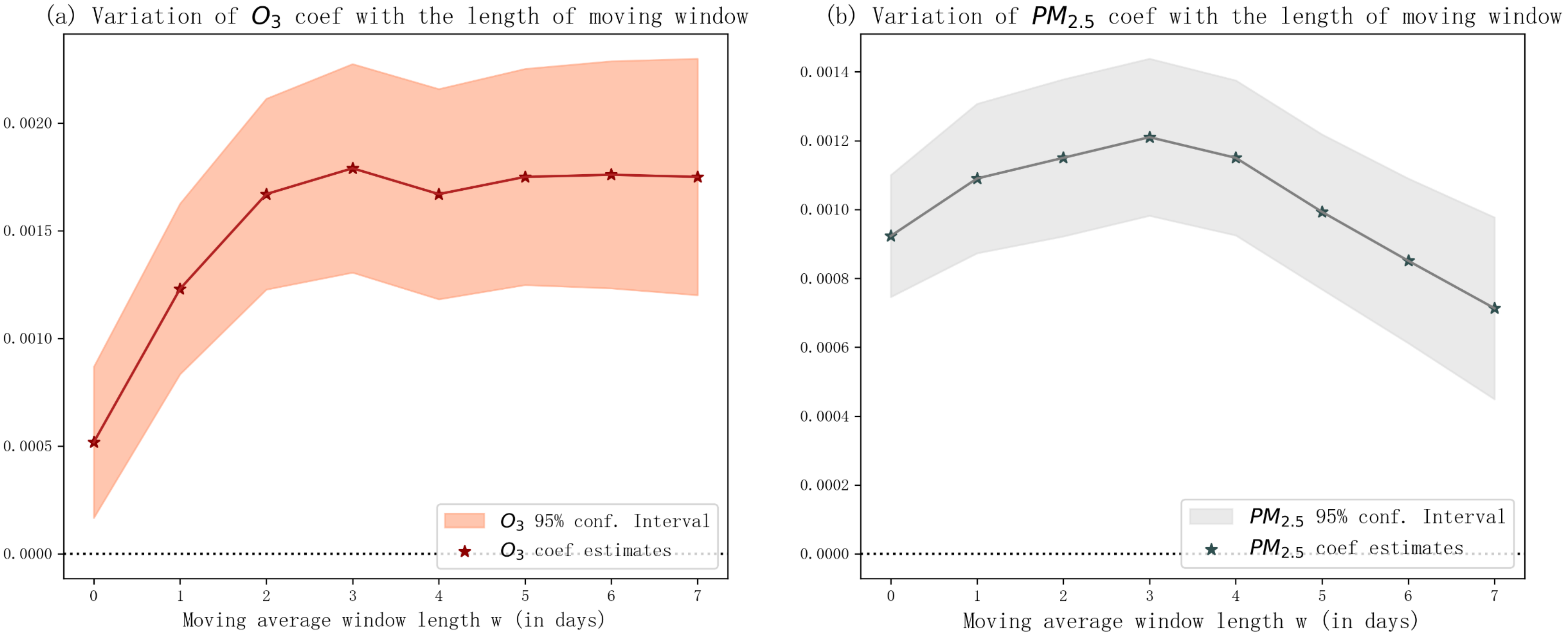
$$ihs(Y_{ct}) = \beta_0 + \beta_1 {O_3}_{ct} + \beta_2 {PM_{2.5}}_{ct} + Weather'_{ct}\theta + FE_{cym} + \epsilon_{ct}$$

| IV | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | 8 wind direction | | 4 wind direction | | 4 wind direction # Region | |
| | Inversion | Inversion #Region | Inversion | Inversion #Region | Inversion | Inversion #Region |
| $O_3$ | 0.000403** | 0.000528*** | 0.000392** | 0.000518*** | 0.000466*** | 0.000583*** |
| | (0.000187) | (0.000182) | (0.000184) | (0.000179) | (0.000165) | (0.000158) |
| $PM_{2.5}$ | 0.000947*** | 0.000928*** | 0.000944*** | 0.000923*** | 0.000893*** | 0.000882*** |
| | (0.000185) | (0.000175) | (0.000188) | (0.000177) | (0.000186) | (0.000178) |
| cdf | 811.7 | 529.3 | 1444.1 | 713.2 | 358.8 | 303.9 |
| rkf | 32.77 | 38.30 | 53.84 | 50.58 | 14.89 | 22.09 |
| N | 185,755 | 185,755 | 185,755 | 185,755 | 185,755 | 185,755 |

Preferred IVs

## 3.4 Dynamic health effects (varying window length *w*)

$$ihs(Y_{ct}) = \beta_0 + \beta_1 MA\left({O_3}_{ct}, w\right) + \beta_2 MA\left({PM_{2.5}}_{ct}, w\right) + MA(Weather_{ct}, w)'\theta + FE_{cym} + \epsilon_{ct}$$



