Chapter 1

Introduction to Globalizing Air Pollution

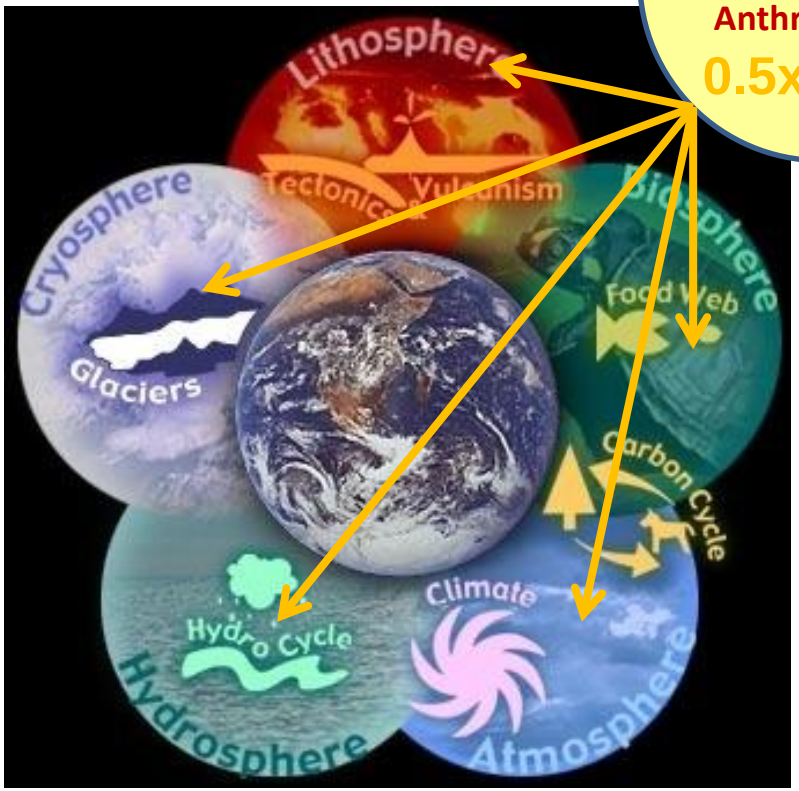
北京大学
PEKING UNIVERSITY

The Earth System

10^{26} g

岩石圈
（陆地、土壤）

人类圈
Anthrosphere
0.5×10^{15} g



10^{22} g

冰圈
（冰川、两极）

$10^{18} \sim 10^{19}$ g

生物圈

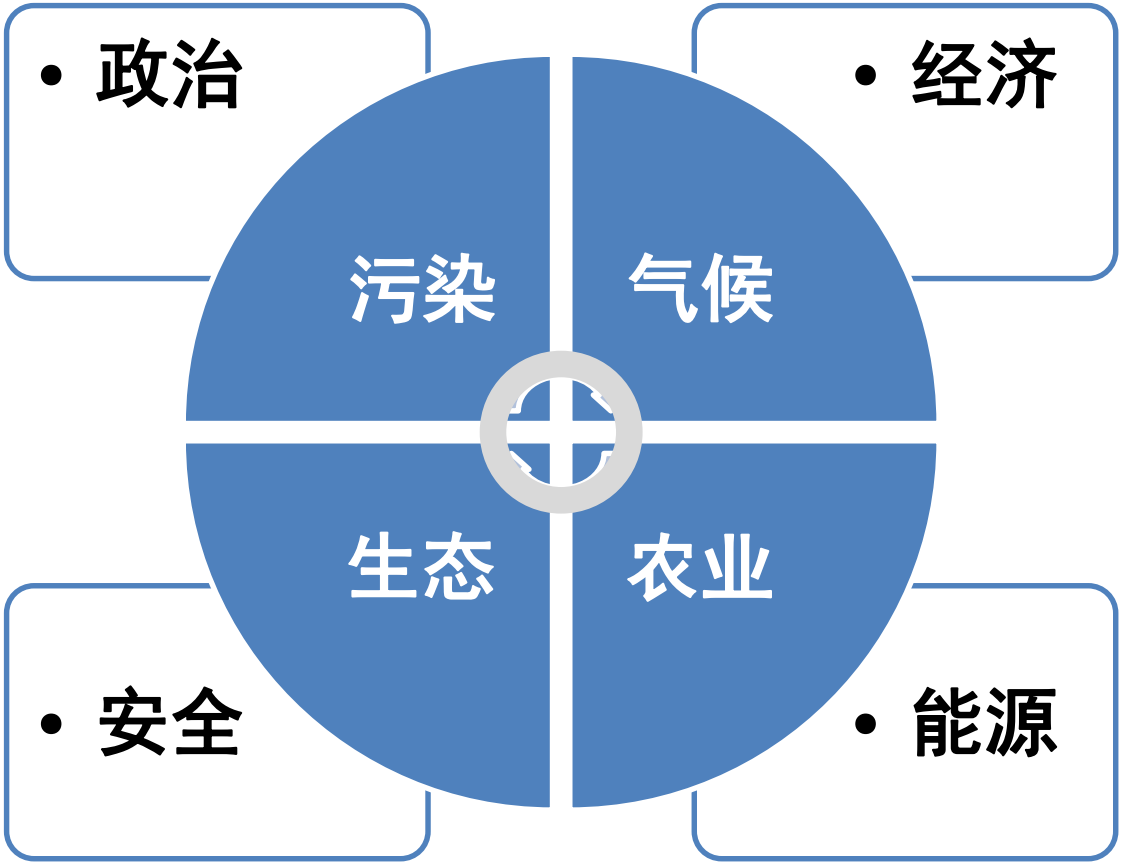
10^{24} g

水圈
（河湖海、降水）

大气圈

10^{21} g

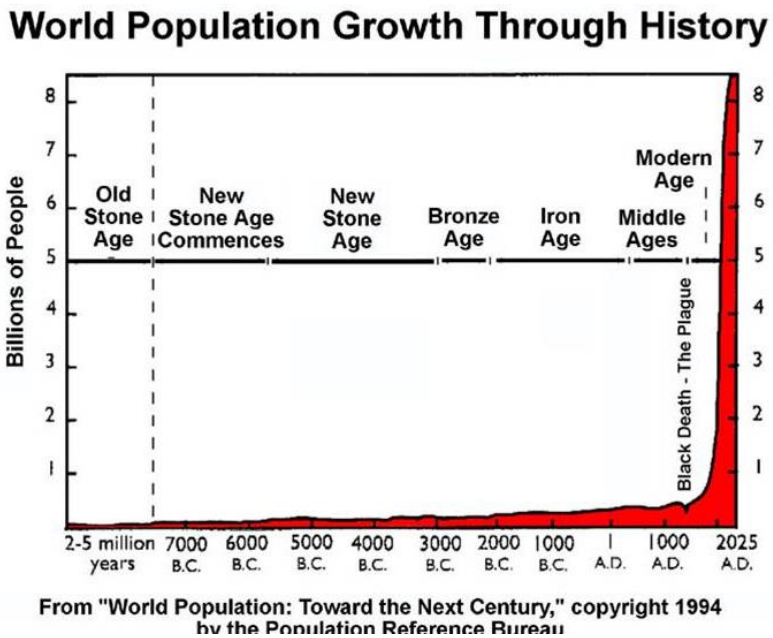
The Environment and Its Importance

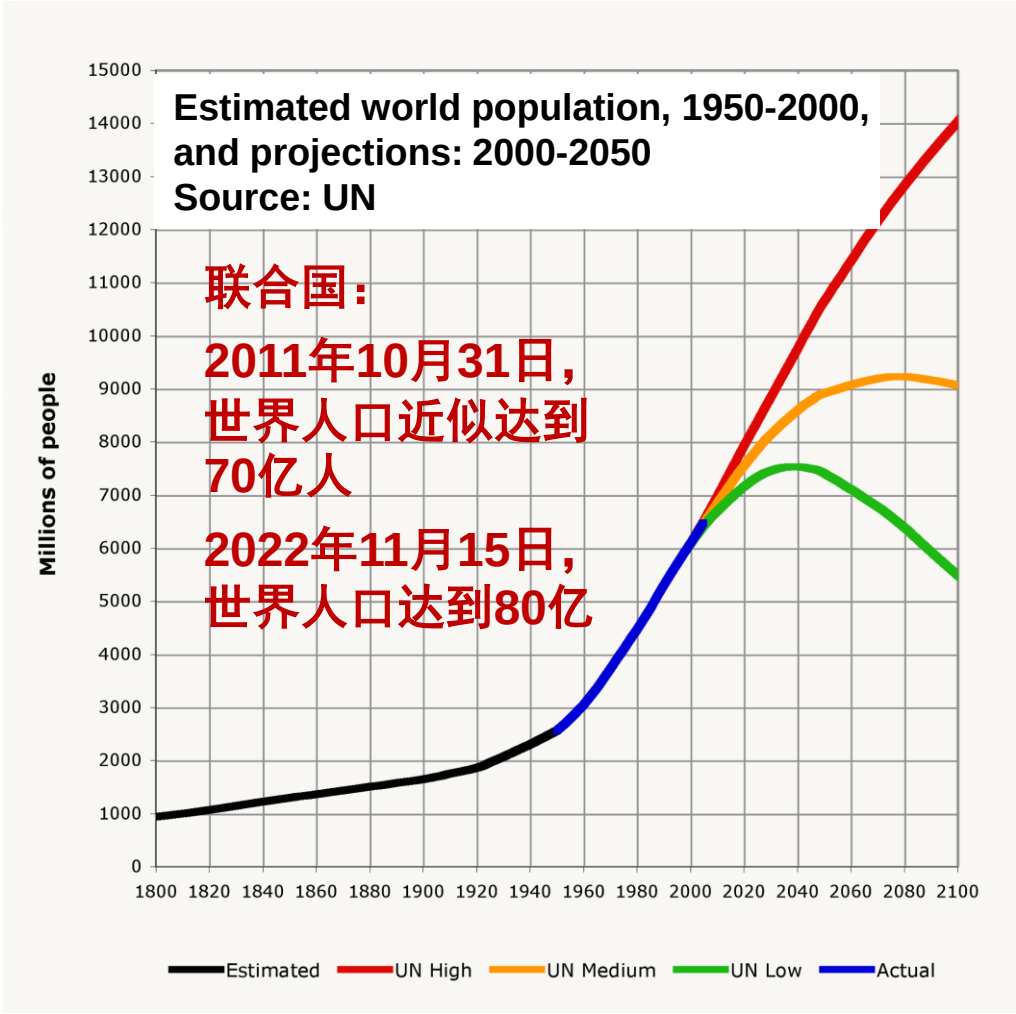


Pressure of World Population

The power of population is indefinitely greater than the power in the earth to produce subsistence for man.

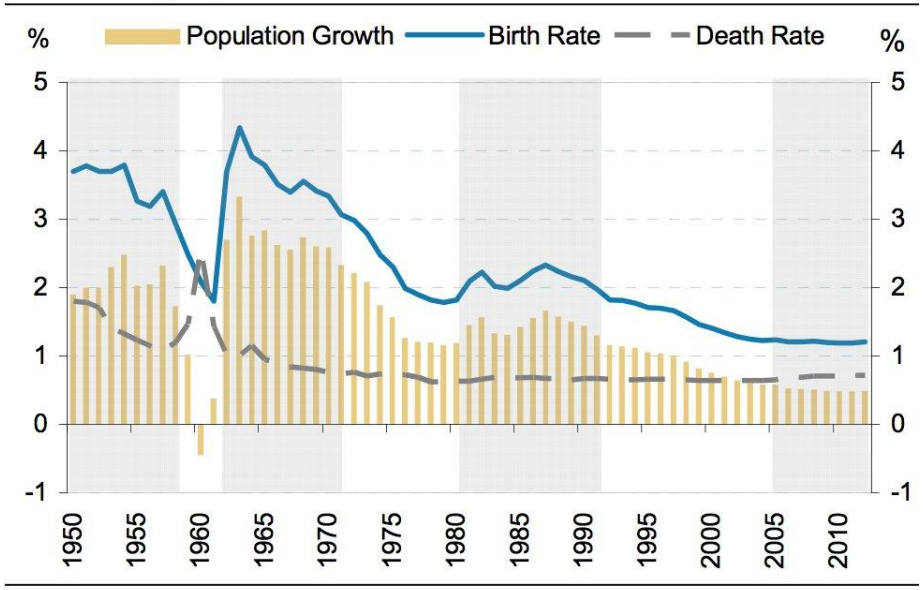
- Thomas Malthus, *An Essay on the Principle of Population*



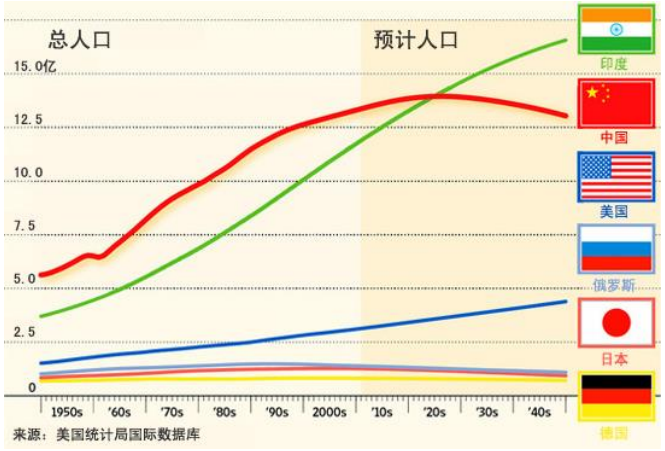


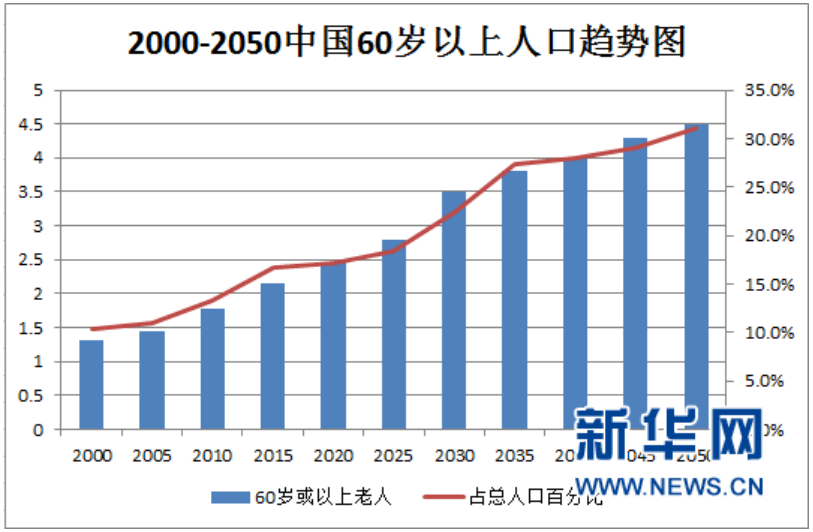
Chinese Population Growth

Declining Birth Rate vs. Stabilized Death Rate

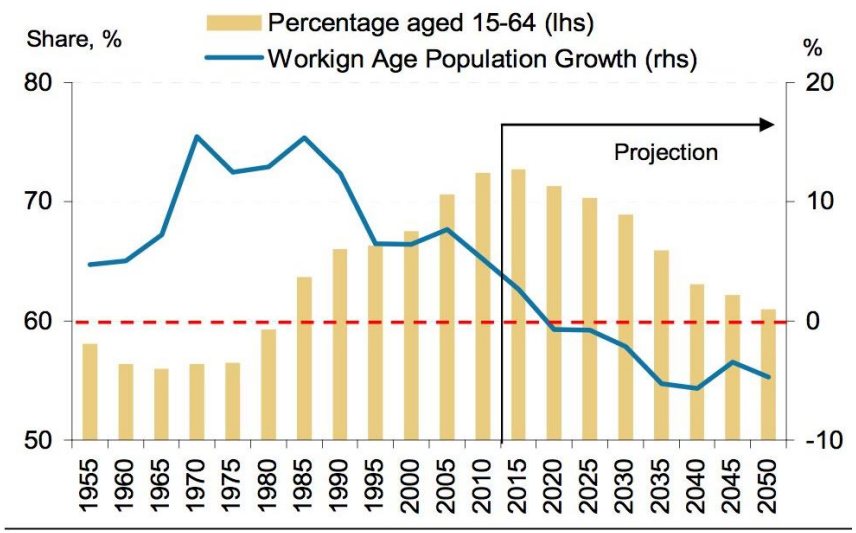


Source: NBS, Morgan Stanley Research; Note: Birth rate is the ratio of new birth to total population; death rate is the ratio of the death to total population.





Working Age Population Is Set to Contract Soon



Source: NBS, UNPD, Morgan Stanley Research

Chinese Population Growth

国家统计局数据：

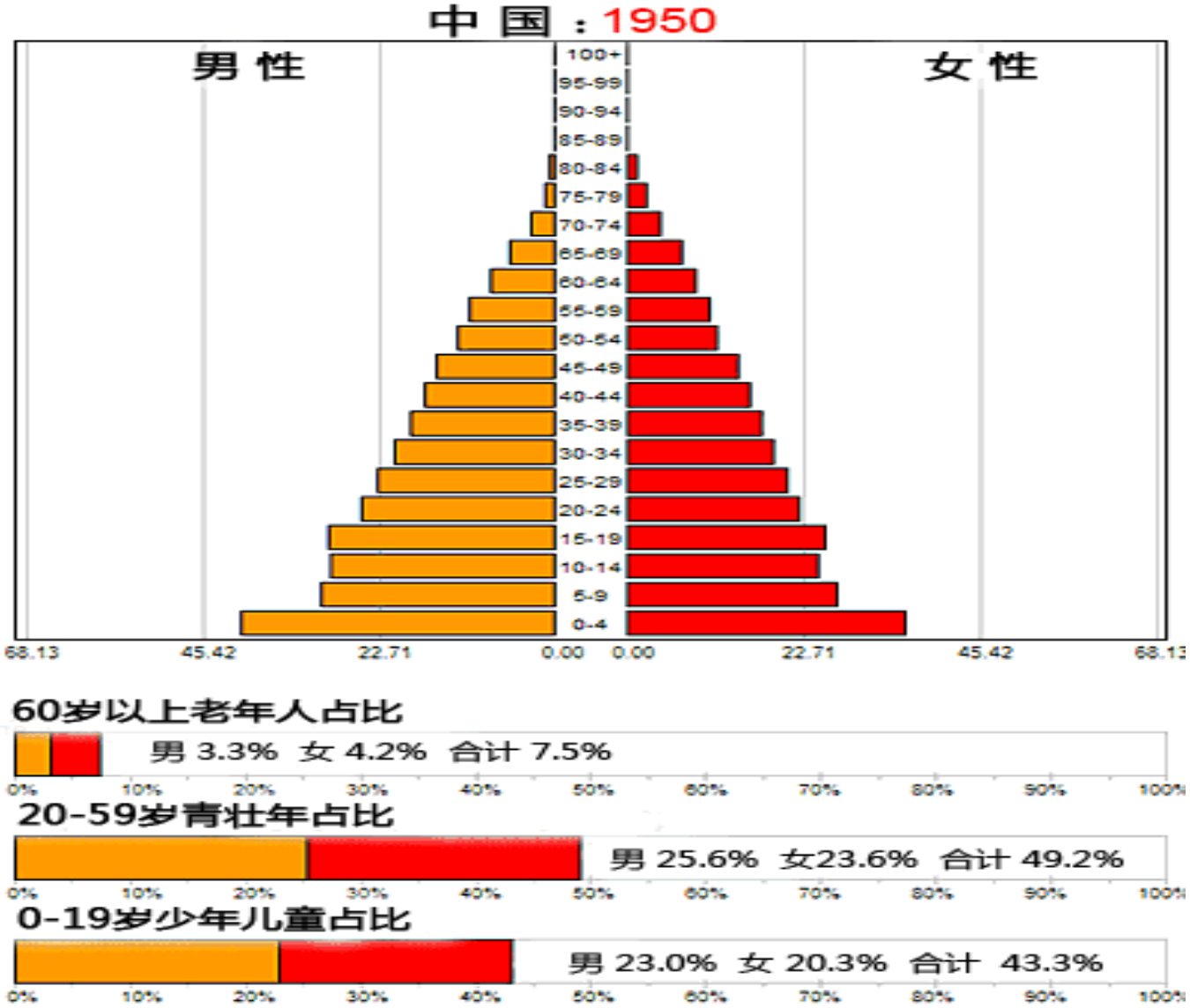
2021年末，全国人口141260万人，比上年末增加48万人。全年出生人口1062万人，出生率为7.52‰；自然增长率为0.34‰

2022年末，全国人口141175万人，比上年末减少85万人。全年出生人口956万人，出生率为6.77‰；自然增长率为-0.60‰

2023年末，全国人口140967万人，比上年末减少208万人。 全年出生人口902万人，出生率为6.39‰；自然增长率为-1.48‰

2024年末，全国人口140828万人，比上年末减少139万人。
全年出生人口为954万人，出生率为6.77‰；自然增长率为-0.99‰

Chinese Population Structure Change: 1950–2050



http://www.360doc.com/content/15/0929/18/14590724_502277109.shtml

Of So Many Types of Pollution, Why Do or Should We Prioritize Air Pollution Control ?

