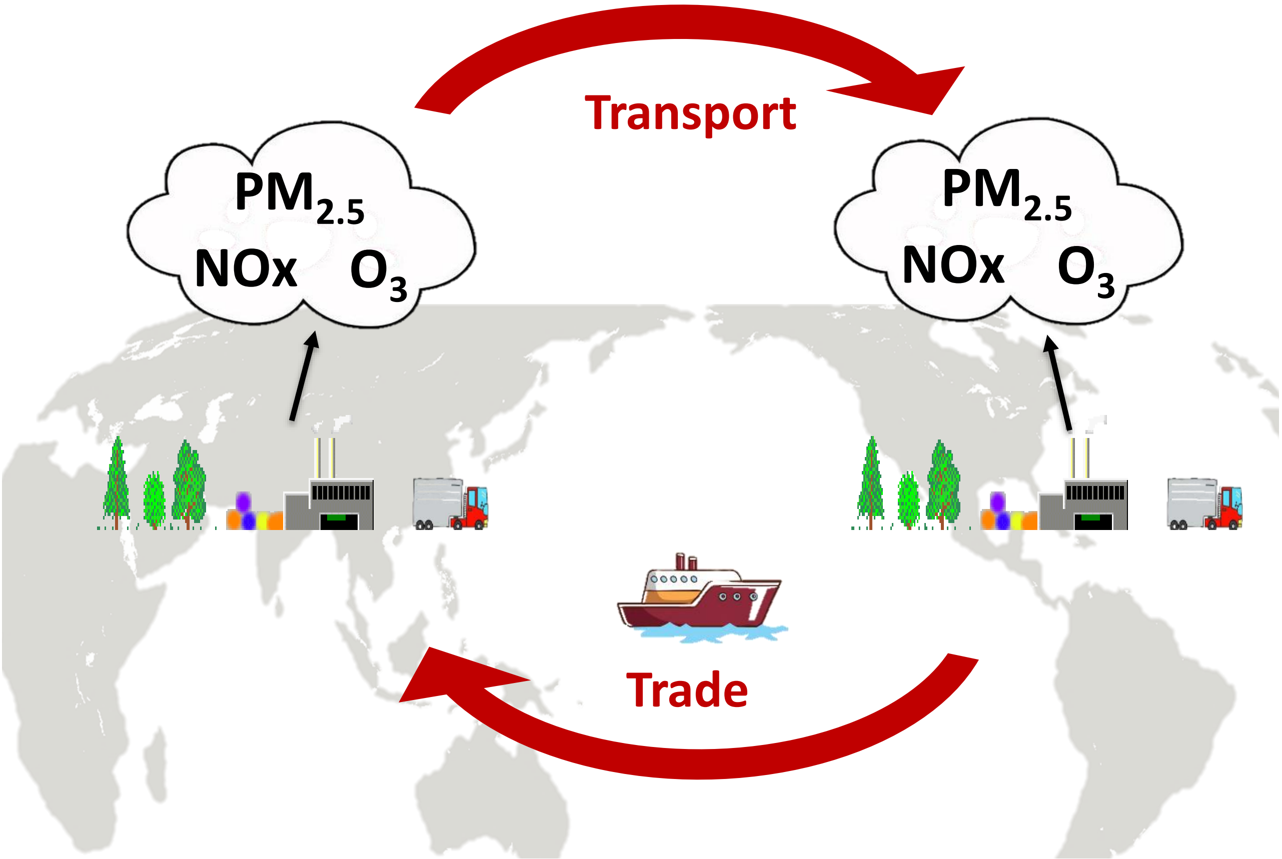
CHAPTER 6

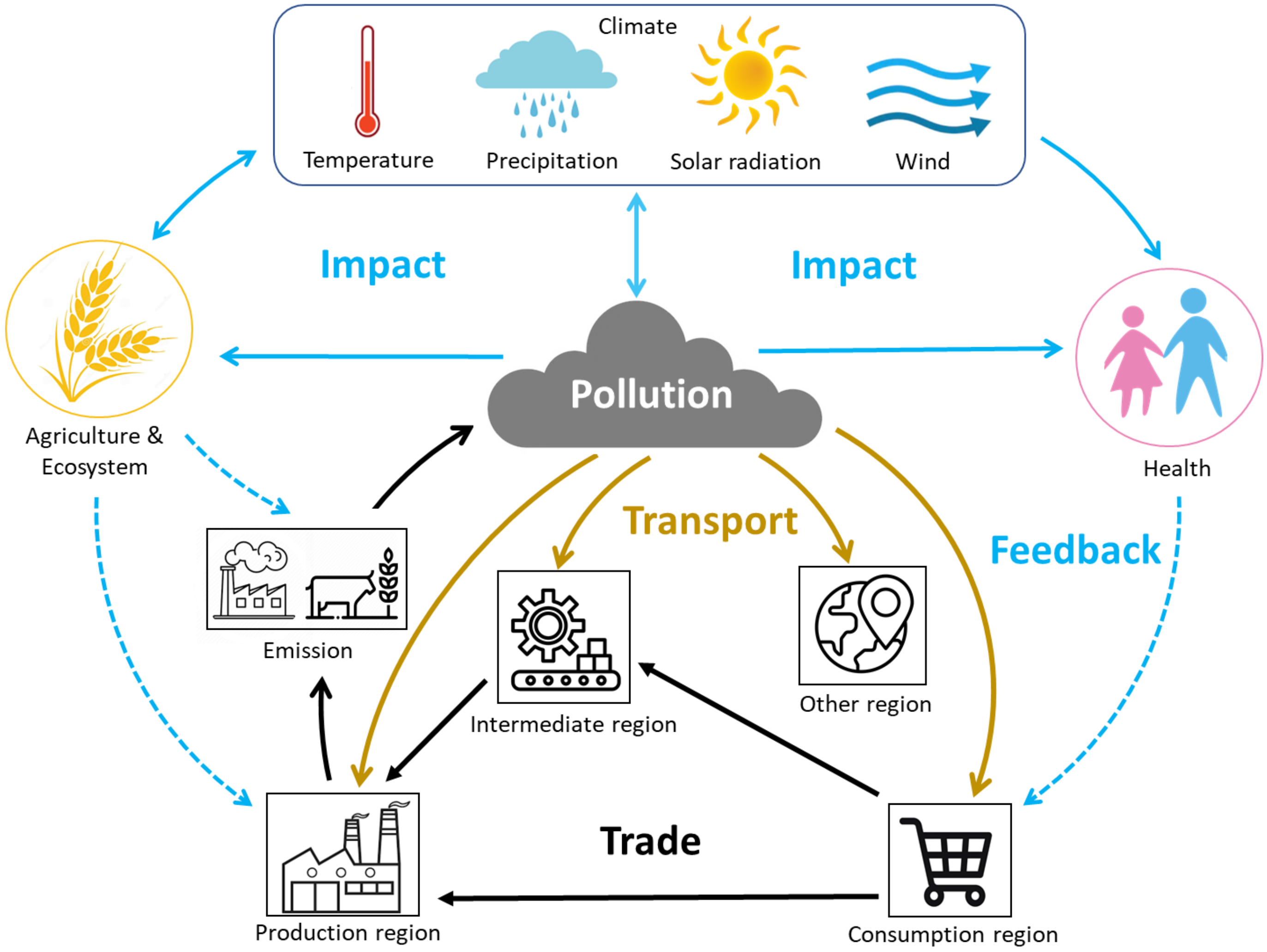
REGIONAL AND GLOBAL TRANSPORT OF AIR POLLUTANTS
&
AIR POLLUTION CONTROL

Globalizing Air Pollution
via Atmospheric Transport, Economic Trade and Their Synergy



Lin JT et al., PNAS 2014; Lin JT et al., Nature Geoscience 2016
Zhang Q et al., Nature 2017; Lin JT et al., Nature Comm. 2019
Wang JX et al., Science Bulletin, 2019; Lin JT et al., Nature Geoscience, 2022
Chen LL et al., Science Bulletin, 2022; Xu JW et al., ACP, 2023, Highlight Paper
Kong H et al., Nature Geoscience, accepted; Lin JT et al., under review

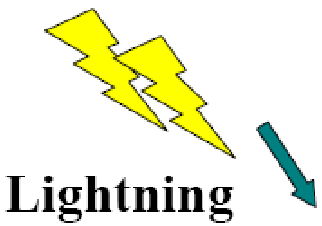
Globalizing Air Pollution



Lin et al., under review

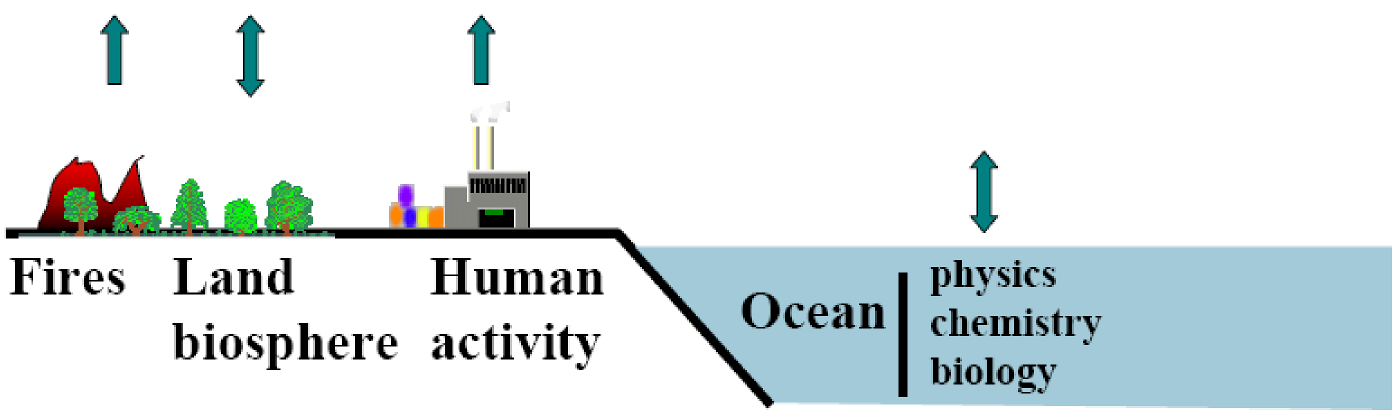
Budget of Air Pollutants

AN ATMOSPHERIC CHEMIST'S VIEW OF THE WORLD



Emis / Dep / Transport & Mixing / Chemistry

$$\frac{\partial C}{\partial t} = E - D - \nabla \cdot C\mathbf{V} - \nabla \cdot \overline{C'\mathbf{V}'} + (P - L)$$



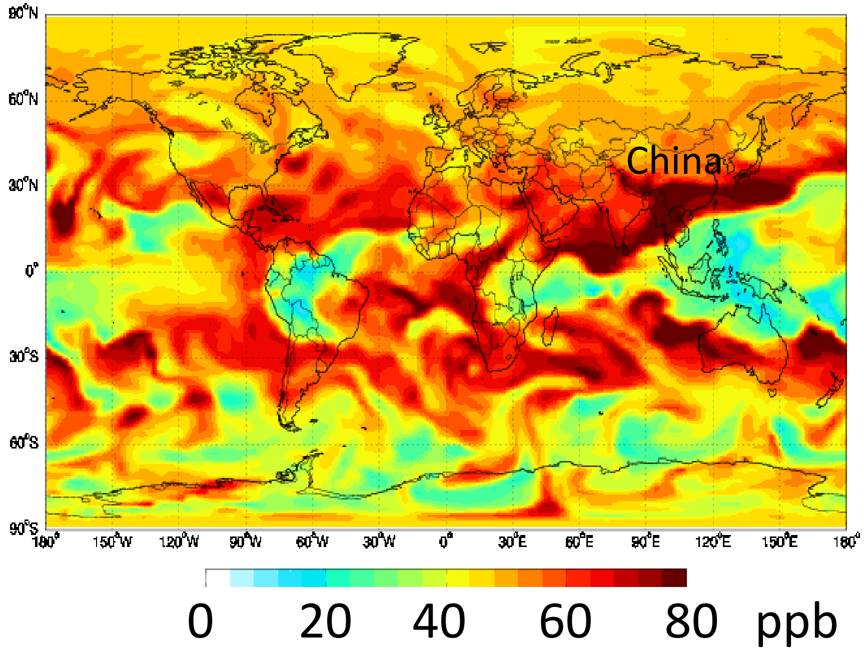
Modified from Don Wuebbles' Lecture

Haze Is Approaching !

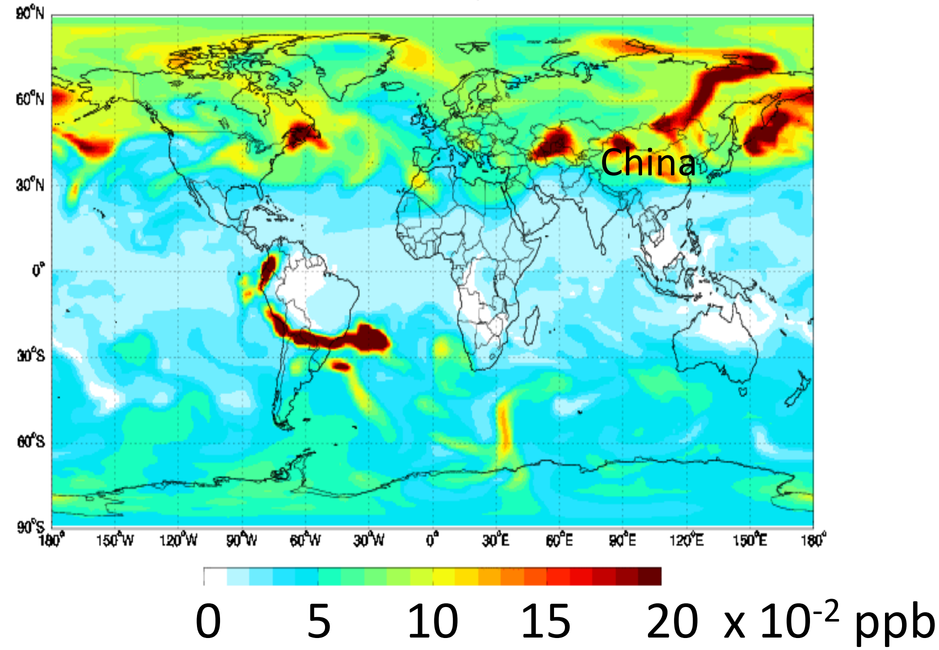
Globalizing Air Pollution: Atmospheric Transport

Simulated by GEOS-Chem Chemical Transport Model

Ozone in Mid-Trop. in Jan 2009



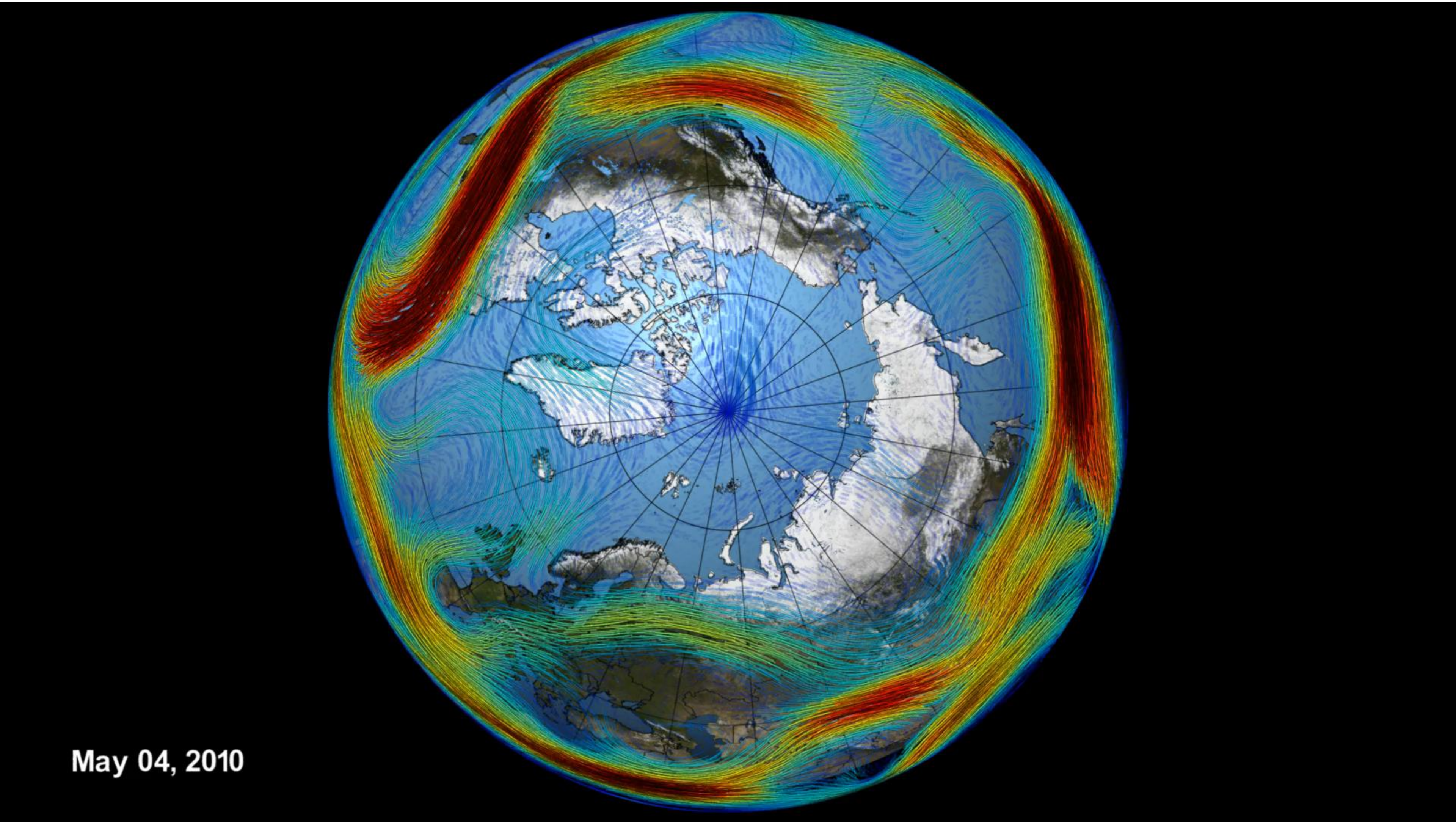
Sulfate in Mid-Trop. in Jan 2009



- **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**

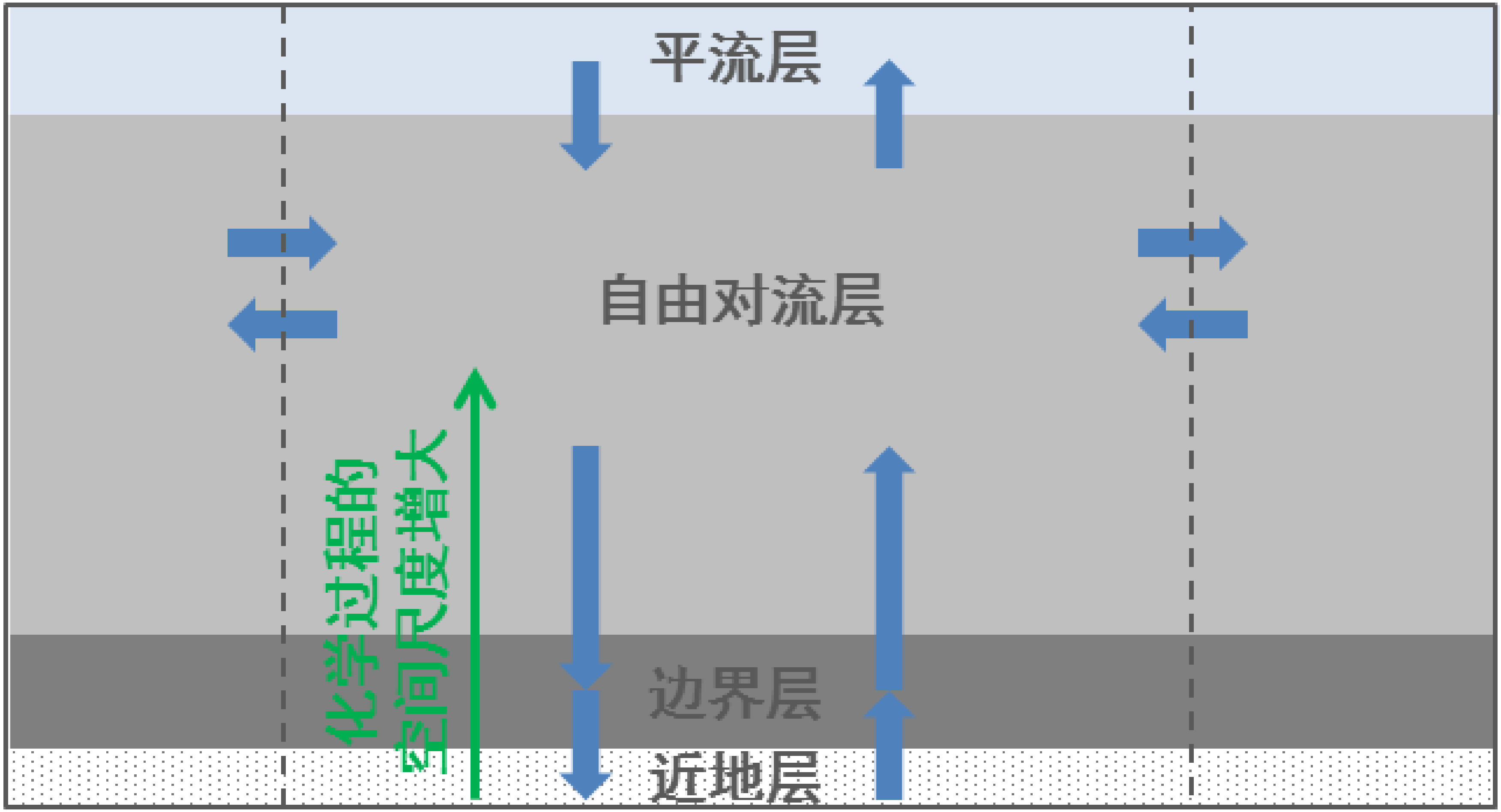
Yan et al., 2014 ACP; 2016 ACP

Atmospheric Circulation



Source: https://svs.gsfc.nasa.gov/4148

Local-Regional-Global Pollution Interconnection



Sources of Air Pollution

- **Local emissions and/or production**
- **Regional transport and transformation**
- **Global transport and transformation**
- **Stratospheric origin, etc.**

❖ **Natural versus anthropogenic sources**

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

➢ **Lifetime of pollutants is the key!**

Spatiotemporal Scale of Atmospheric Motion (Transport)

Larger than	Scale	Name
20,000 km (weeks)		Planetary scale
2,000 km (1 week)		Synoptic scale
200 km (1 day)	Meso-α	Mesoscale
20 km (hours)	Meso-β	Mesoscale
2 km (mins)	Meso-γ	Mesoscale (convection)
200 m (mins)	Micro-α	Boundary-layer turbulence
20 m (secs)	Micro-β	Surface-layer turbulence
2 m (secs)	Micro-γ	Inertial subrange turbulence
2 mm (secs)	Micro-δ	Fine-scale turbulence
Air molecules (< 1 sec)	Molecular	Viscous dissipation subrange

Characteristic Distance of Transport

- **Primary Pollutant:**

  $$D = U \times \tau = \text{Wind Speed} \times \text{Lifetime}$$

- **Secondary Pollutant:**

  $$D = U \times \tau^*, \text{ where } \quad \tau_s < \tau^* < \tau_p + \tau_s$$

τ^*: Characteristic time

τ_p: Lifetime of primary pollutants in conversion to secondary pollutants

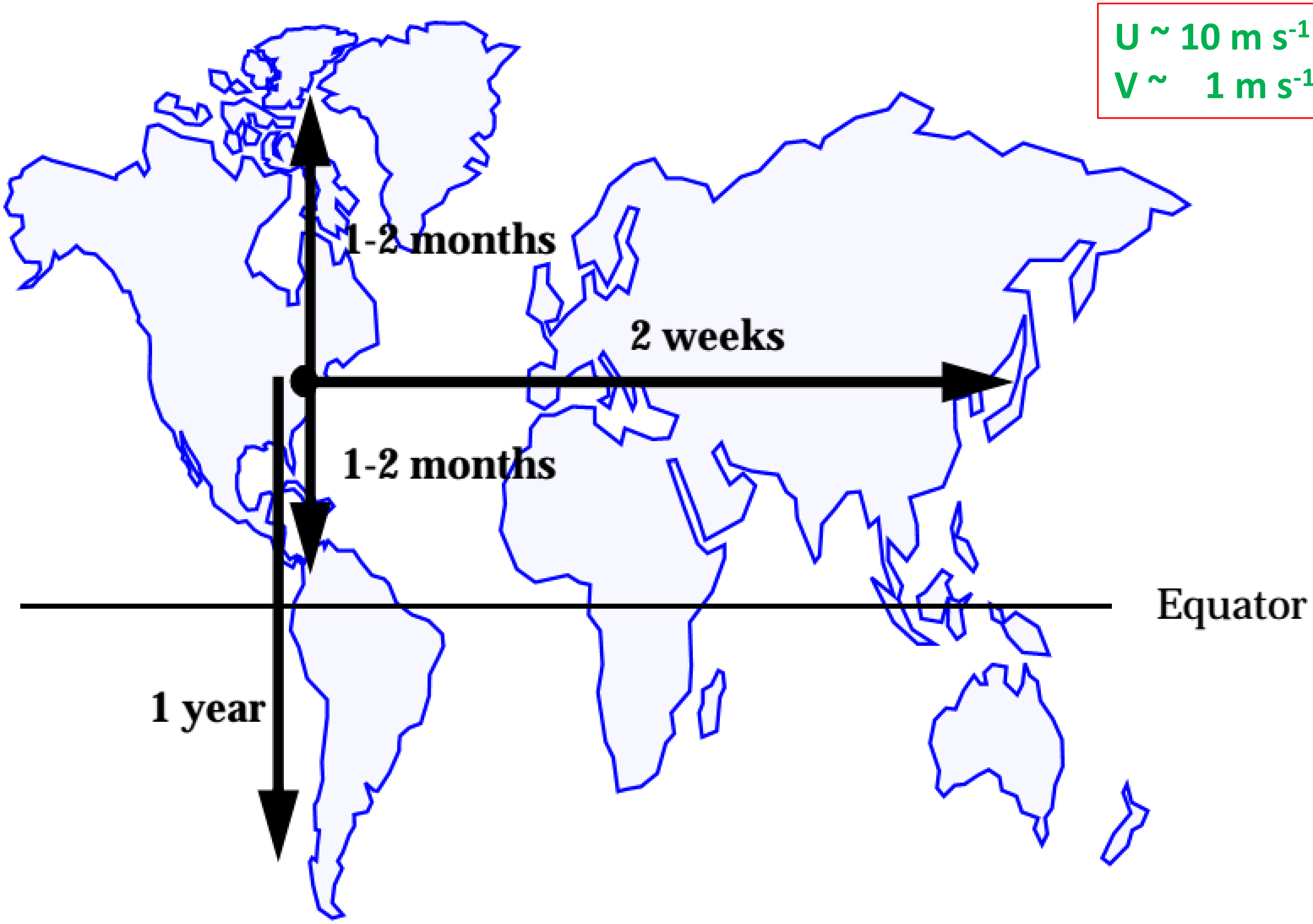
τ_s: Lifetime of secondary pollutants

e.g., Emission → [SO_2] → [SO_4] → deposition

Recall: Emission of NO → [NO] → [NO_x] → [NO_z] ?