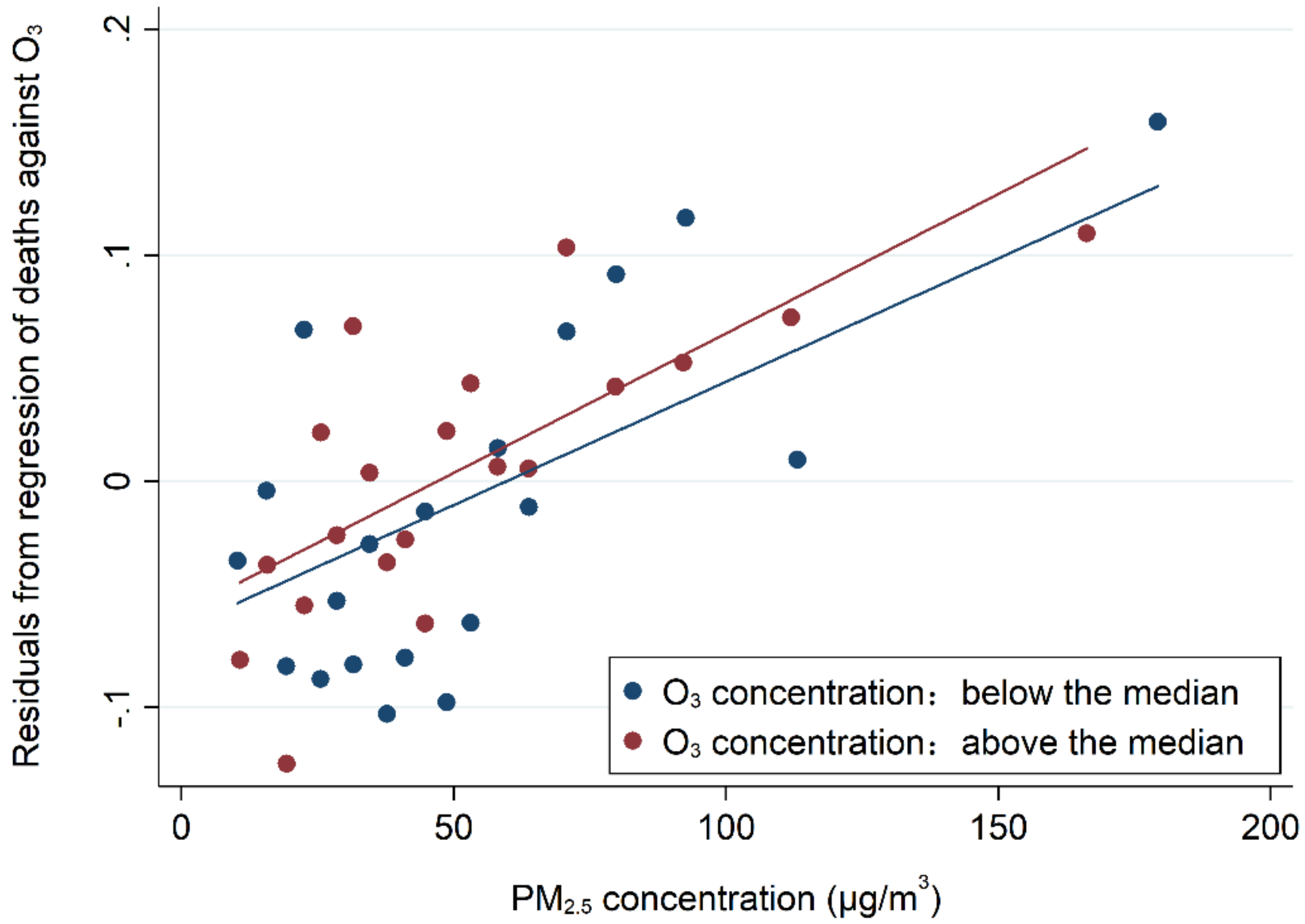
# 4. Main Results

## 4.1 Benchmark Results

| | (1) total | (2) cir | (3) ihd | (4) cer | (5) copd | (6) lc |
|---|---|---|---|---|---|---|
| MA($O_3$ , 2) | 0.00167*** | 0.00151*** | 0.00118*** | 0.00123*** | 0.000806*** | 0.00124*** |
| | (0.000226) | (0.000339) | (0.000343) | (0.000347) | (0.000253) | (0.000260) |
| MA($PM_{2.5}$, 2) | 0.00115*** | 0.00158*** | 0.00143*** | 0.00128*** | 0.000797*** | 0.0000985 |
| | (0.000228) | (0.000279) | (0.000261) | (0.000311) | (0.000230) | (0.000266) |
| $E_{Ozone}$ | 0.098*** | 0.090*** | 0.078*** | 0.079*** | 0.080*** | 0.117*** |
| | (0.013) | (0.02) | (0.023) | (0.022) | (0.025) | (0.025) |
| $E_{PM}$ | 0.062*** | 0.086*** | 0.086*** | 0.075*** | 0.073*** | 0.009 |
| | (0.012) | (0.015) | (0.016) | (0.018) | (0.021) | (0.023) |
| cdf | 1045.5 | 1045.5 | 1045.5 | 1045.5 | 1045.5 | 1045.5 |
| rkf | 35.31 | 35.31 | 35.31 | 35.31 | 35.31 | 35.31 |
| N | 185,034 | 185,034 | 185,034 | 185,034 | 185,034 | 185,034 |

Short-term effects of fine particulate matter on lung cancer death were not identified, longer-term observation windows may be required (Fu J. et al., 2015; Guo H. et al., 2020 ).