Air pollution:

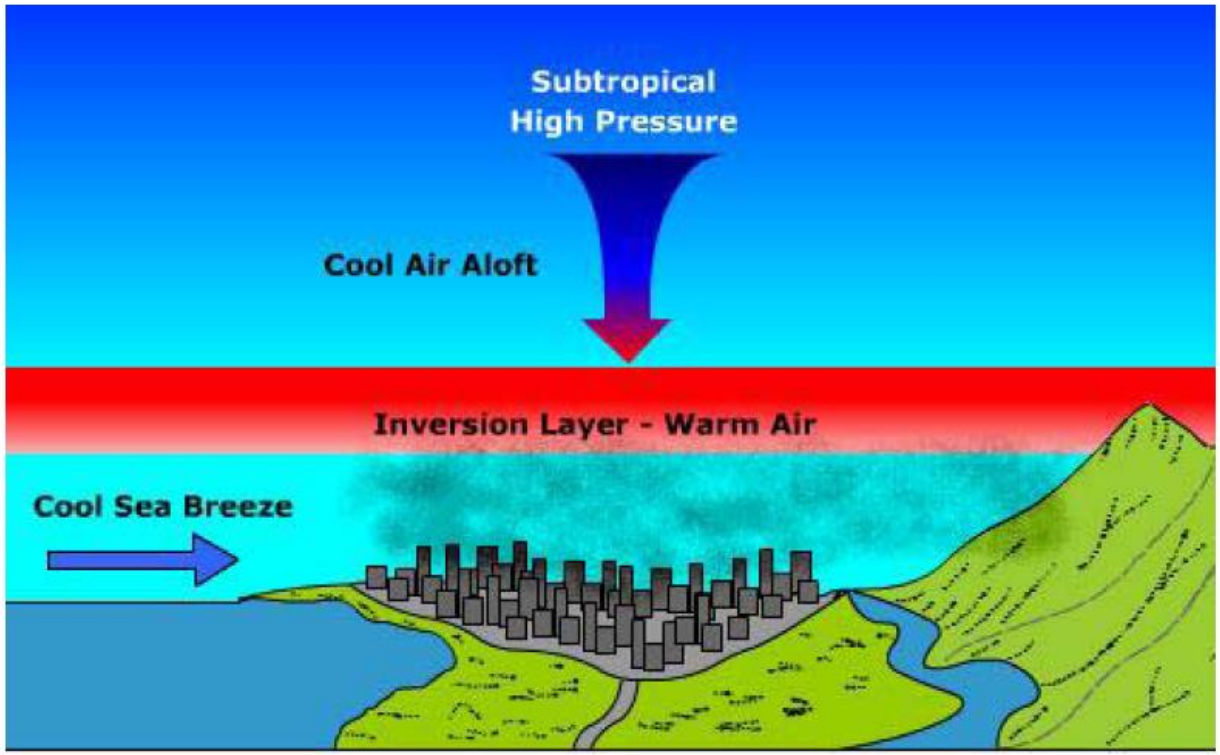
- **Exert the greatest human health impact**
- **“Visibility” or “sensibility” of pollution**
- **From local to regional and global**

Current Atmospheric Environmental Problems:
Local + Nonlocal Sources of Air Pollution as Focal Point

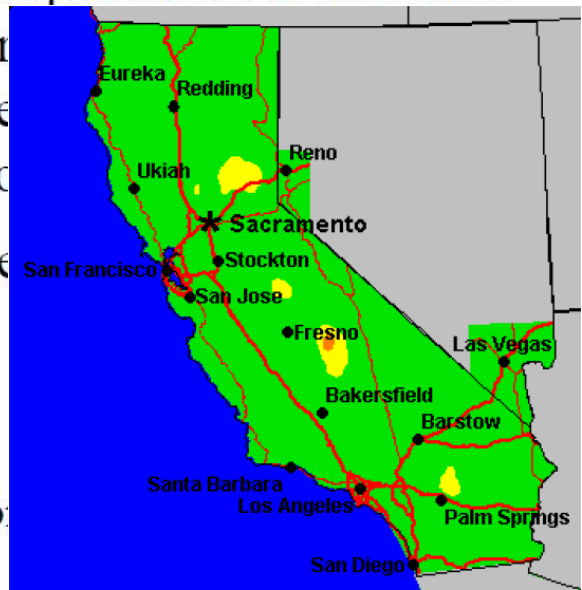
- **Environment:**
  - **Primary air pollution (PM, O_3, etc.)**
  - **Climate Change (GHGs, PM, O_3, etc.)**
  - **Heavy metals, PAHs, bioaerosols, microplastics, etc.**
- **Politics:**
  - **Local and nonlocal sources and impacts: global change**
  - **Emission source attribution, responsibility and control**
- **Economics:**
  - **Environmental protection and cost attribution**

Who should pay for better environment, and how ?

Photochemical ‘Smog’ in Los Angeles



compresses as it descends



- adiabatic heating that occurs lowers the relative humidity pre
of clouds
- Cool sea breeze – causes inversion – limits the mixing
- much insolation to penetrate to the surface – photochemical reactio

The Great Smog of London, Dec 1952

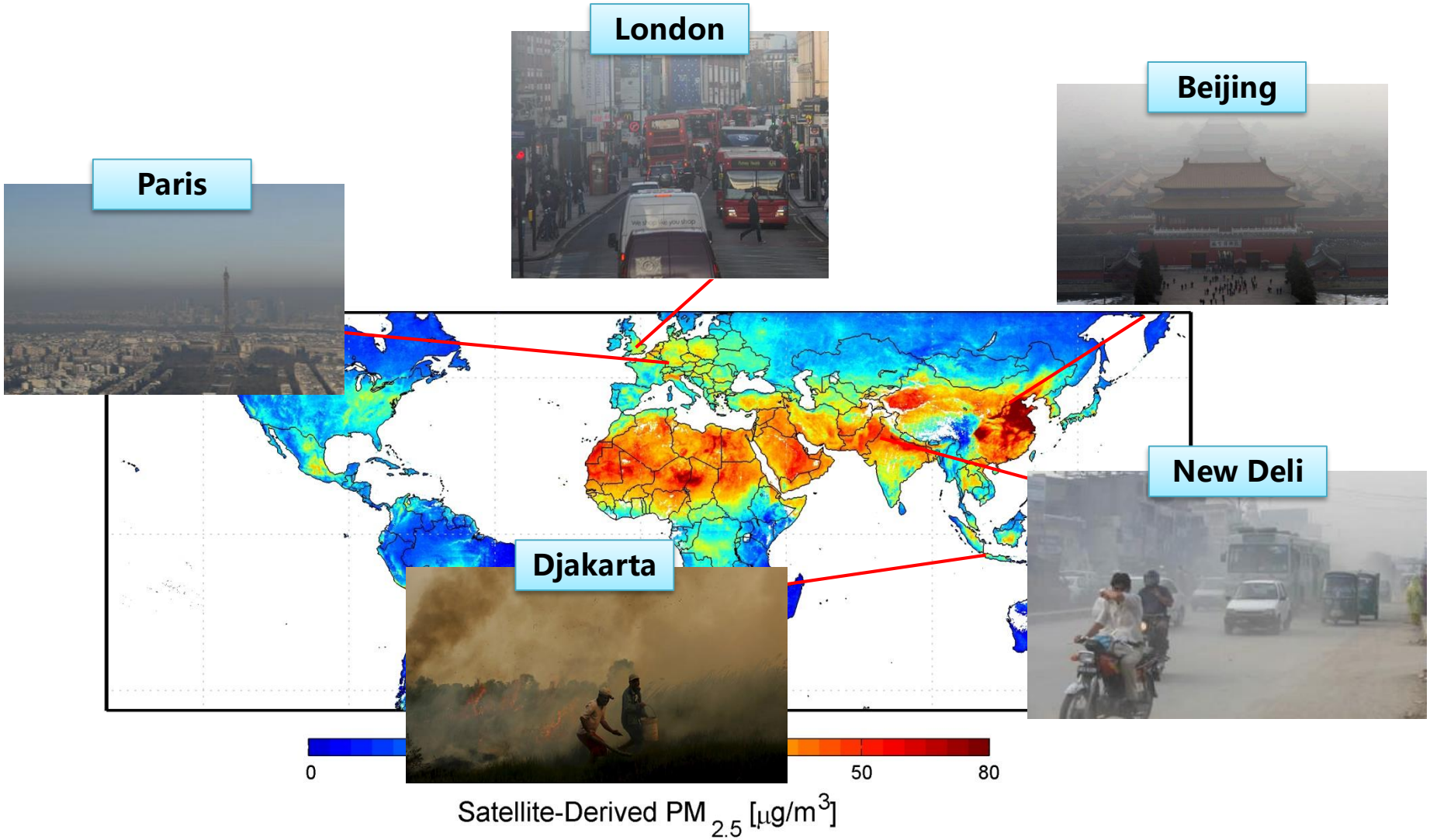
Cold and stagnant weather
Inversion
Burning of coal
12000+ people died

Severe Haze Problem in China

- Emissions of PM and precursors
- High humidity, sunlight
- Stagnant atmosphere
- Wind direction/speed

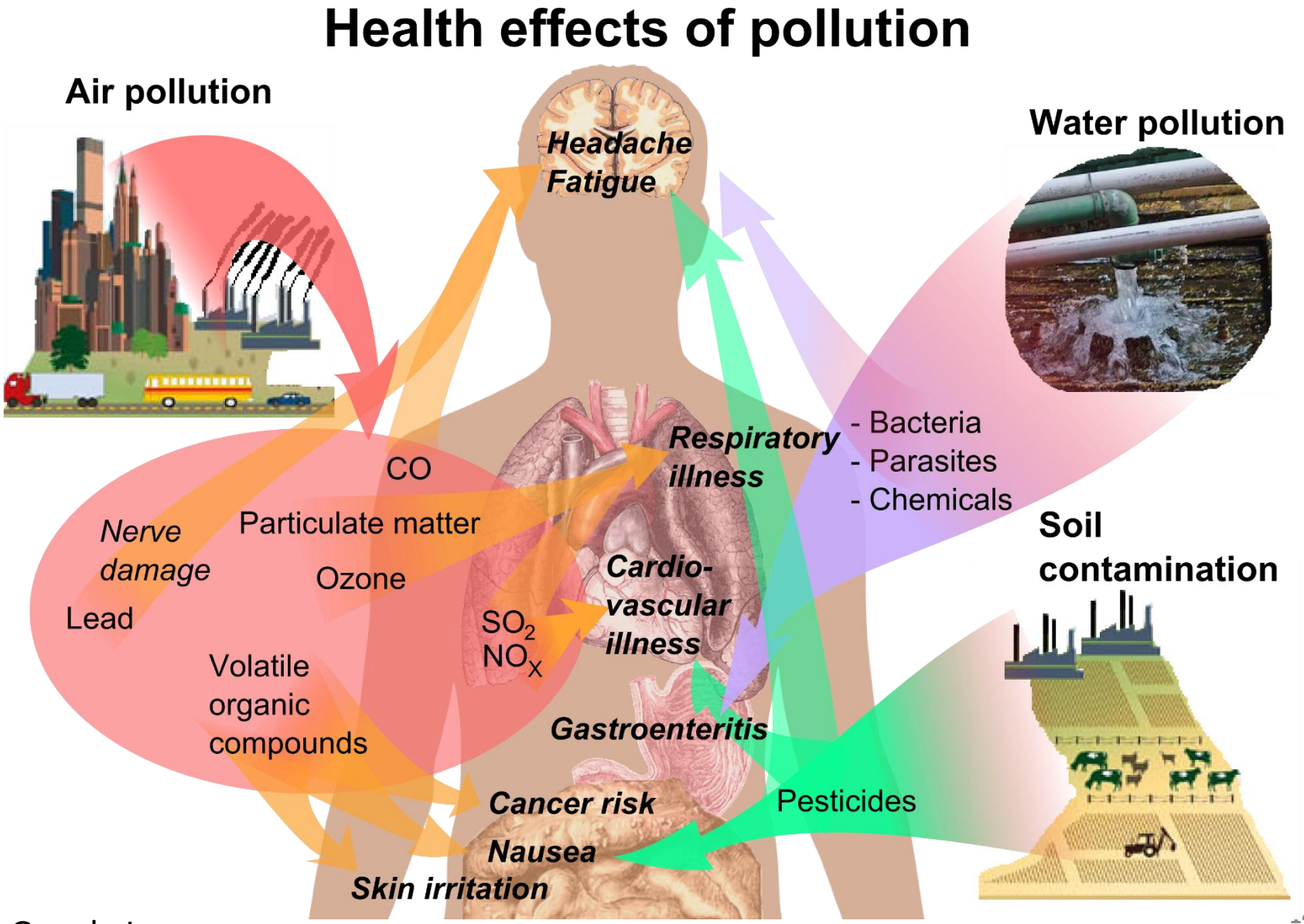
Tong Zhu

Global PM Pollution



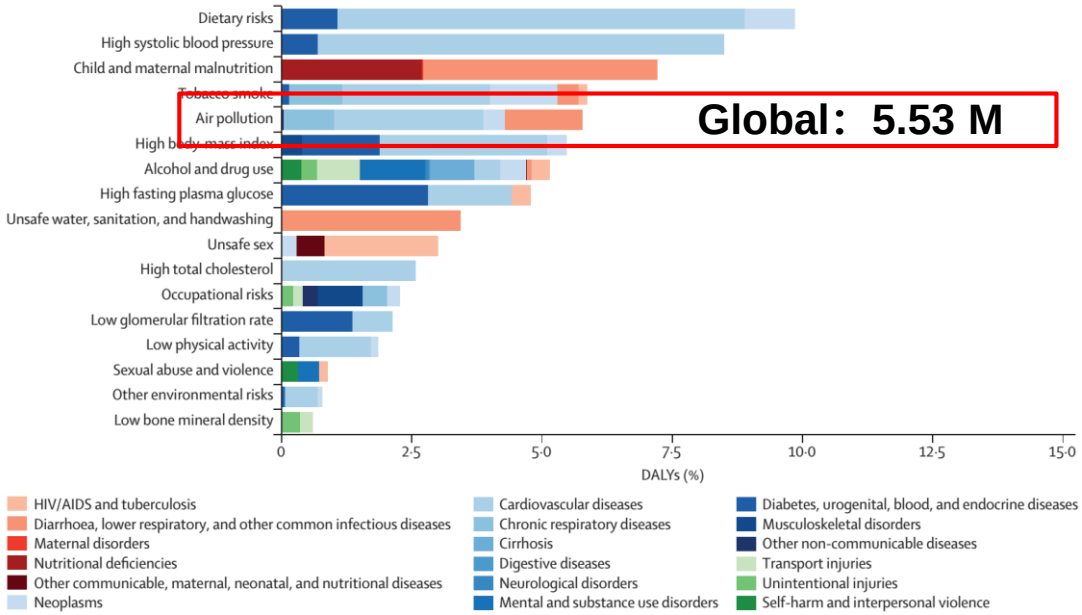
Modified from Xujia Jiang

How Pollution Affects the Human Body ?

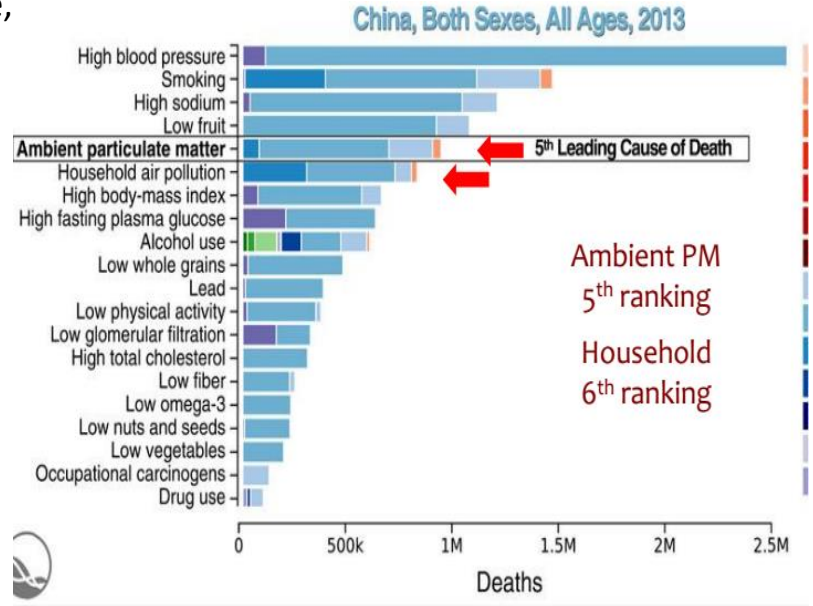


Google Image

Air Pollution Is The Leading Environmental Risk Factor of Global Burden of Disease



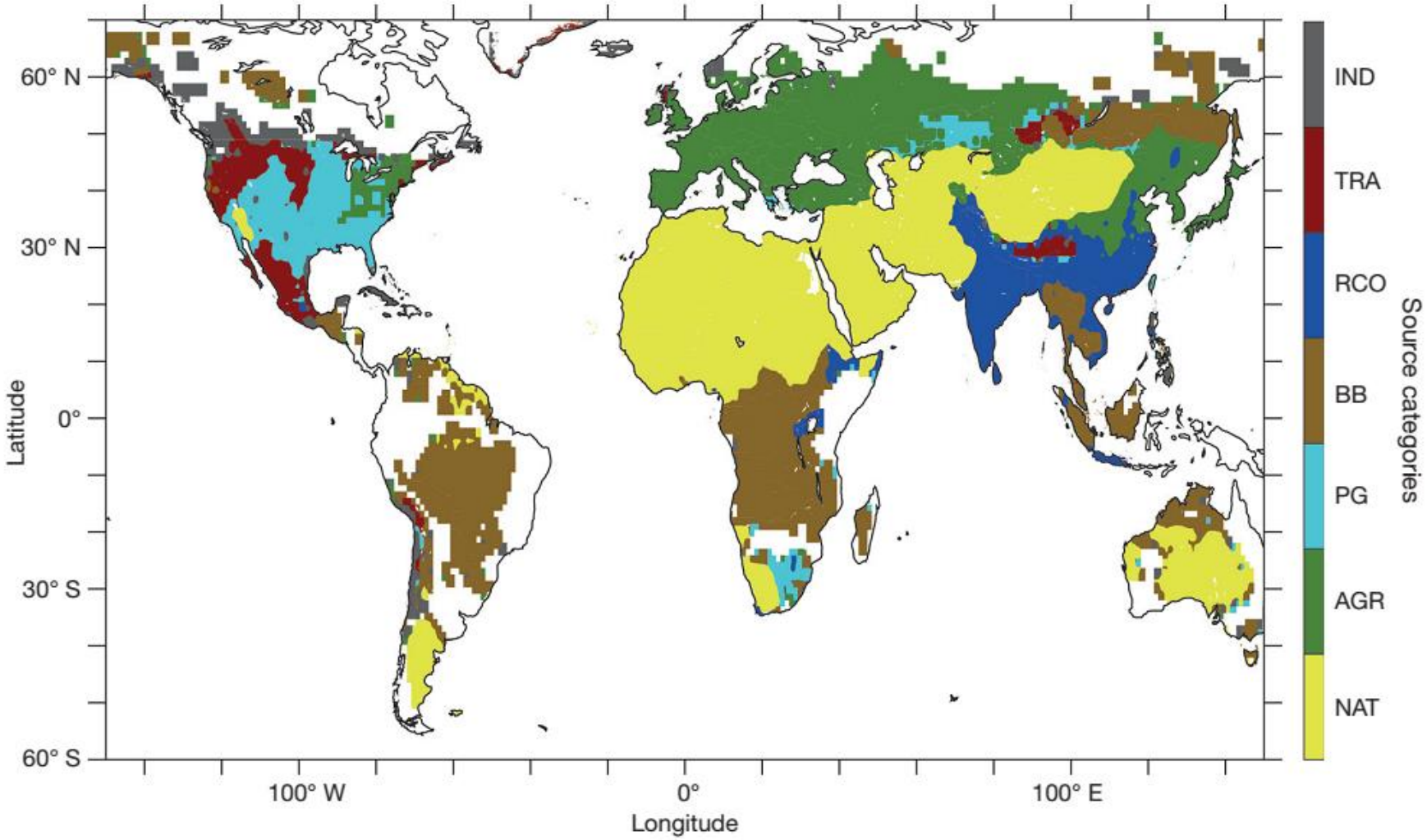
Four main PM-related diseases: Ischemic heart disease (IHD), Stroke, Lung cancer, Chronic obstructive pulmonary disease (COPD)



Forouzanfa et al., 2016, Lancet (GBD 2013)

Outdoor $PM_{2.5}$ Induced Deaths from a Source Perspective

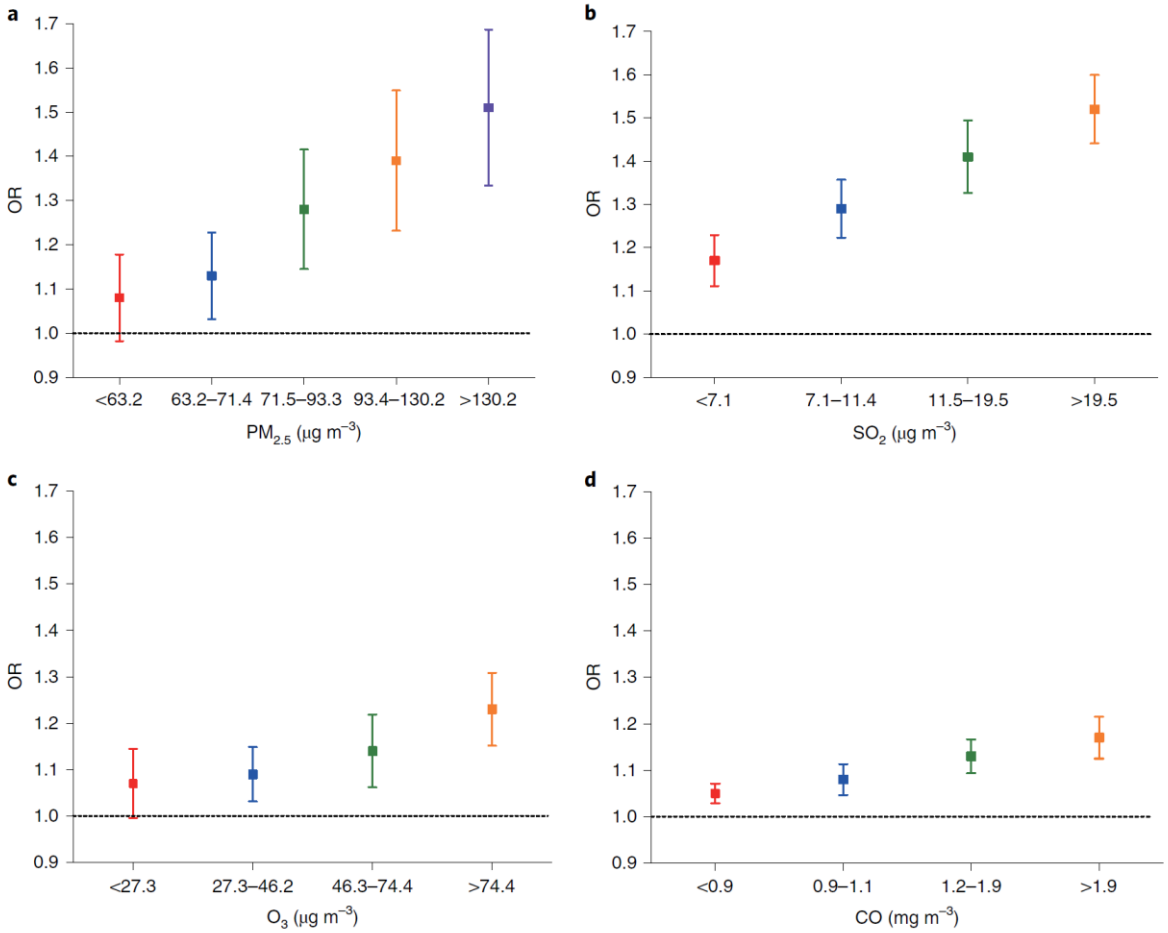
Largest source of deaths at each location in 2010