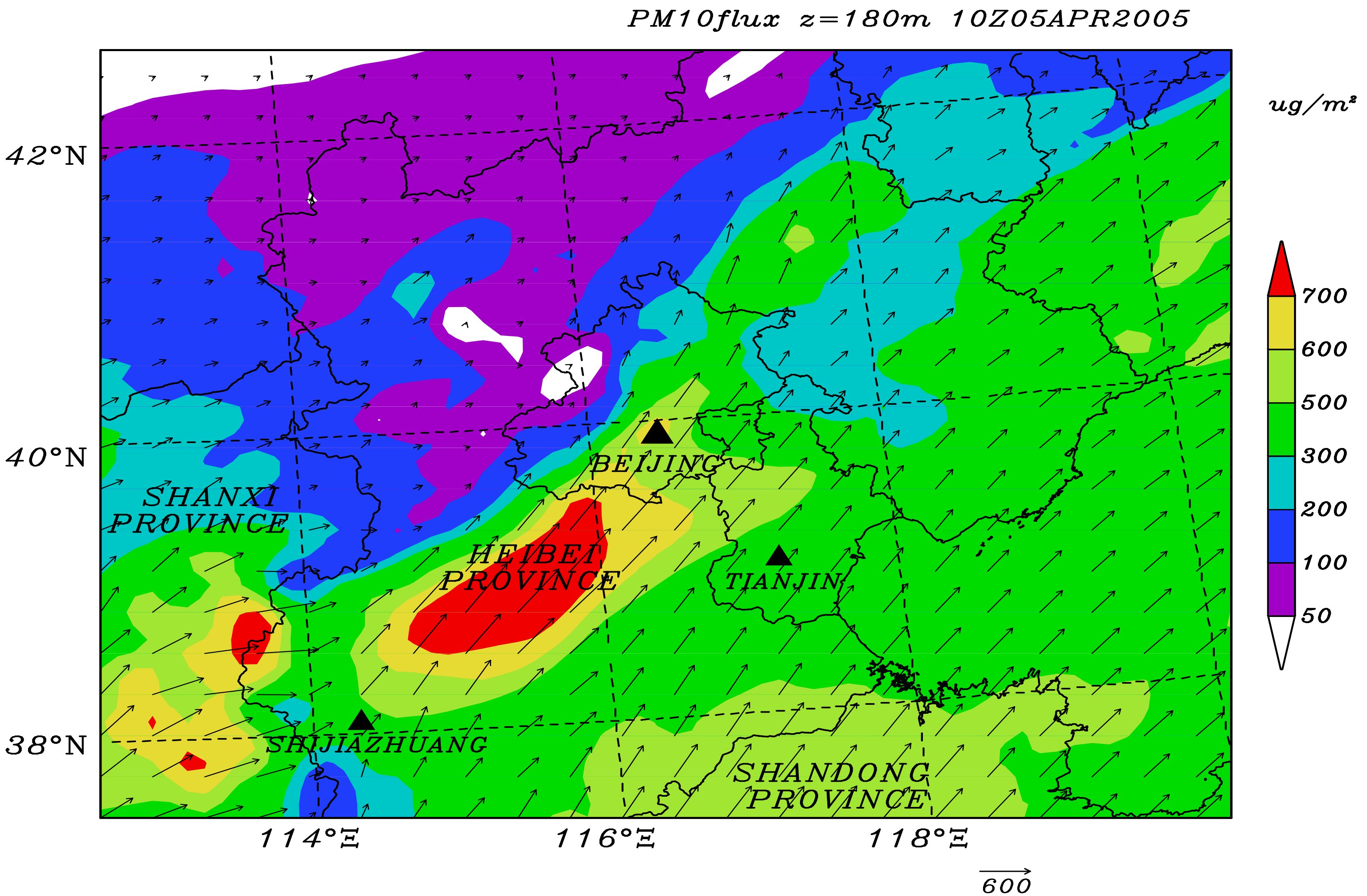
Characteristic Time Scales of Horizontal Transport

U ~ 10 m s^{-1}
V ~ 1 m s^{-1}



Jacob, 1999

Regional Transport and Transformation Affecting Beijing



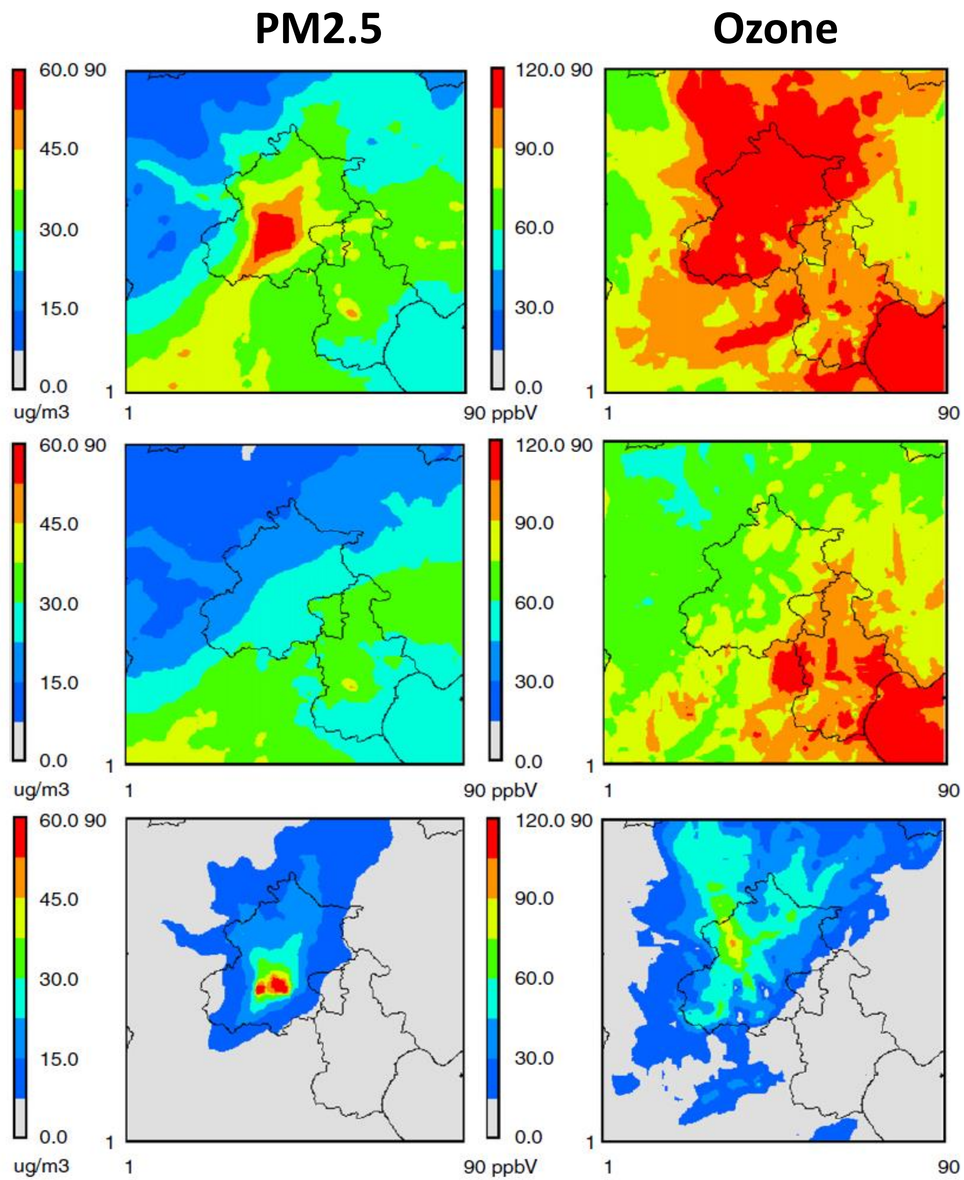
An et al., ACP 2007

Regional Transport and Transformation Affecting Beijing

Total

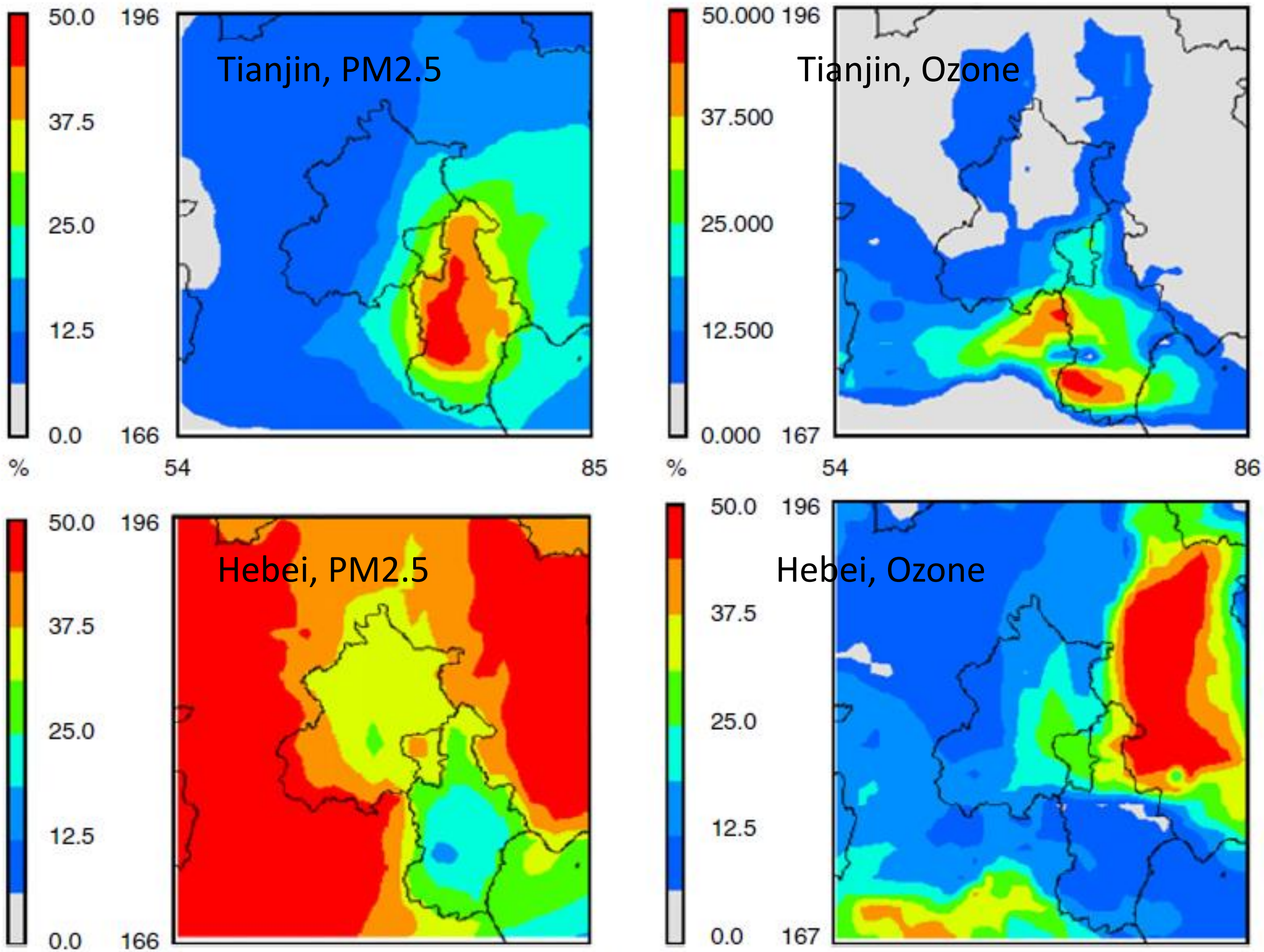
Transported

Total – Transported
[Local + nonlinearity]



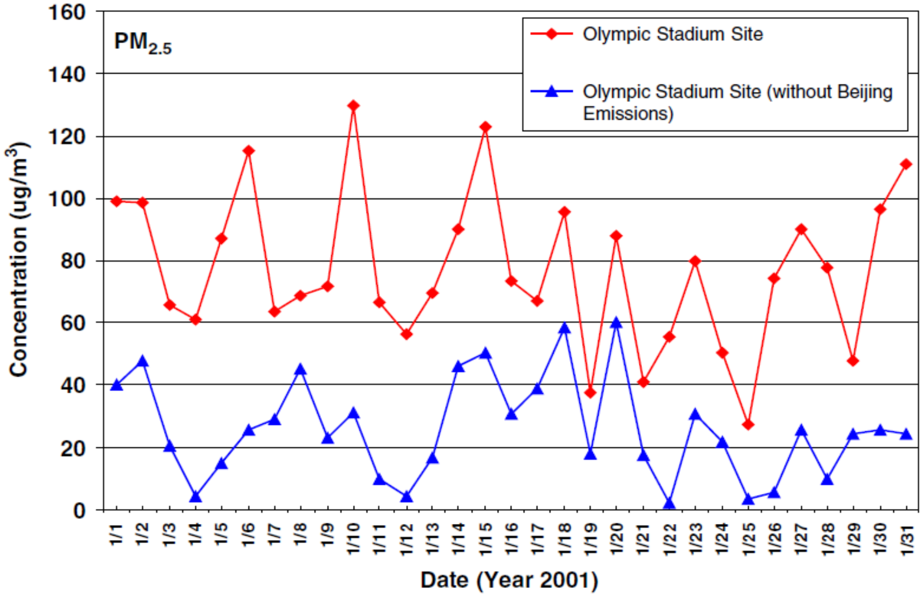
An et al., ACP 2007

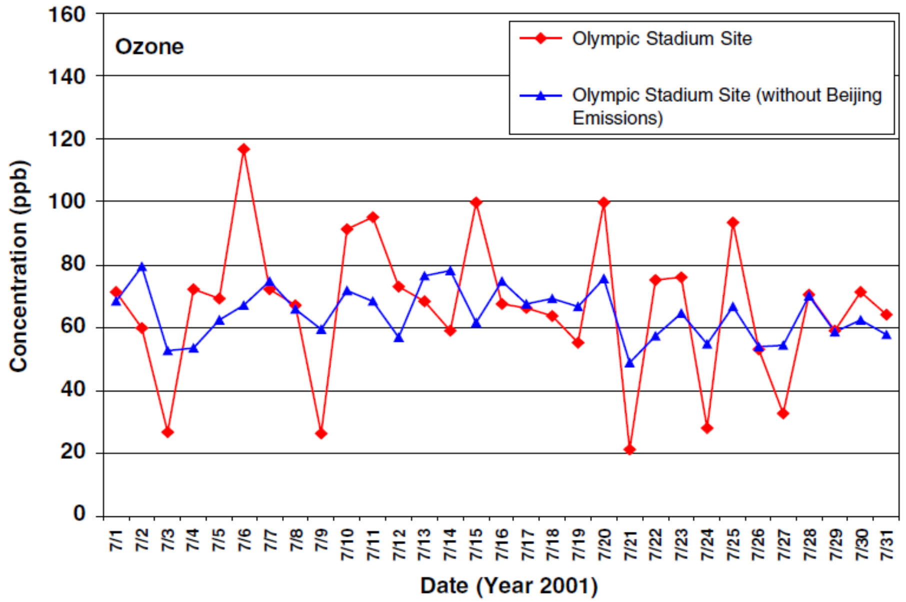
Regional Transport and Transformation Affecting Beijing



An et al., ACP 2007

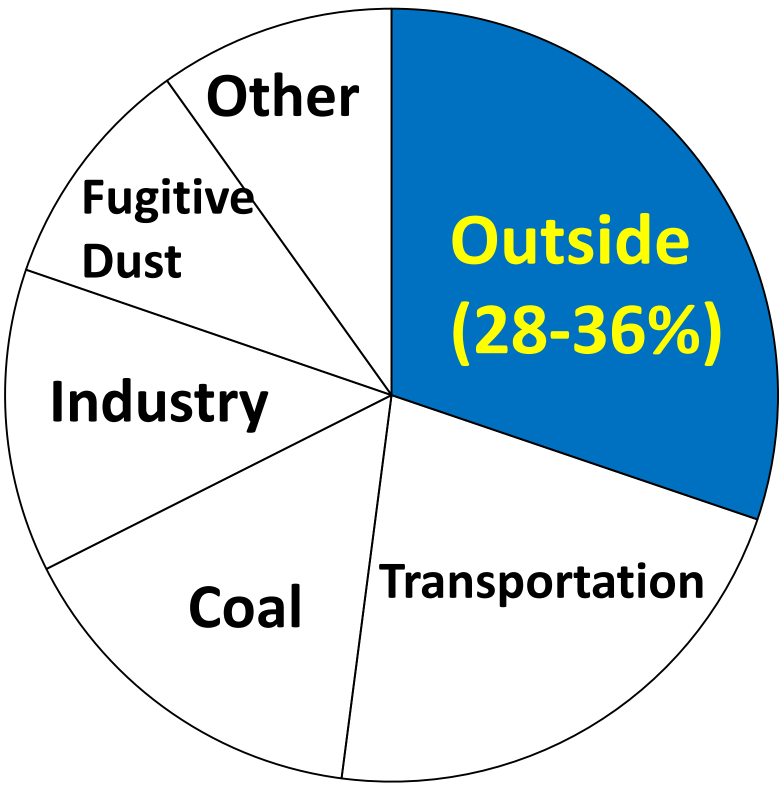
Regional Transport and Transformation Affecting Beijing



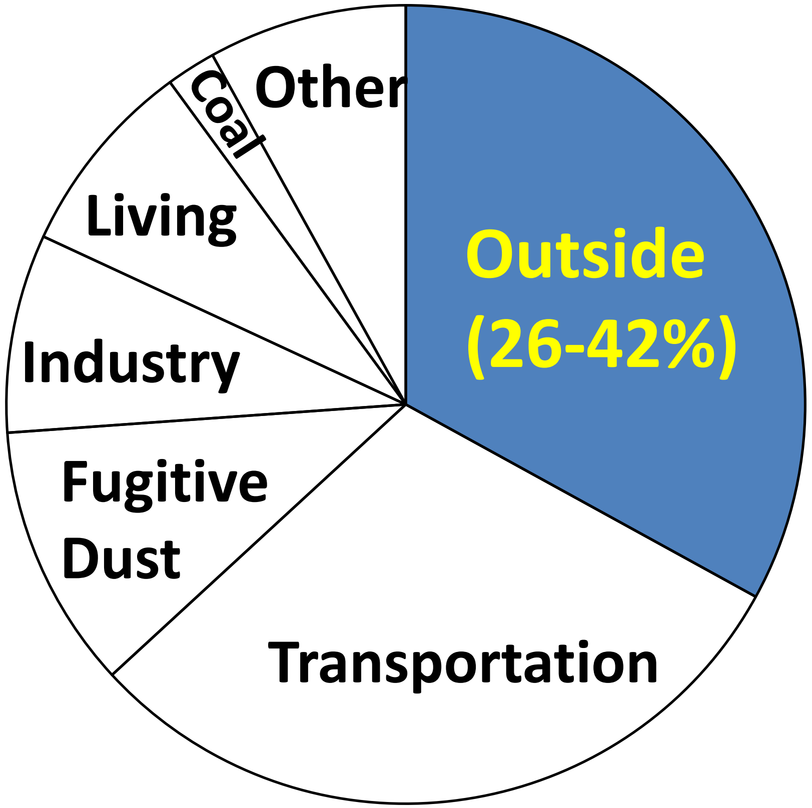


Atmospheric $PM_{2.5}$ Transport Affects Beijing

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



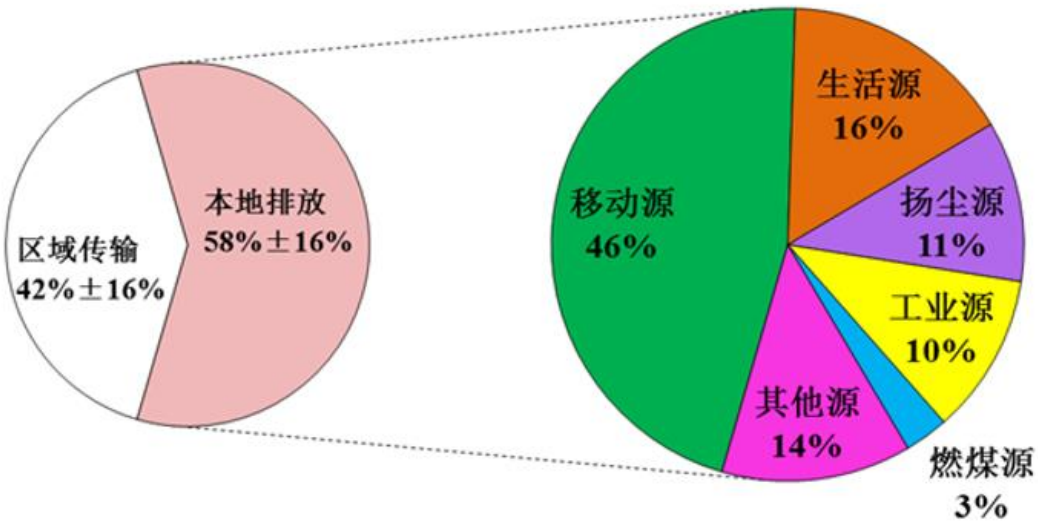
Sources of Beijing's $PM_{2.5}$
(北京市环保局，2018)

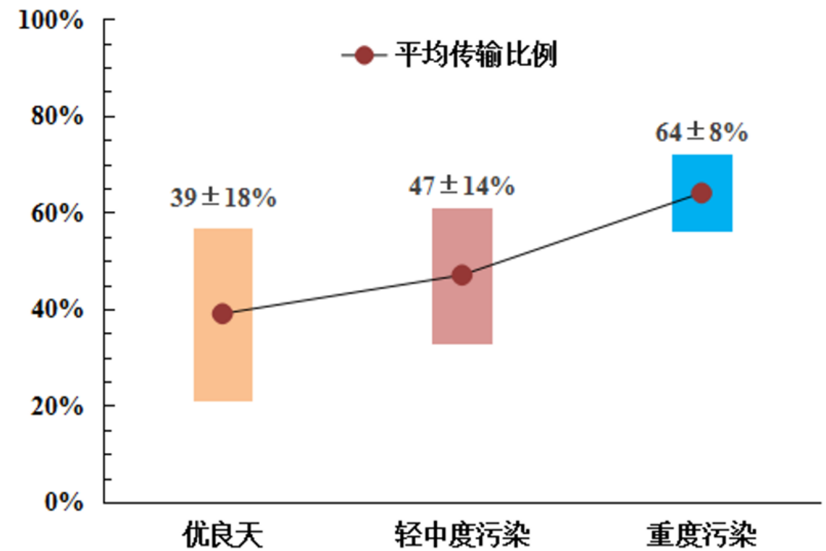


区域输送贡献：
- 年平均：26%-42%
- 中度污染（115-150 μg/m^3）：34%-50%
- 重污染日（＞150 μg/m^3）：55%-75%

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)





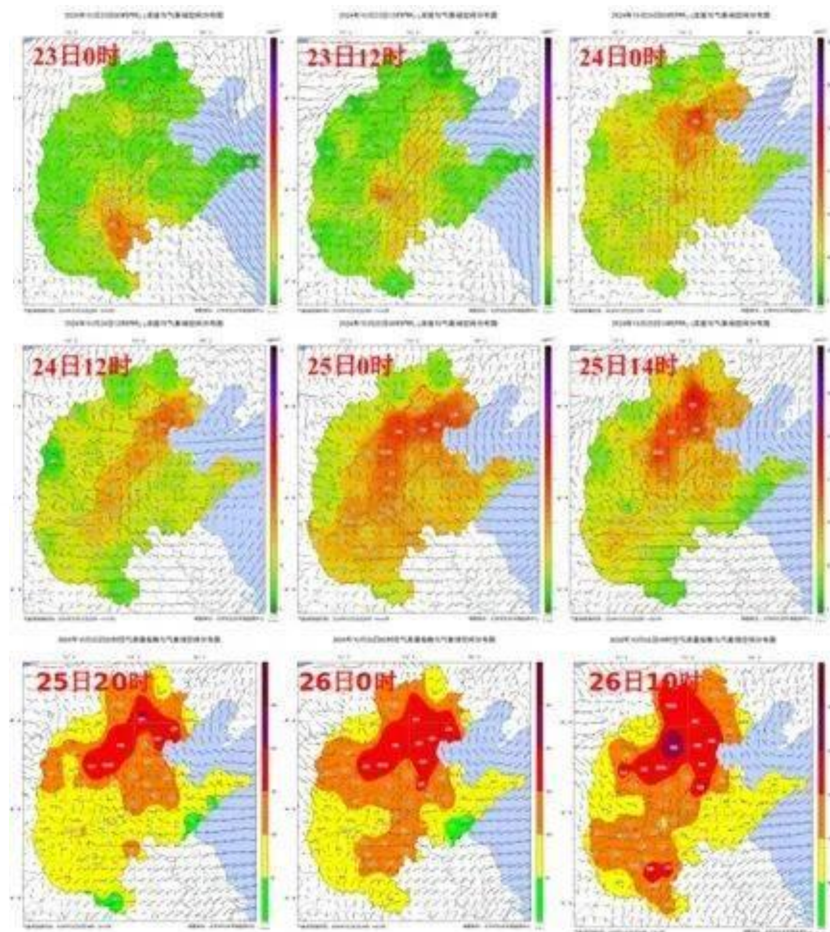
- ✓ 32±4% in 2014 (第一轮)
- ✓ 34±8% in 2018 (第一轮)
- ✓ 42±16% in 2021 (第一轮)