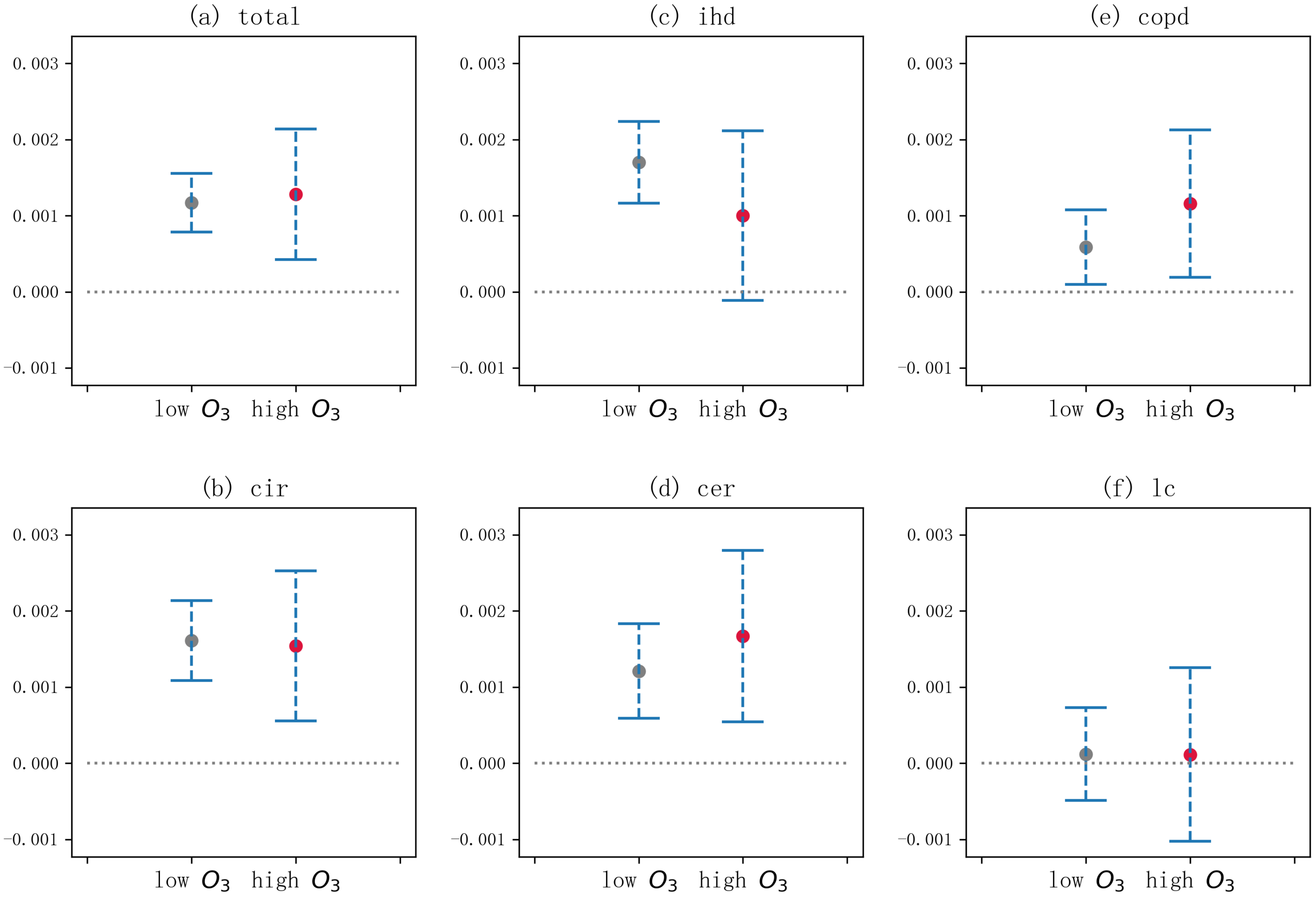
# 4.2 Synergistic effects of co-exposure




Note: The y-axis is the residuals of total number of non-accidental deaths (total), after controlling for meteorological conditions , fixed effects and $O_3$ concentration.