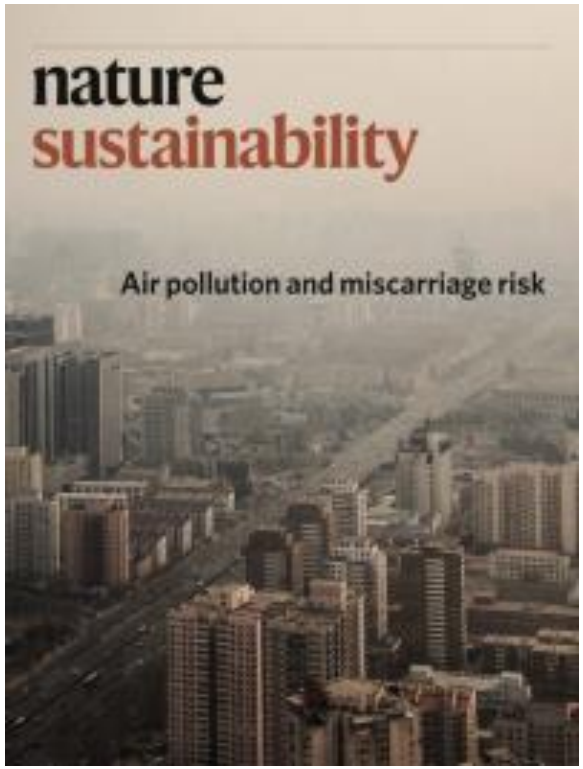


Lelieveld et al., 2015, Nature

Linking Maternal Air Pollution Exposure to MAFT

Odds ratio for 10.0 μg/m³ increase in $PM_{2.5}$, SO_2 and O_3 or 1 mg/m³ increase in CO

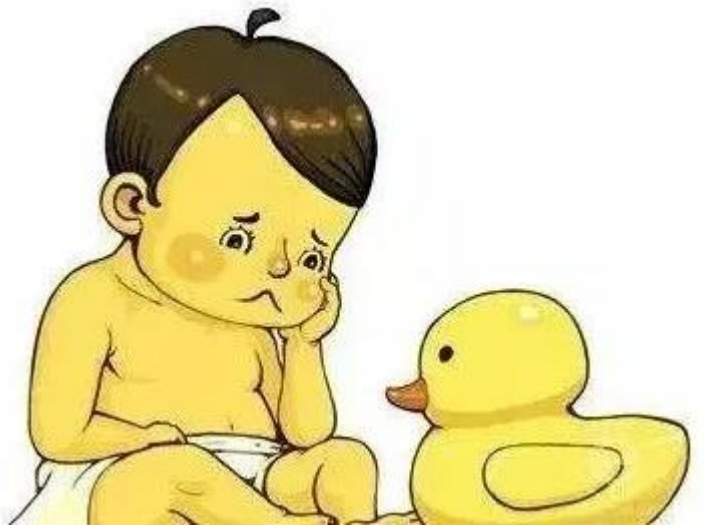




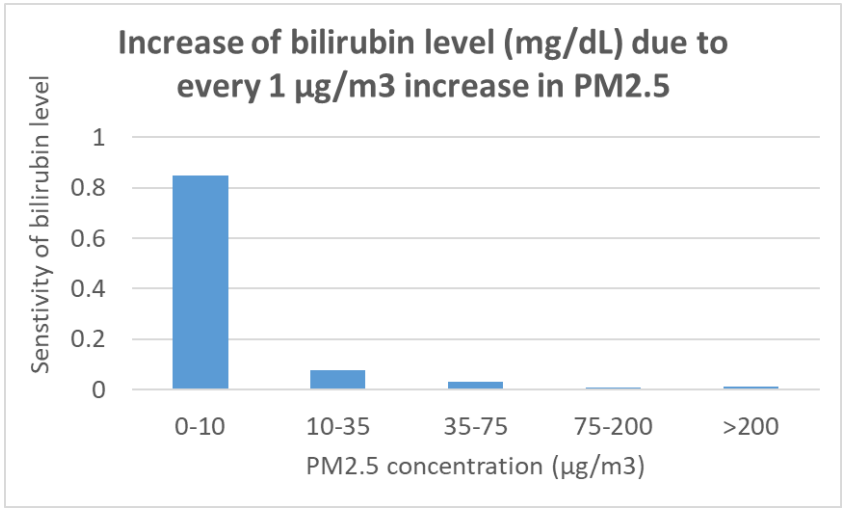
Zhang LQ et al., 2019, Nature Sustainability

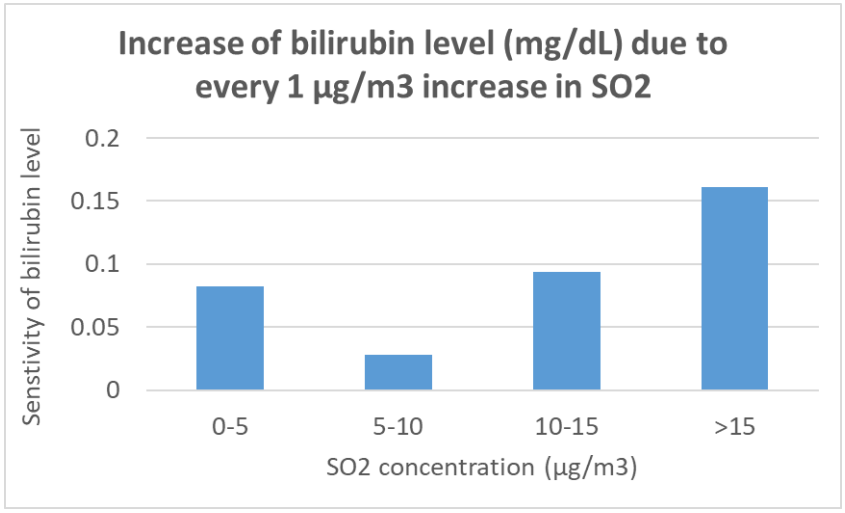
MAFT = Missed abortion in the first trimester 稽留流产

Linking Air Pollution Exposure to Neonatal Jaundice



Baidu Image

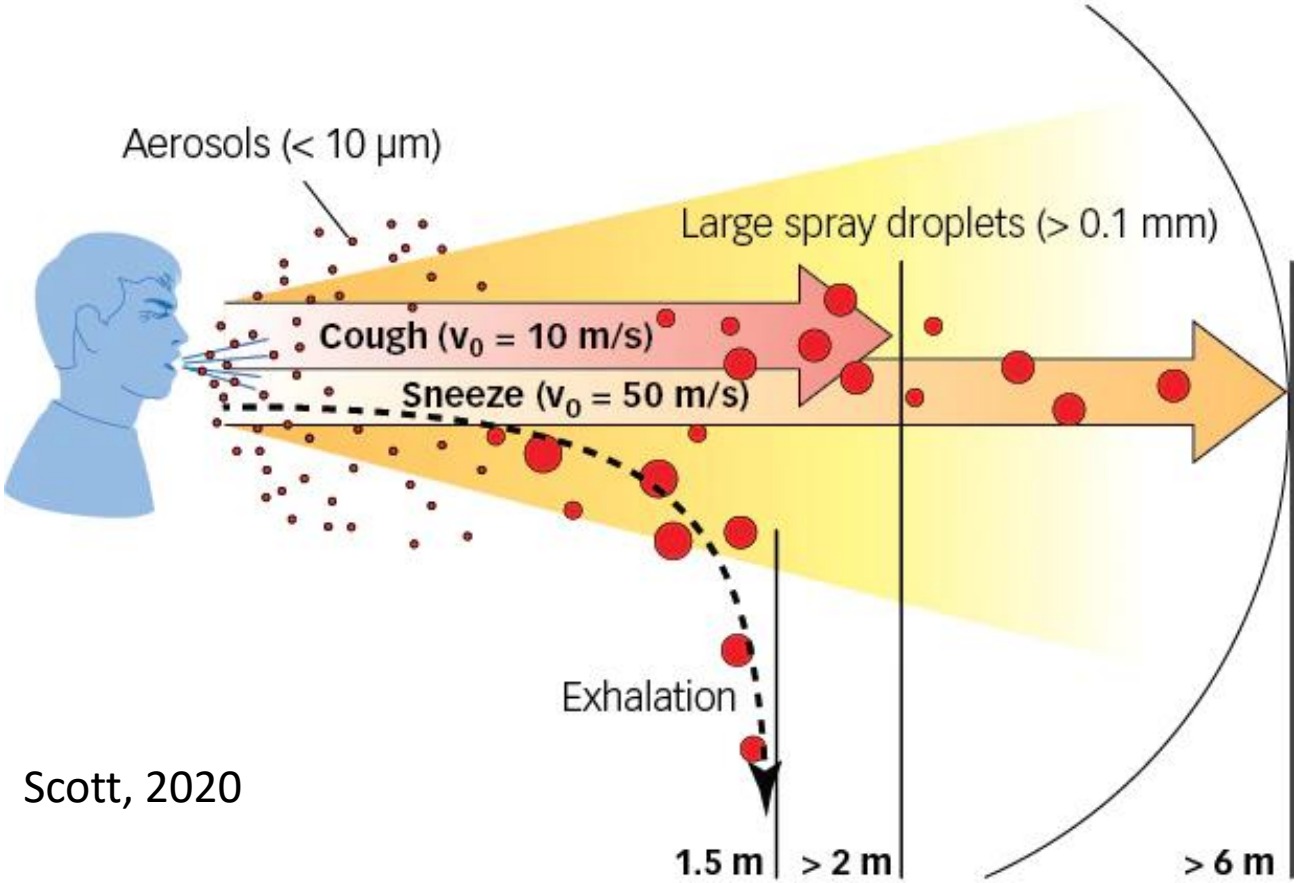




Zhang LQ et al., 2019, Nature Communications

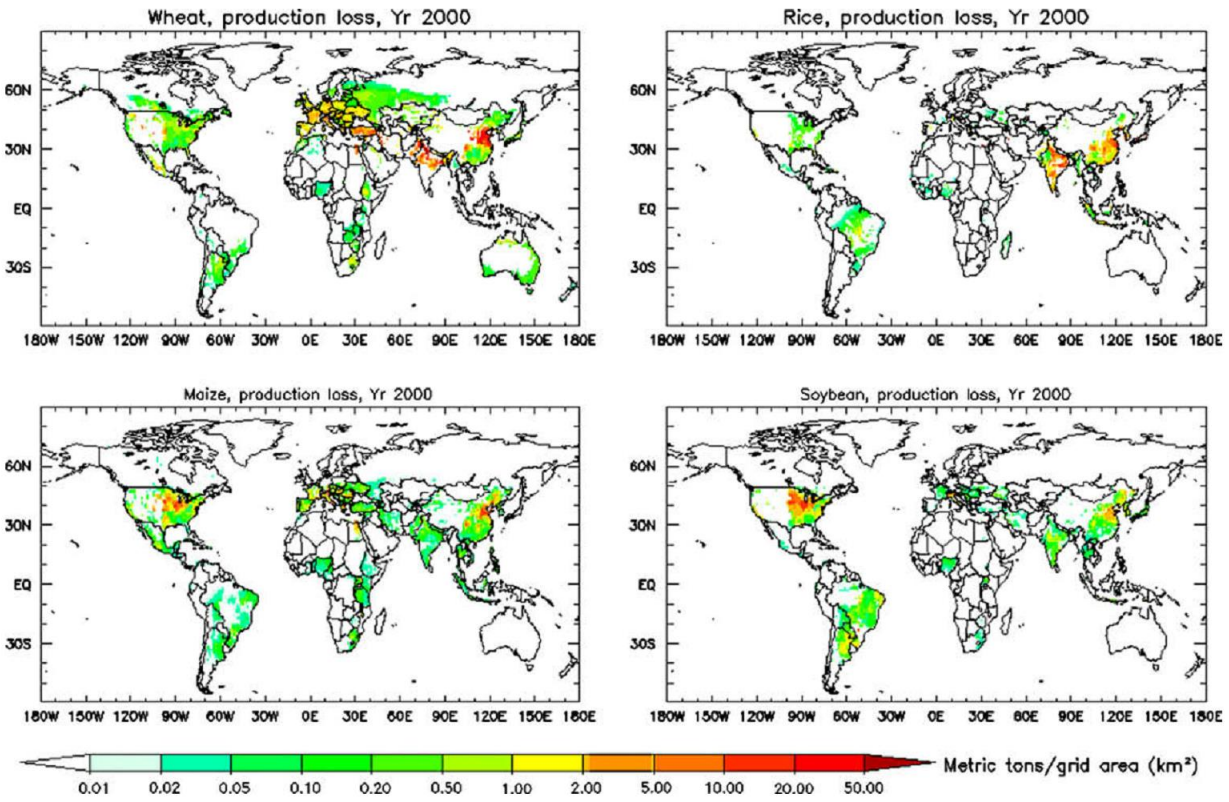
Likely Transmission of COVID-19 through PM

Figure 3: How COVID-19 is transmitted through aerosol particles



Scott, 2020

Air Pollution: Impacts of O_3 on Crop Yield

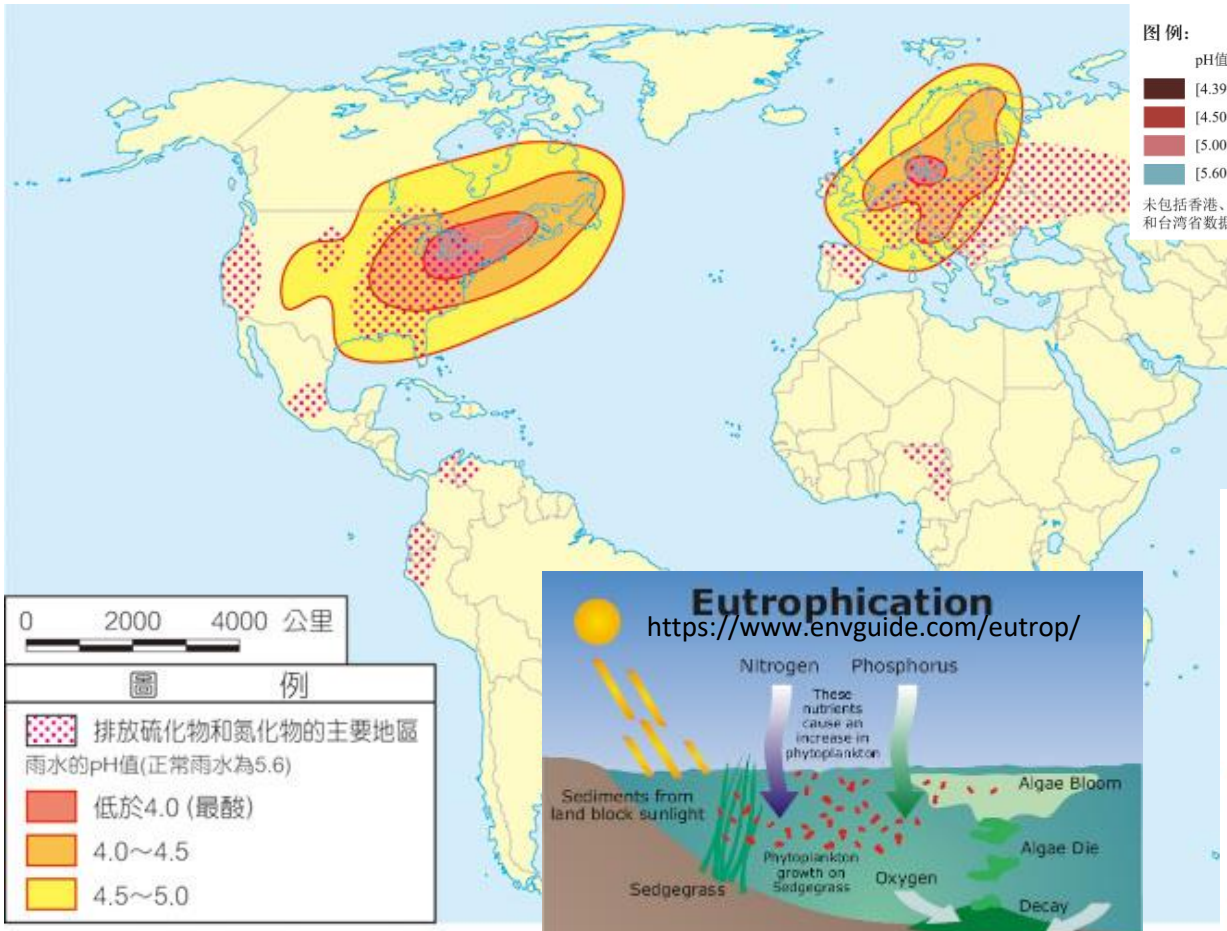


	WORLD	EU25	N.Am	China	India
Wheat					
AOT40	12.3%	4.1%	4.1%	19.0%	27.6%
M7	7.3%	4.6%	4.4%	9.8%	13.2%
Rice					
AOT40	3.7%	4.7%	3.2%	3.9%	8.3%
M7	2.8%	3.5%	2.6%	3.1%	5.7%
Maize					
AOT40	2.4%	3.1%	2.2%	4.7%	2.0%
M12	4.1%	5.1%	3.6%	7.1%	4.0%
Soybean					
AOT40	5.4%	20.5%	7.1%	11.4%	4.7%
M12	15.6%	27.3%	17.7%	20.8%	19.1%

Van Dingenen et al., 2009, AE

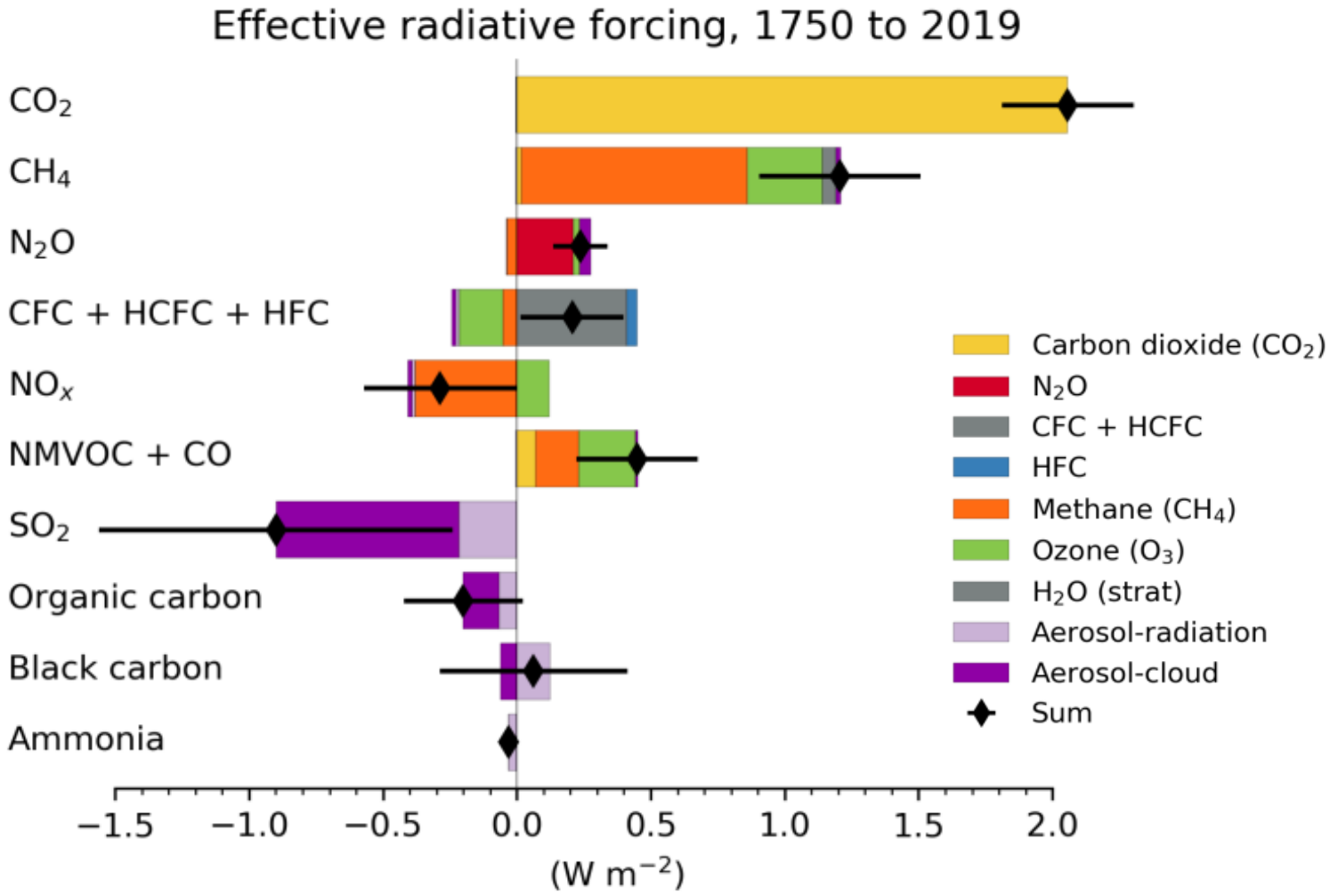
Air Pollution: Acid Deposition

中国生态环境状态公报 2020



Effects of Acid Rain

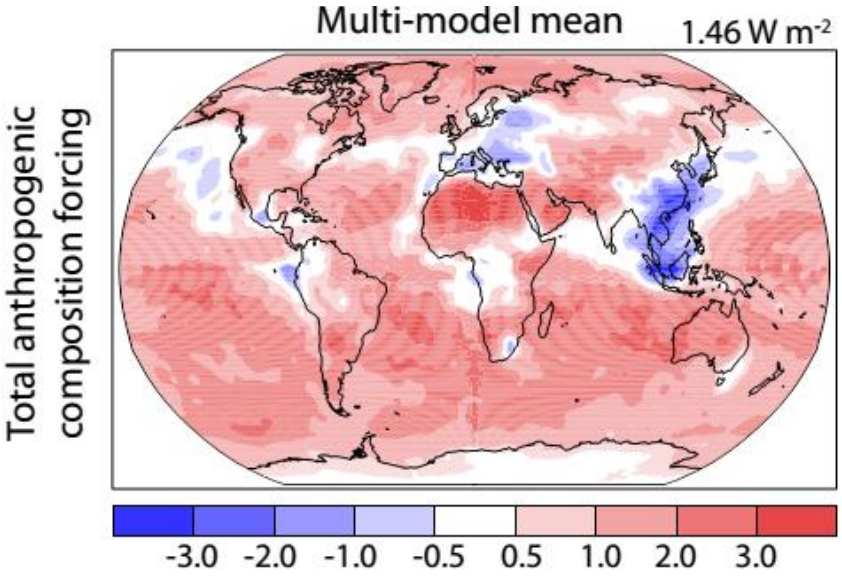
Air Pollution: Impacts on Climate



IPCC, 2021

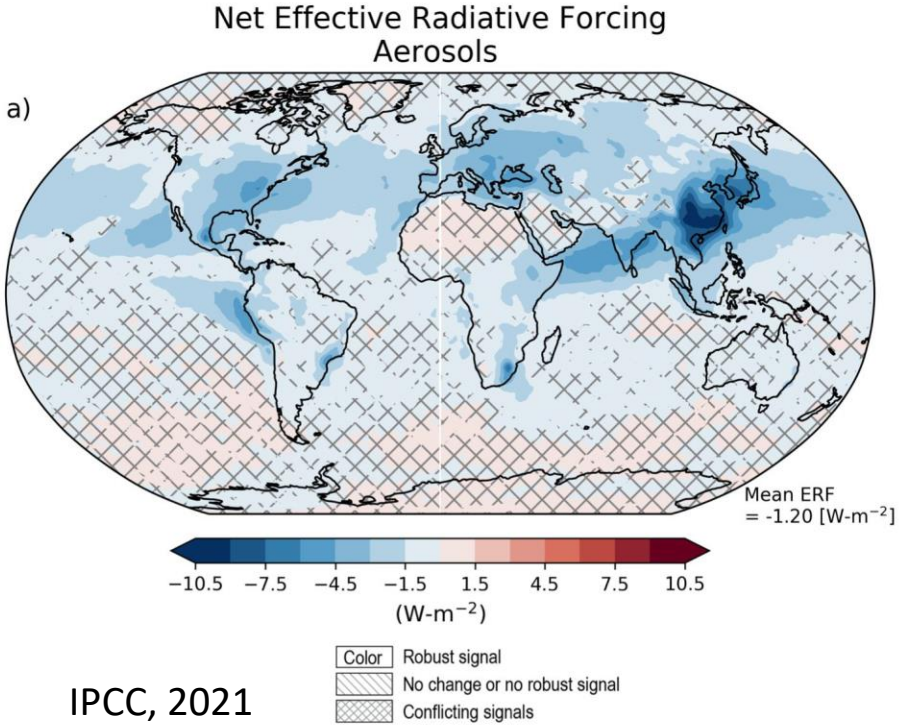
Spatial Distribution of Aerosol Radiative Forcing: Pattern Effect