Severe Regional PM Pollution Transport to Beijing

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

Severe Regional PM Pollution Transport to Beijing

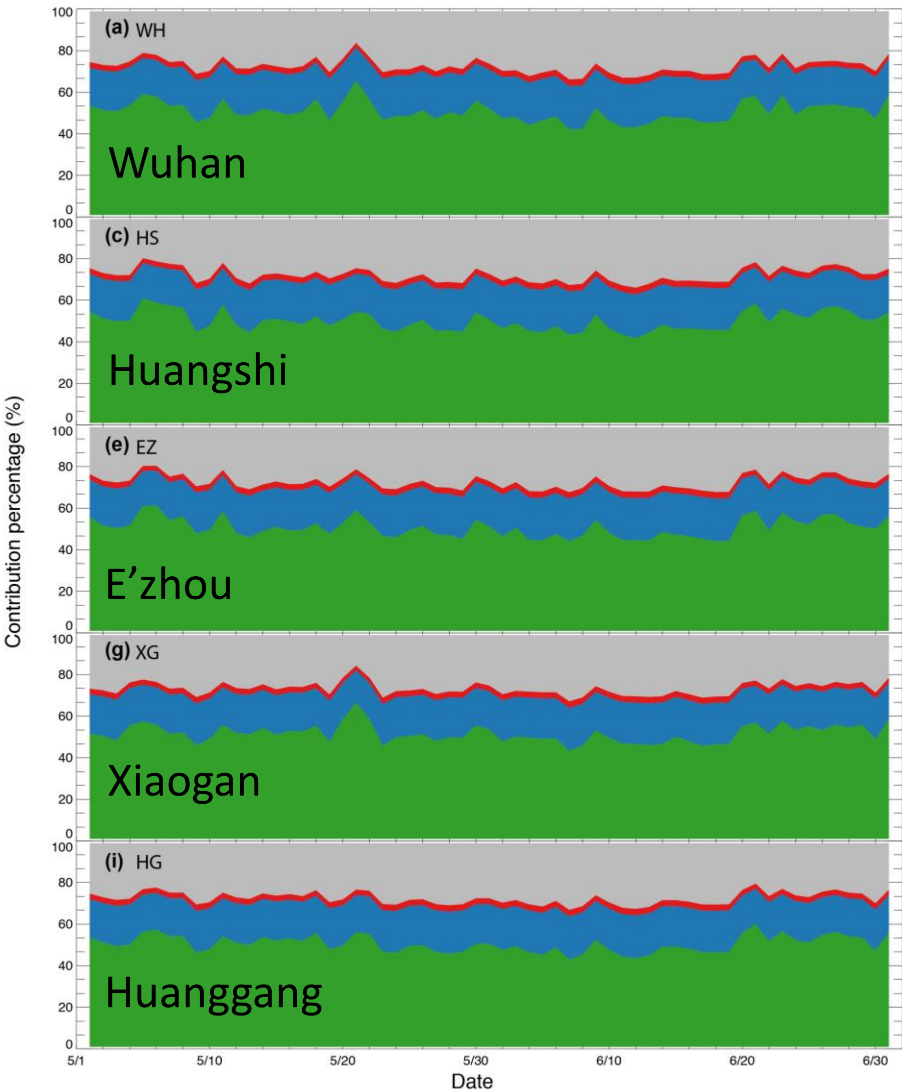
Transport-driven growth of BJ's PM on 2024/10/26



10月24日13时-26日14时，区域传输贡献77%，其中东南通道35%，西南通道18%，东南通道占据主导。

https://www.sohu.com/a/820625924_204474

Key Roles of Local Production and Atmospheric Transport for Ozone Pollution over Central China

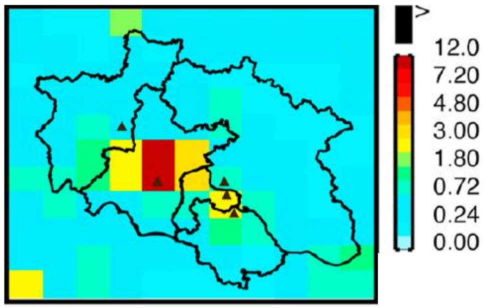


Yan YY et al., 2021, AE

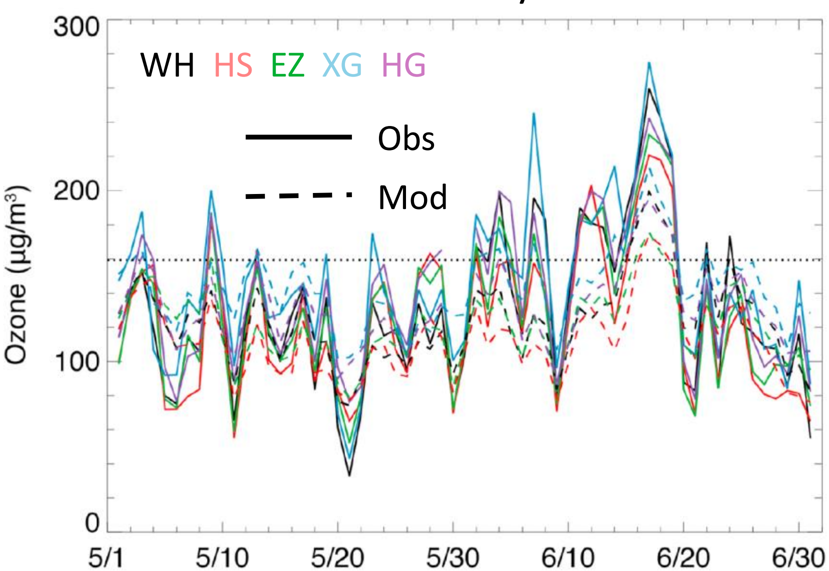
Contributors:

- ✓ Local emis
- ✓ Cross-city
- ✓ Asian BG
- ✓ Global BG

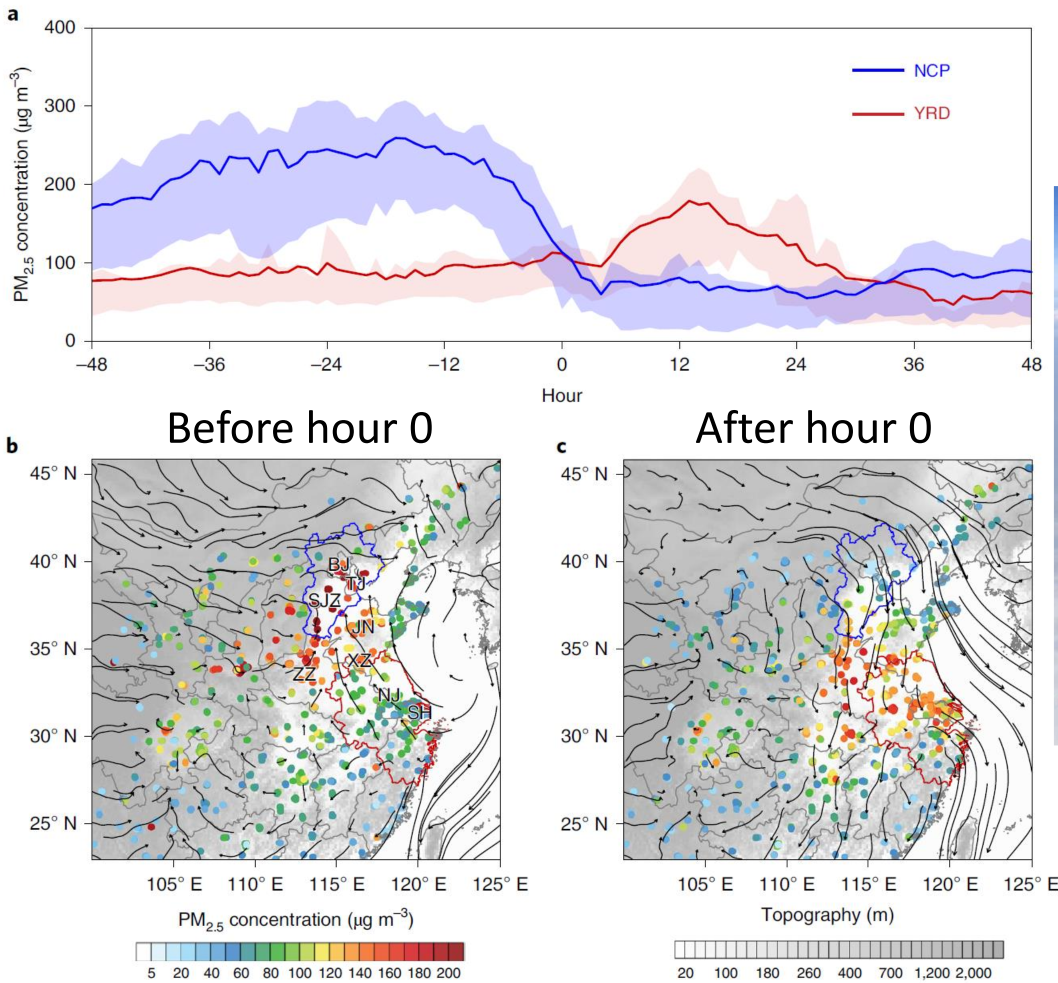
Anthro NOx emis (g/m^2)

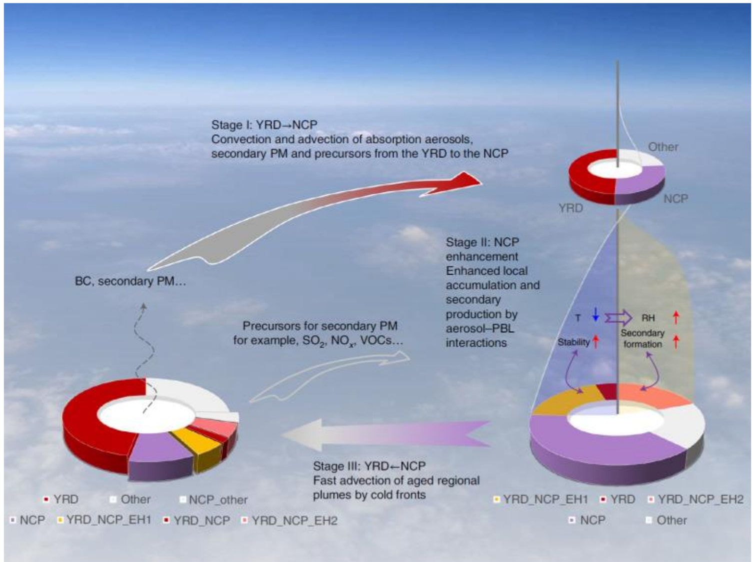


MDA8 ozone in May-June 2018



Two-way Transport of $PM_{2.5}$ Between NCP and YRD

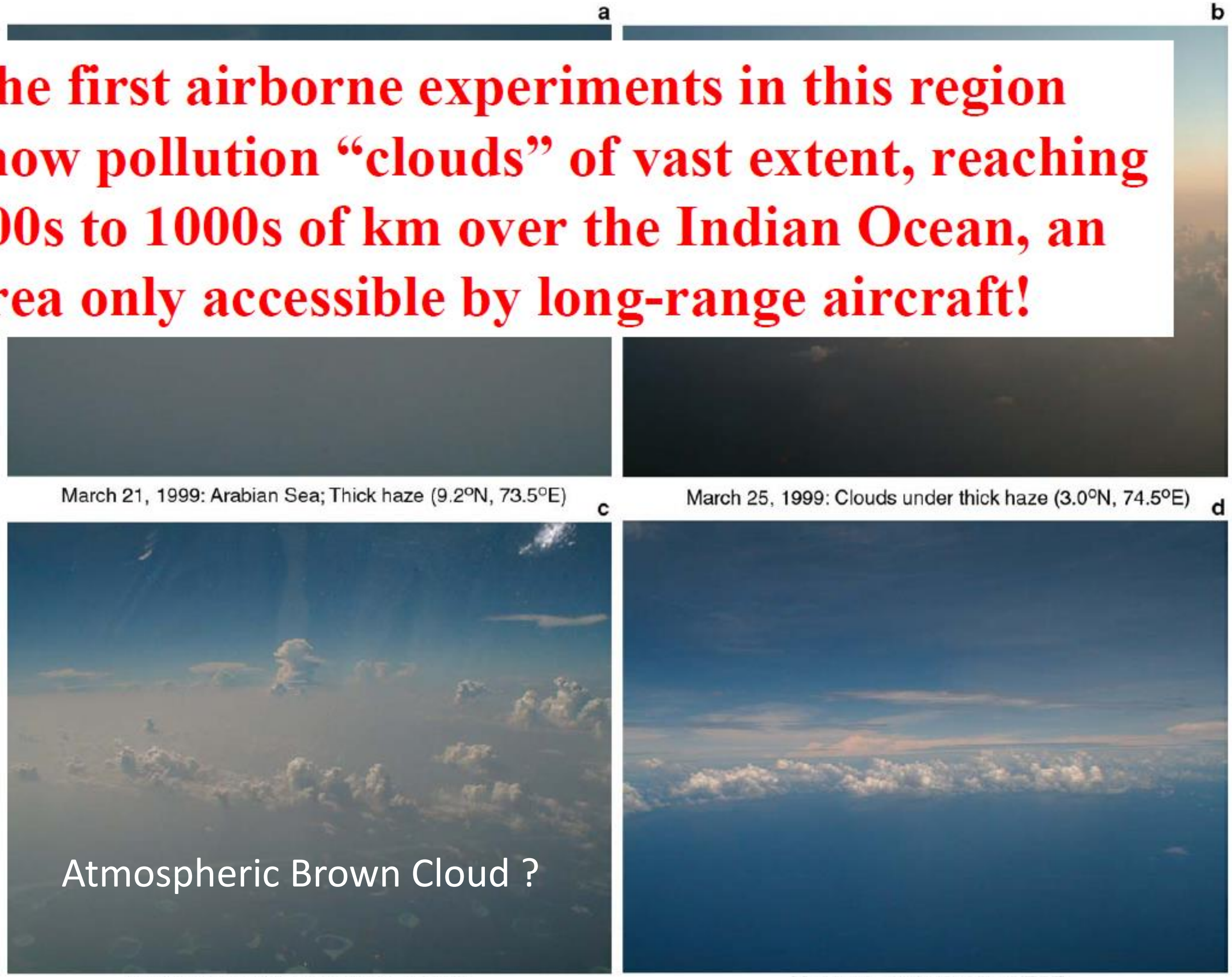




Huang et al., 2020, Nature Geoscience

Long-range Transport of Asian PM to the Tropics

The first airborne experiments in this region show pollution "clouds" of vast extent, reaching 100s to 1000s of km over the Indian Ocean, an area only accessible by long-range aircraft!



March 21, 1999: Arabian Sea; Thick haze (9.2ºN, 73.5ºE)

March 25, 1999: Clouds under thick haze (3.0ºN, 74.5ºE)

February 24, 1999: Just North of ITCZ;
Haze extends up to top of Cu (0.5ºN, 73.3ºE)

March 24, 1999: South of ITCZ;
Almost pristine clouds (7.5ºS, 73.5ºE)

Photo credit: Center for Clouds, Chemistry and Climate; Scripps Institution of Oceanography; University of California, San Diego
Image available at: http://sio.ucsd.edu/supp_groups/siocomm/pressreleases/Indoexagu.html

Pathways and Time of Trans-Pacific Transport

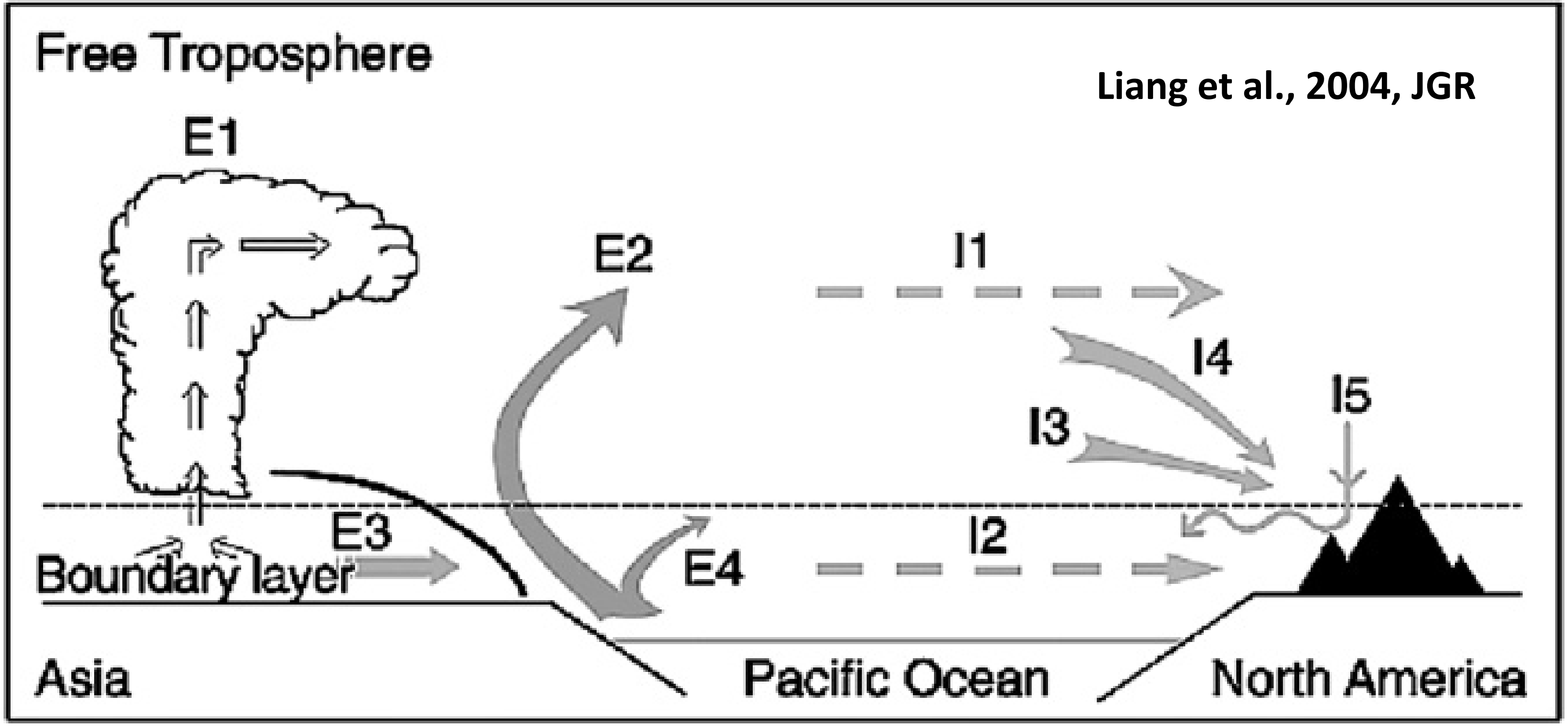
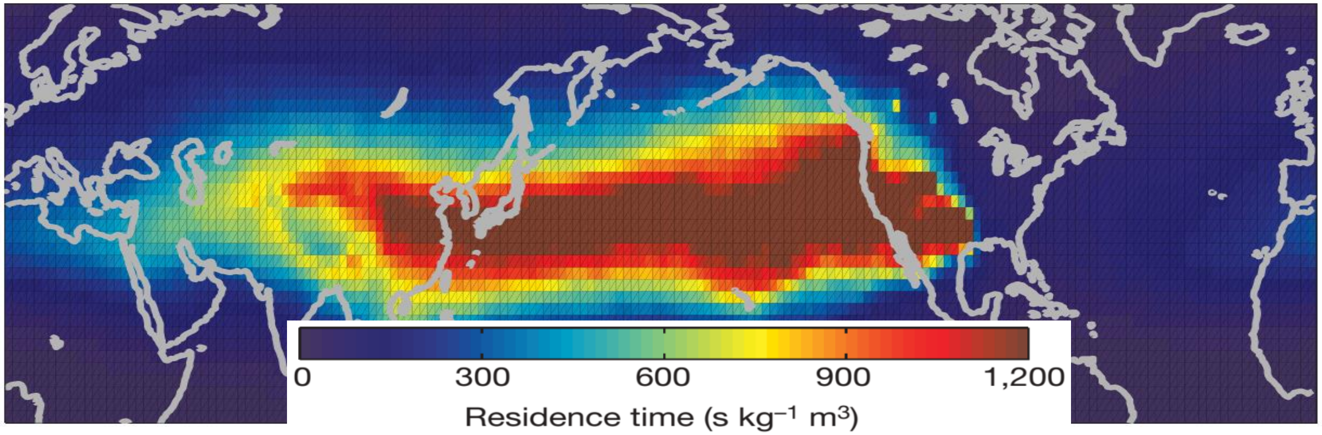


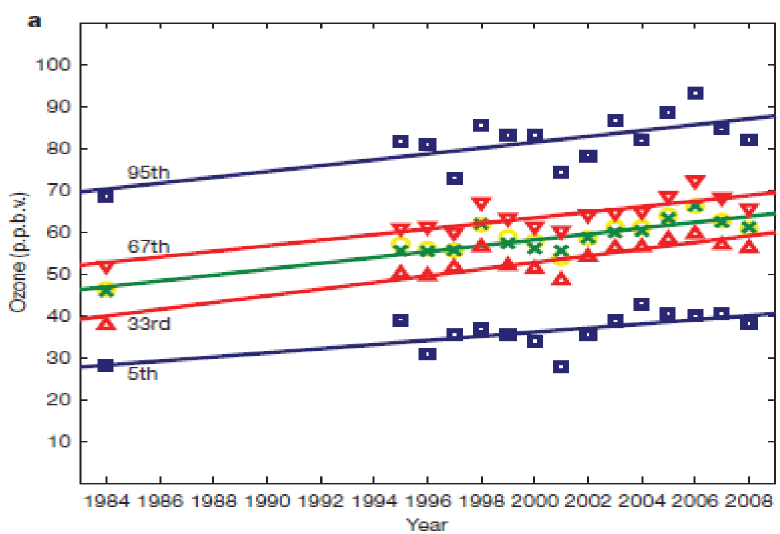
Table 1. 11-Year Average Inter-Continental Transport Times for Two Sets of Tracers in April (Unit: Weeks)

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

Atmospheric O_3 Transport from China to U.S.