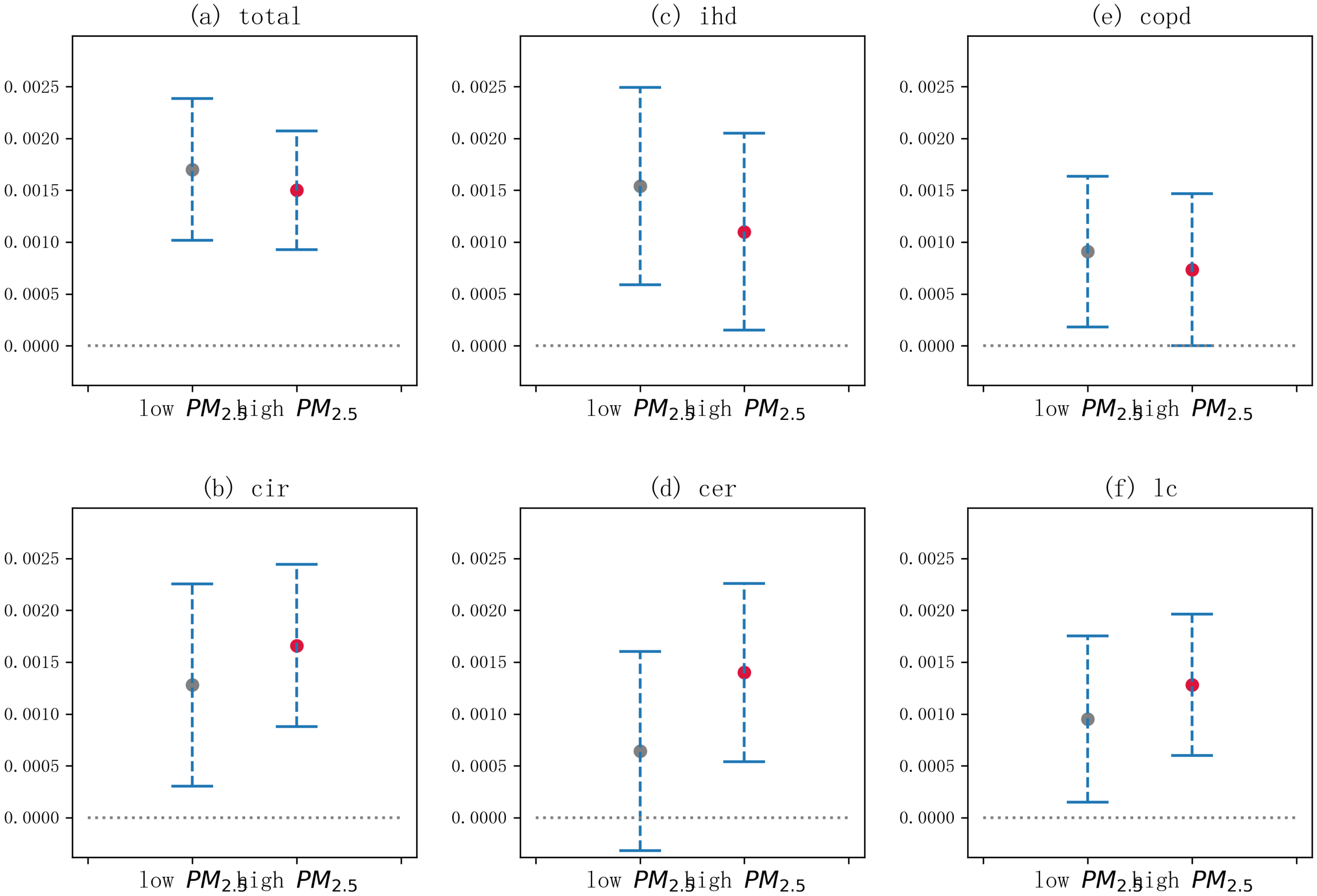
# 4.2 Synergistic effects of co-exposure

Marginal health effects of $PM_{2.5}$ under different $O_3$ concentrations



## 4.2 Synergistic effects of co-exposure

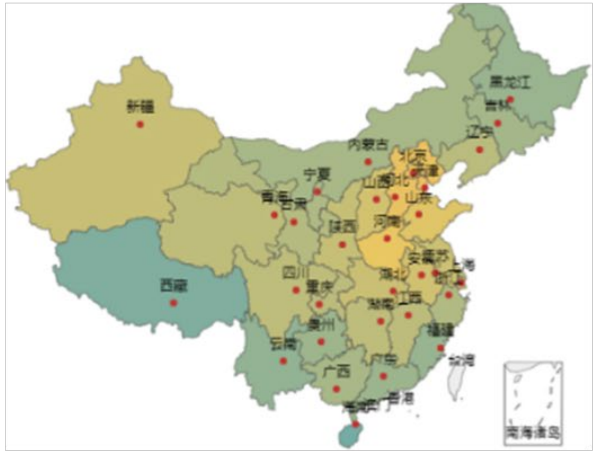
Marginal health effects of $O_3$ under different $PM_{2.5}$ concentrations