Total RF: 1850–2000



IPCC, 2013

Aerosol ERF: 1850–[1995-2014 mean]



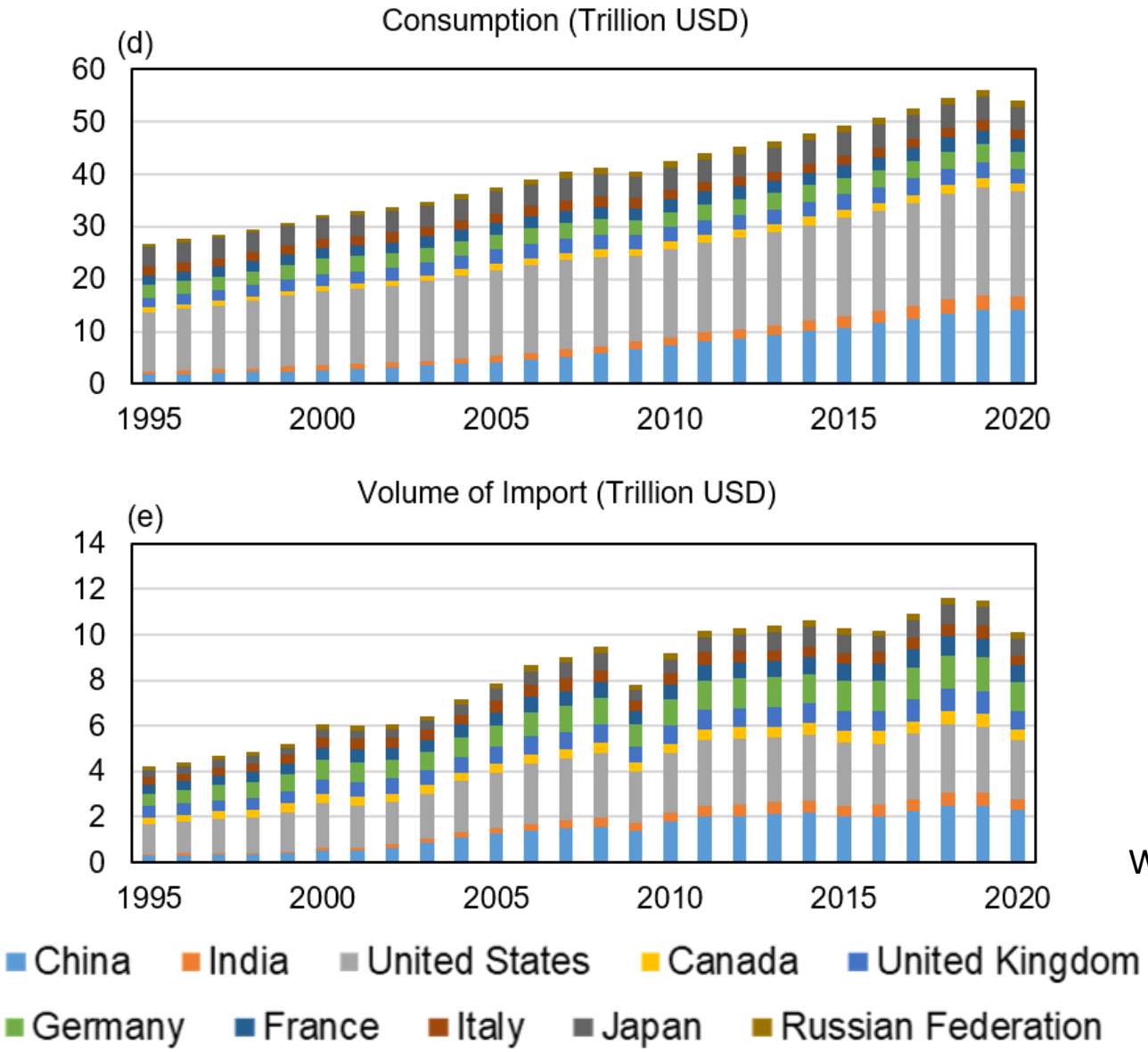
IPCC, 2021

China: A Key Player

G7+ Country	Population 2018 (Million)	GDP 2018 (Billion US$)	Export 2018 (Billion US$)	$PM_{2.5}$ Emissions 2012 (Tg)	NOx Emissions 2014 (Tg)	SO_2 Emissions 2014 (Tg)
China Mainland	1393 (1) *1.5*	13608 (2) *0.34*	2656 (1) *0.30*	11.88 (1) *4.4*	34.0 (1) *1.5*	37.5 (1) *3.0*
US	327	20544	2510	1.30	10.8	4.3
France	67	2778	870	0.18	0.8	0.2
UK	66	2855	857	0.08	0.9	0.3
Japan	127	4971	917	0.15	2.3	0.8
Germany	83	3948	1872	0.14	1.2	0.4
Italy	60	2084	655	0.14	0.7	0.1
Canada	37	1713	551	0.22	1.8	1.2
Russia	144	1658	510	0.47	3.8	5.1

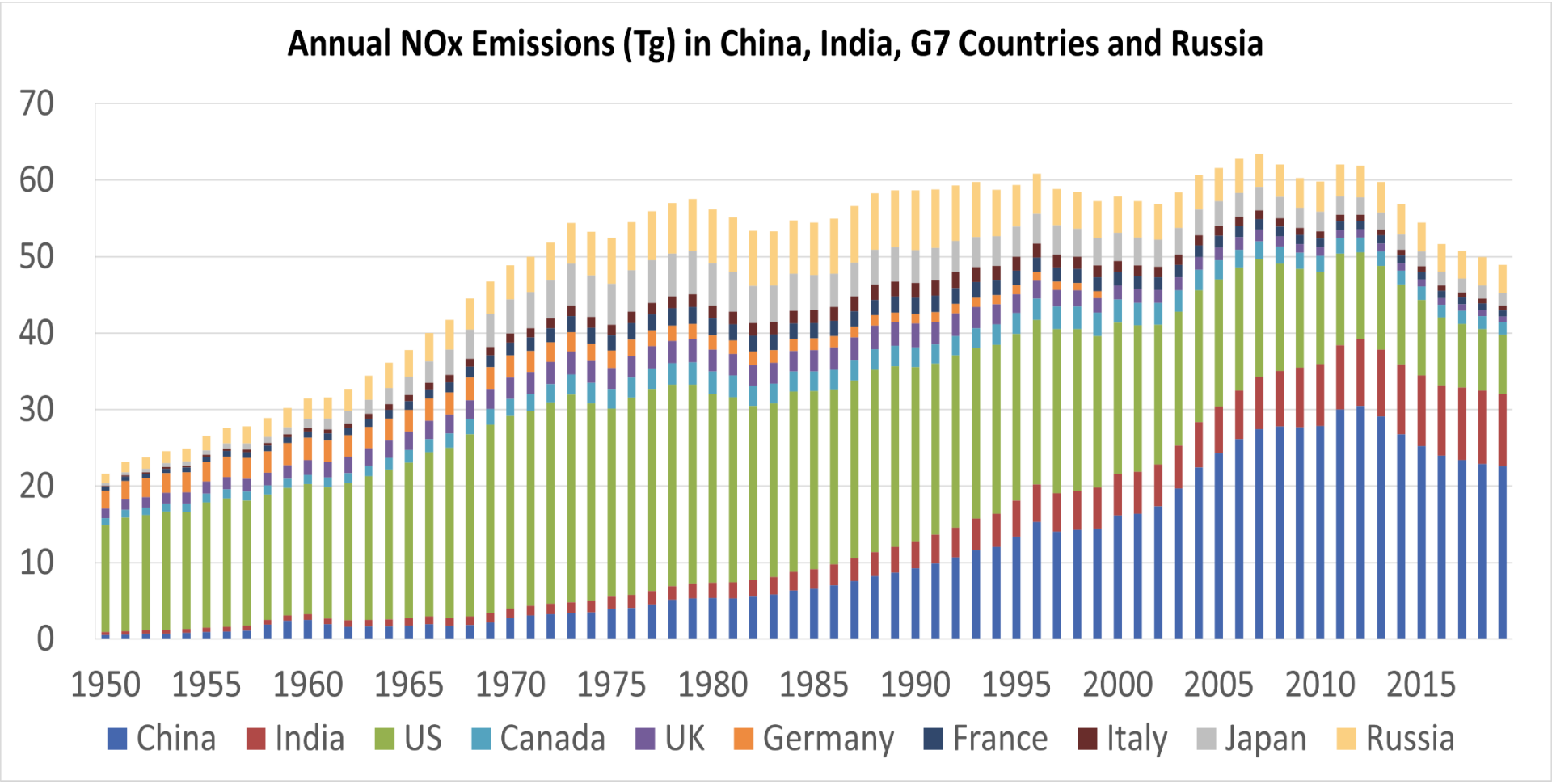
Data sources: GDP, Export and population data from World Bank; $PM_{2.5}$ emissions from EDGAR v4.3.2; NOx and SO_2 emissions from CEDS

Consumption and Trade: 1995-2020



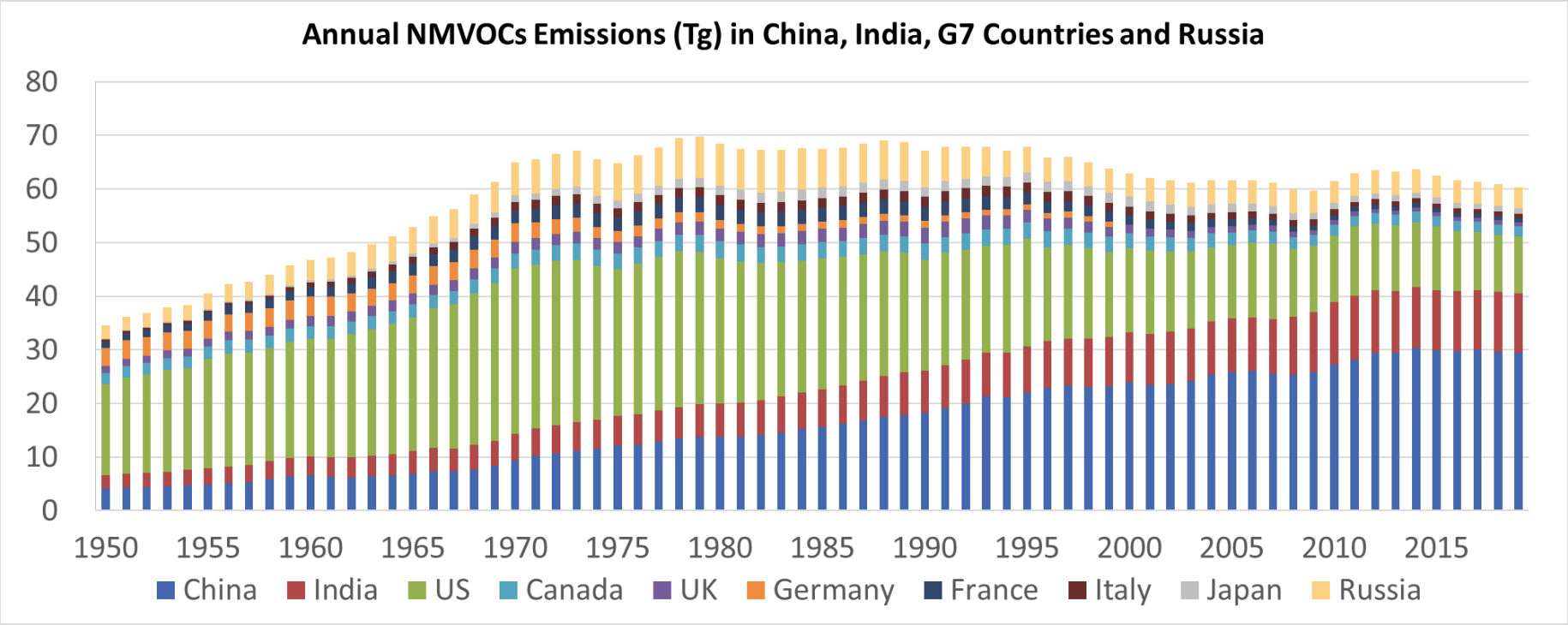
World Bank

Anthropogenic Emissions of NOx: 1950-2019



CEDS v2 inventory

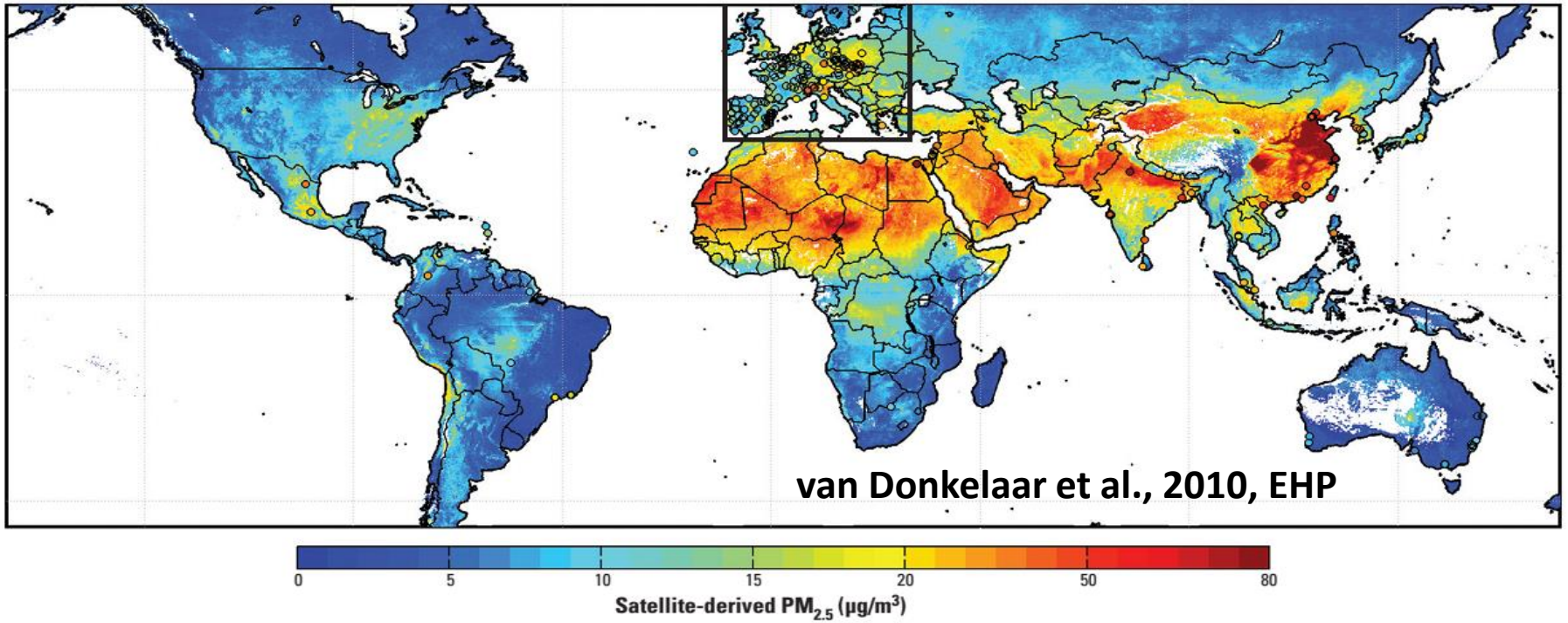
Anthropogenic Emissions of NMVOC: 1950-2019



CEDS v2 inventory

China Has Severe PM Pollution

Surface $PM_{2.5}$ concentration derived from satellite (2000-2006 mean)



23,000,000 Chinese
live in areas with > 100 µg/m³

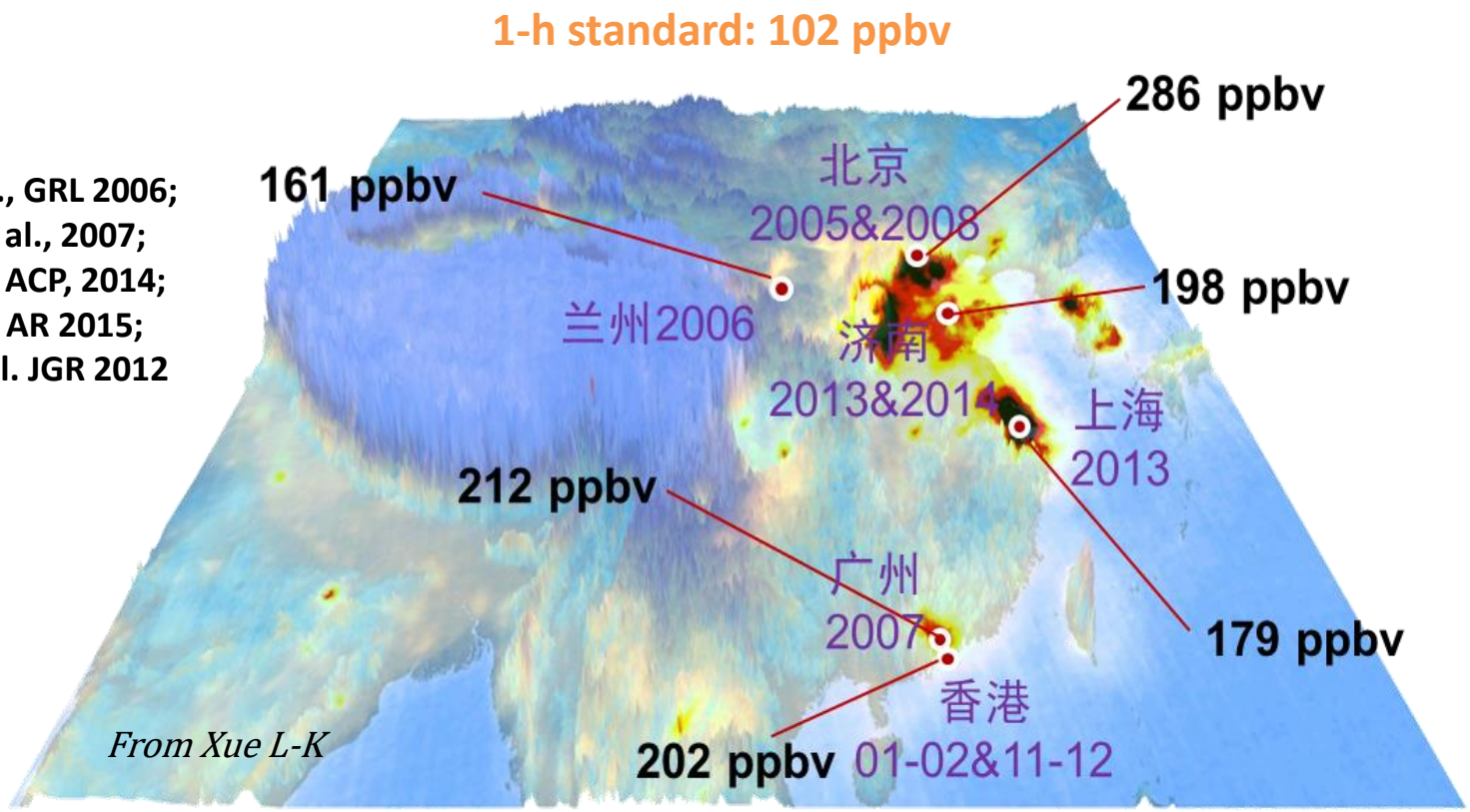
v.s.