Cooper et al., 2010, Nature





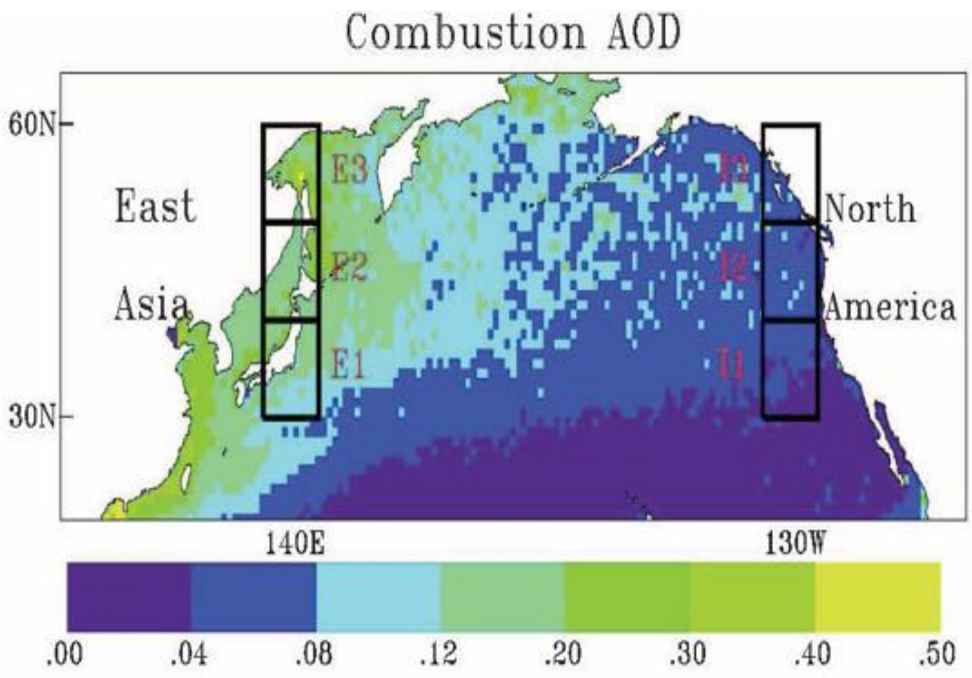
Percentile	1995–2008 increase (p.p.b.v. yr^{-1})	*P*
95th	0.56 ± 0.71	0.11
67th	0.62 ± 0.39	0.00
50th	0.63 ± 0.34	0.00
33rd	0.64 ± 0.35	0.00
5th	0.48 ± 0.53	0.07

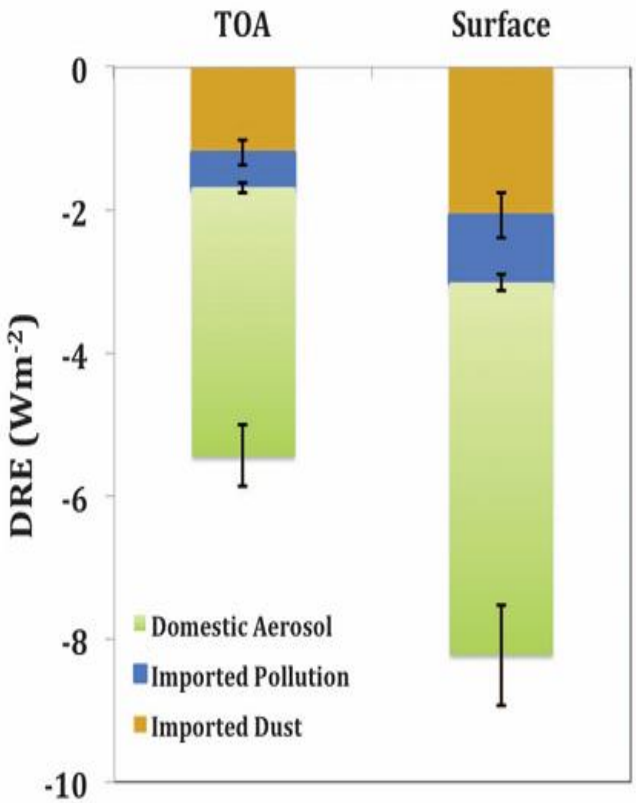
Percentile	1984–2008 increase (p.p.b.v. yr^{-1})	*P*
95th	0.70 ± 0.45	0.01
67th	0.67 ± 0.25	0.00
50th	0.70 ± 0.22	0.00
33rd	0.80 ± 0.24	0.00
5th	0.49 ± 0.34	0.01

Asian PM Transport Affects North America

Yu et al., 2012, Science

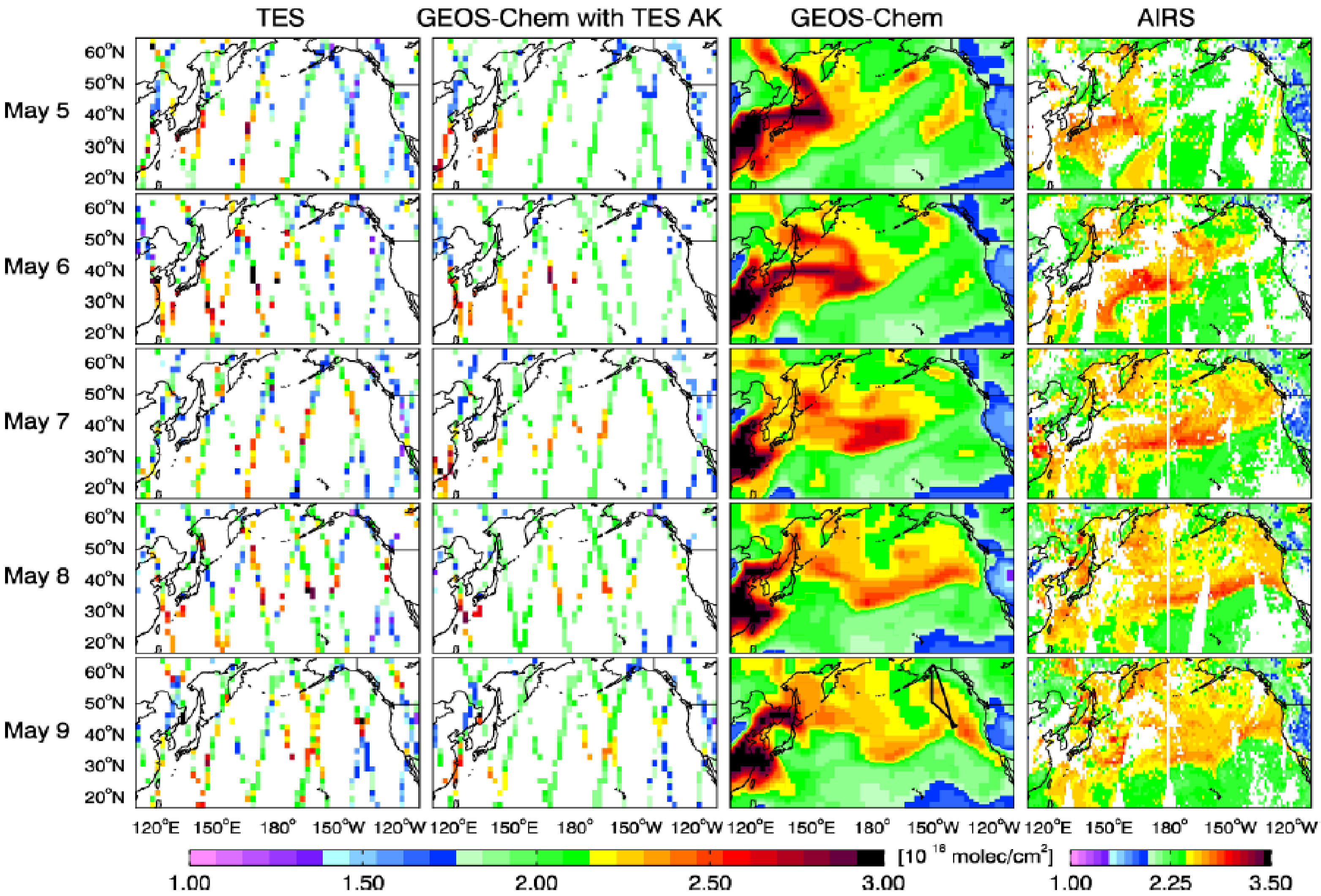
- East Asian PM pollution contributes 6% of N.A. DRE





East Asian Influence: Satellite Obs. and CTMs

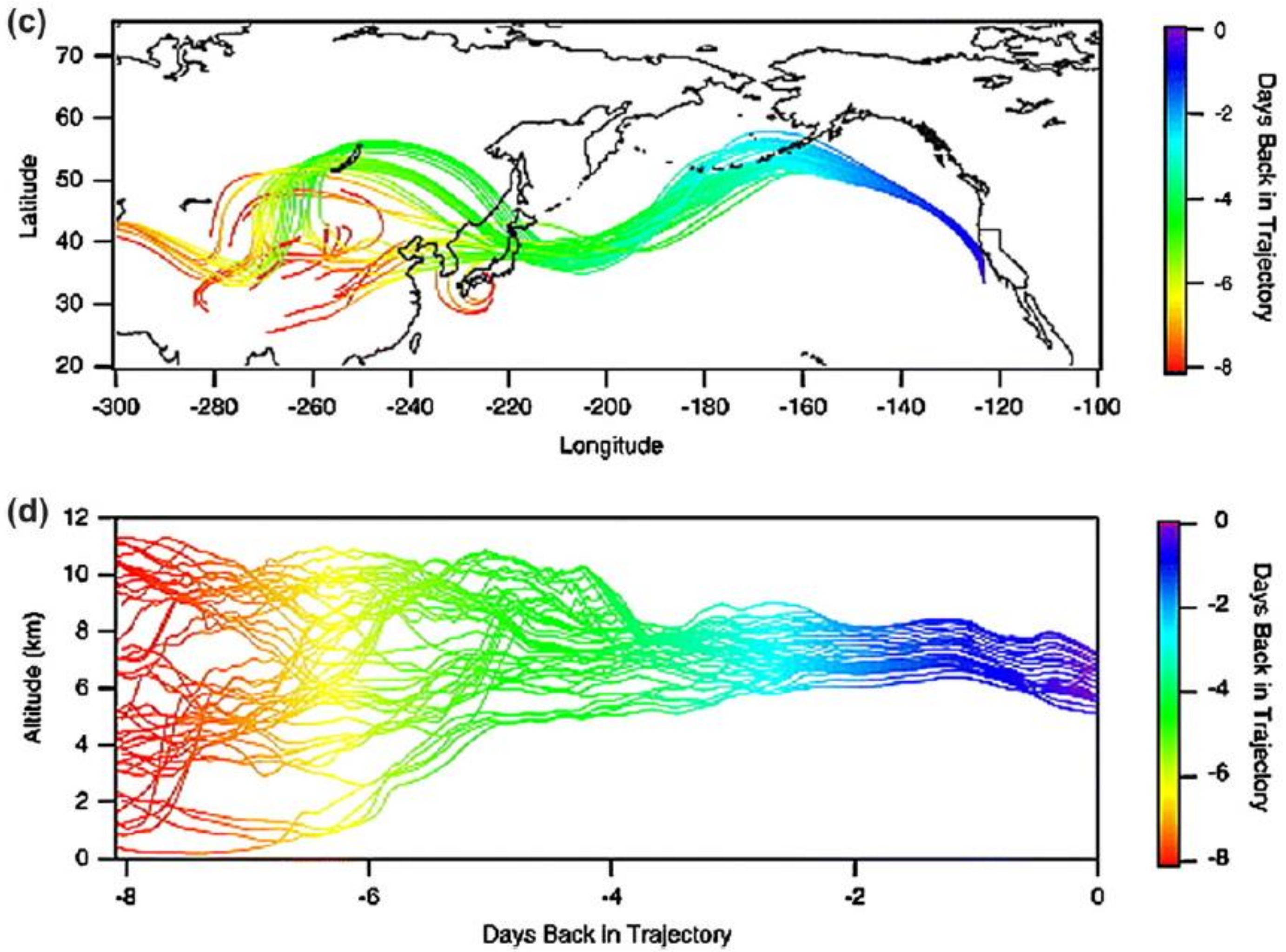
Carbon Monoxide



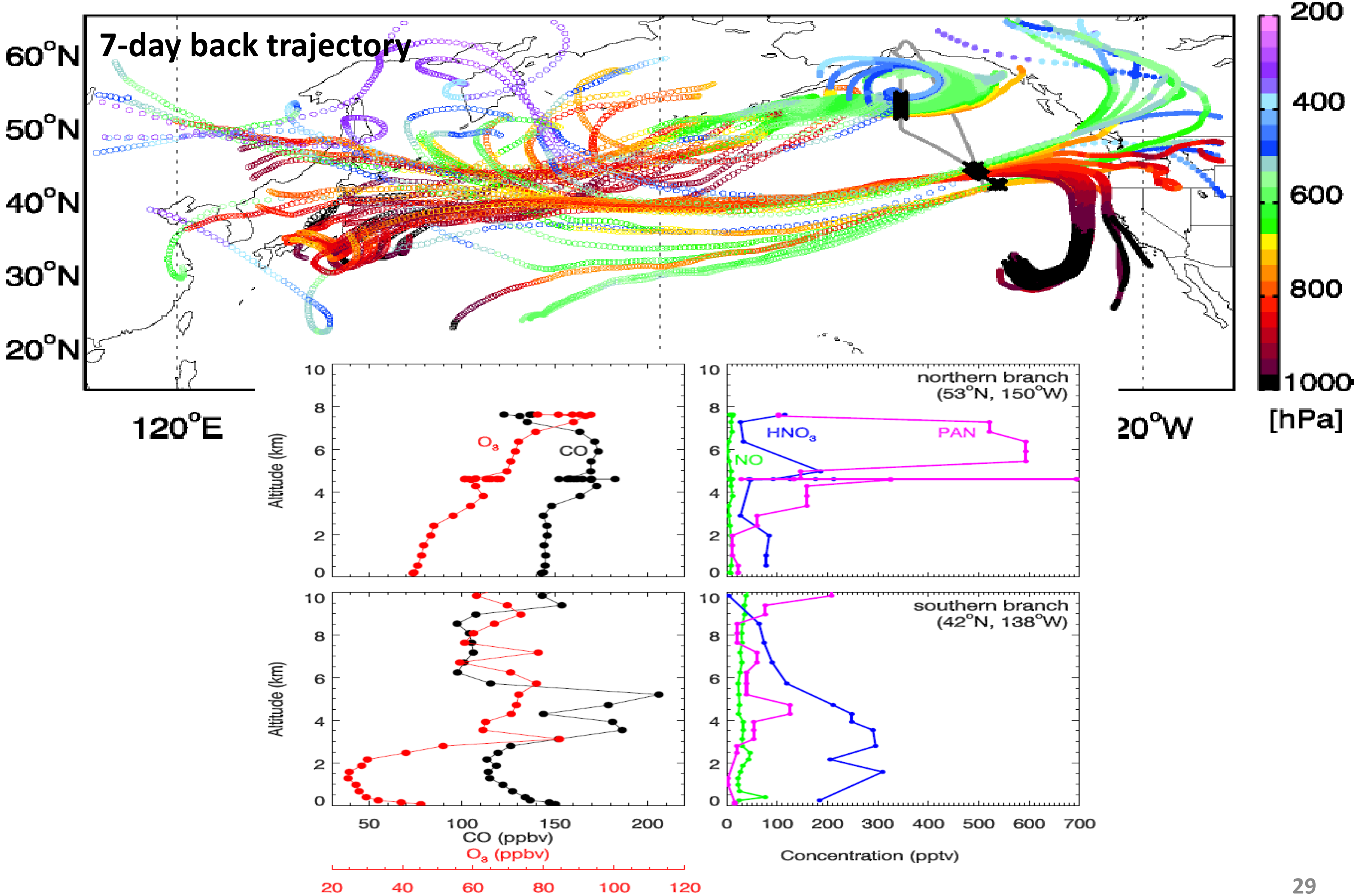
Zhang et al., 2008, ACP

Asian Influence: Back Trajectory Analysis

Ozone



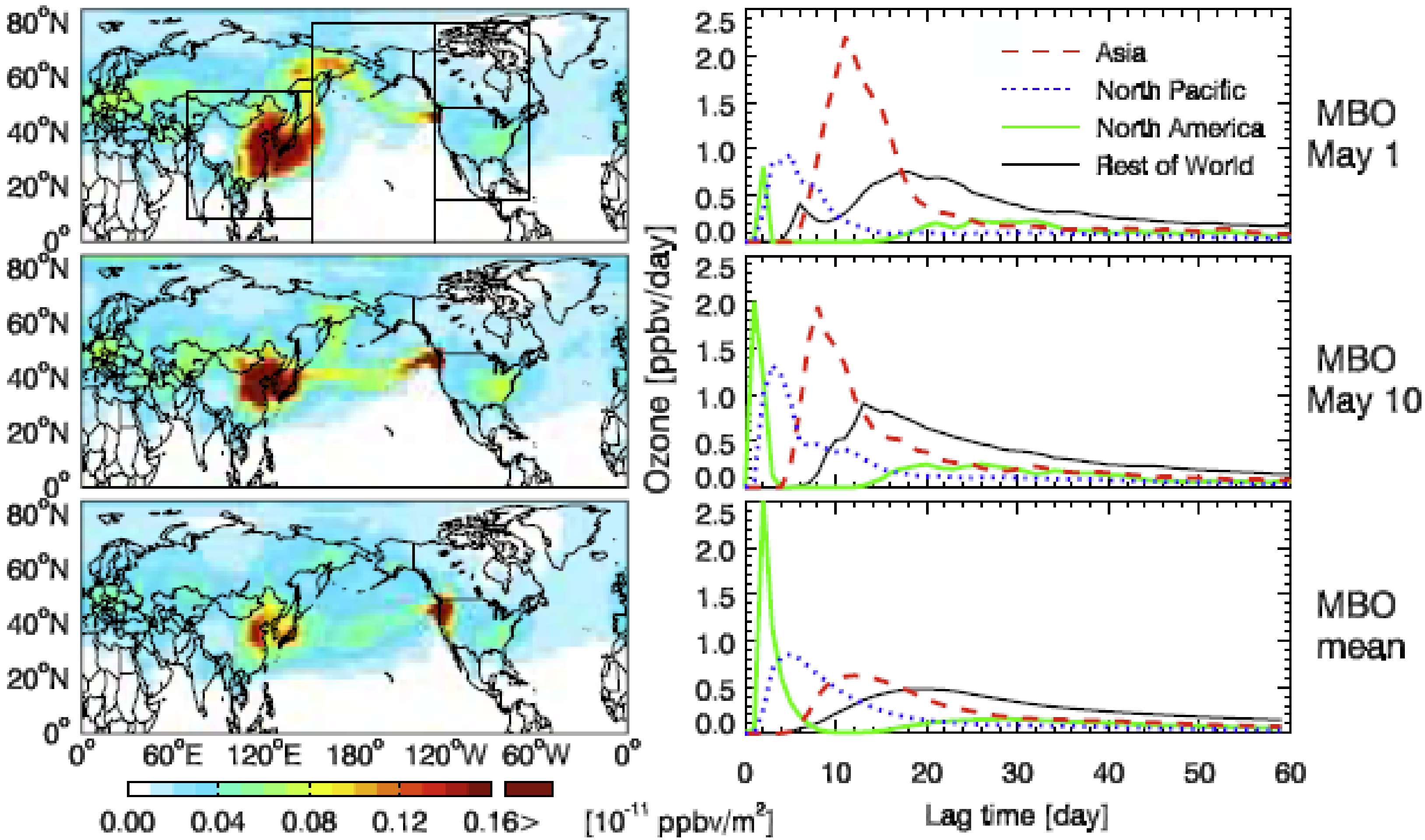
Trans-Pacific Transport and Transformation



Zhang et al., 2008, ACP

Adjoint Modeling for Intercontinental Transport

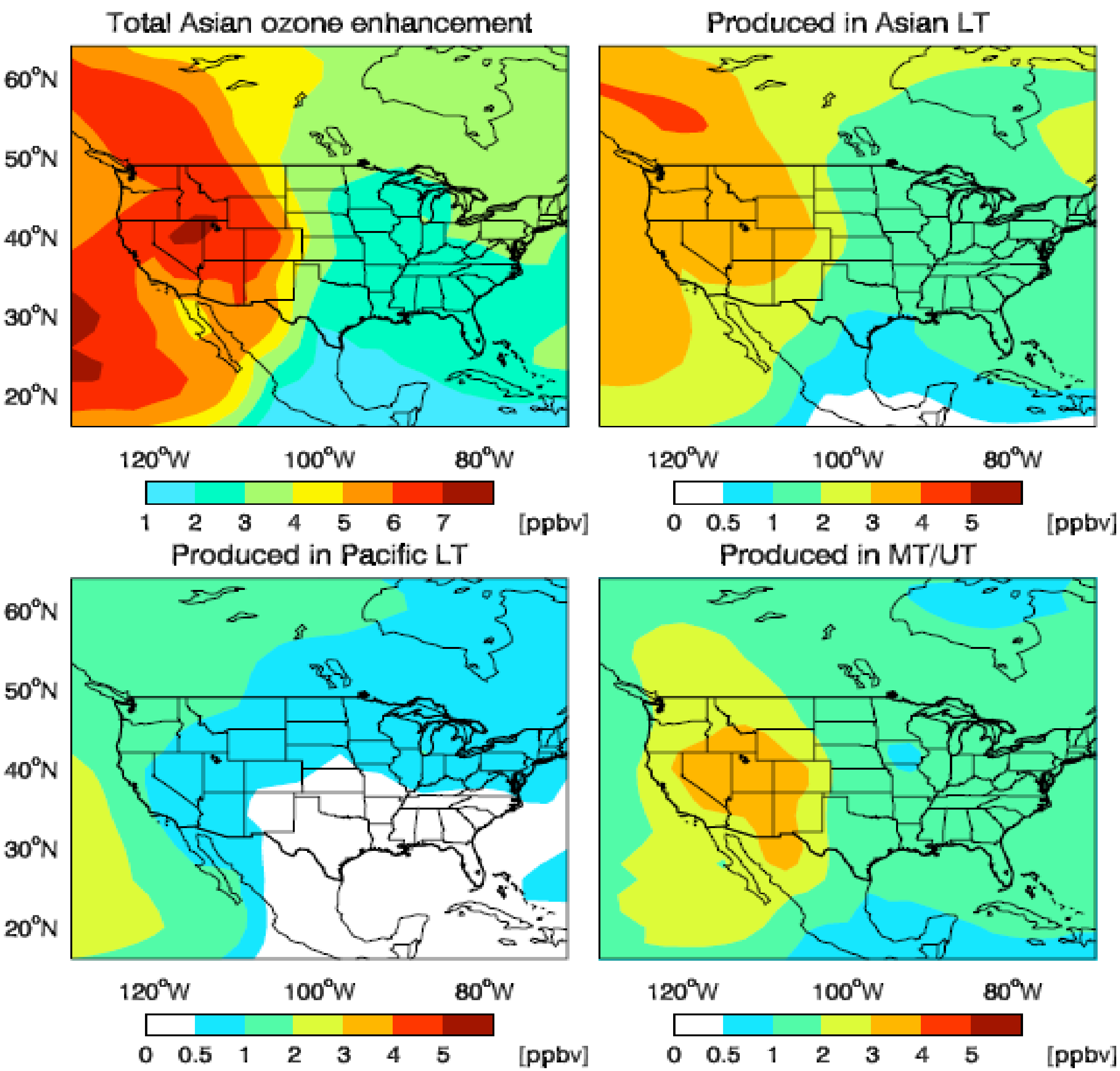
Ozone



Zhang et al., 2010, GRL

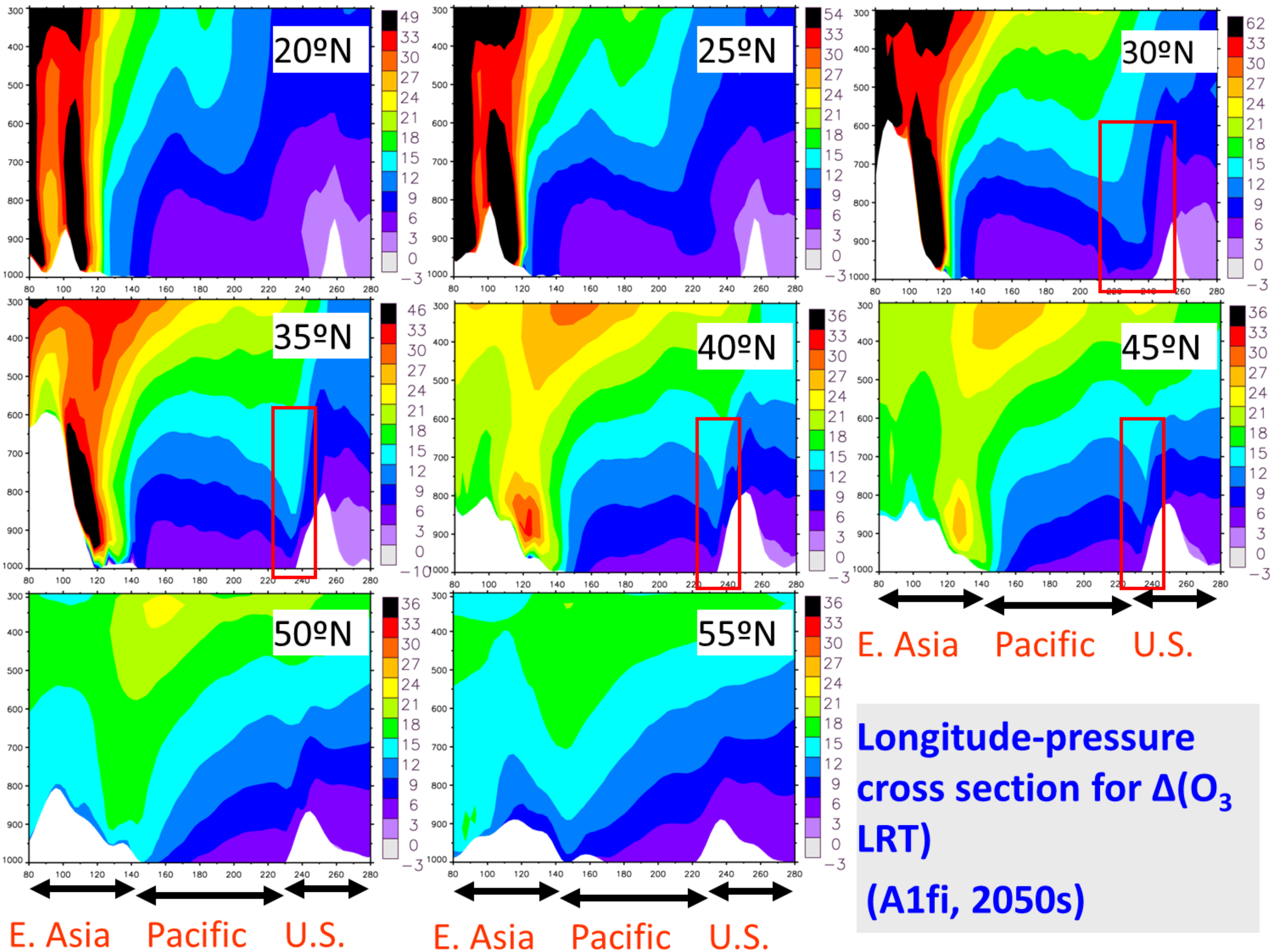
An adjoint model is the transpose of a forward model; it is used for inversion studies