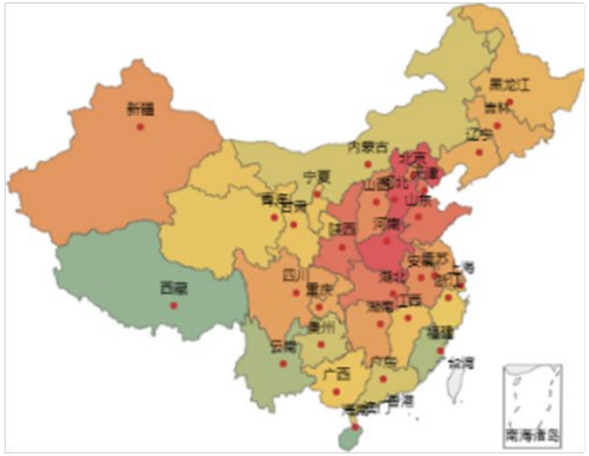
# 4.3 Heterogeneity Analysis

## Seasonal and regional variation in $PM_{2.5}$ and $O_3$ pollution in China

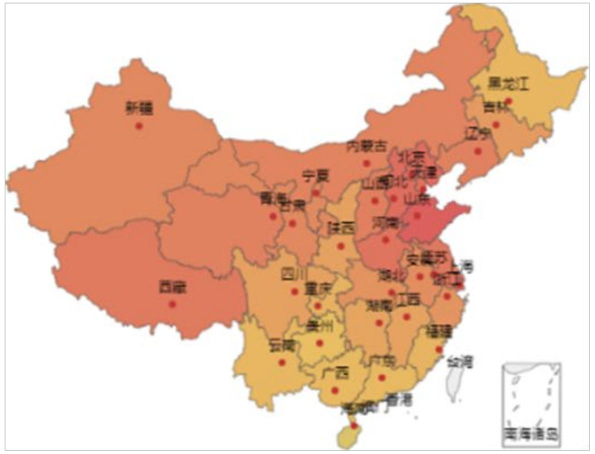
(a) Summer $PM_{2.5}$ concentration by province



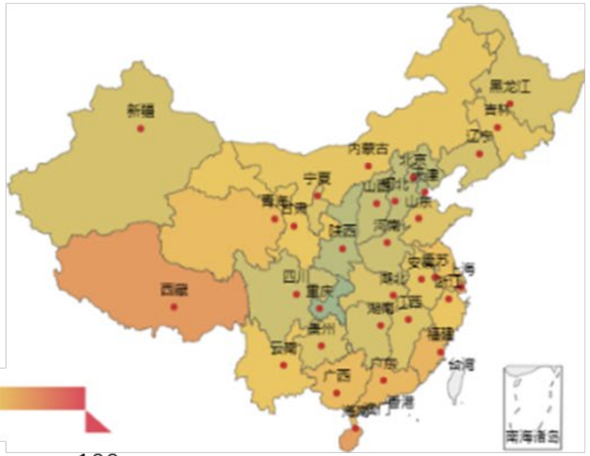
(b) Winter $PM_{2.5}$ concentration by province