Beijing in 2013：
89 µg/m³

v.s. **WHO Guideline: 5 µg/m³, WHO IT1: 35 µg/m³**

China Is Facing Increasingly Severe Ozone Pollution

Wang et al., GRL 2006;
Zhang et al., 2007;
Xue et al., ACP, 2014;
Shi et al. AR 2015;
Zhang et al. JGR 2012



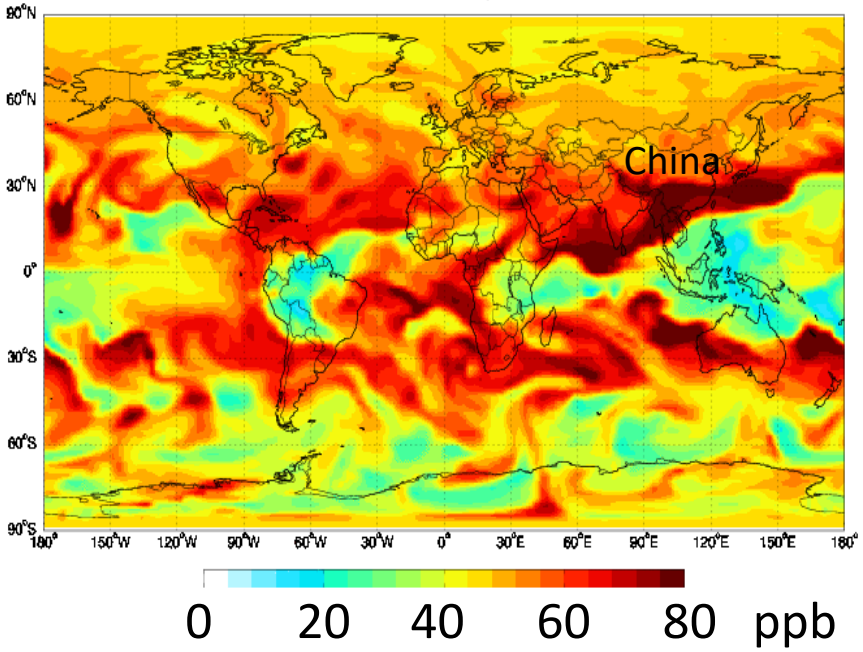
Globalizing Air Pollution: Haze Is Approaching !

https://v.qq.com/x/page/f03620mzezq.html

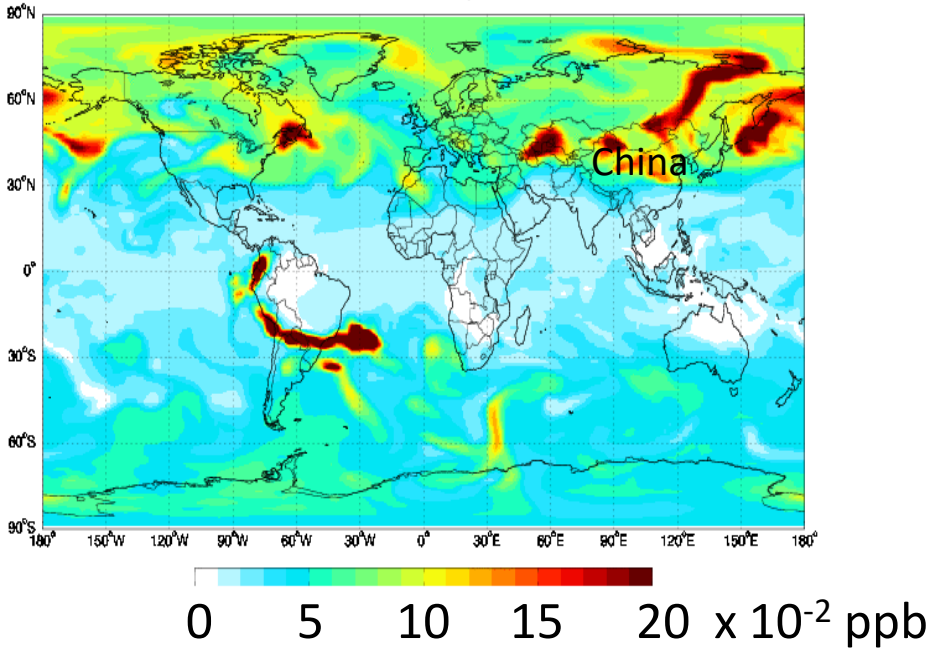
Globalizing Air Pollution: Atmospheric Transport

Simulated by GEOS-Chem Chemical Transport Model

Ozone in Mid-Trop. in Jan 2009



Sulfate in Mid-Trop. in Jan 2009



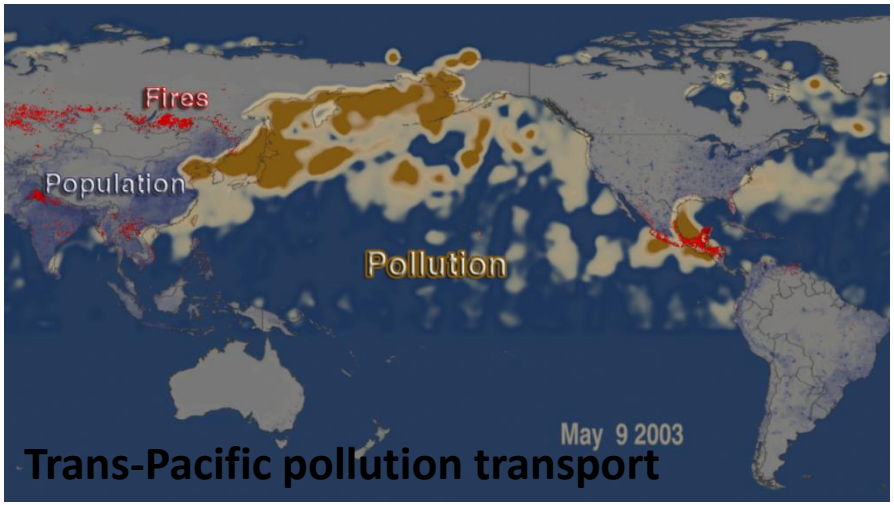
- **Both local sources and transport of pollution are obvious**
- **The extent of transport depends on emissions, chemistry, etc.**
- **China is both a *source* and a *receptor* region**

Yan et al., 2014 ACP; 2016 ACP

Globalizing Air Pollution: News Coverage

- Nature 2011: Nitrogen pollution disrupts Pacific Ocean
- Nature 2012: Emissions from Asia put US cities over O_3 limit
- Science 2013: Dust and biological aerosols from Sahara and Asia influence precipitation in West US
- Nature 2015: Asian pollution hitchhikes south
- Nature 2015: Pollutants waft over the Himalayas

http://www.nature.com/news/pollutants-waft-over-the-himalayas-1.17312



http://www.nasa.gov/centers/goddard/news/topstory/2008/pollution_measure.html

Science News 2014: China blamed for U.S. ozone

- **California petition: The EPA's $29 Million fine should be removed, as the ozone standard exceedance is much due to transport from Asia/China**
- **Seyed Sadredin: "This is not just going to be a San Joaquin Valley problem."**
- **Daniel Jacob: "It's really important that we start to take our air quality policies beyond the state and national level and start to think about air quality on an international level."**
- **Paul Monks: "The benefits of emission controls could be significantly counterbalanced by increasing background ozone levels."**

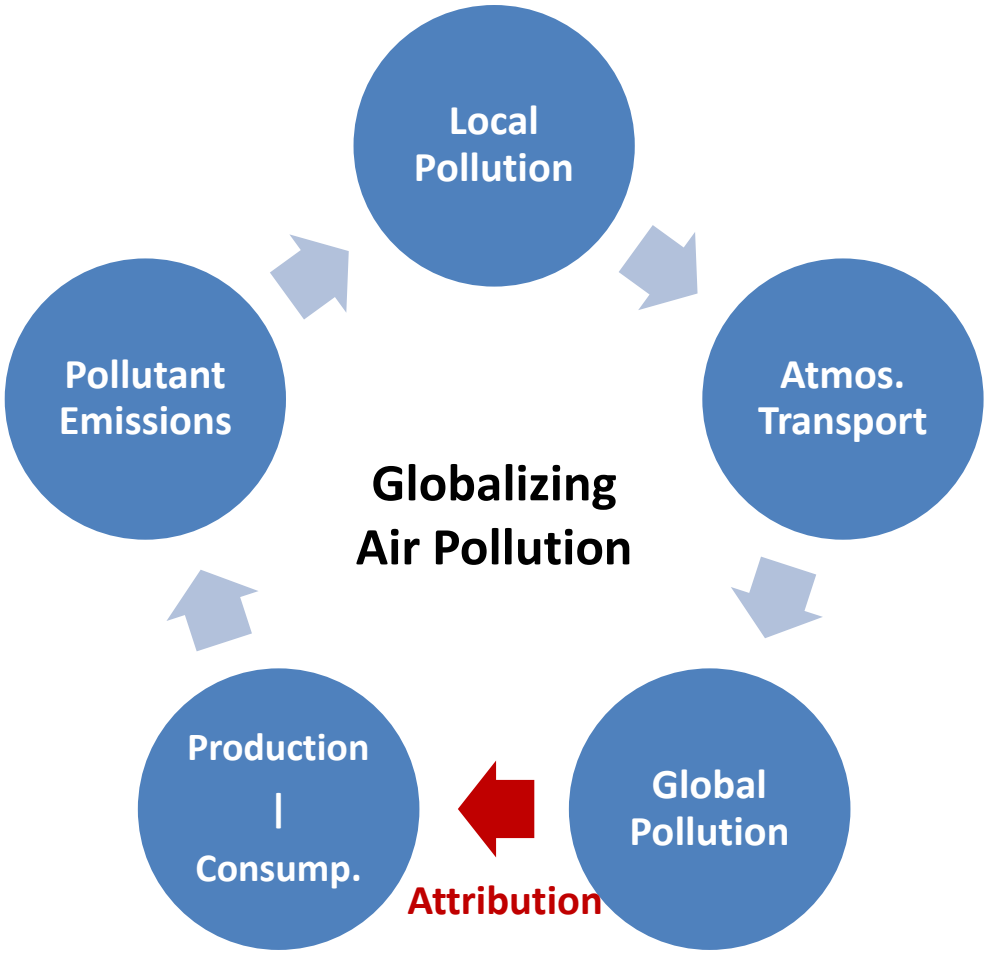
http://science.sciencemag.org/content/345/6202/1233.full

Key Questions on Globalizing Air Pollution

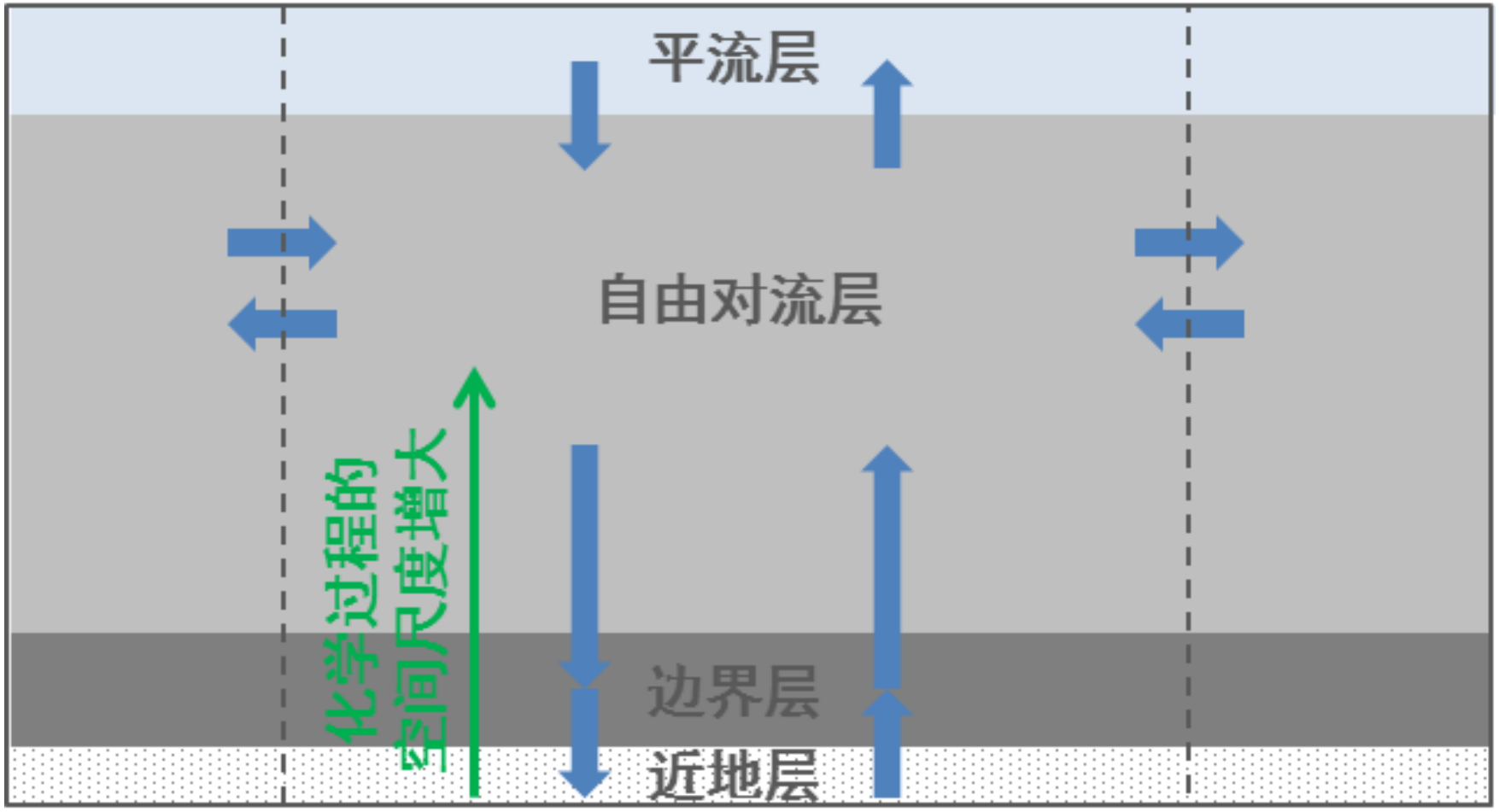
- Severity and trends of air pollution and its globalization
  - Historical and global view
  - Measurements & modeling
- Environmental consequences of globalizing air pollution
  - Air quality, health, agriculture, ecosystems, etc.
- Physical and chemical mechanisms of pollution transport
  - Meteorology, chemistry, lifetime, etc.
  - Modeling and measurements
- Socioeconomic drivers of globalizing air pollution
  - Role of production, consumption, and trade
  - Interdisciplinary integrated analysis

Physical-chemical-transport Mechanism of Air Pollution

Global & Historical Perspective ⇨ Cooperative & Win-Win Thinking

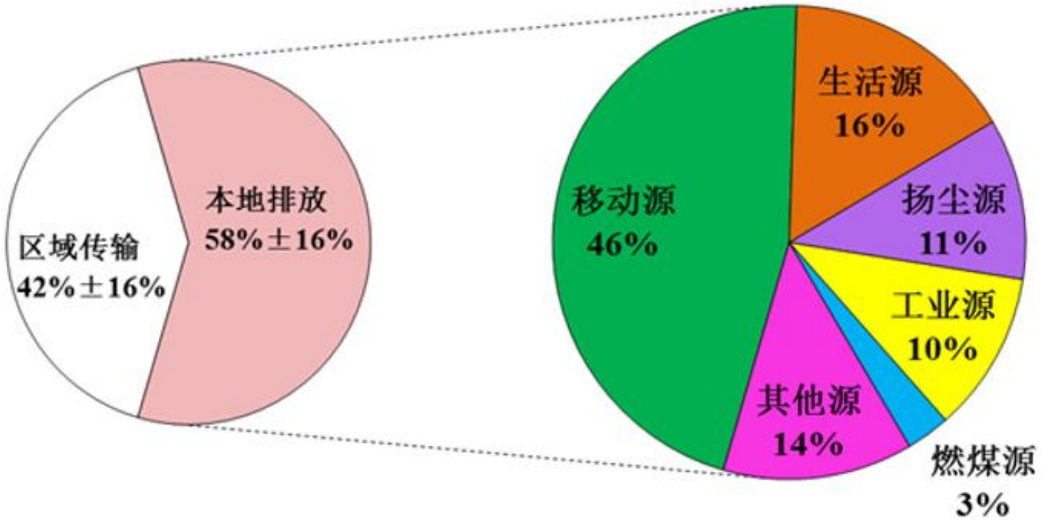


Local-Regional-Global Pollution Interconnection

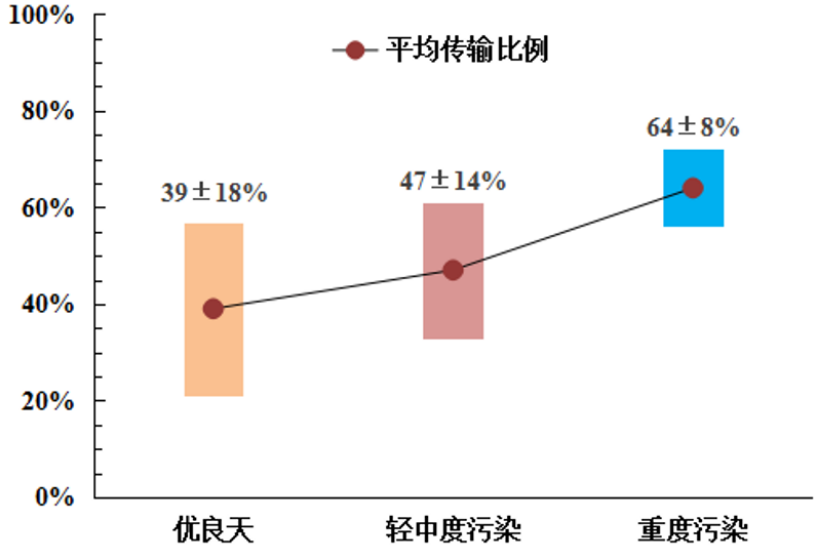


Increasing Role of Atmospheric Transport to Beijing's $PM_{2.5}$

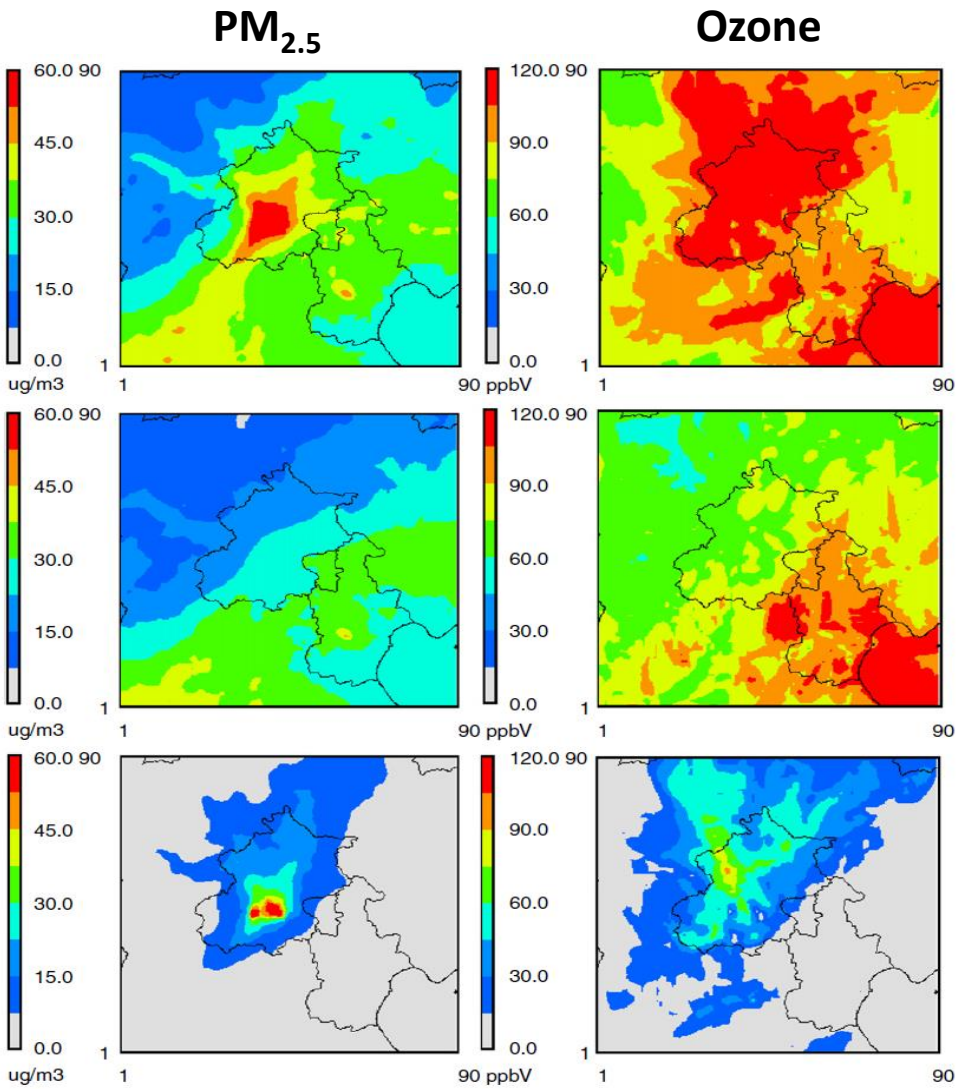
Sources of Beijing's $PM_{2.5}$ (北京市生态环境局，2021)



- ✓ 32±4% in 2014 (第一轮)
- ✓ 34±8% in 2018 (第二轮)
- ✓ 42±16% in 2021 (第三轮)



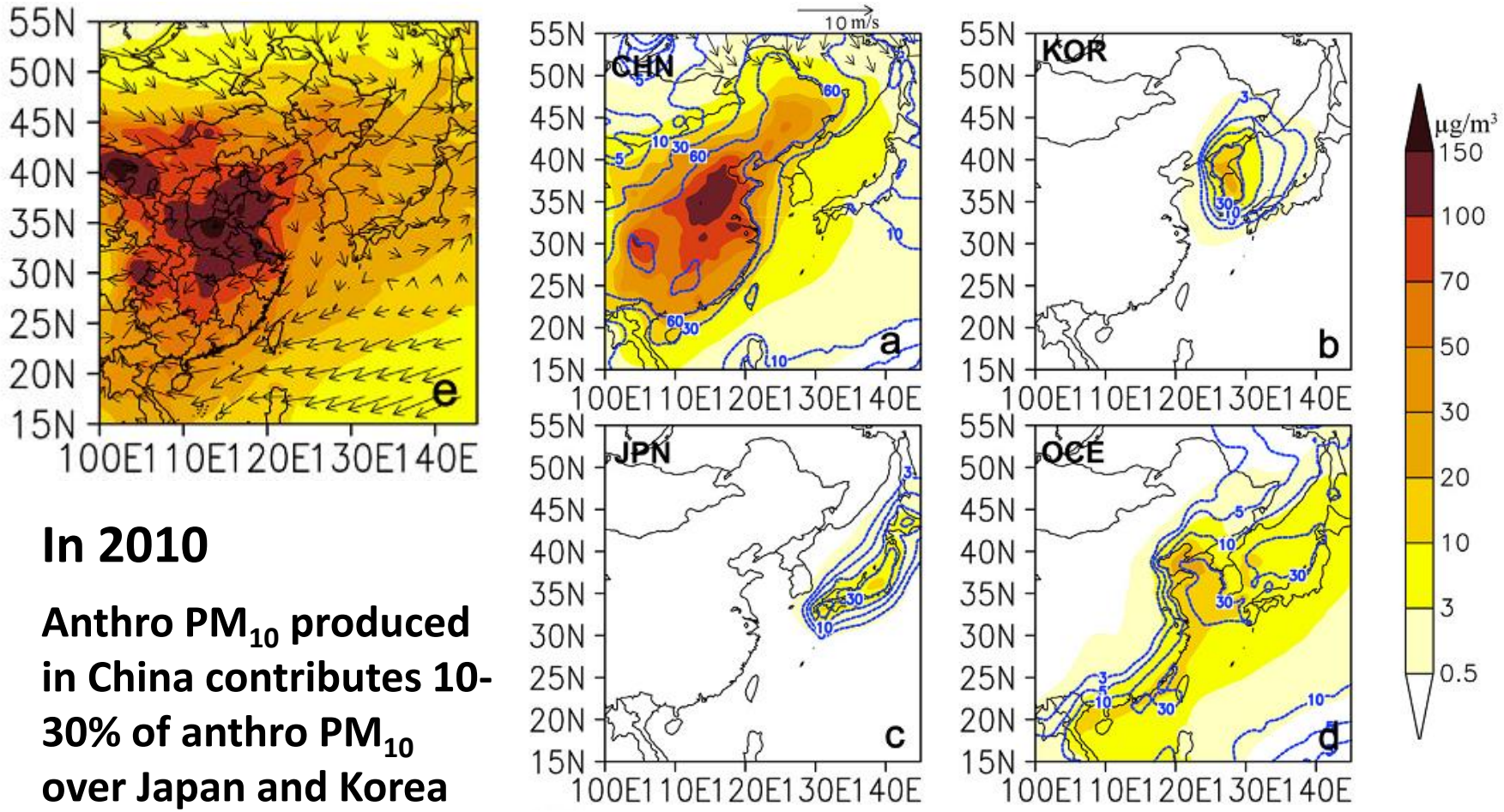
Role of Transport and Chemistry in Regional Pollution



Nonlinear impacts!