Springtime U.S. O_3 Enhancement due to Transpacific Transport



Zhang et al., 2008, ACP

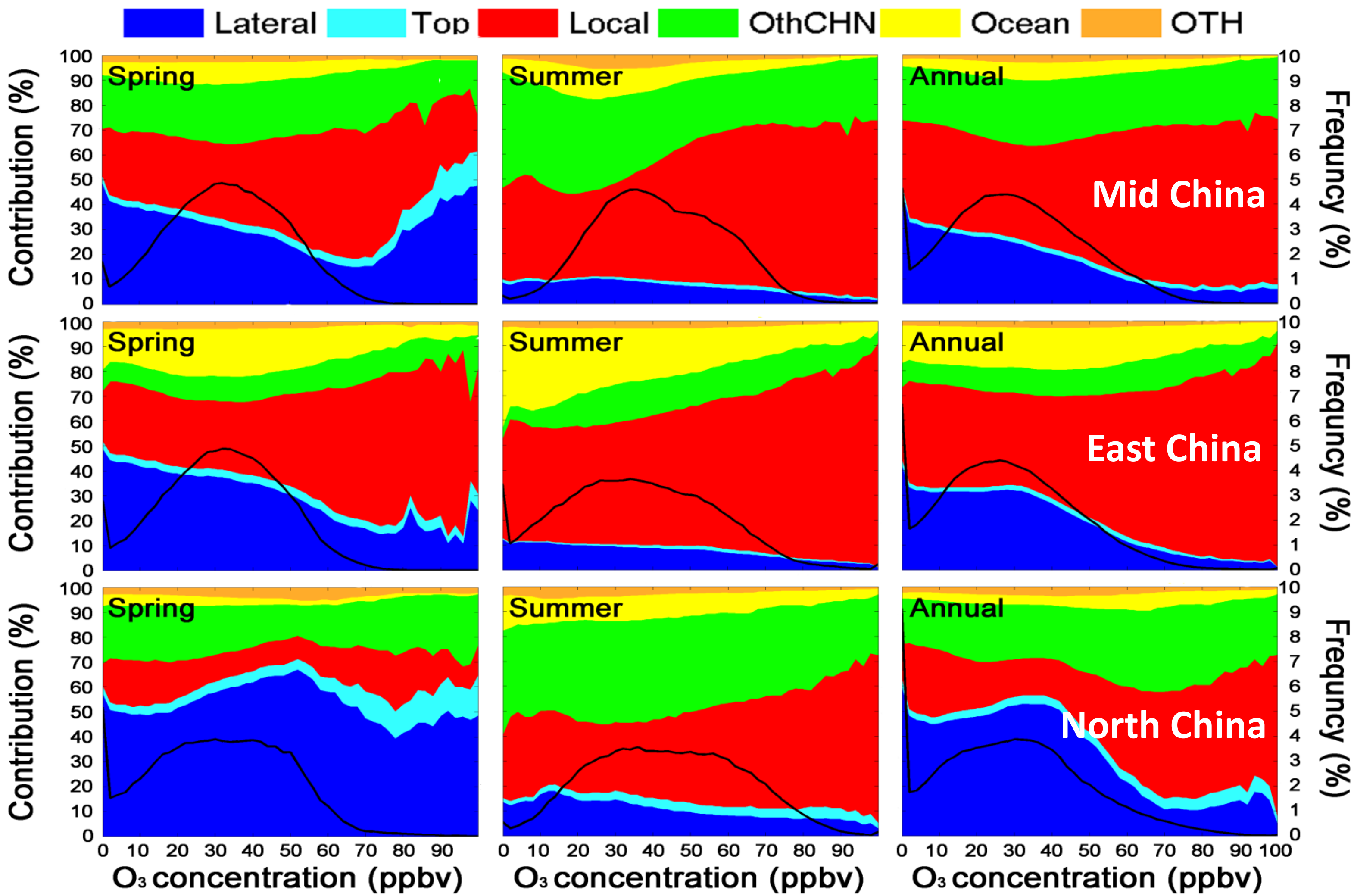
U.S. JJA O_3 Increase due to Transpacific Transport: 1990s–2050s



Longitude-pressure cross section for Δ(O_3 LRT)

(A1fi, 2050s)

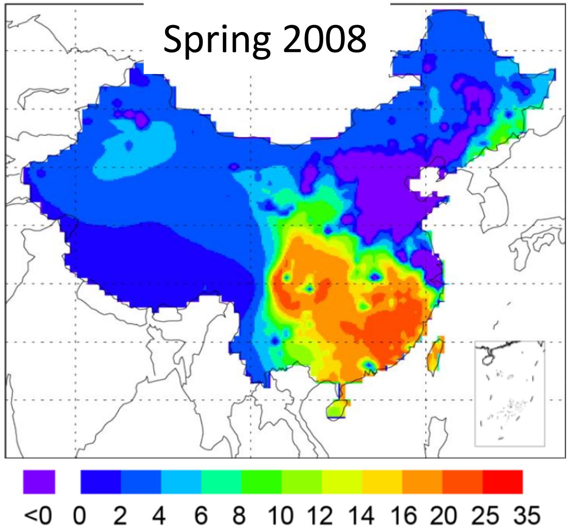
Strong Inflow of Ozone into Eastern China



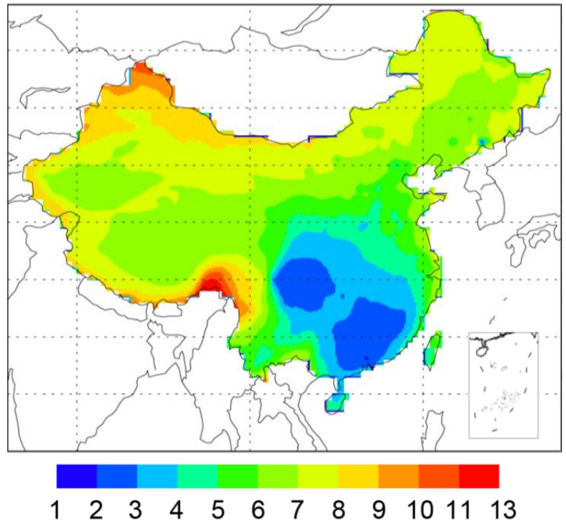
Li et al., 2016, AR

Large Natural & Foreign Influences on China's O_3 Pollution

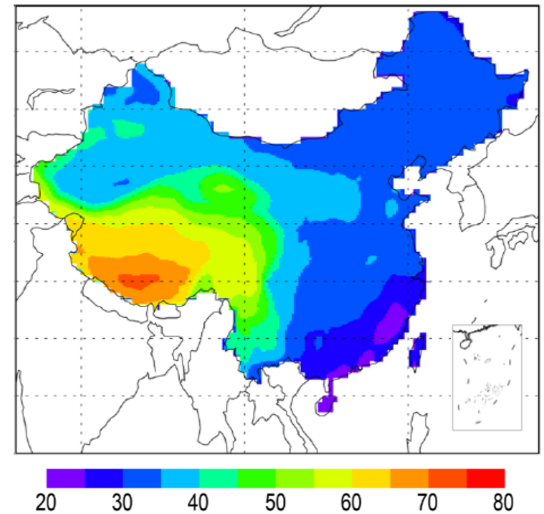
Domestic anthropogenic O_3 (ppb)



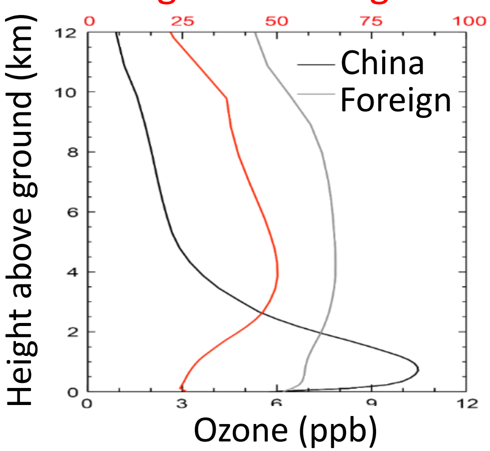
Foreign anthropogenic O_3 (ppb)



Natural O_3 (ppb)

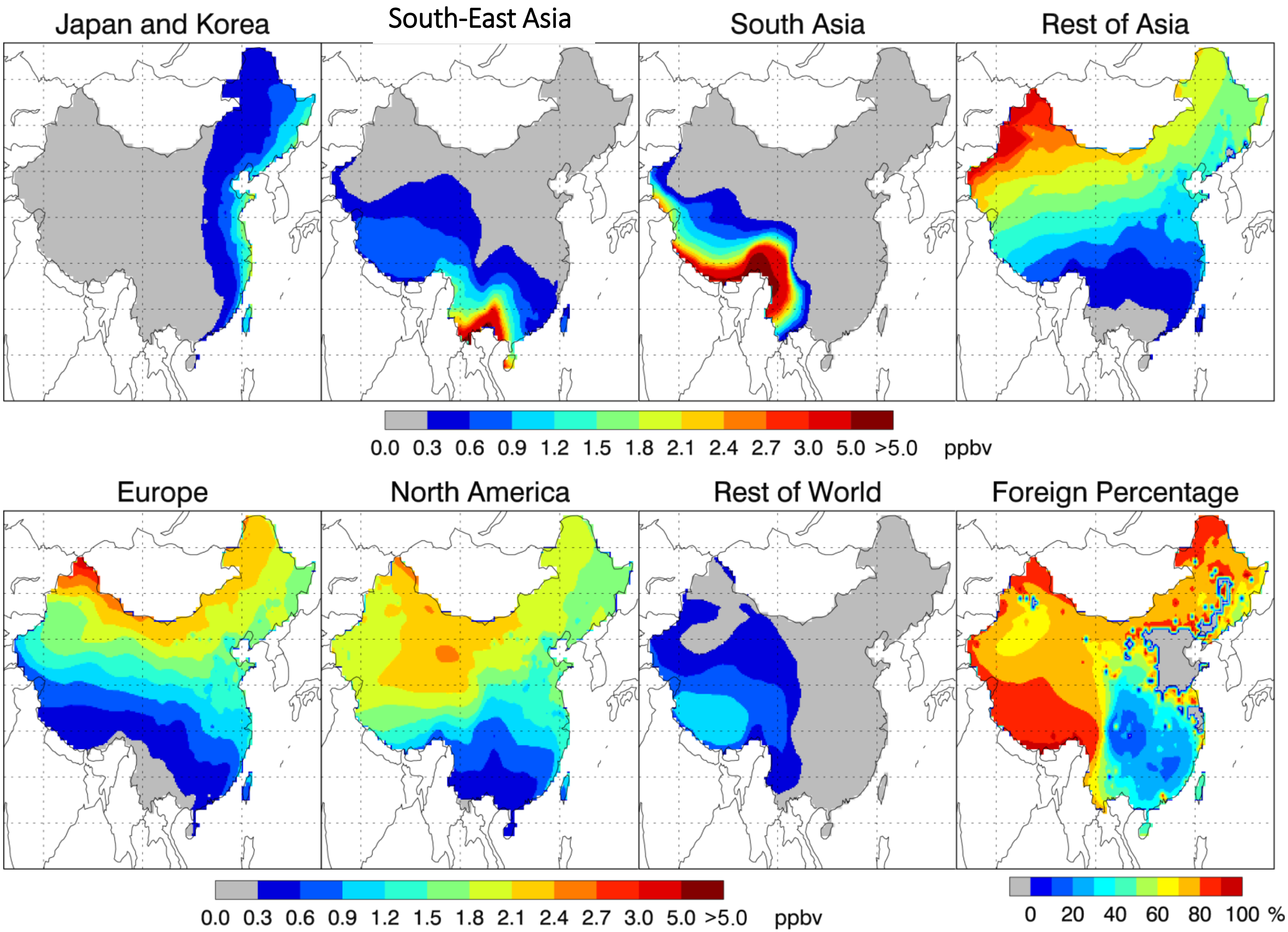


% of O_3 produced within foreign source regions



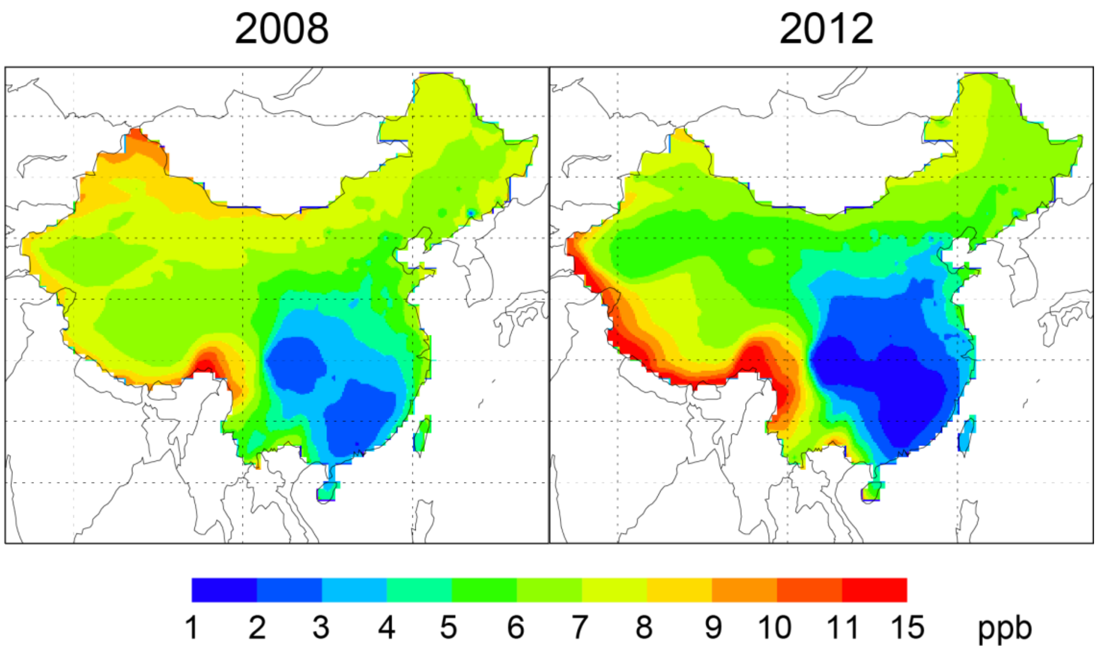
Ni et al., ACP, 2018

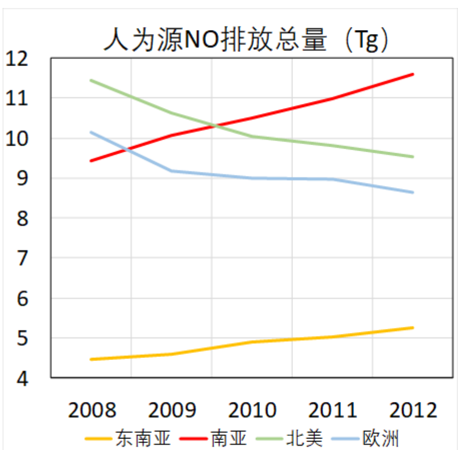
Foreign Pollution Greatly Affect China's O_3: Spring 2008

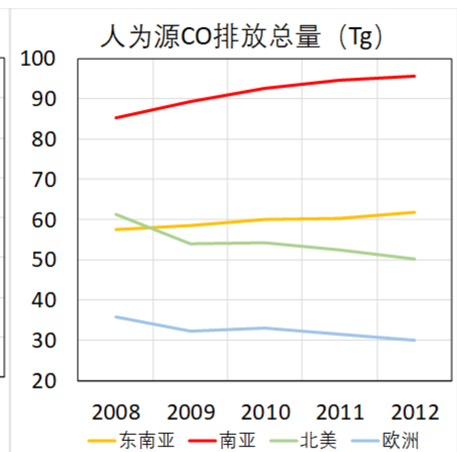


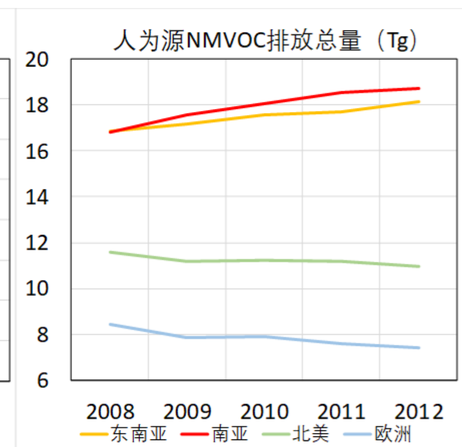
Ni, R.-J. et al., 2018, ACP

Changes in Springtime Foreign Anthropogenic Surface O_3



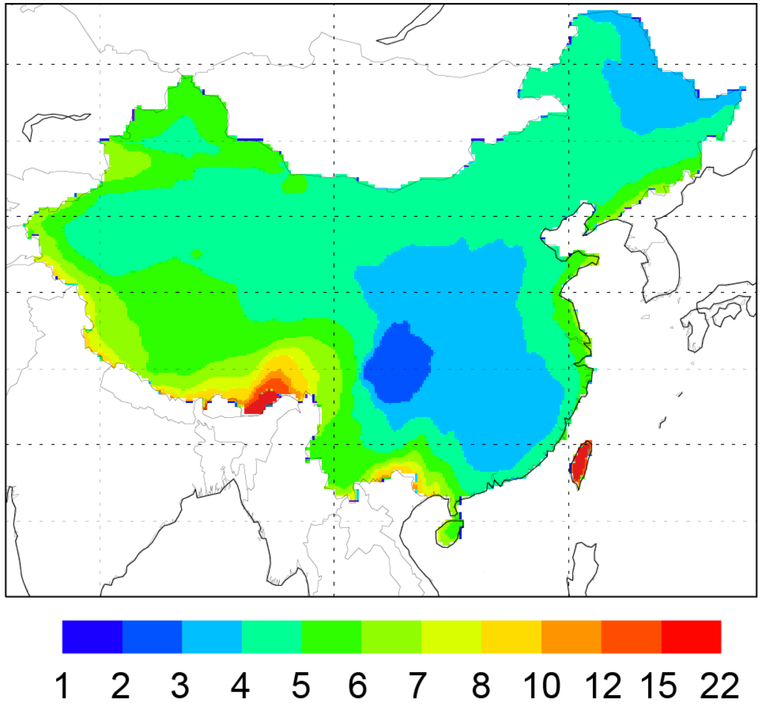


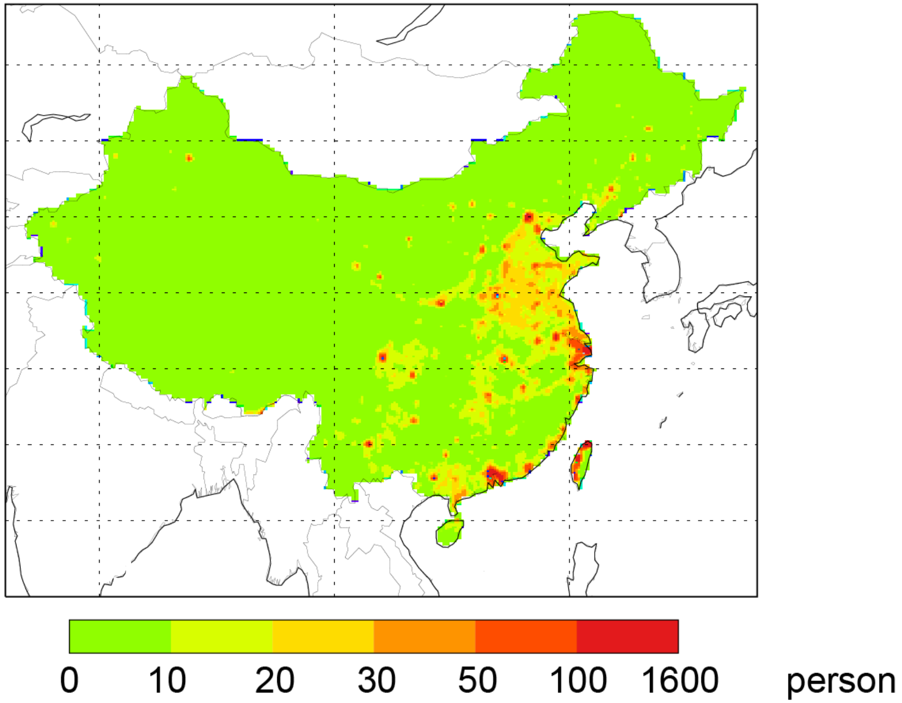




Ni et al., ACP, 2018

Mortality in Mainland China Caused by Atmospheric Transboundary Pollution From Other Regions

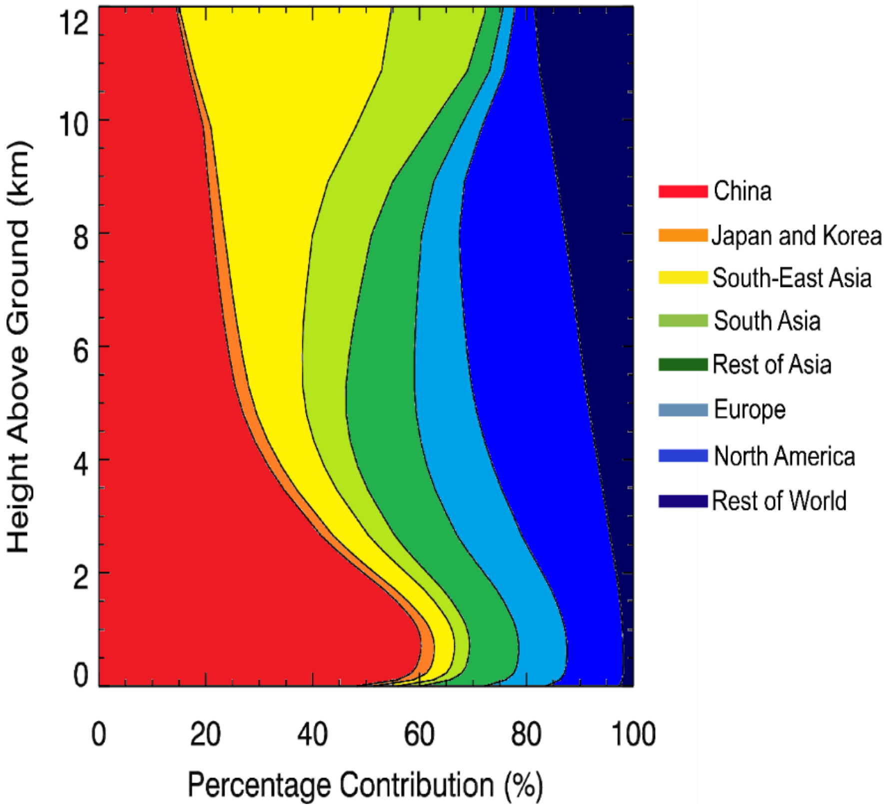




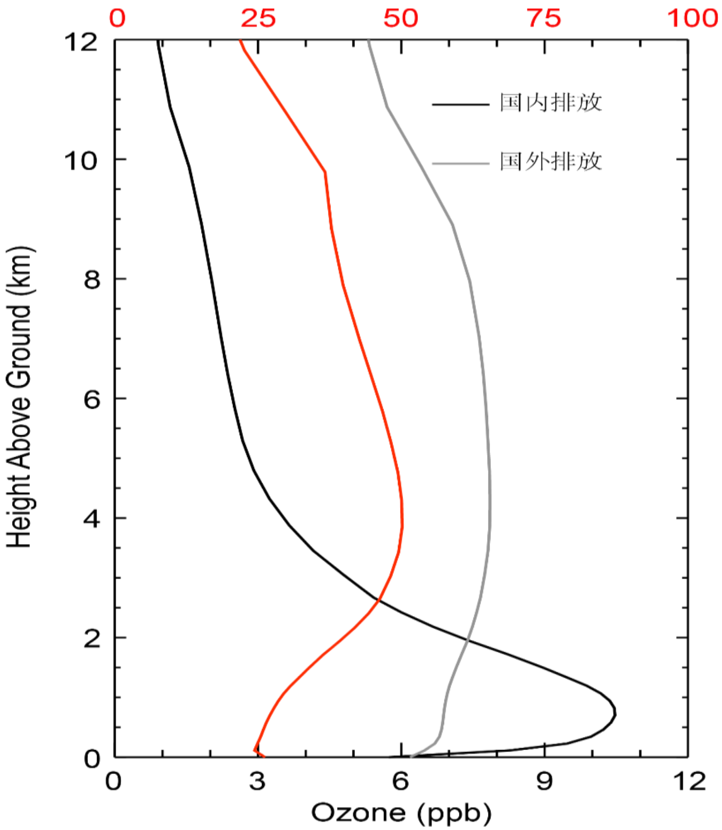
Ni et al., in prep

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



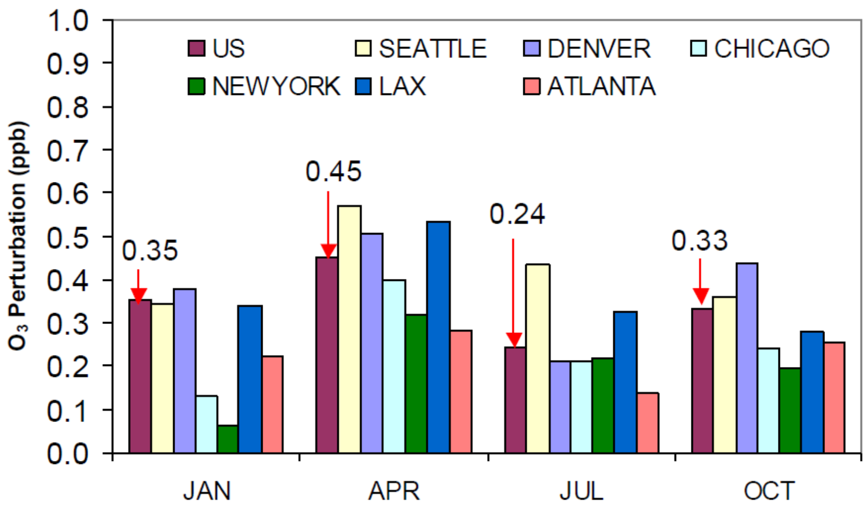
Method: *Zero-out* + *Tagged O_3* + *Linear weighting*

Ni et al., ACP, 2018

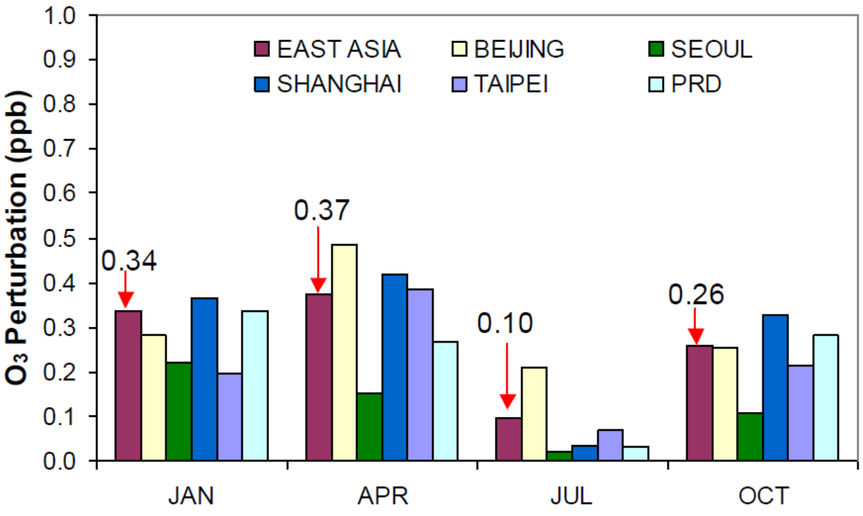
Transboundary Ozone from E. Asia versus NA