(c) Summer $O_3$ concentration by province

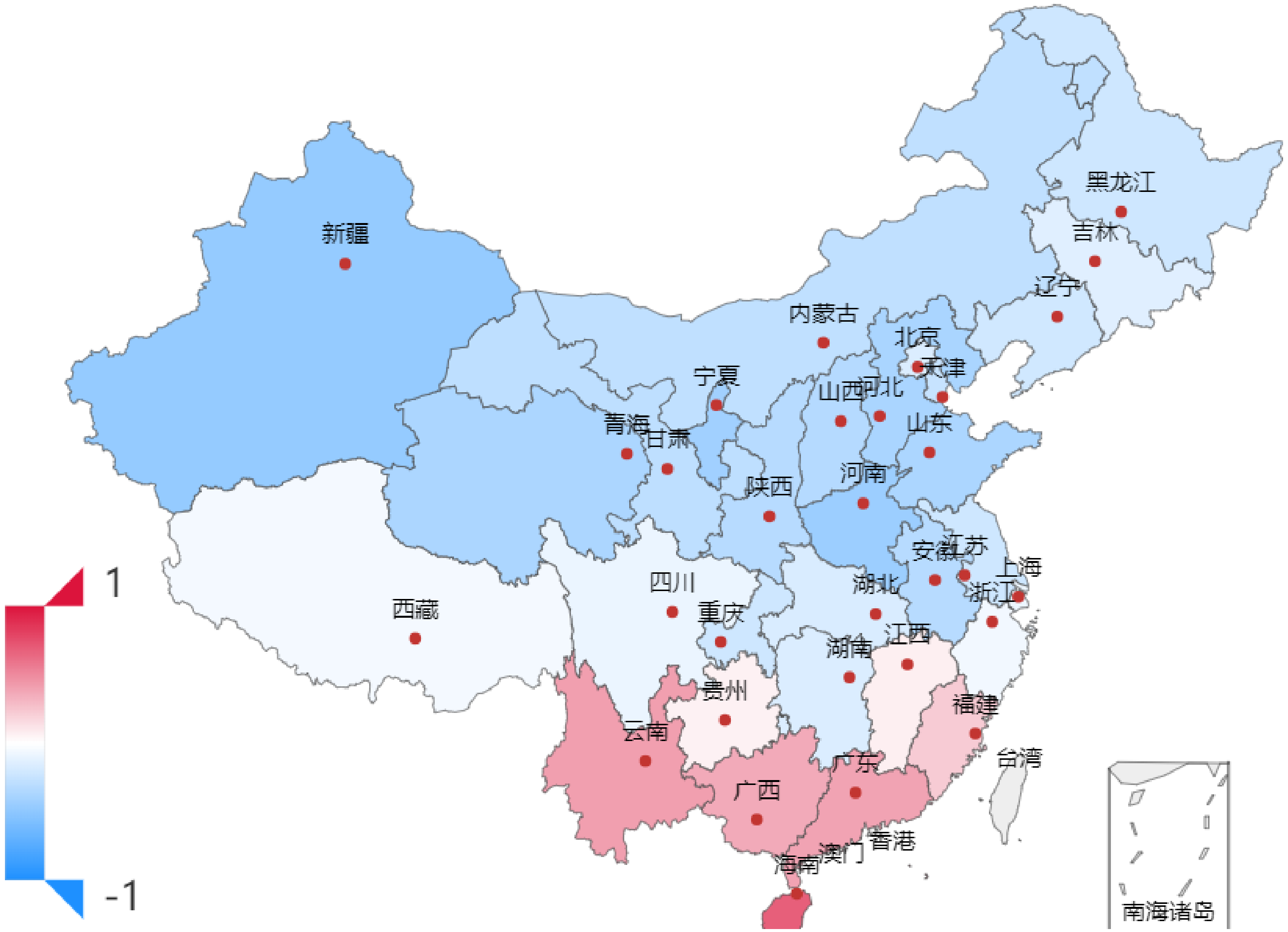


(d) Winter $O_3$ concentration by province



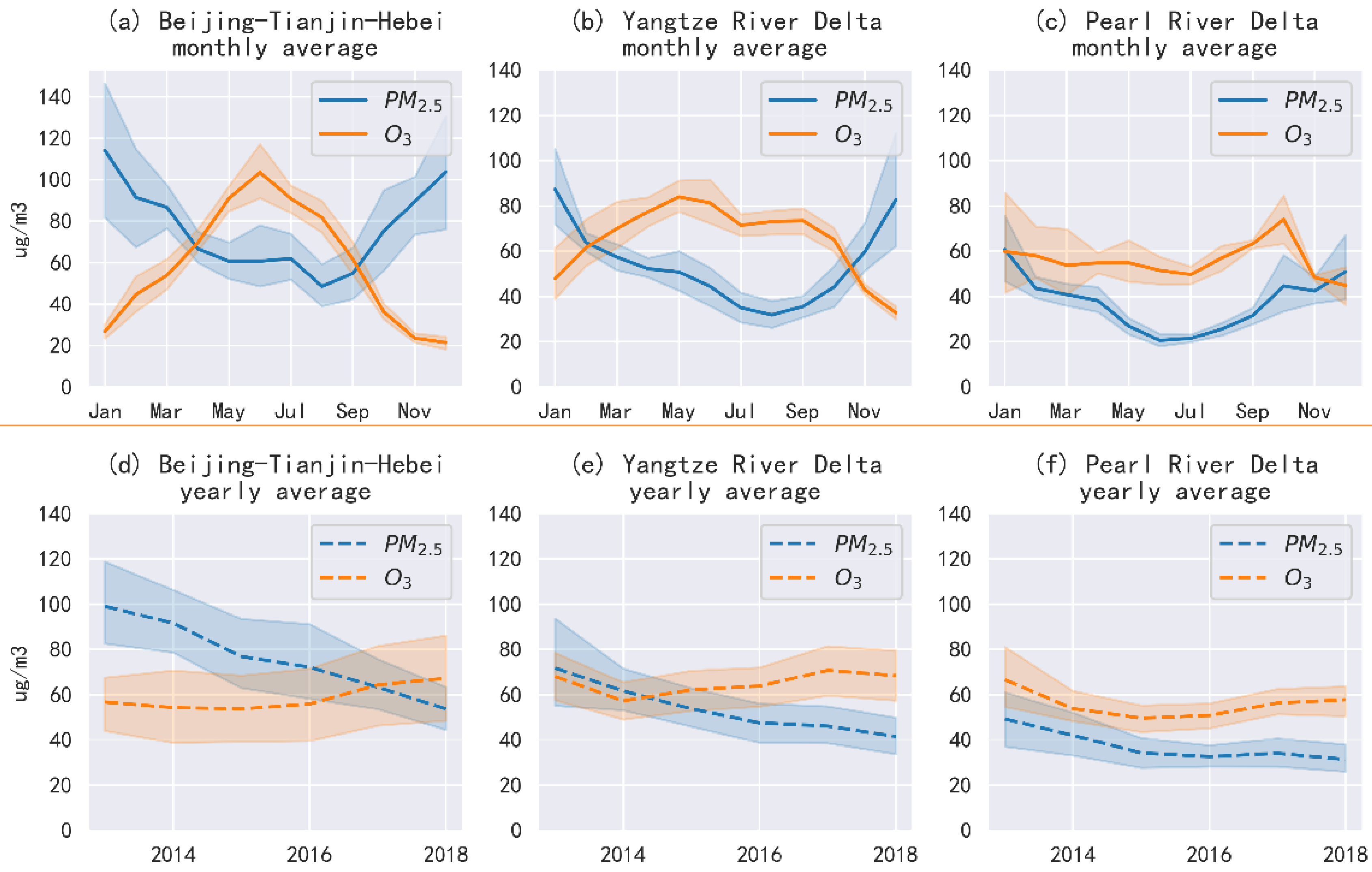
# 4.3 Heterogeneity Analysis

Spatial heterogeneity in the correlation between $O_3$ and $PM_{2.5}$ concentrations



# 4.3 Heterogeneity Analysis

Heterogeneity of $O_3$ and $PM_{2.5}$ pollution characteristics in major urban agglomerations



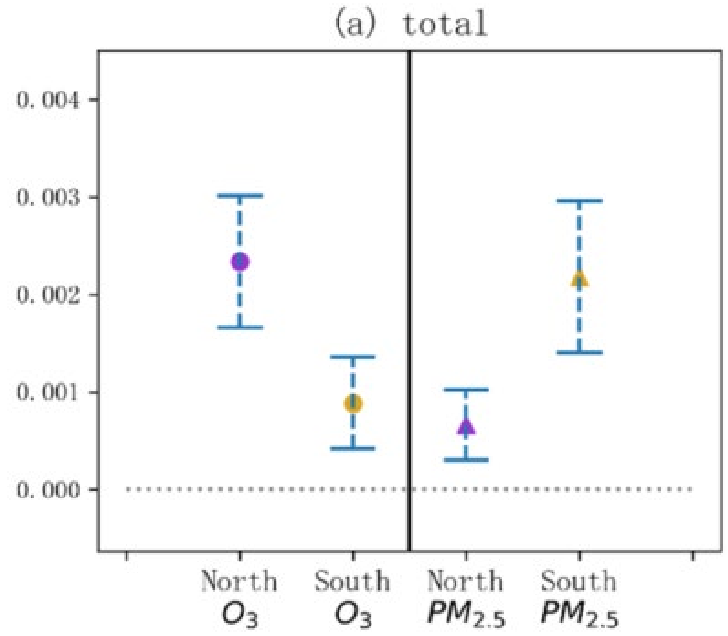

***seasonal***

***annual trend***

## A. North-South Heterogeneity

- **Regression by sample of southern/northern provinces**