An et al., 2007

PM Transport Between Asian Countries



In 2010

Anthro PM_{10} produced in China contributes 10-30% of anthro PM_{10} over Japan and Korea

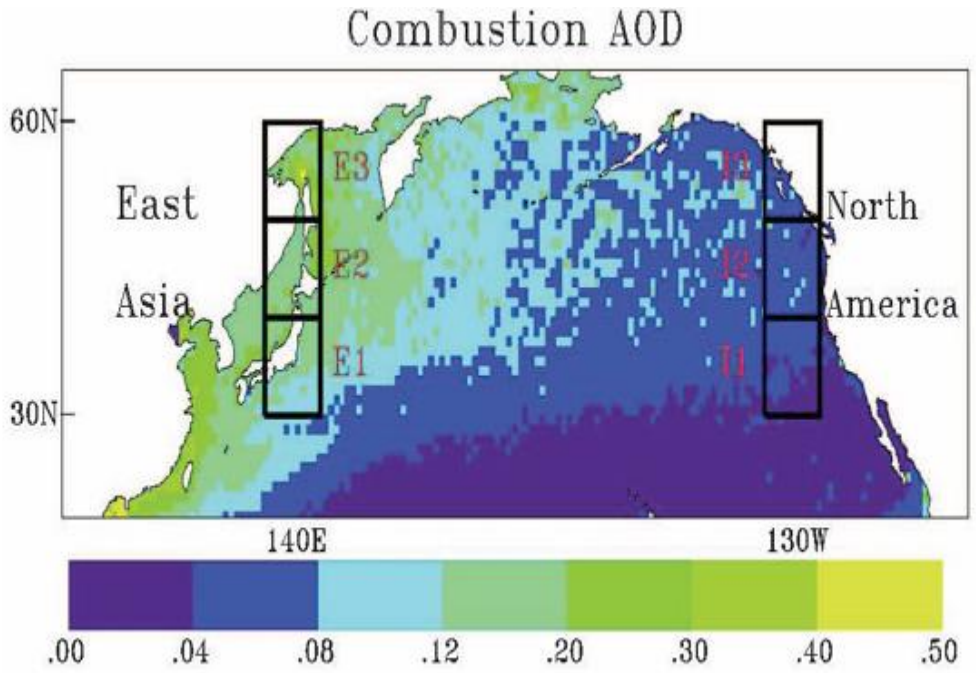
NAQPMS + tagging

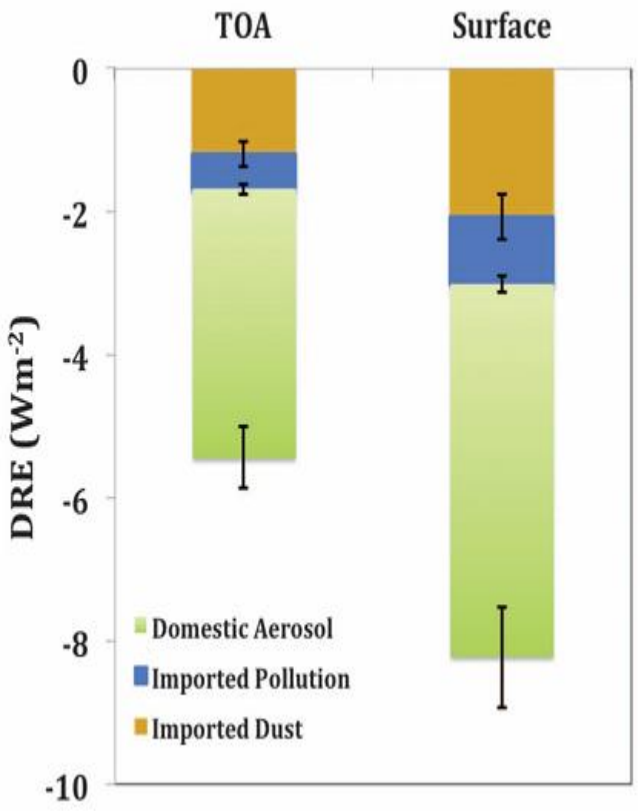
Li et al., 2014, AE

Asian PM Transport Affects North America

Yu et al., 2012, Science

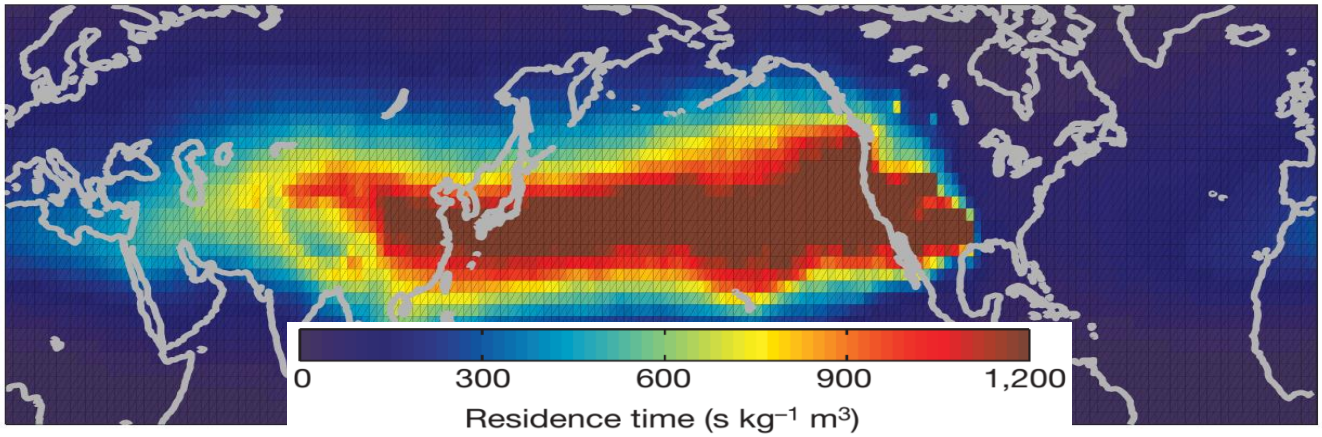
- **East Asian PM pollution contributes 6% of N.A. DRE**

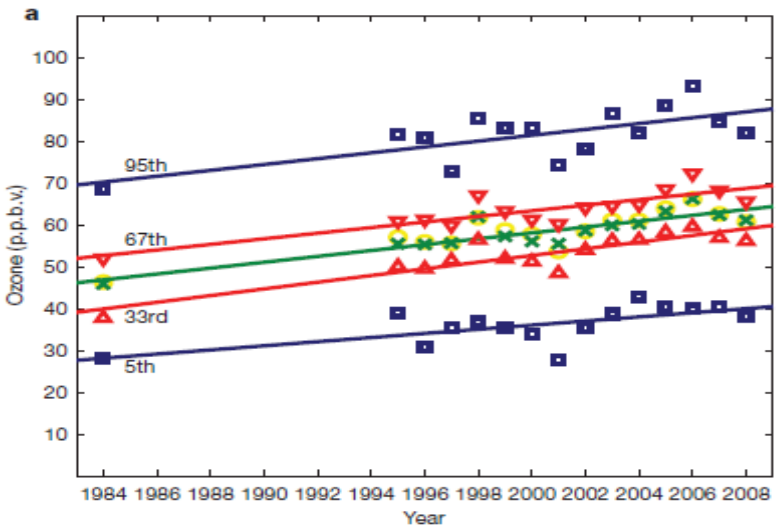




Atmospheric O_3 Transport from China to U.S.

Cooper et al., 2010, Nature



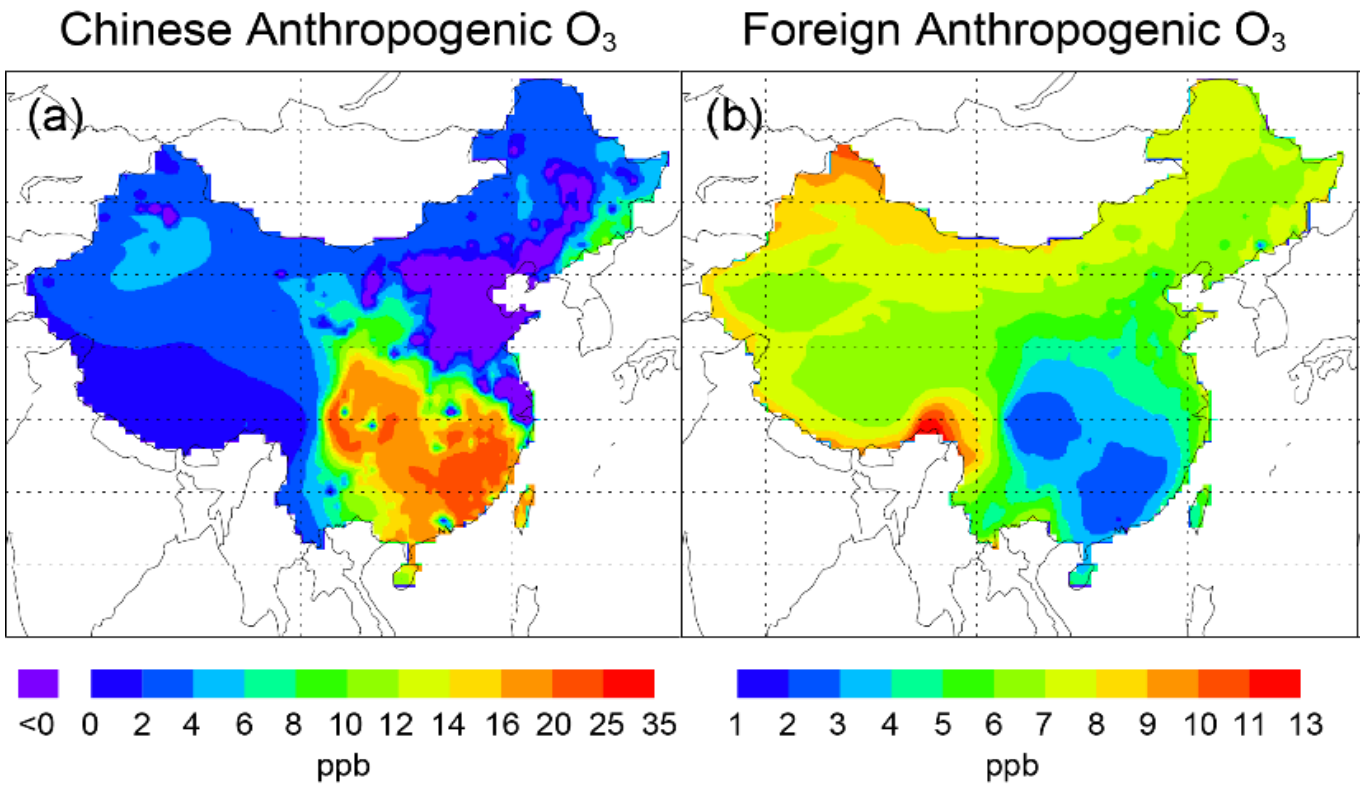


Percentile	1995–2008 increase (p.p.b.v. yr^{-1})	*P*
95th	0.56 ± 0.71	0.11
67th	0.62 ± 0.39	0.00
50th	0.63 ± 0.34	0.00
33rd	0.64 ± 0.35	0.00
5th	0.48 ± 0.53	0.07

Percentile	1984–2008 increase (p.p.b.v. yr^{-1})	*P*
95th	0.70 ± 0.45	0.01
67th	0.67 ± 0.25	0.00
50th	0.70 ± 0.22	0.00
33rd	0.80 ± 0.24	0.00
5th	0.49 ± 0.34	0.01

Foreign Pollution Greatly Affect China's O_3

- **2–11 ppb of Surface O_3 over China in Spring 2008 are Foreign**

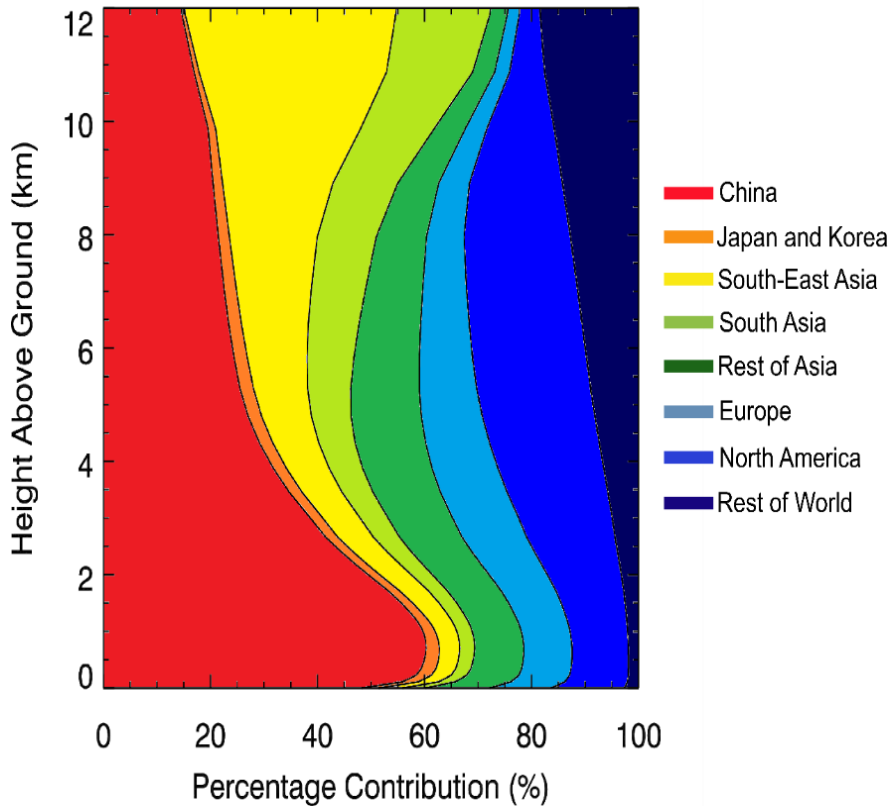


Method: *Zero-out* + *Tagged O_3* + *Linear weighting*

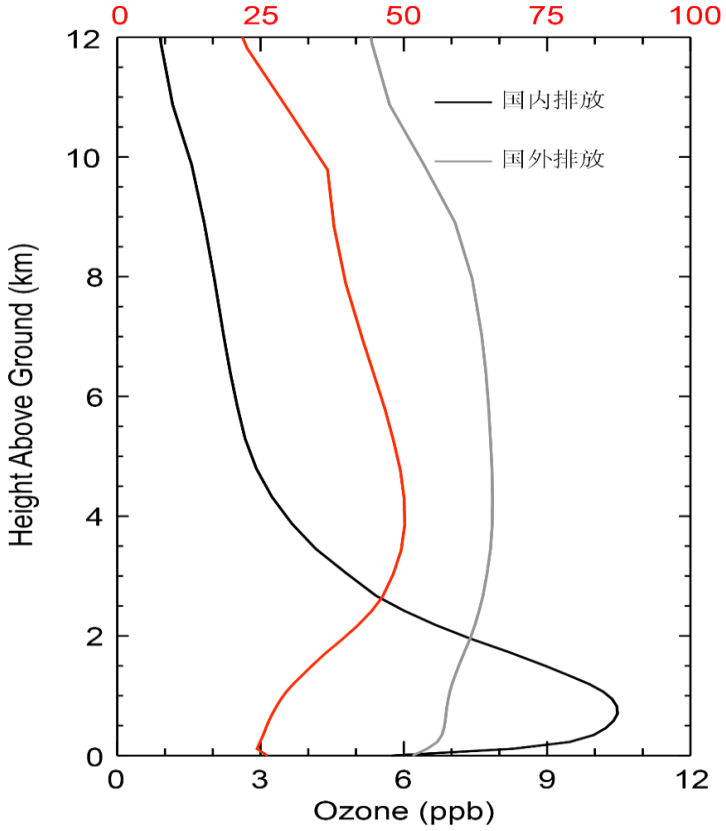
Ni et al., ACP, 2018

Large Fractions of Tropospheric Anthropogenic O_3 over China in Spring 2008 are Foreign