WRF-Chem simulation at 36 x 36 km^2

20% changes in anthro emis in E. Asia



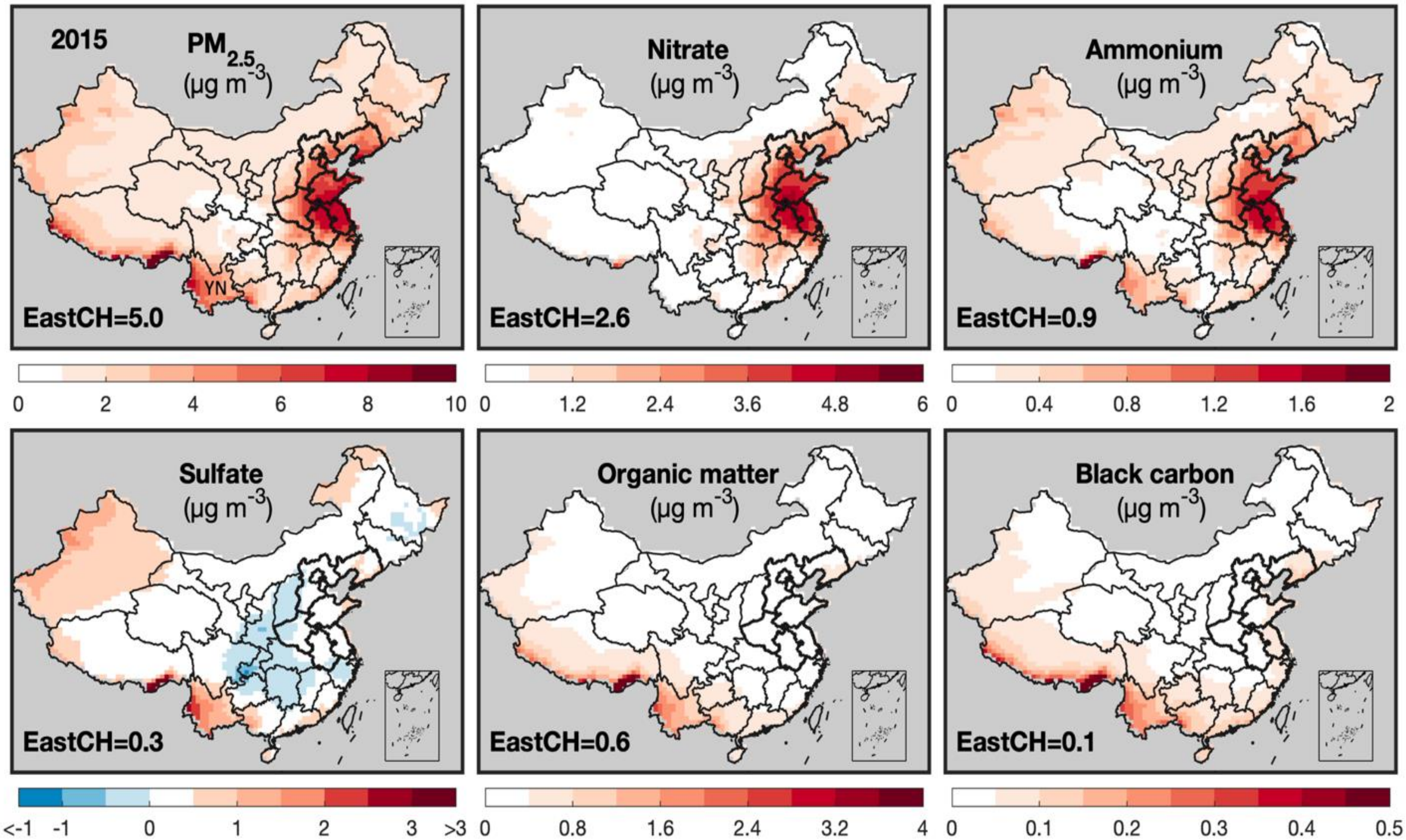
20% changes in anthro emis in NA



HTAP, 2010 (P206)

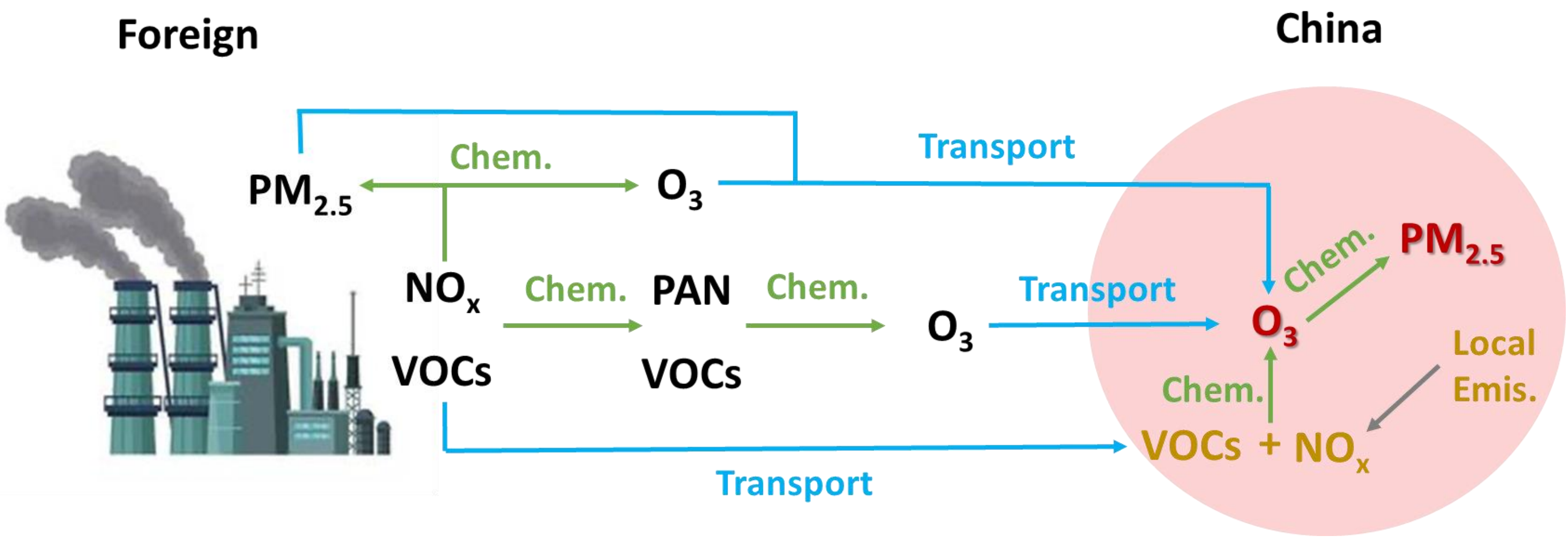
Foreign Pollution Transport Worsens Chinese $PM_{2.5}$

Foreign Contribution to E. China = Direct Transport (30%) + Chemistry (70%)



Xu et al., ACP, 2023, Highlight Paper

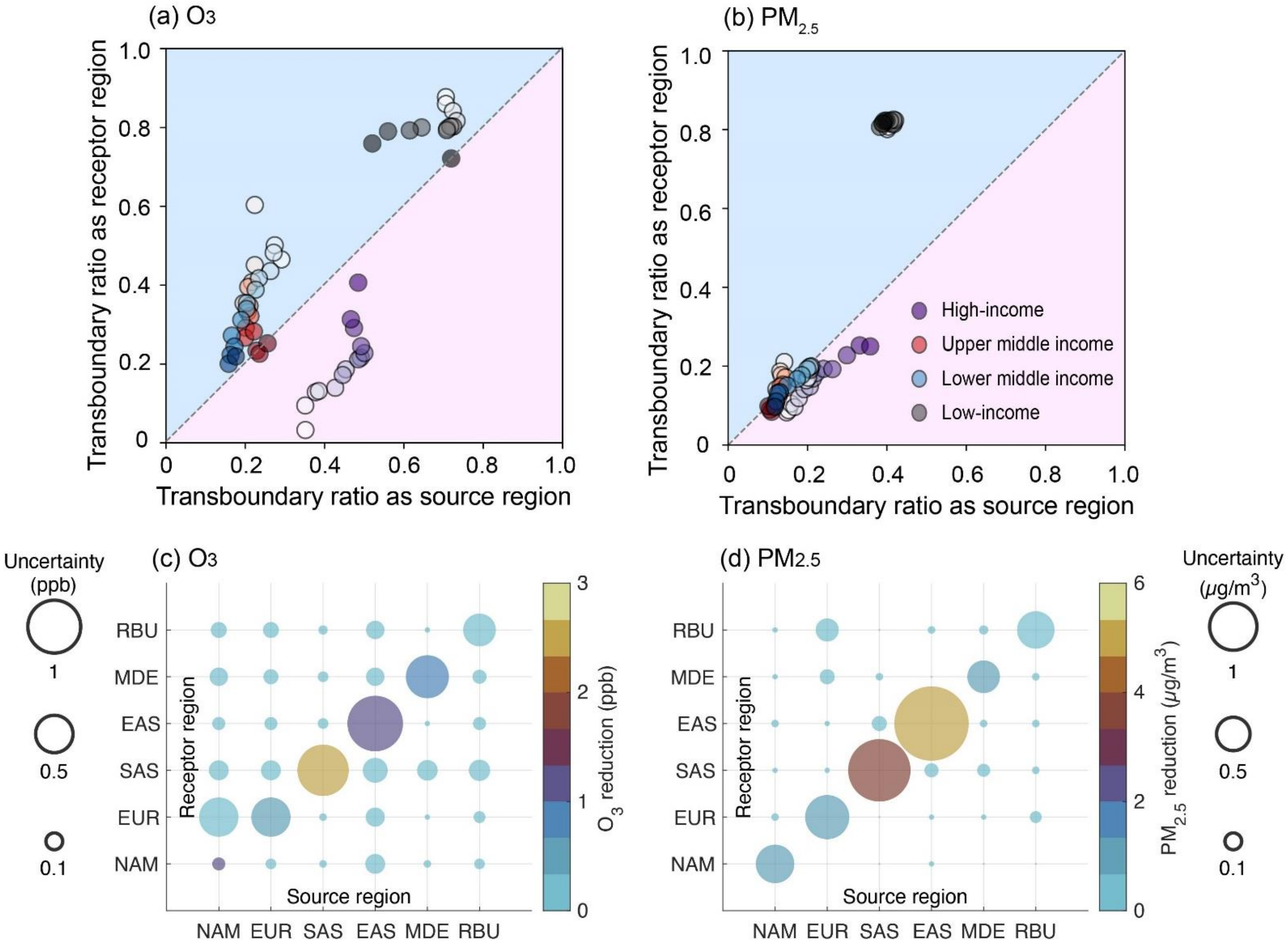
Complex Chemical-Transport Mechanism



Transboundary pollution mechanisms:

1. **Emission or formation and then transport**
2. **Formation during transport**
3. **Transport and then interaction with pollution @ receptor**

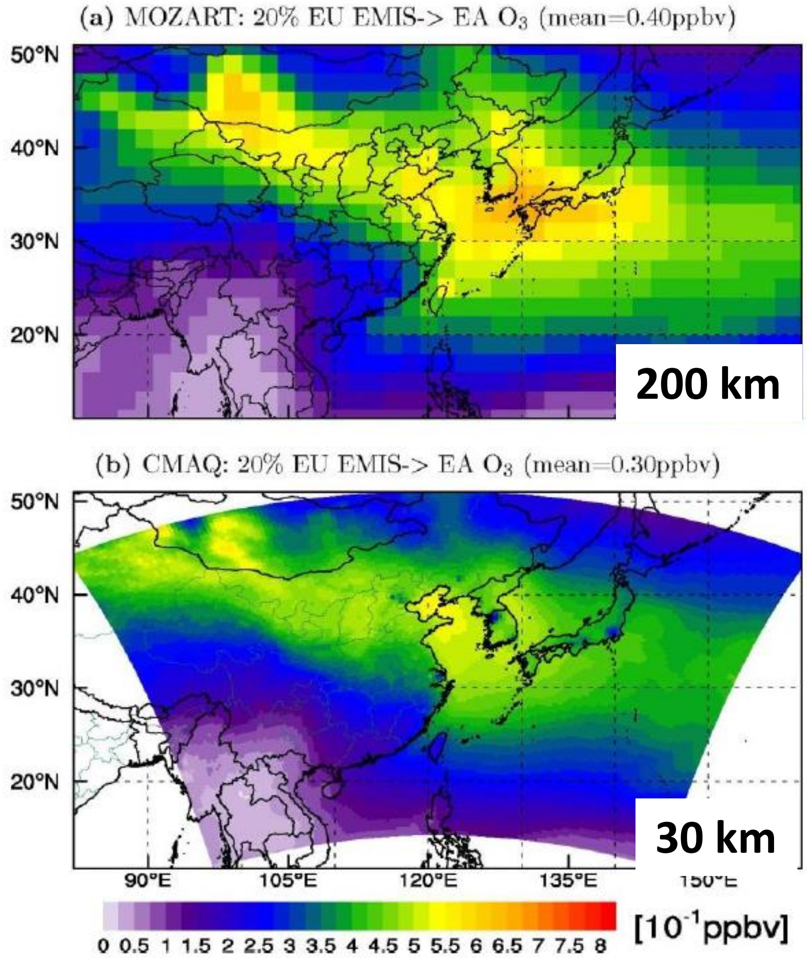
Historical Transboundary Pollution via Atmospheric Transport



Lin et al., under review

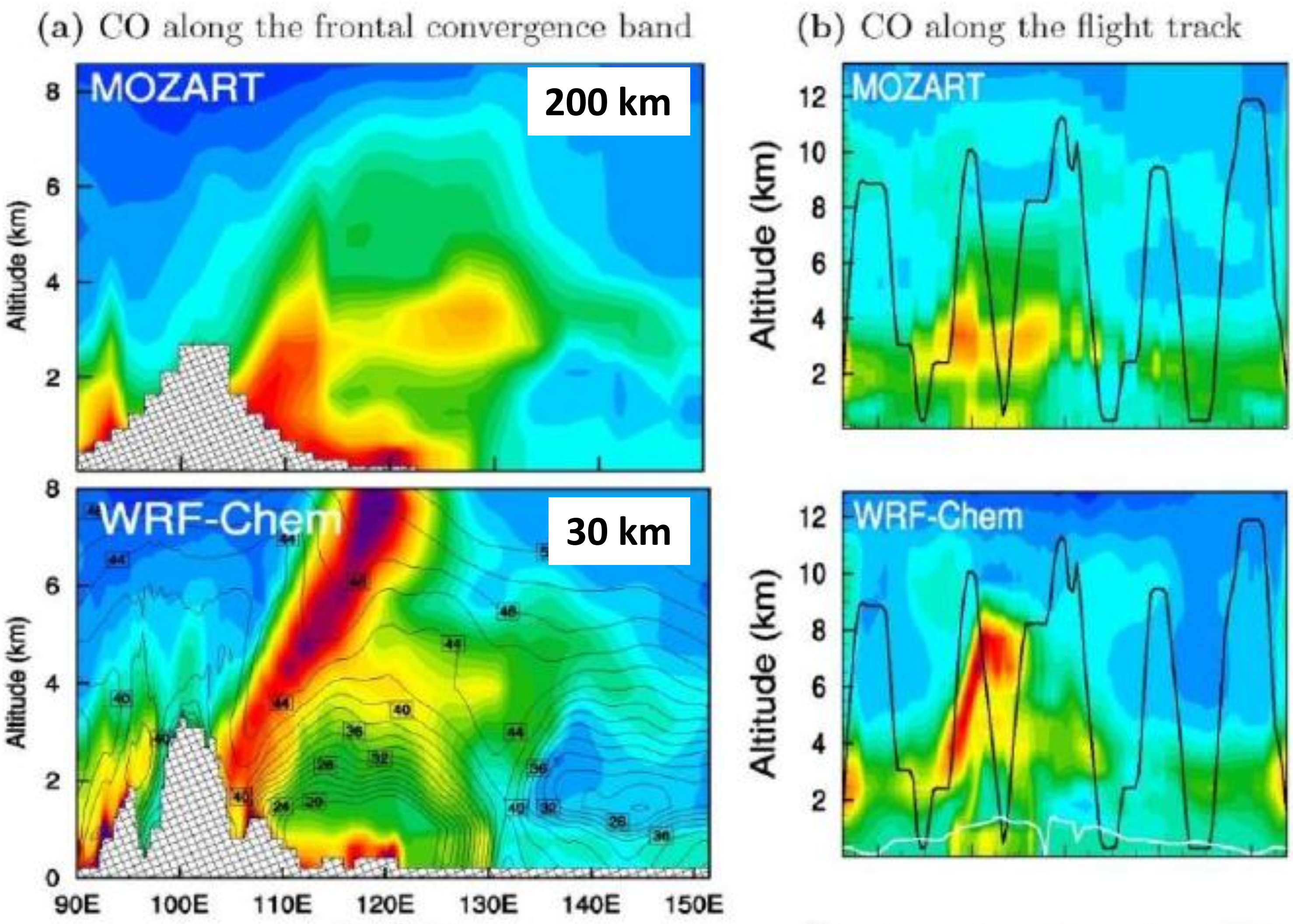
Uncertainty in Import Due to Model Resolution

Effects of reducing EU anthro emis by 20% on China' ozone in March 2001



Lin et al., 2010, ACP

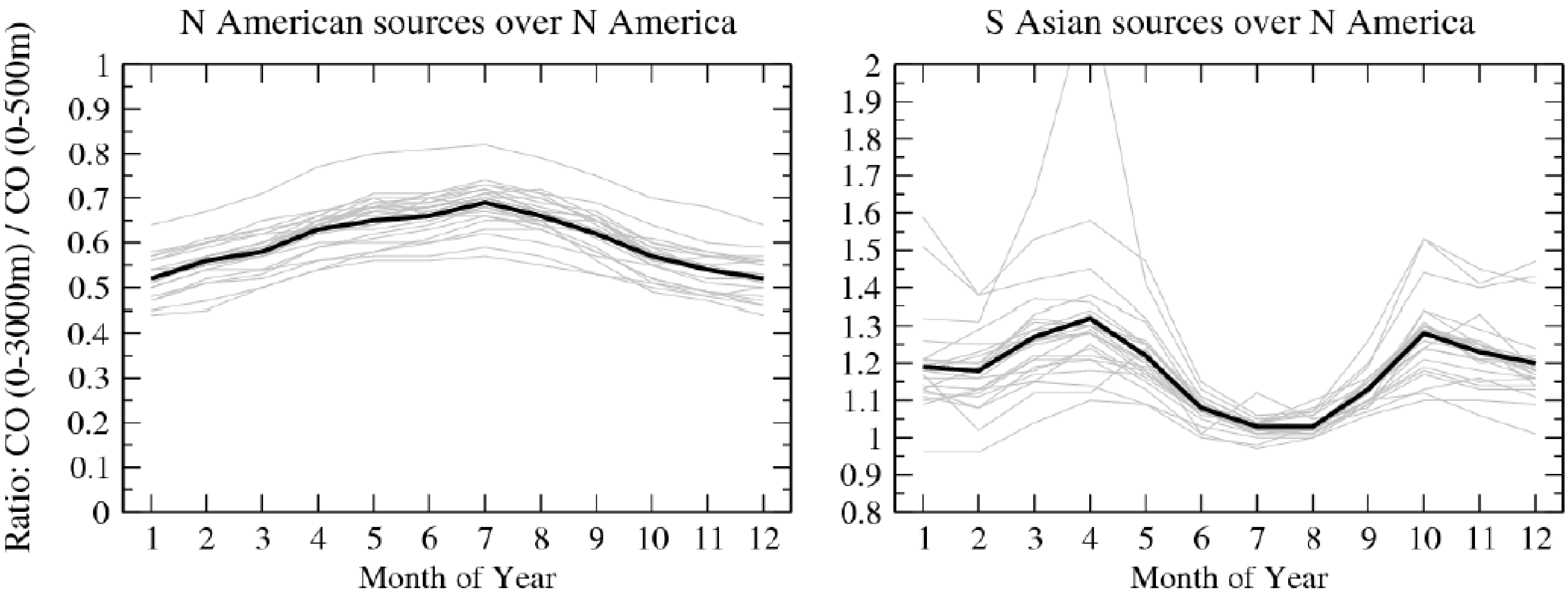
Uncertainty in Export Due to Model Resolution