  - $O_3$: The marginal hazard in the north is significantly greater than that of the south;
  - $PM_{2.5}$: The marginal hazard in the south is significantly greater than the north.

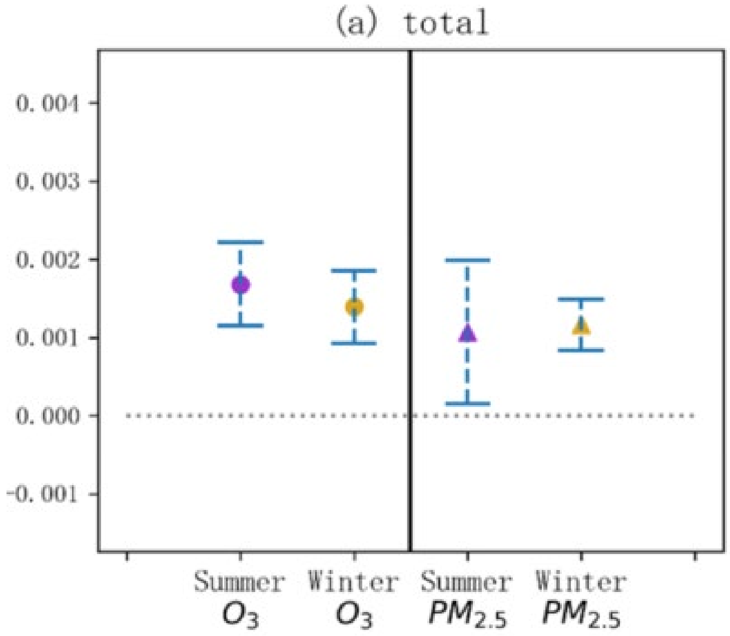
- **Policy Implications**
  - Although the $PM_{2.5}$ concentration in the north is relatively higher, the health hazards of $O_3$ should not be ignored;
  - Although the $O_3$ concentration in the south is relatively high , the health hazards of $PM_{2.5}$ should not be ignored.