% of anthropogenic O_3 contributed by a region



% of O_3 produced within foreign source regions

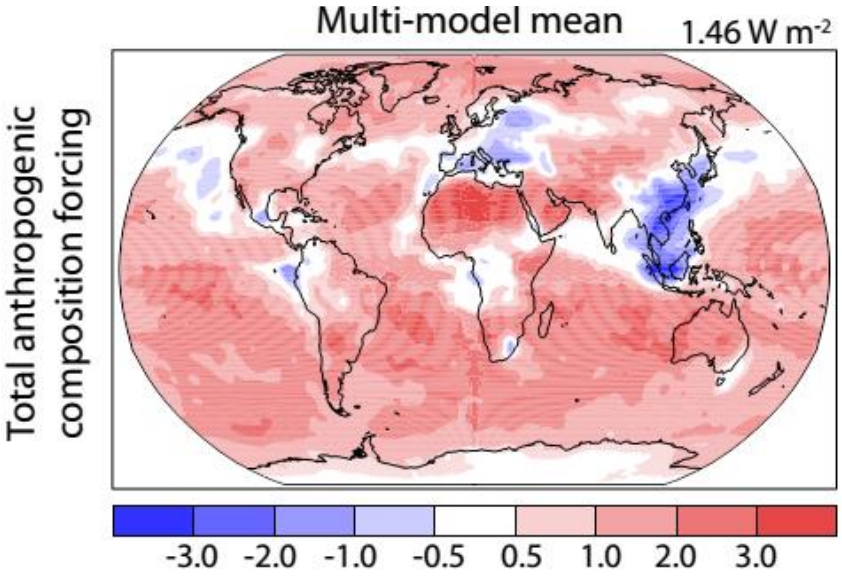


Method: *Zero-out* + *Tagged O_3* + *Linear weighting*

Ni et al., ACP, 2018

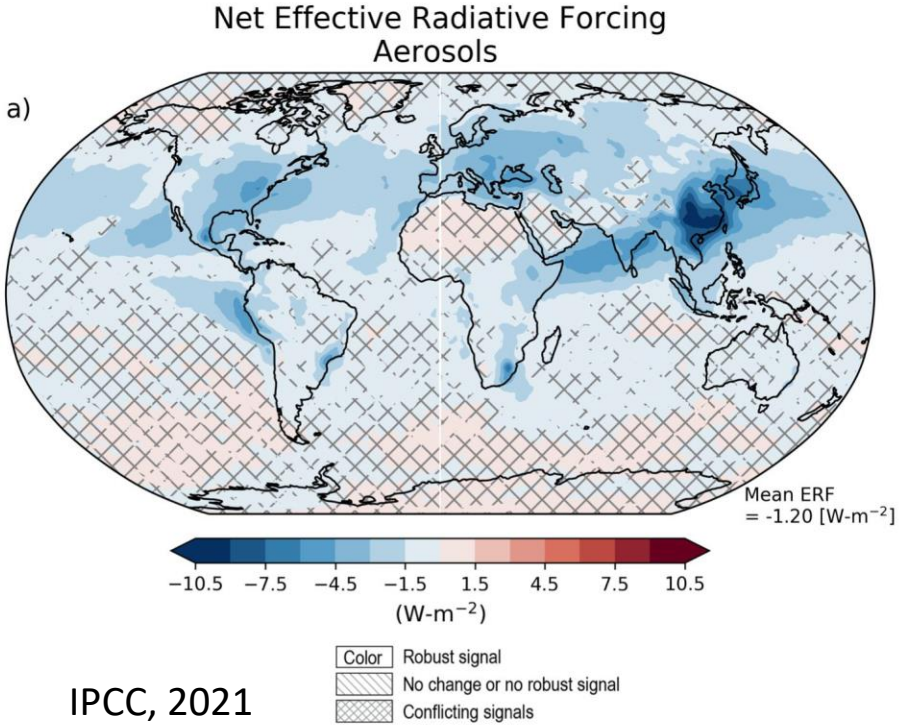
Radiative Forcing: Spatial Distribution

Total RF: 1850–2000



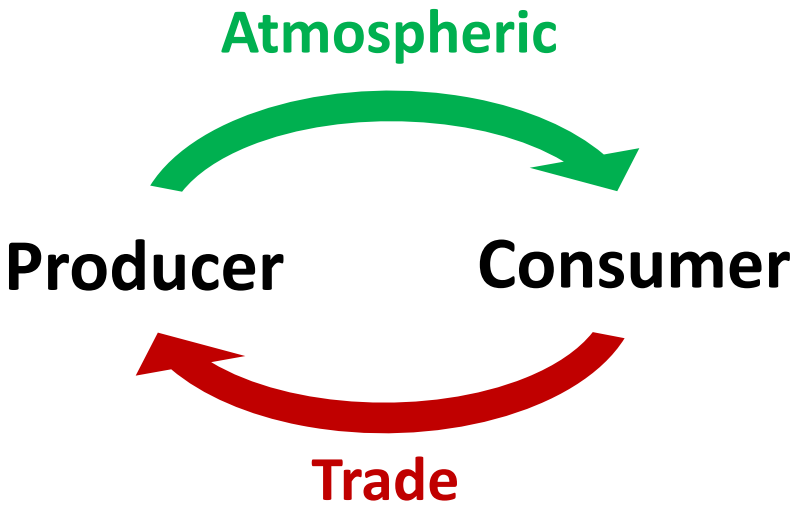
IPCC, 2013

Aerosol ERF: 1850–2014



IPCC, 2021

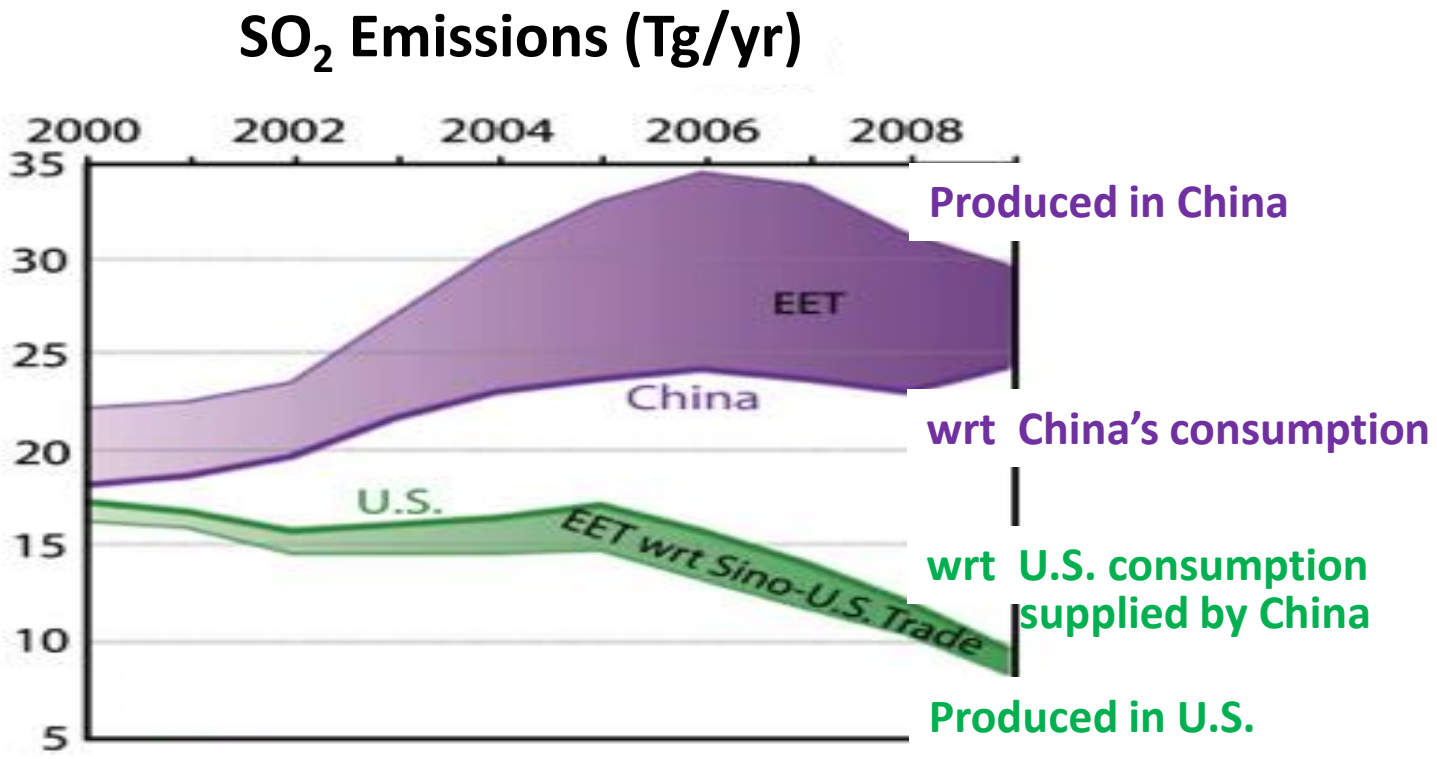
Looped Mechanism of Pollution Transport



- **Atmosphere: Move pollution from producer to consumer**
- **Trade : Move Pollution from consumer to producer**

Lin et al., 2014, PNAS; Cozzarelli Prize Winner

Trade Redefines Chinese and U.S. Emissions

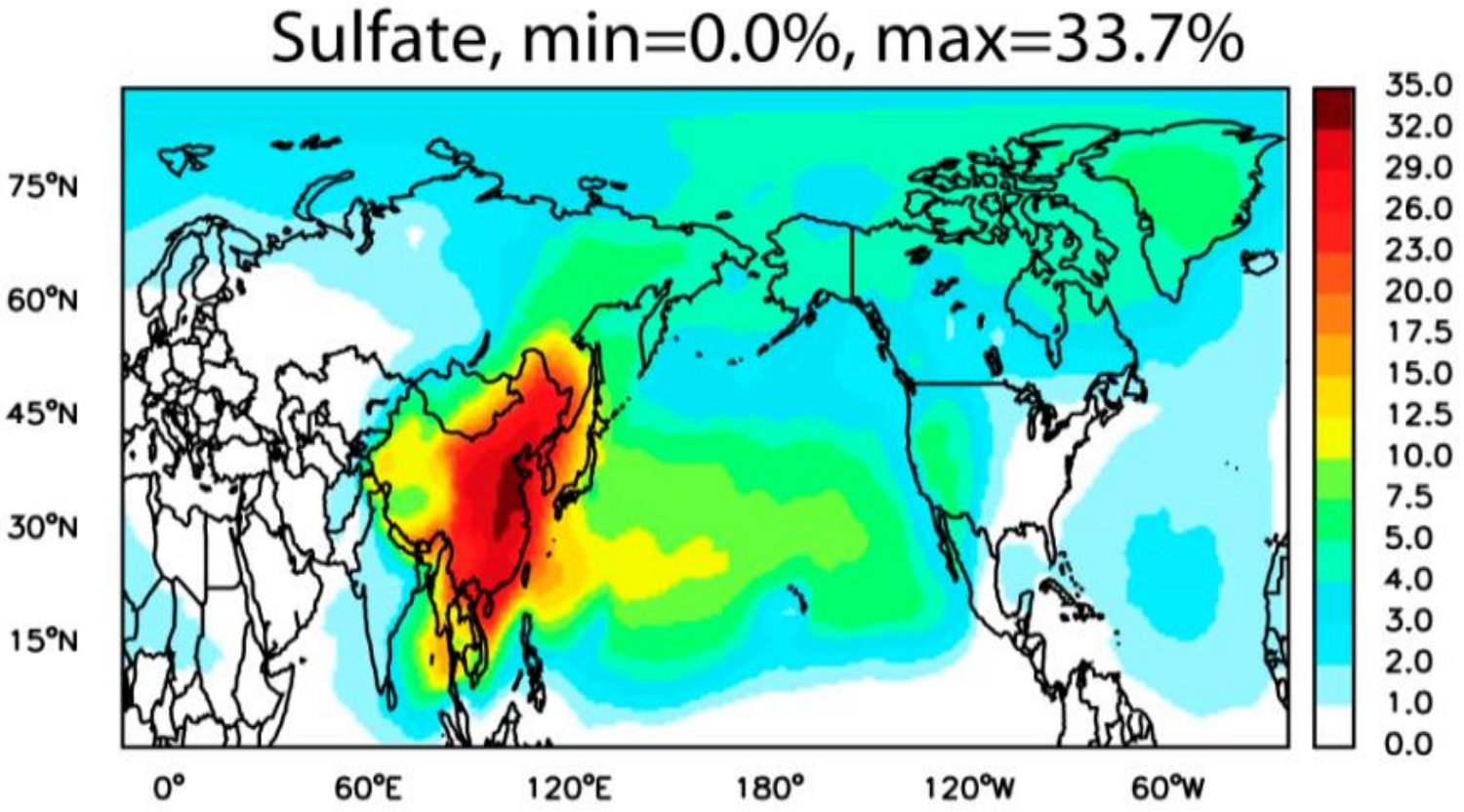


- Trade increases Chinese emis, but decreases U.S. emis
- Export-to-world contributes **36%** of Chinese SO_2 emis in 2006
- Sino-US-trade-related SO_2 emis are **19%** of U.S. emis in 2006

Lin et al., 2014, PNAS; Cozzarelli Prize Winner

Goods Export Contributes ~ 30% of China's Sulfate

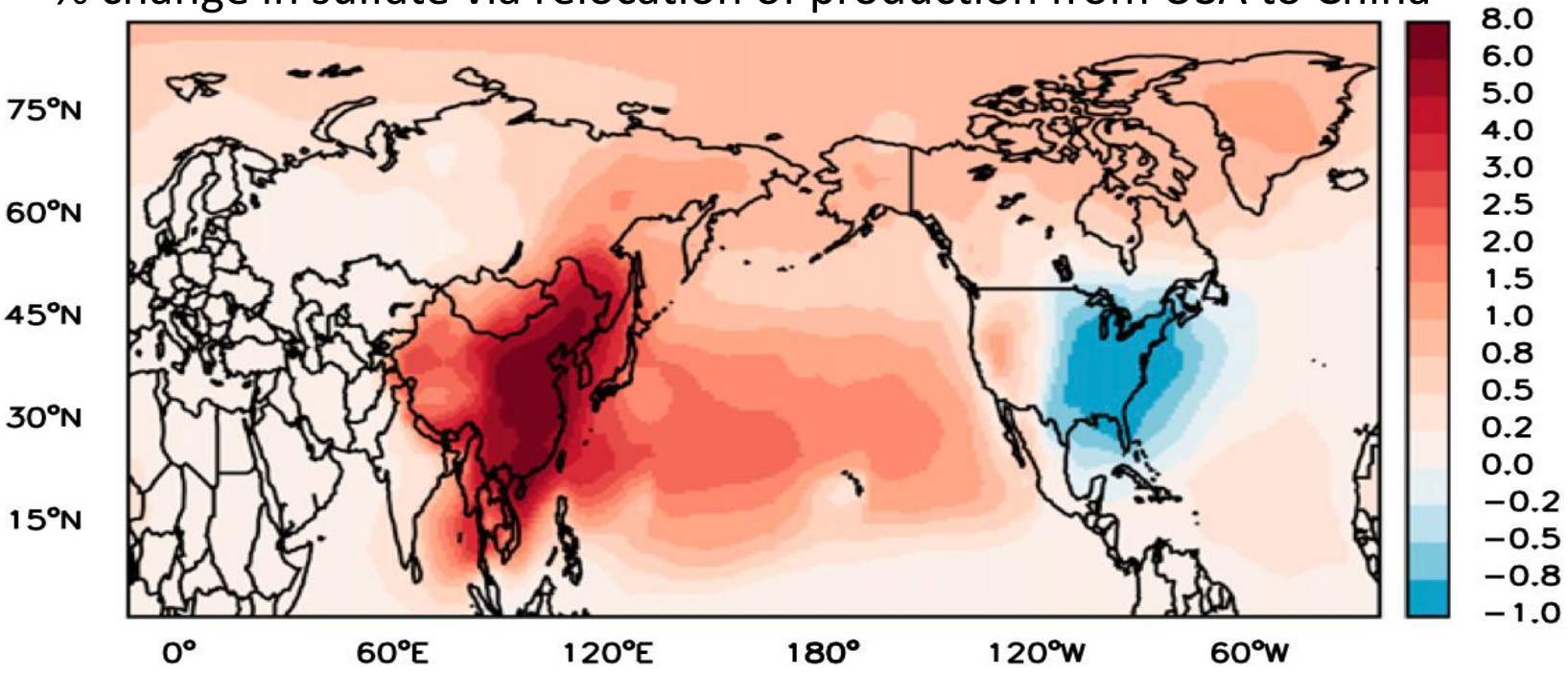
% contribution of China's export-related pollution to total pollution anywhere in the world



Lin et al., 2014, PNAS; Cozzarelli Prize Winner

USA Consumption & China's Sulfate Pollution

% change in sulfate via relocation of production from USA to China



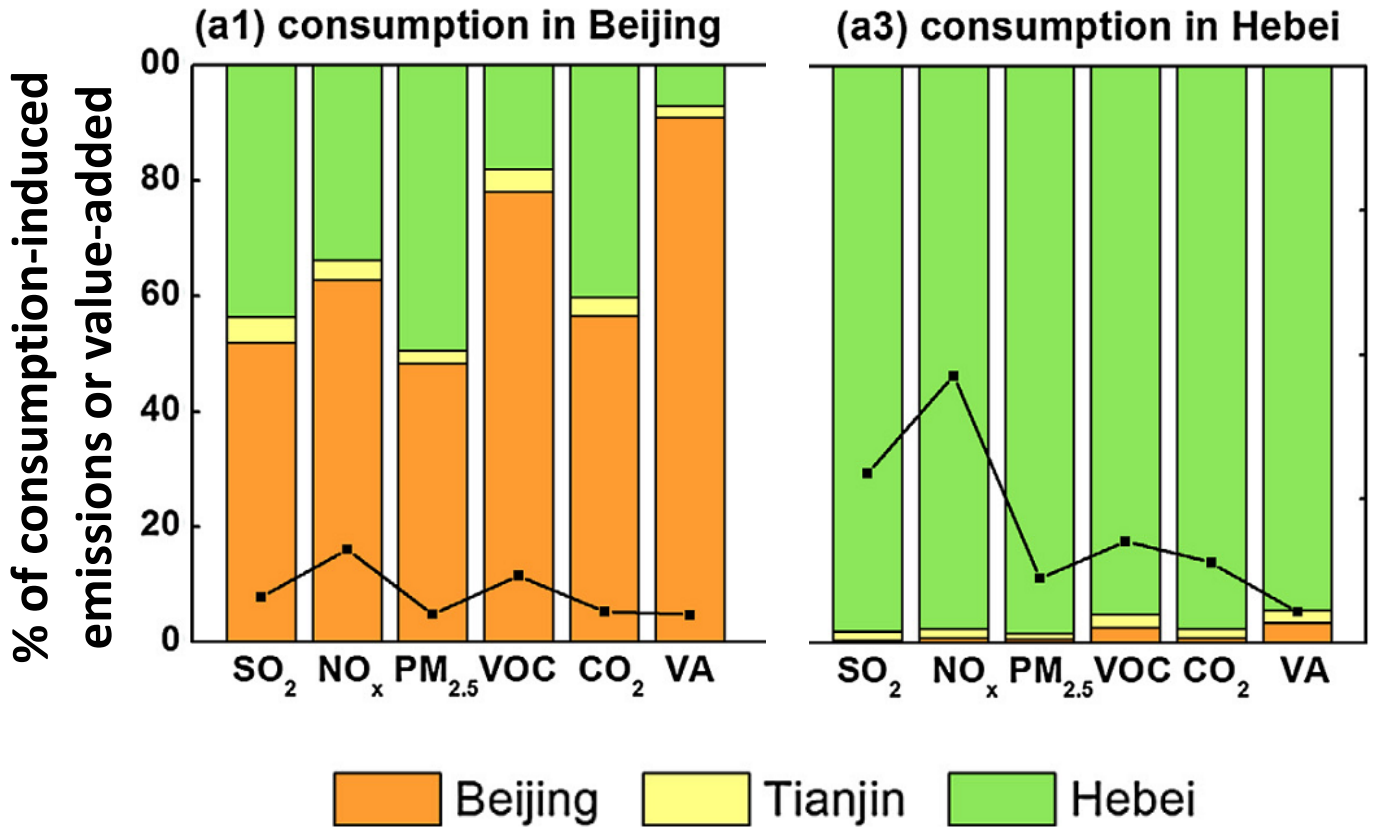
USA imports goods from China rather than self-production:

(accounting for differences in emission intensity)

- Increase sulfate over China
- Decrease sulfate in E. USA but increase sulfate in W. USA

Lin et al., 2014, PNAS; Cozzarelli Prize Winner

Pollution Transfer: Beijing → Hebei



Zhao et al., Applied Energy, 2016

Trade-driven Pollution Transport: A Critical Issue in China's GO-WEST Movement

Pollution in Tenggeli Desert (2014/08/31)

http://baike.baidu.com/view/14786821.htm?fr=aladdin

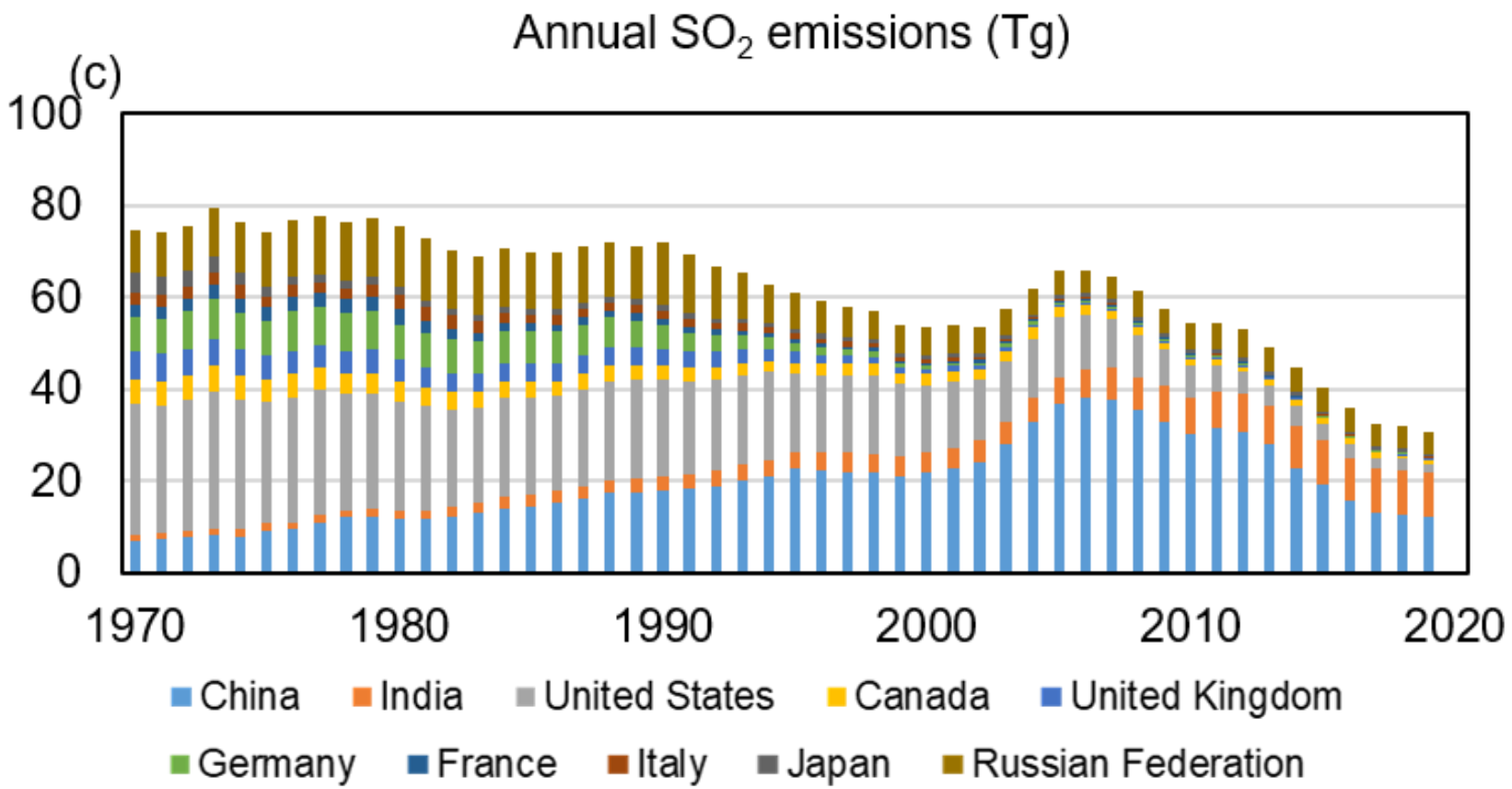
Suggested Reading

- United Nations Environment Programme https://www.unenvironment.org/explore-topics/environment-under-review
- NOAA Global Climate Report https://www.ncdc.noaa.gov/sotc/global/201807
- NASA World of Change http://earthobservatory.nasa.gov/Features/WorldOfChange/index.php
- 中国气候变化蓝皮书（2021、2022、2023、2024）
- Movie: An Inconvenient Truth
- Movie: The Day After Tomorrow
- 采访：柴静采访丁仲礼
- 博弈论：囚徒困境、零和游戏 v.s. 非零和游戏