March 2001

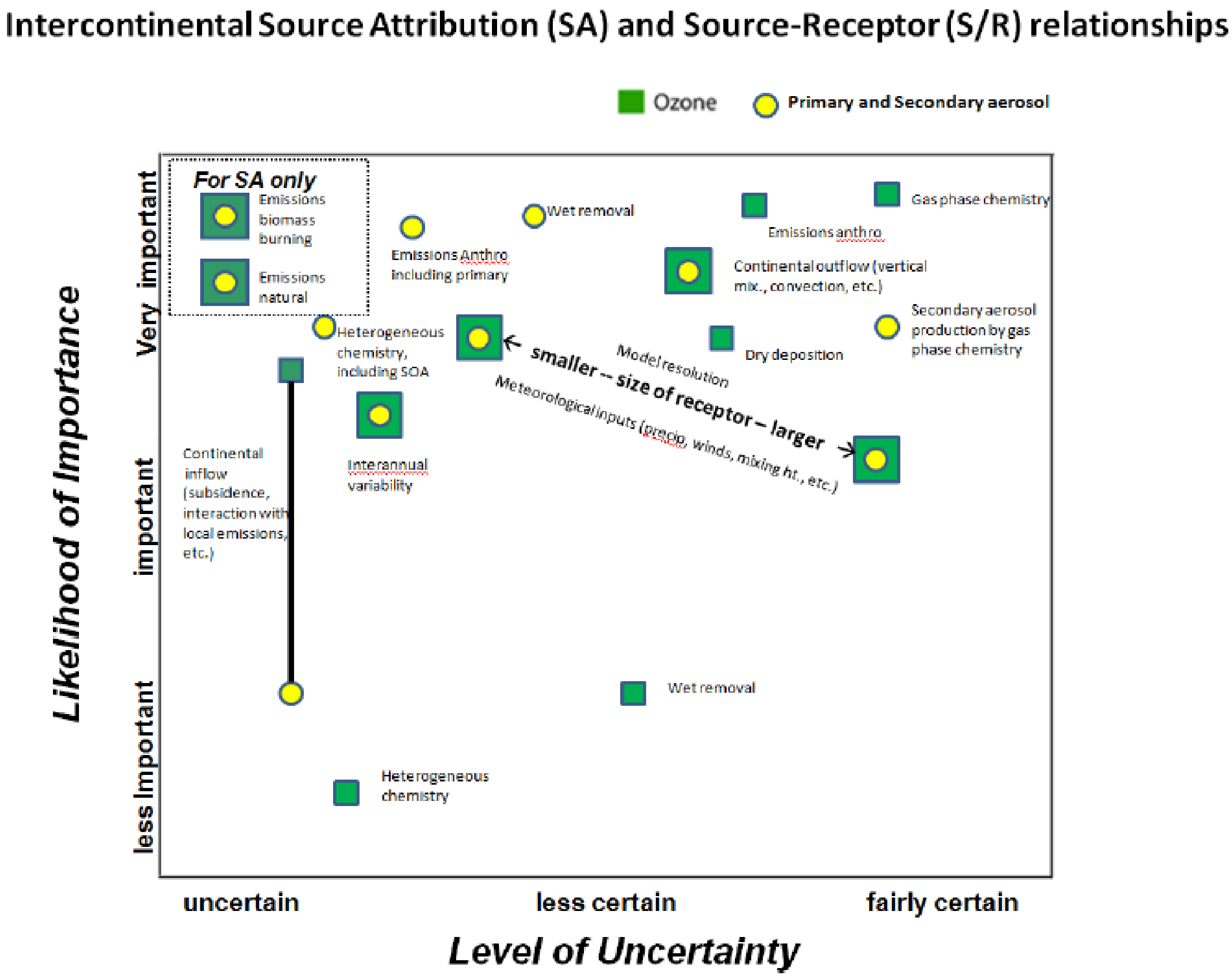
Lin et al., 2010, ACP

Uncertainty Due to Model Transport Process



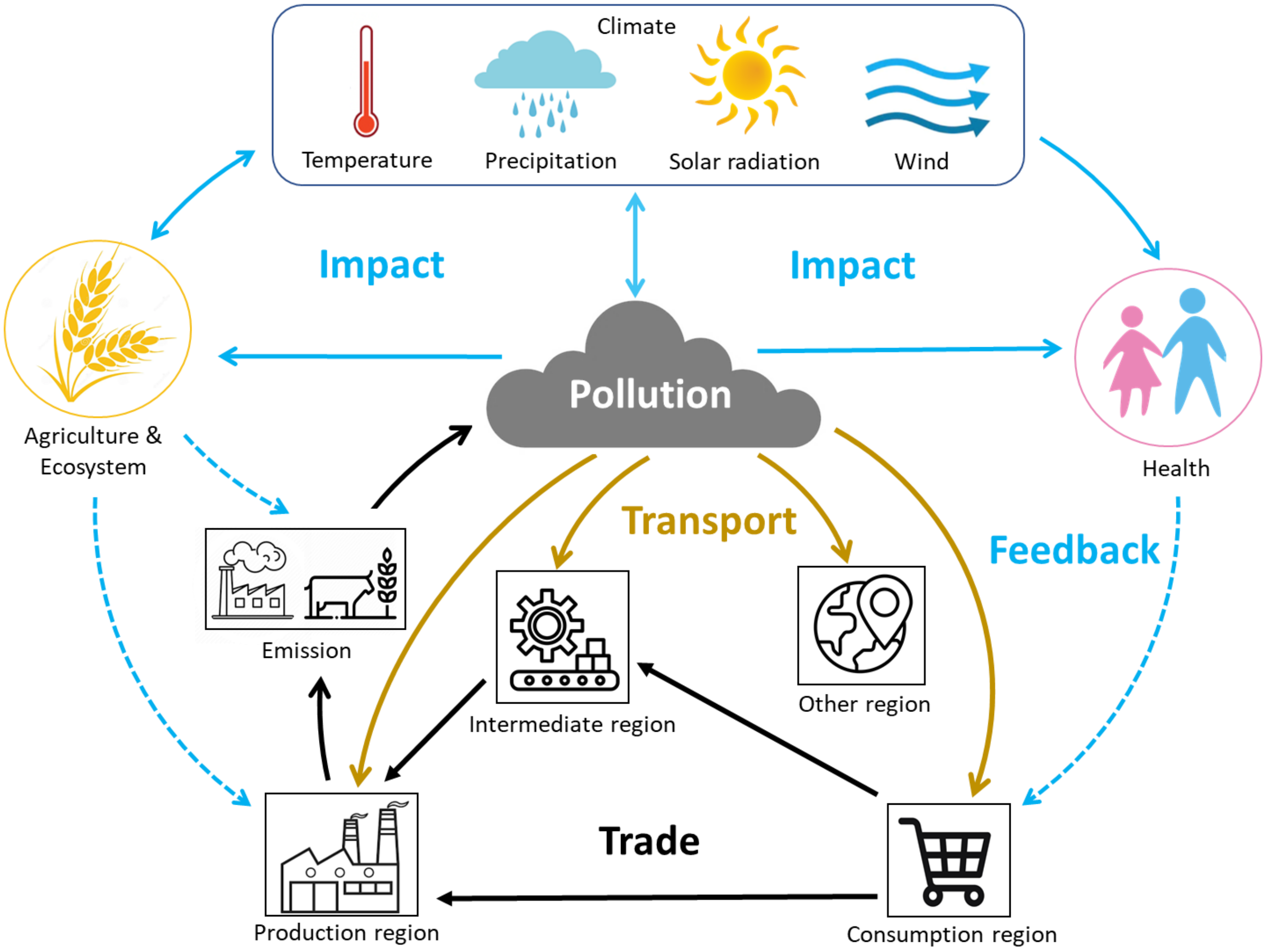
HTAP, 2010

Uncertainties in Model Assessment



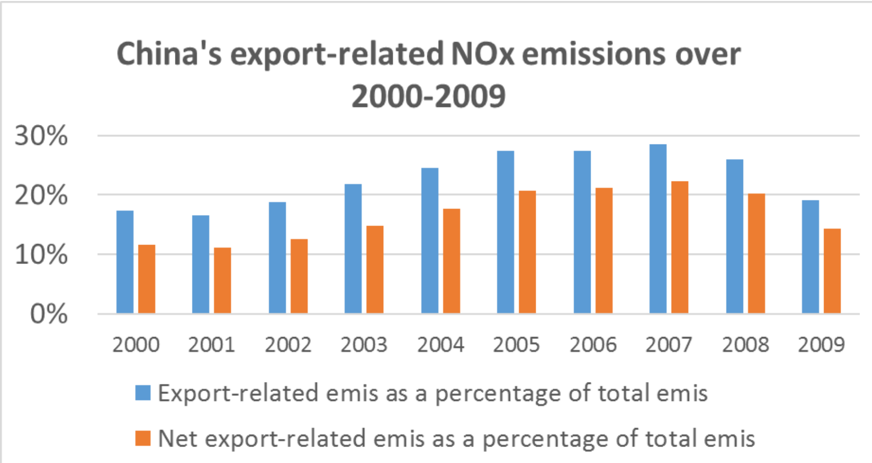
HTAP, 2010

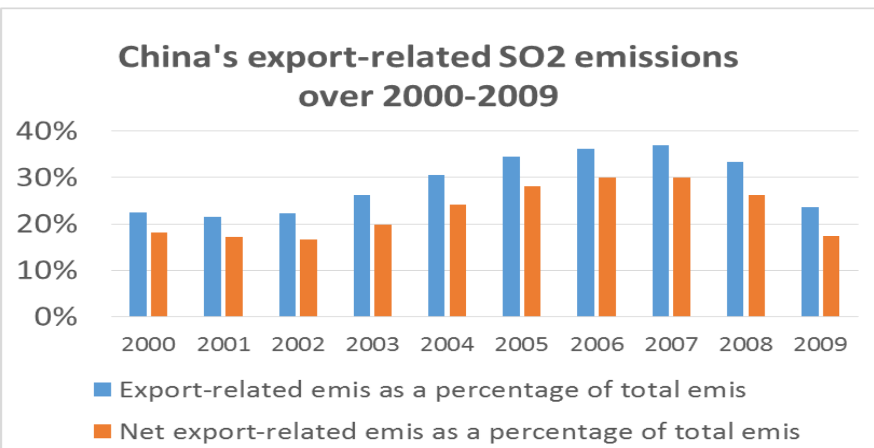
Trade-Transport Synergy



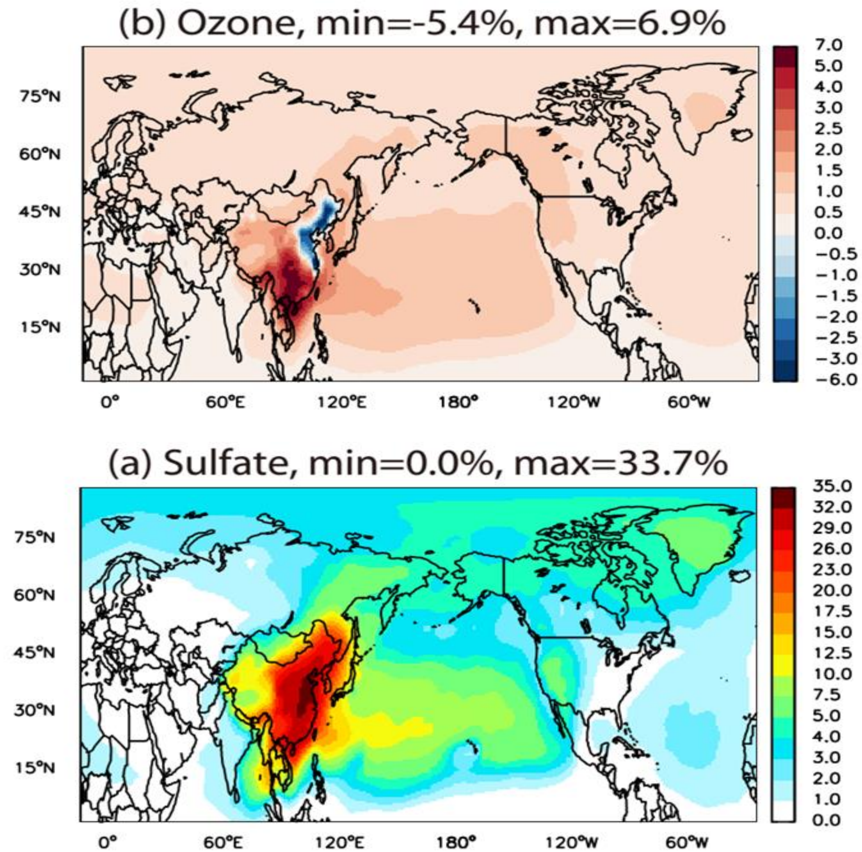
Lin et al., under review

Trade Redefines Chinese Emissions & Pollution





% contribution of China's export-related pollution to total pollution in 2006

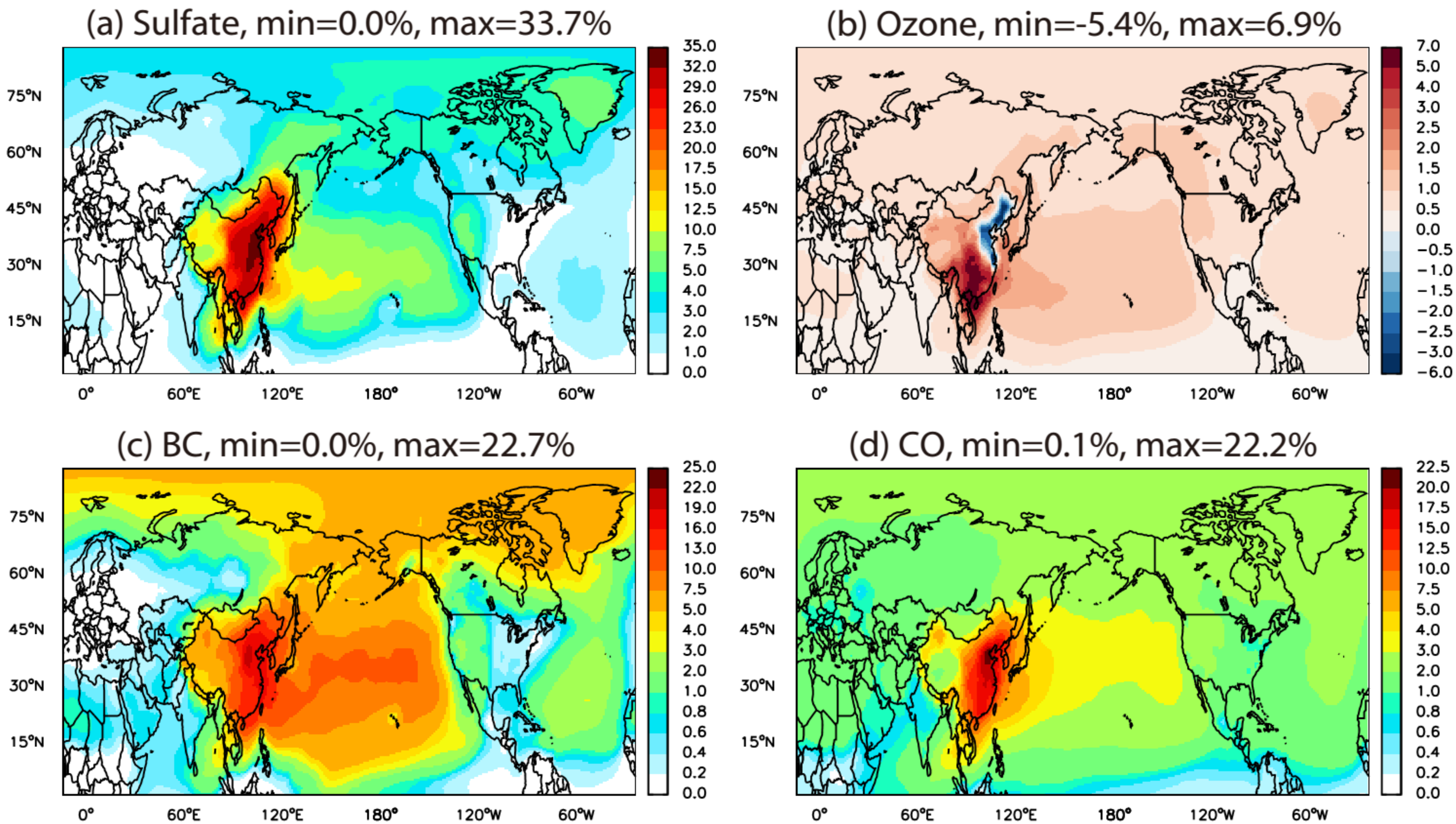


Lin et al., 2014, PNAS; Winner of Cozzarelli Prize

入选NSFC资助项目优秀成果（十二五期间地球科学共25项）

Export of Goods Contributes to China’s Pollution

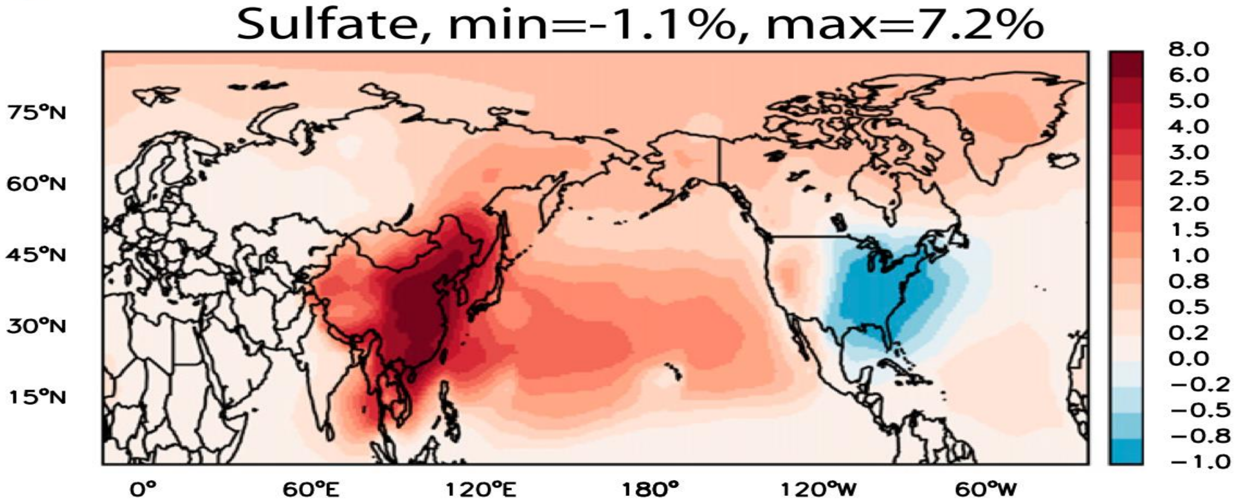
% contribution of China’s export-related pollution to total pollution anywhere in the world



Lin et al., 2014, PNAS

USA Consumption And China's Sulfate Pollution

% change in sulfate



USA imports goods from China versus self-production:
(accounting for differences in emission intensity)

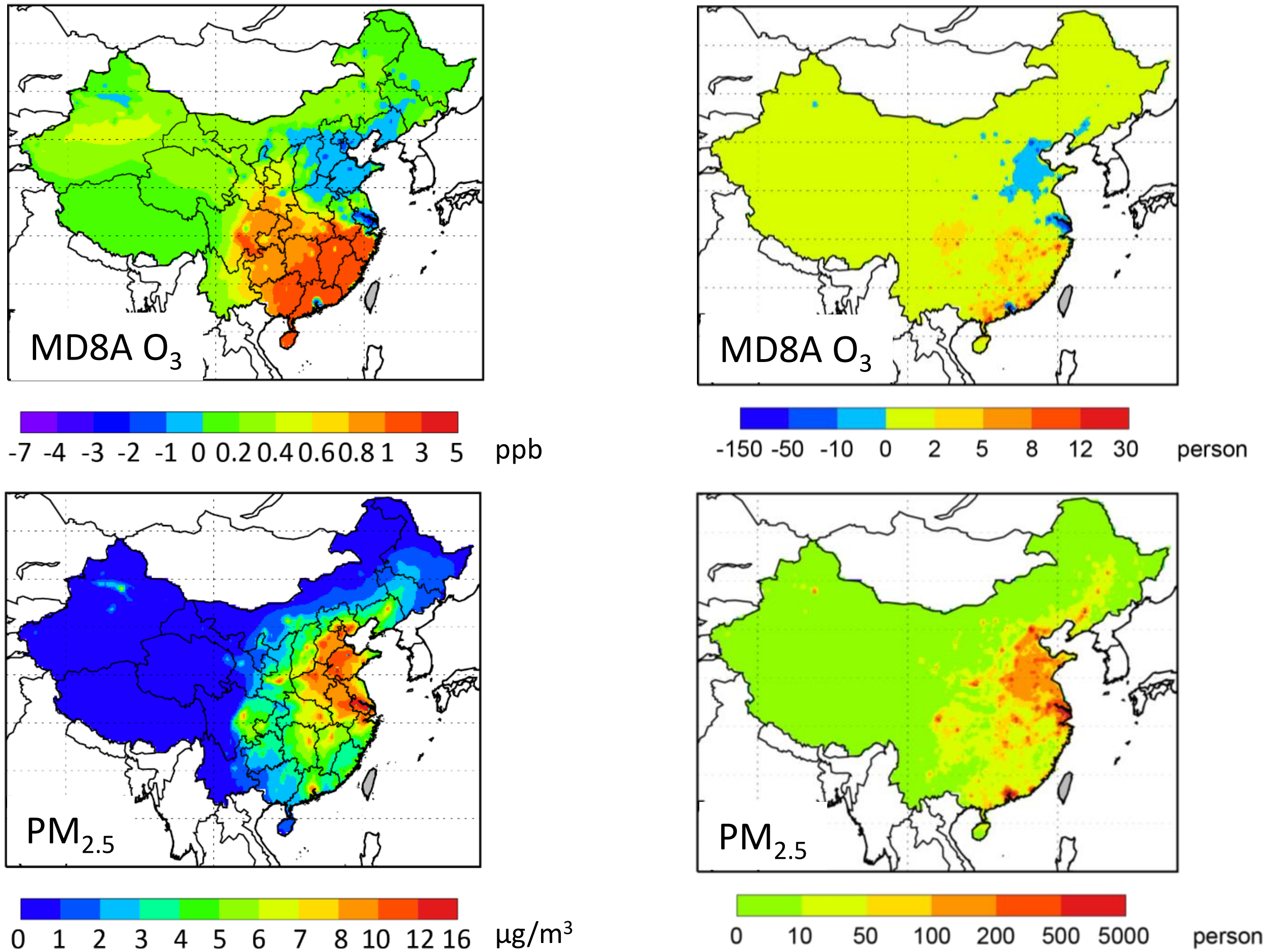
- **Increase China's sulfate PM**
- **Decrease USA's sulfate PM overall, GOOD for USA**

This contrasts with the traditional view that Chinese pollution reduces USA air quality via atmospheric transport

Lin et al., 2014, PNAS

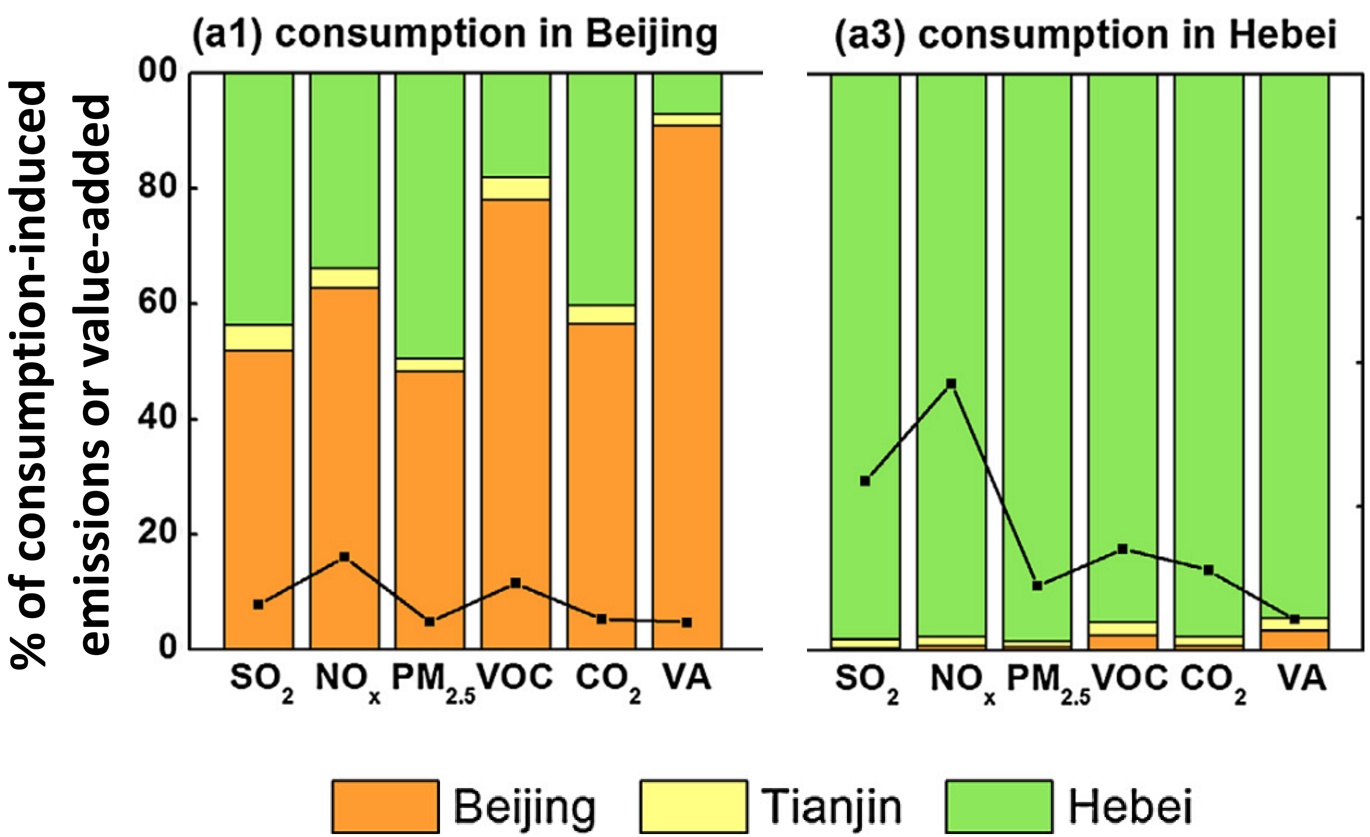
Mortality in Mainland China Caused by Trade-related Transboundary Pollution From Other Regions

Transboundary pollution in 2015 | **Transboundary deaths in 2015**



Ni et al., in prep

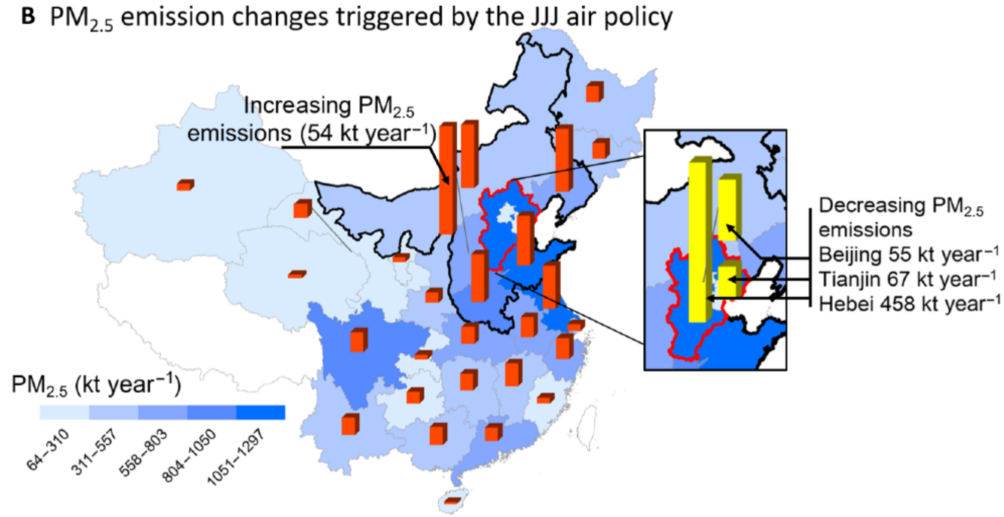
Pollution Embedded in Trade: Beijing → Hebei



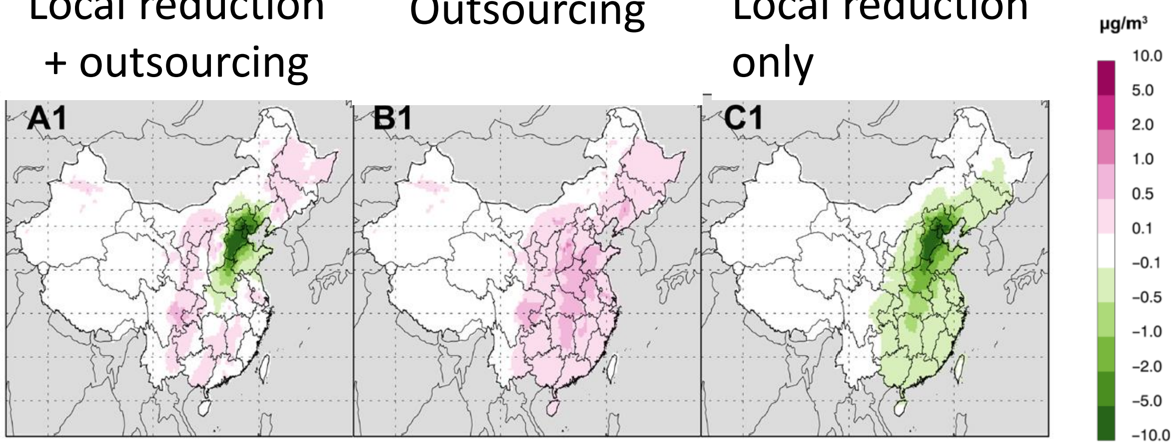
Zhao et al., Applied Energy, 2016

Potential Policy-Driven Outsourcing Within China

Regional environmental policy
- Region: Beijing-Tianjin-Hebei (JJJ)
- Target: $PM_{2.5}$ 25% ↓ (reduction)
- Measures:
  - Electricity: 30–70% import
  - Metal: 29–40% ↓
  - Nonmetal: 36–55% ↓
  - Coal: 13–57% ↓