Regression by North/South

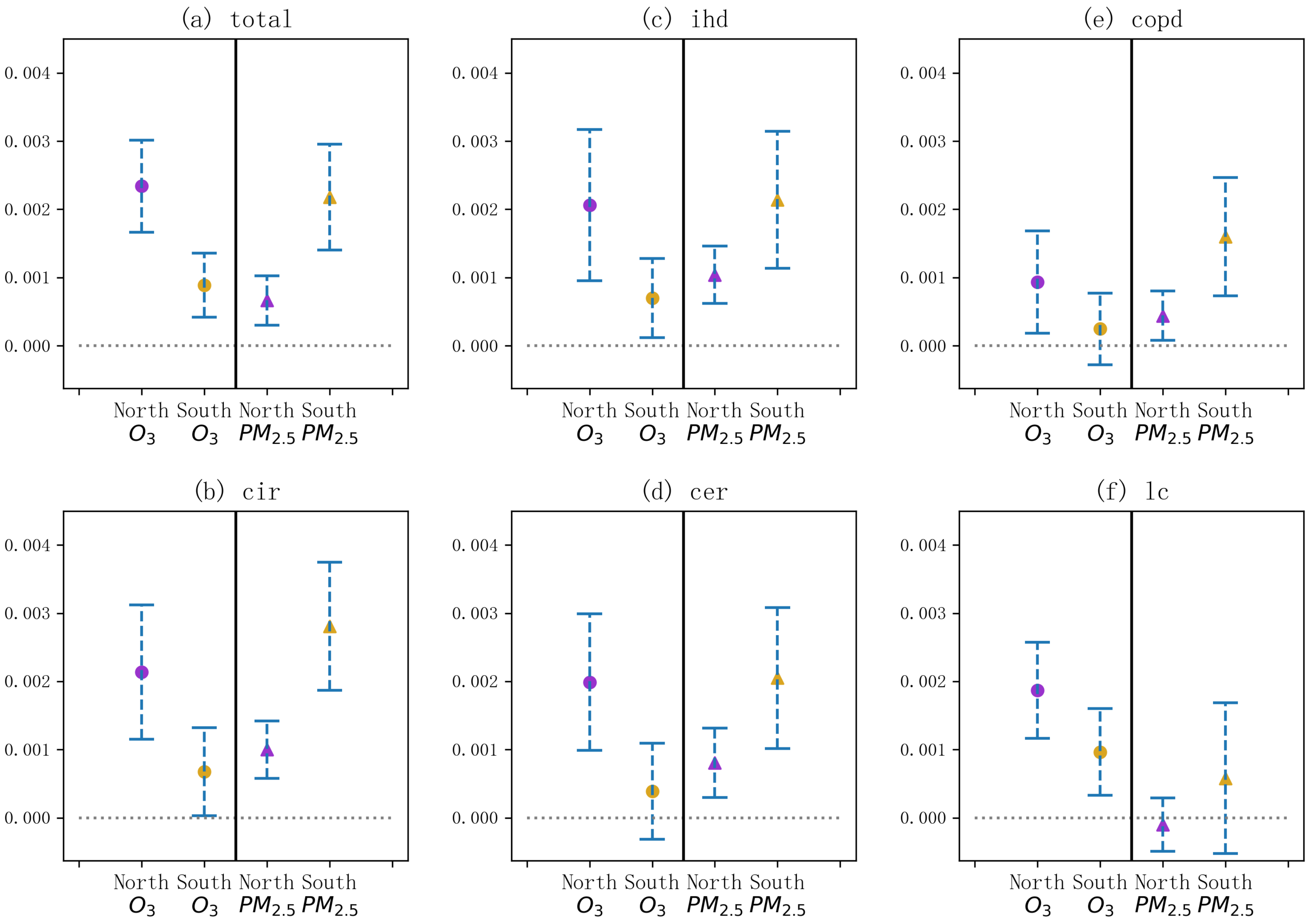
## B. Seasonal Heterogeneity

- **Summer (Apr-Sep)/winter (Oct-Mar) subsamples**
  - Basically no significant difference




Regression by Summer/Winter

# North-South Heterogeneity (full results)



# 5. Summary

- Main findings
  - Short-term co-exposure to both ozone and fine particulate matter significantly increases mortality
  - From 2013 to 2018, $PM_{2.5}$ decreased by 44%, reducing deaths by 2.75% ; $O_3$ rised 9.9%, increasing deaths by 0.96%
  - High exposure to $O_3$ enhances the effect of $PM_{2.5}$ on death from cerebrovascular diseases and COPD; High exposure to $PM_{2.5}$ enhances the effect of $O_3$ on death from cardiovascular and cerebrovascular diseases and lung cancer.
  - The marginal mortality effect of $PM_{2.5}$ pollution in the south is 145% higher than that in the north, while the marginal mortality effect of $O_3$ pollution in the north is 163% higher than that in the south.
- To be improved
  - To be expanded to 605 district/county monitoring sites
  - The mechanisms and causes of north-south heterogeneity remain to be further verified
  - Do not identify long-term hazards of co-exposure to both pollutants

Thank you!