Quiz

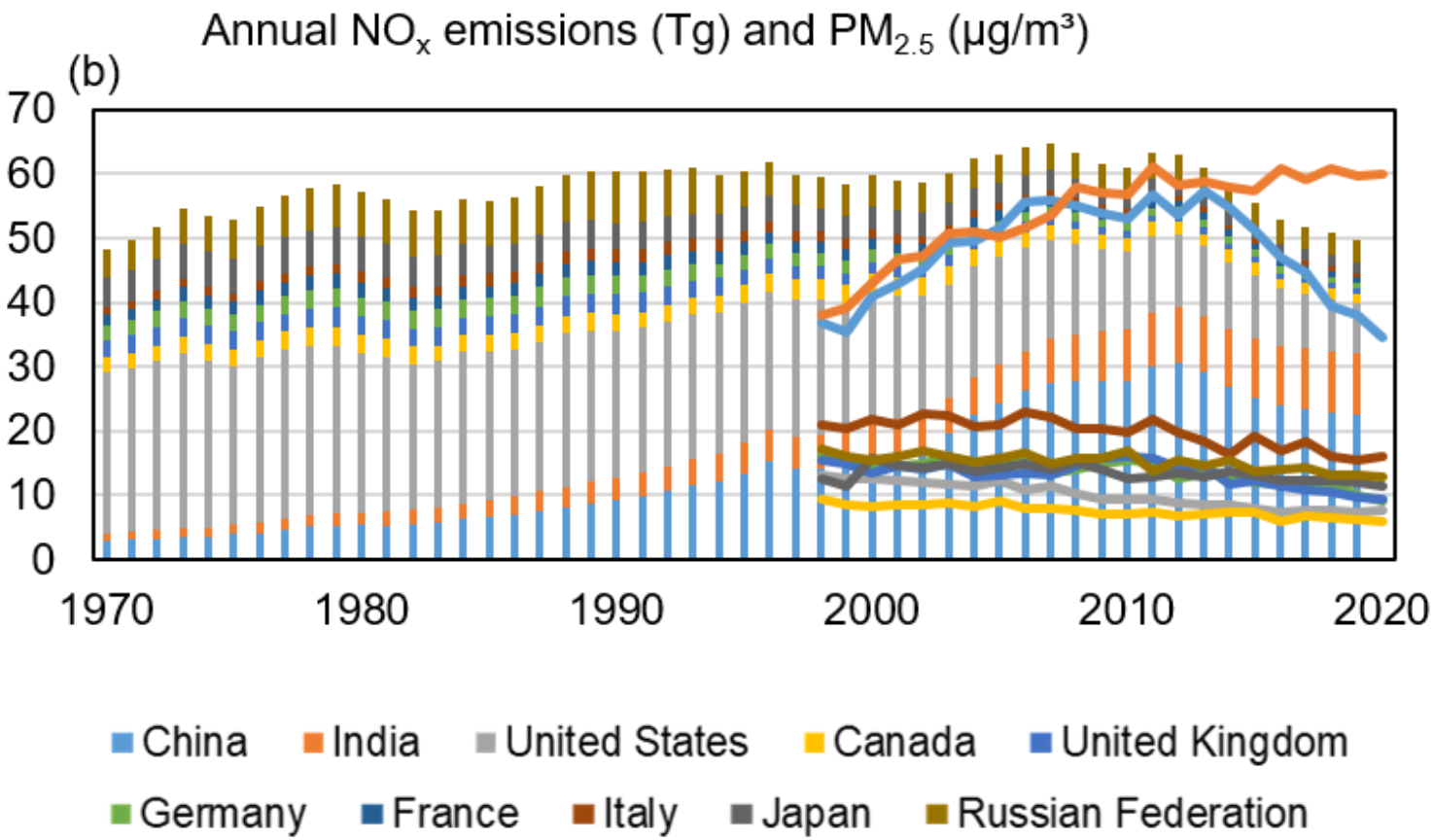
1. How can climate change affect ozone and PM pollution in terms of local and nonlocal sources?
2. What socioeconomic and atmospheric (climatic) factors determine the transboundary transport of air pollutants?
3. How to better design pollution control strategies in light of transboundary pollution, in light of the roles of transport and trade?

Anthropogenic Emissions of SO_2: 1970-2019



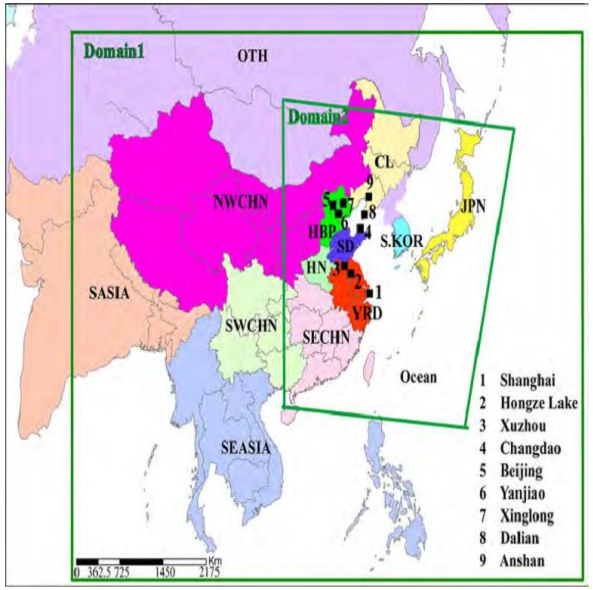
CEDS-GBD-Map

Anthropogenic Emissions of NOx: 1970-2019



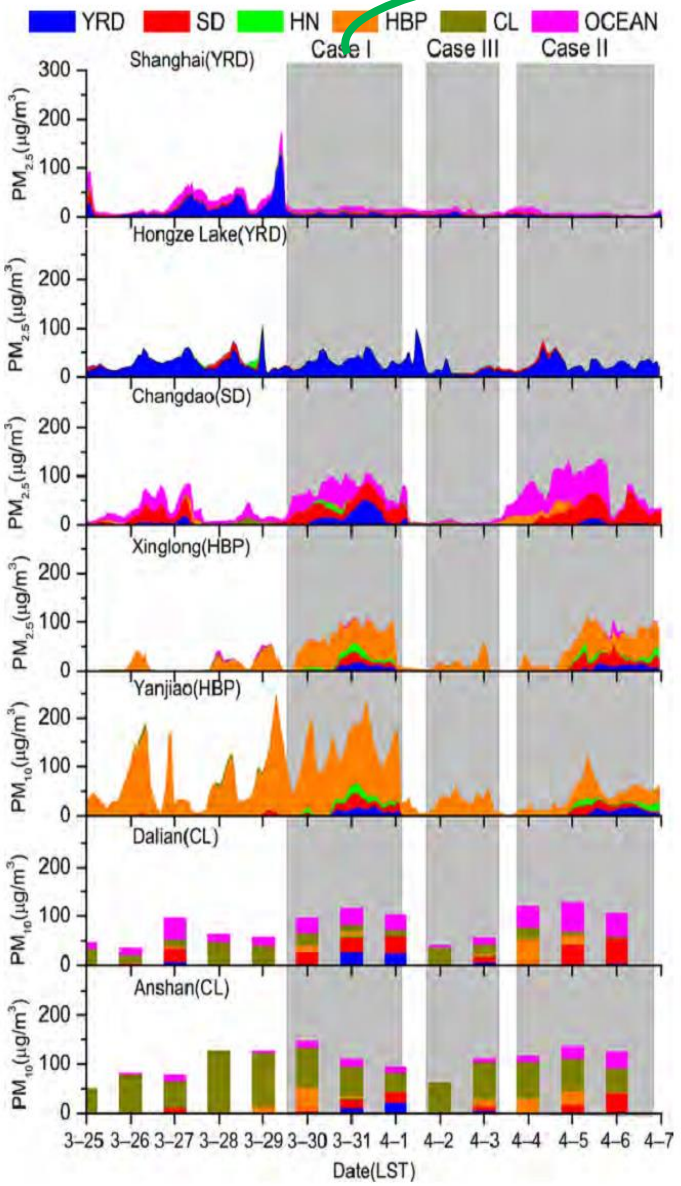
CEDS-GBD-Map

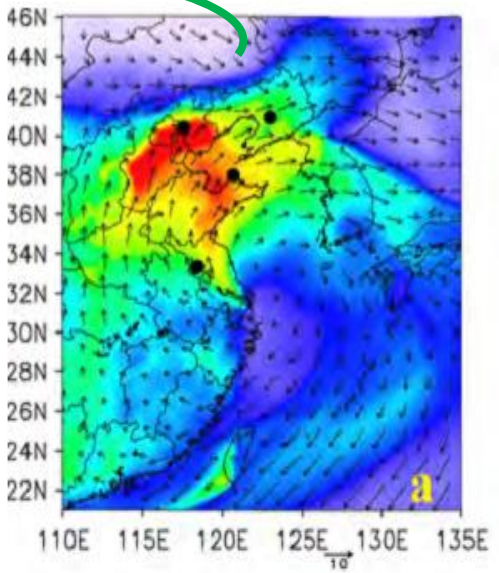
Transport of PM Between China's City Clusters

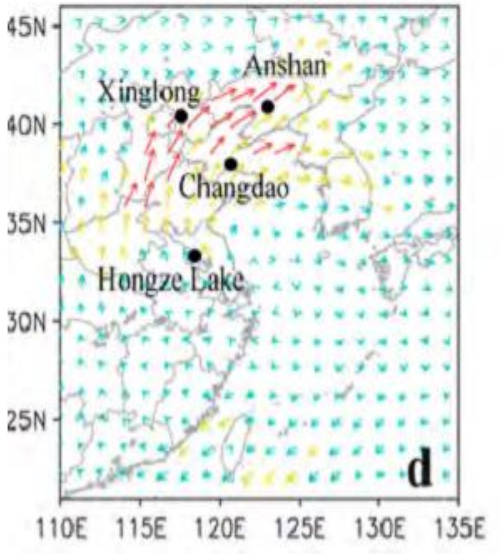


Spring 2011

NAQPMS + tagging







Li et al., 2013, Tellus B

Pathways and Time of Transpacific Transport

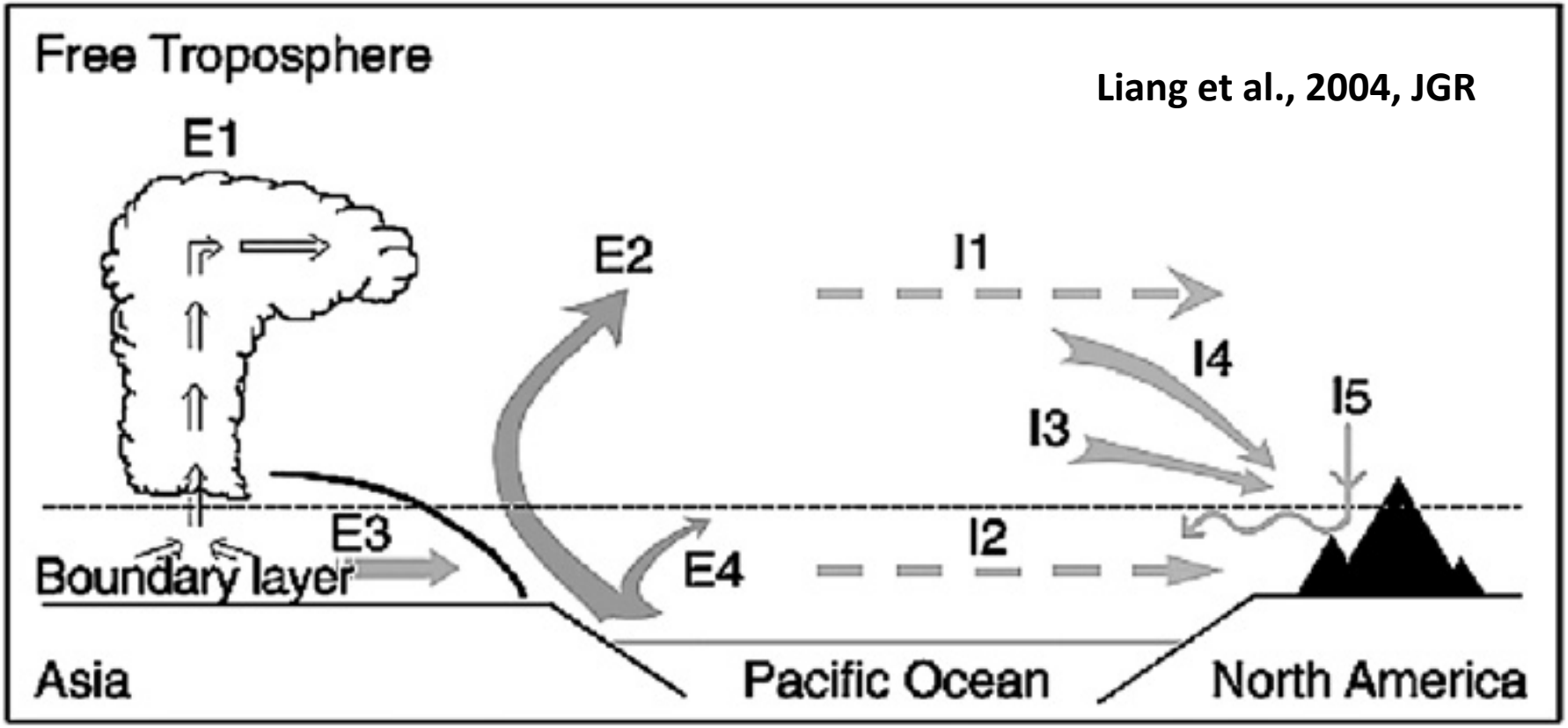


Table 1. 11-Year Average Inter-Continental Transport Times for Two Sets of Tracers in April (Unit: Weeks)

Tracer Lifetime	EA->CPO	EU->Beijing	NA->Paris
1–2 weeks	2.5	2.0	2.0
4–8 weeks	5.1	4.1	4.5

Sources of Air Pollution

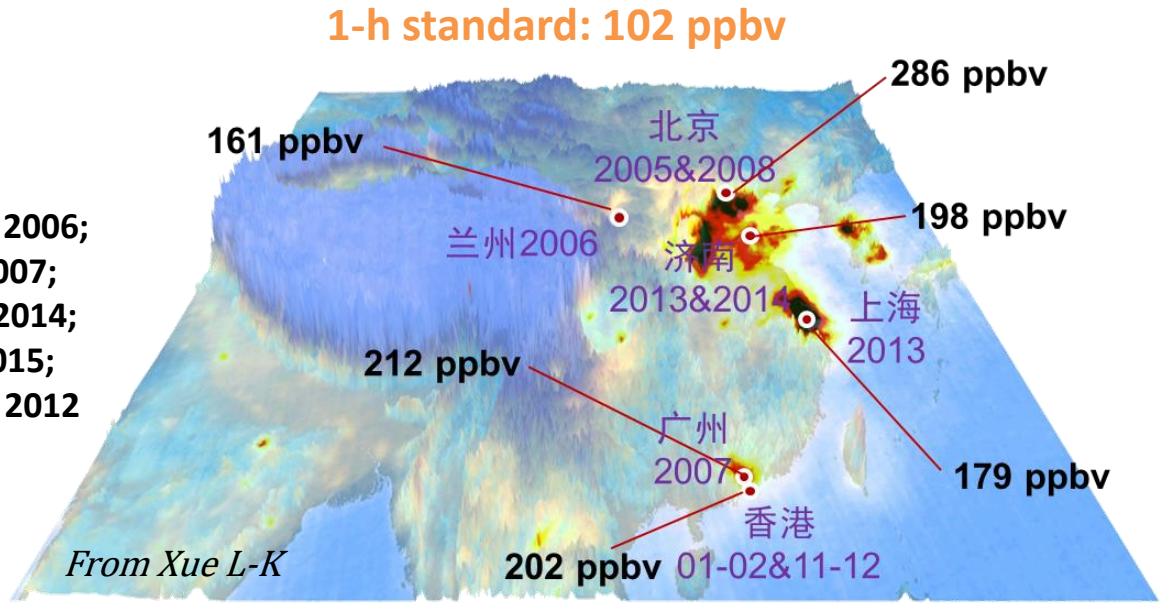
- Anthropogenic & Natural
- Local emissions and formation
- Regional transport and transformation
- Global transport and transformation
- Stratospheric origin, etc.

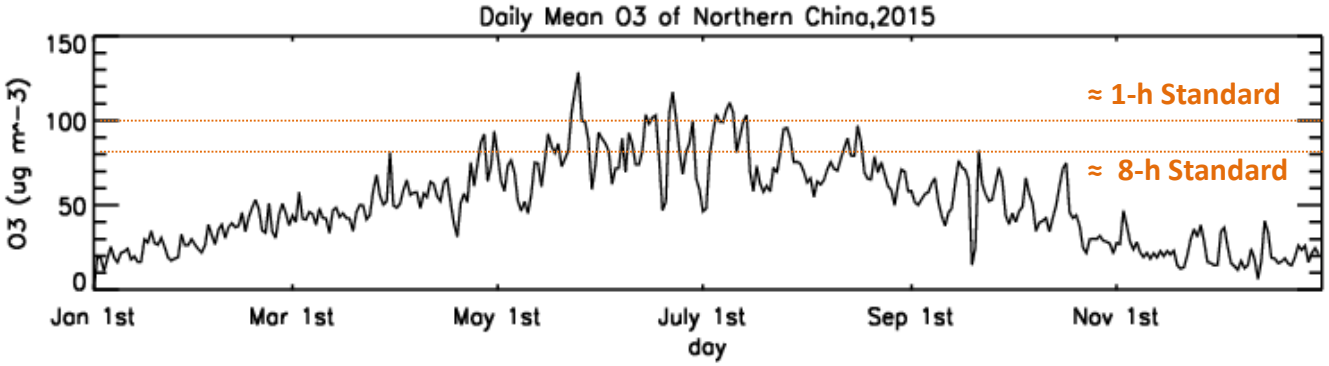
*** Transport and transformation of air pollutants along the pathway

*** Lifetimes of pollutants are the key!

China Is Facing Increasingly Severe Ozone Pollution

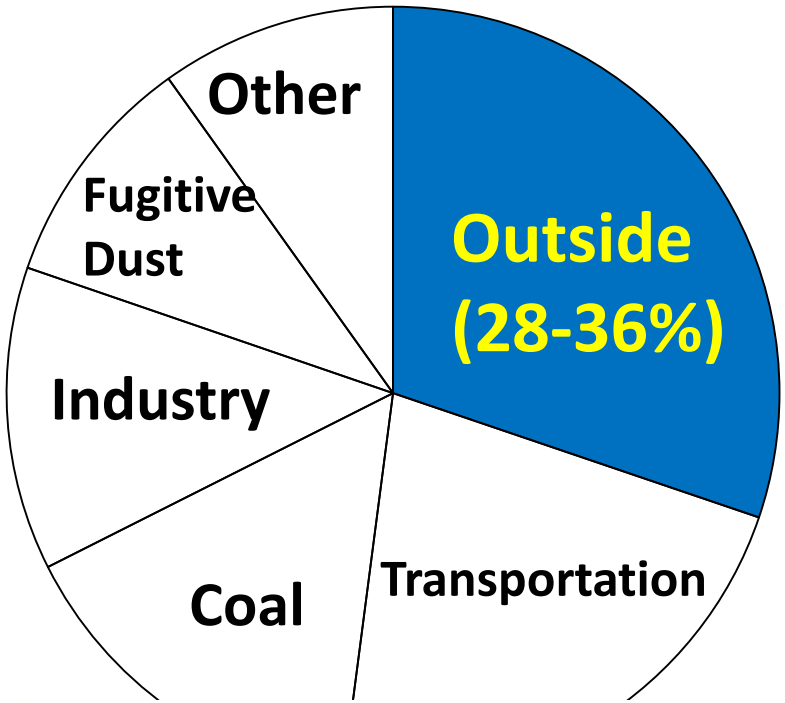
Wang et al., GRL 2006;
Zhang et al., 2007;
Xue et al., ACP, 2014;
Shi et al. AR 2015;
Zhang et al. JGR 2012



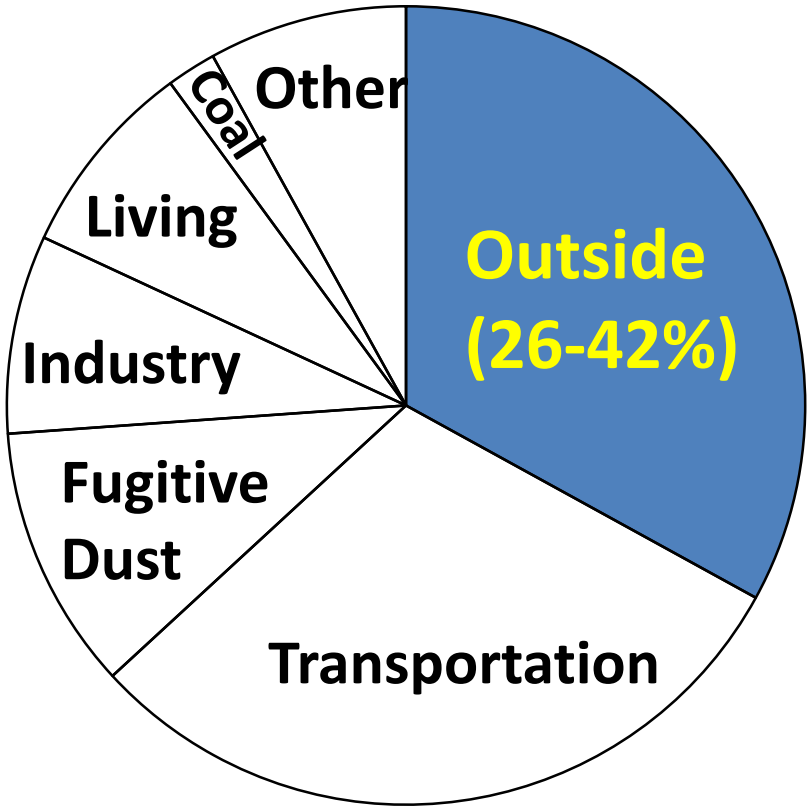


Atmospheric $PM_{2.5}$ Transport Affects Beijing

Sources of Beijing's $PM_{2.5}$ (北京市环保局，2014)



Sources of Beijing's $PM_{2.5}$ (北京市环保局，2018)



区域输送贡献：

- 年平均：26%-42%
- 中度污染（115-150 μg/m³）：34%-50%
- **重污染日（＞150 μg/m³）：55%-75%**

Severe Regional PM Pollution Transport to Beijing

Back-trajectory analysis of BJ's PM on 2014/10/10

Role of Transport and Chemistry in Regional Pollution