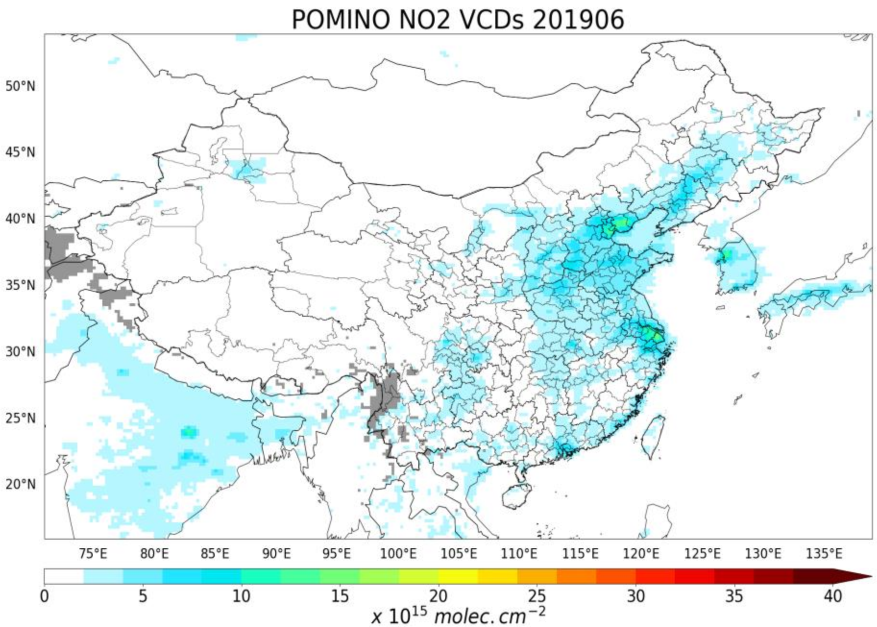
Local reduction + outsourcing	Outsourcing	Local reduction only



Fang et al., Science Advances, 2019

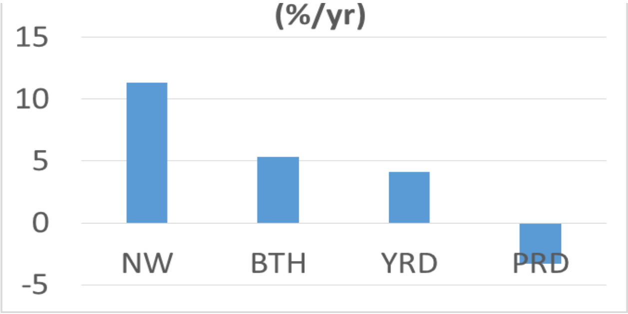
China's Cross-regional Pollution Embedded in Trade

POMINO – Peking U. OMI NO_2 Monthly Animation



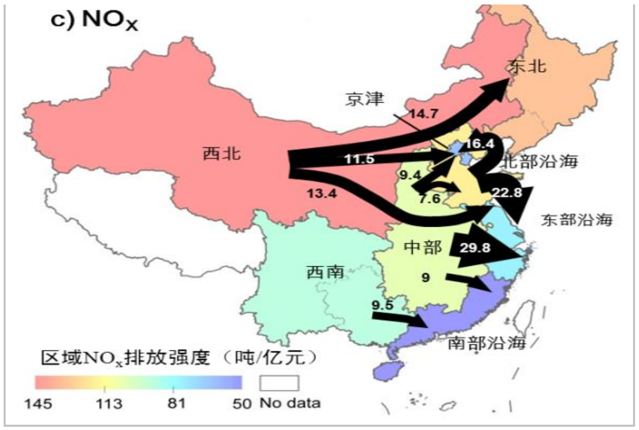
Lin et al., ACP, 2014; Lin et al., ACP, 2015; Liu et al., AMT, 2019; Zhang et al., NRSB, 2022
www.phy.pku.edu.cn/~acm/acmProduct.html#POMINO

Much stronger NO_2 growth over Northwest, 2005-2013



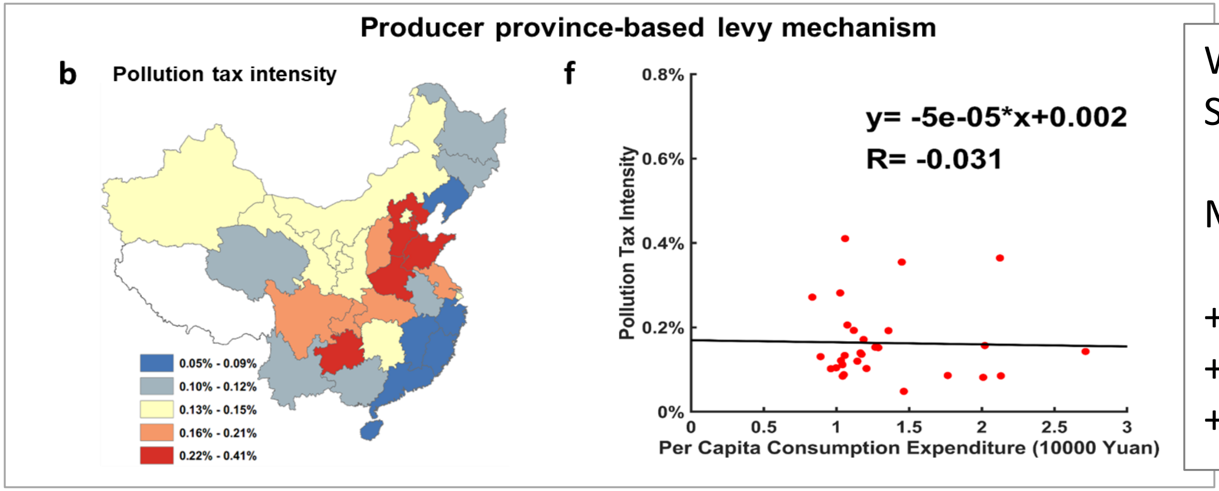
Cui et al., ACP, 2016

Large Westward Transfer of NOx Emissions via Trade



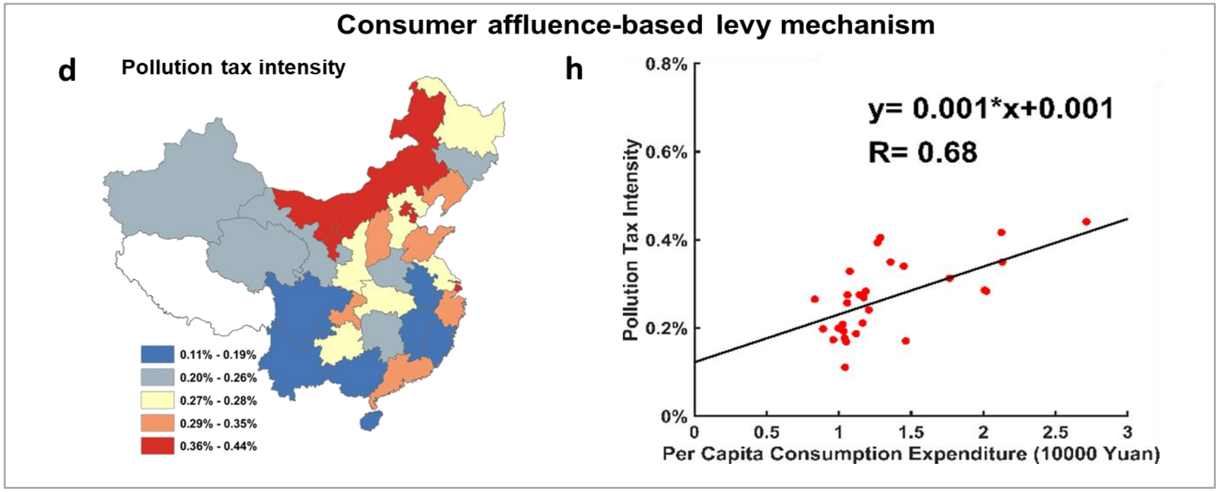
Zhao et al., ACP, 2015

Shifted Economic Burden of Environmental Taxation Via Inter-Provincial Trade Within China



Wang et al., 2019
Science Bulletin

Method:
Emission inventory
+ *Input-output table*
+ *Urban consumption*
+ *Official tax rates*



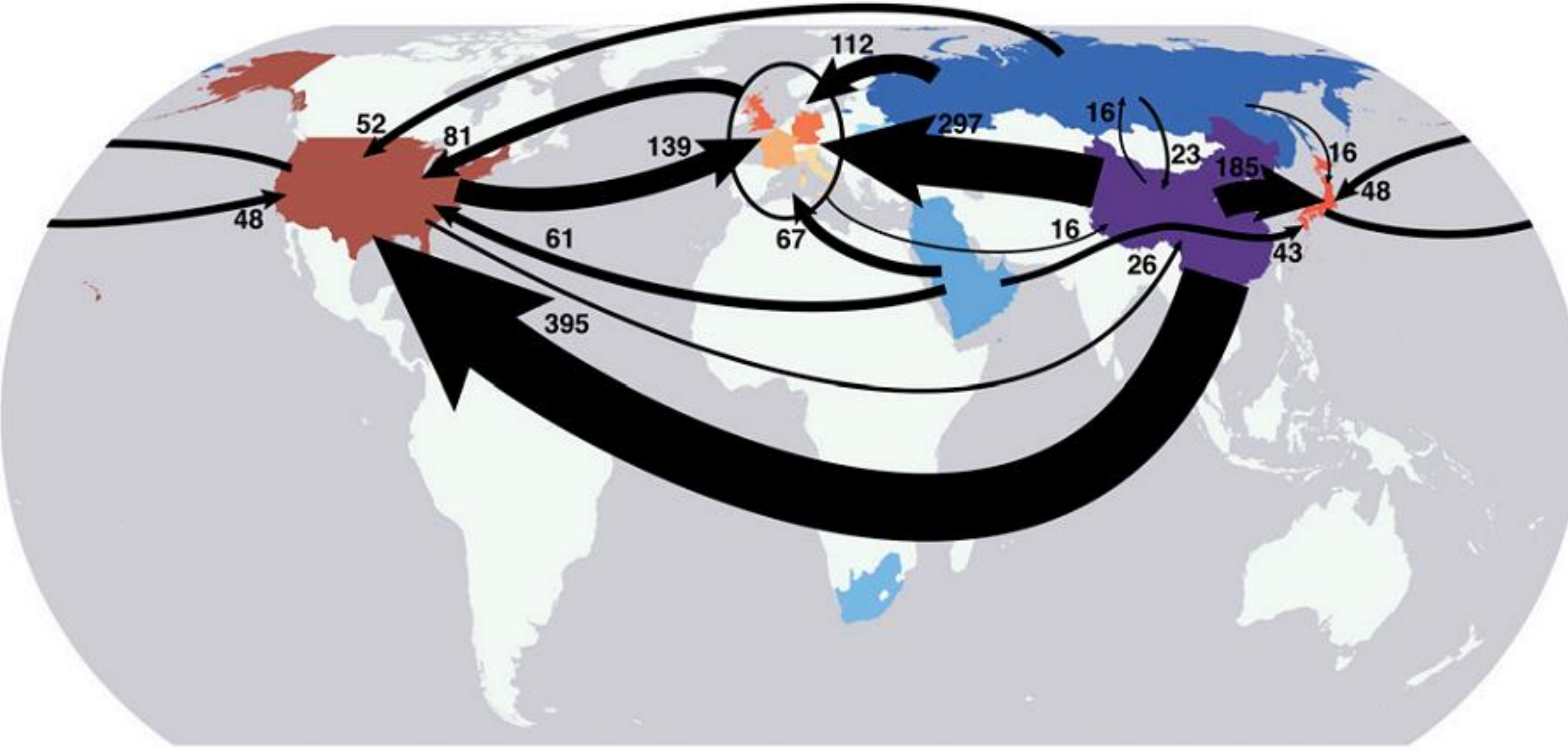
Trade-driven Pollution Transport: A Critical Issue in China's GO-WEST Movement

Pollution in Tenggeli Desert (2014/08/31)

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

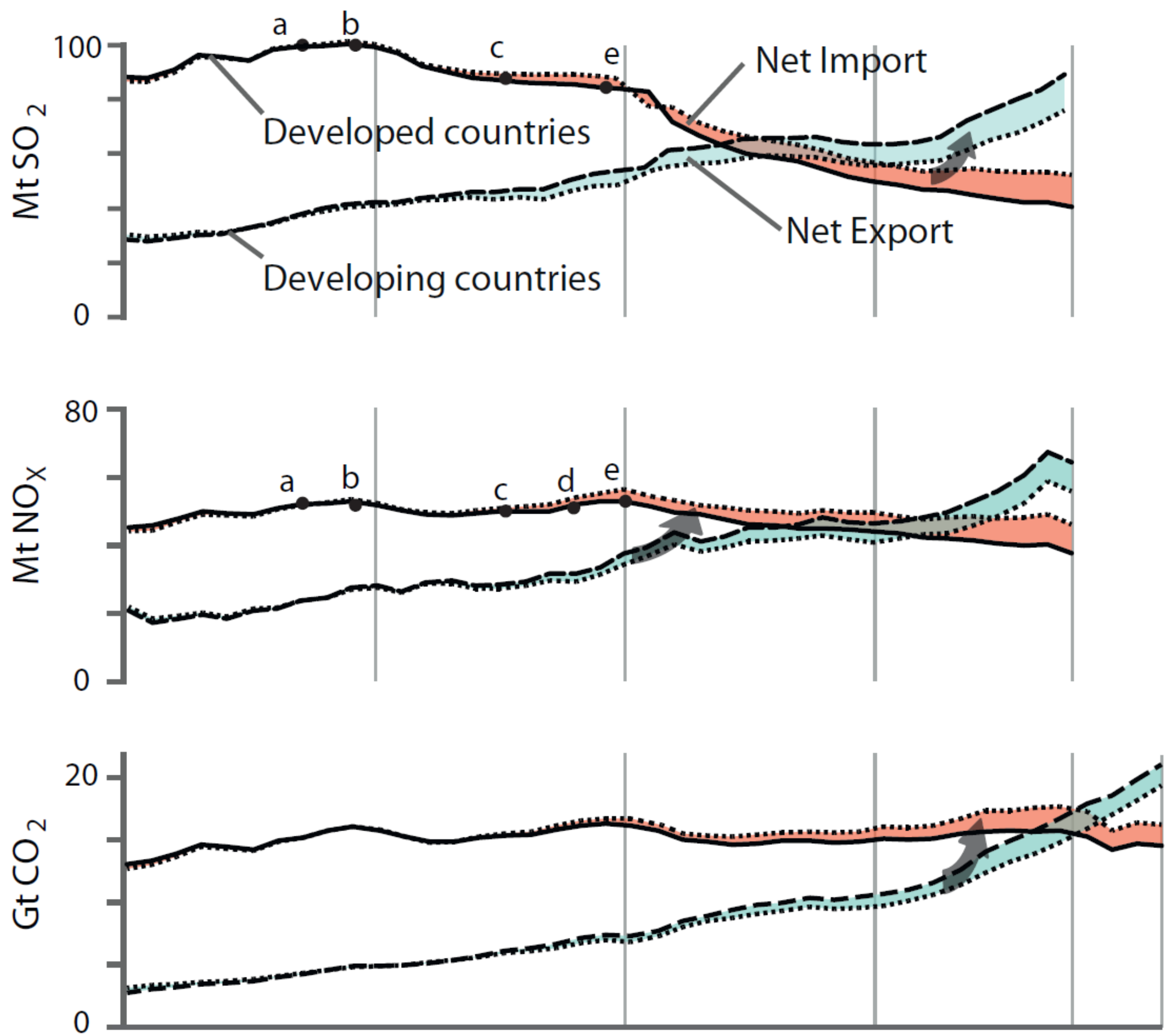
Global Trade Leads to Complex Emission Transfer

CO_2 emission transfer via trade



Davis and Caldaria, 2010, PNAS

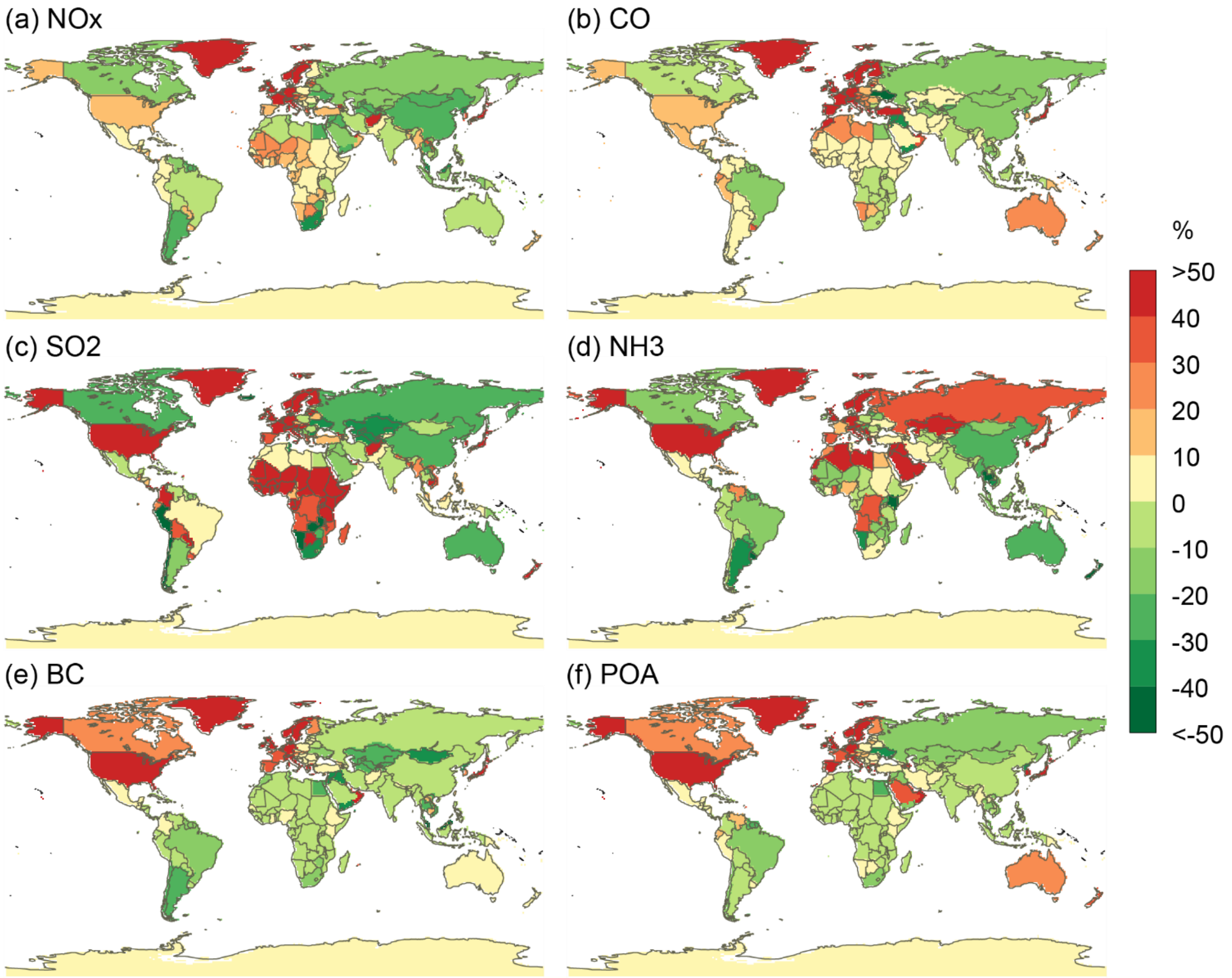
Consumption and Trade Drives Emission Redistribution



Kanemoto et al., 2014, GEC

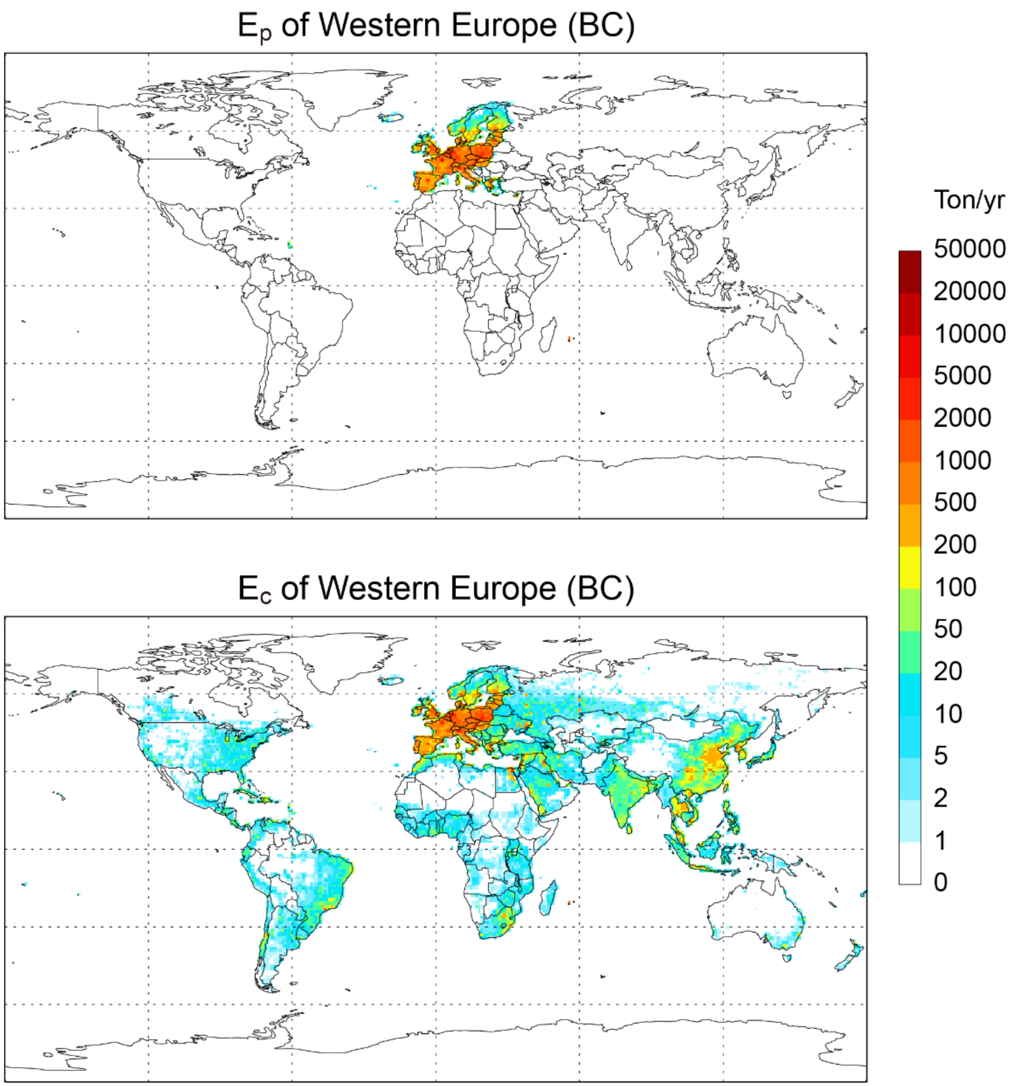
Trade Transfers Emissions from Rich to Poorer Regions

Consumption-based minus Production-based Emissions in 2007



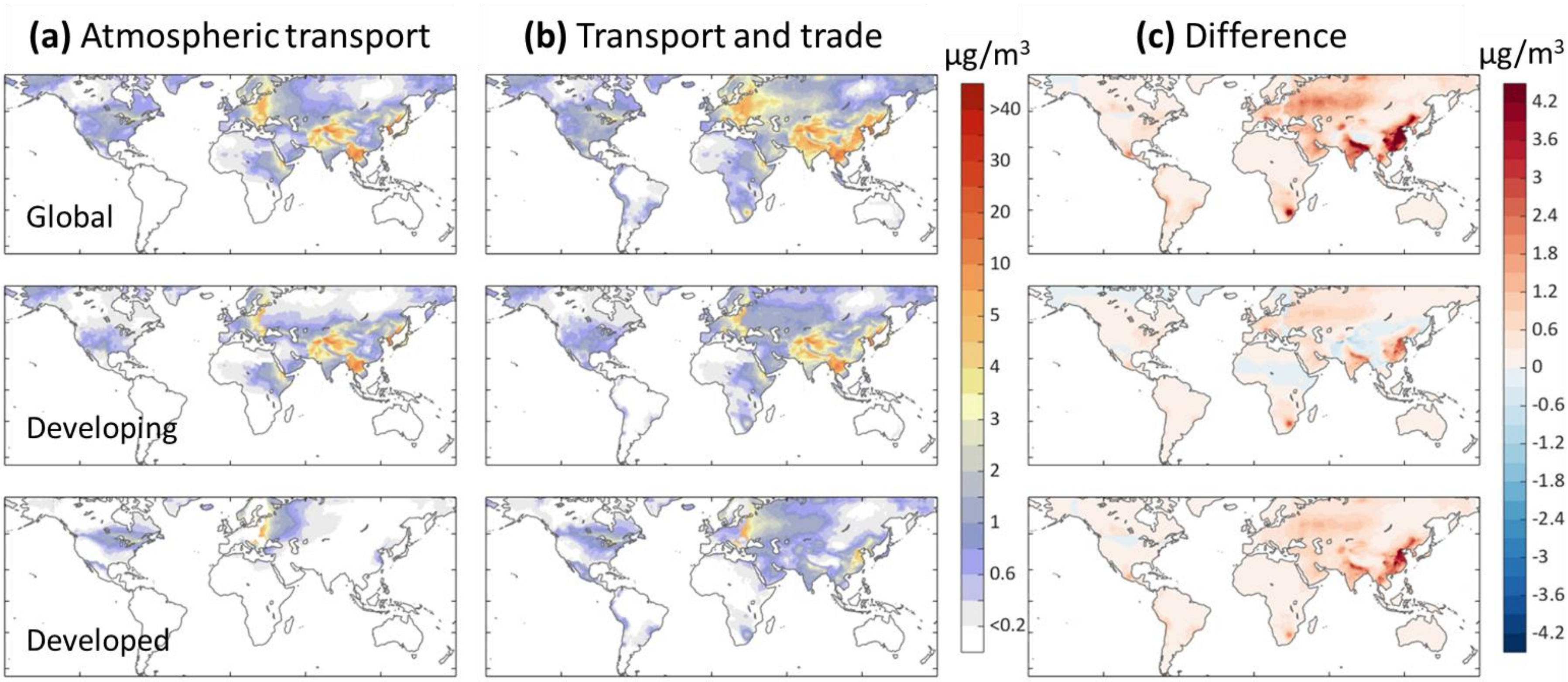
Lin et al., 2016, Nature Geoscience

Trade Redistributes Emissions



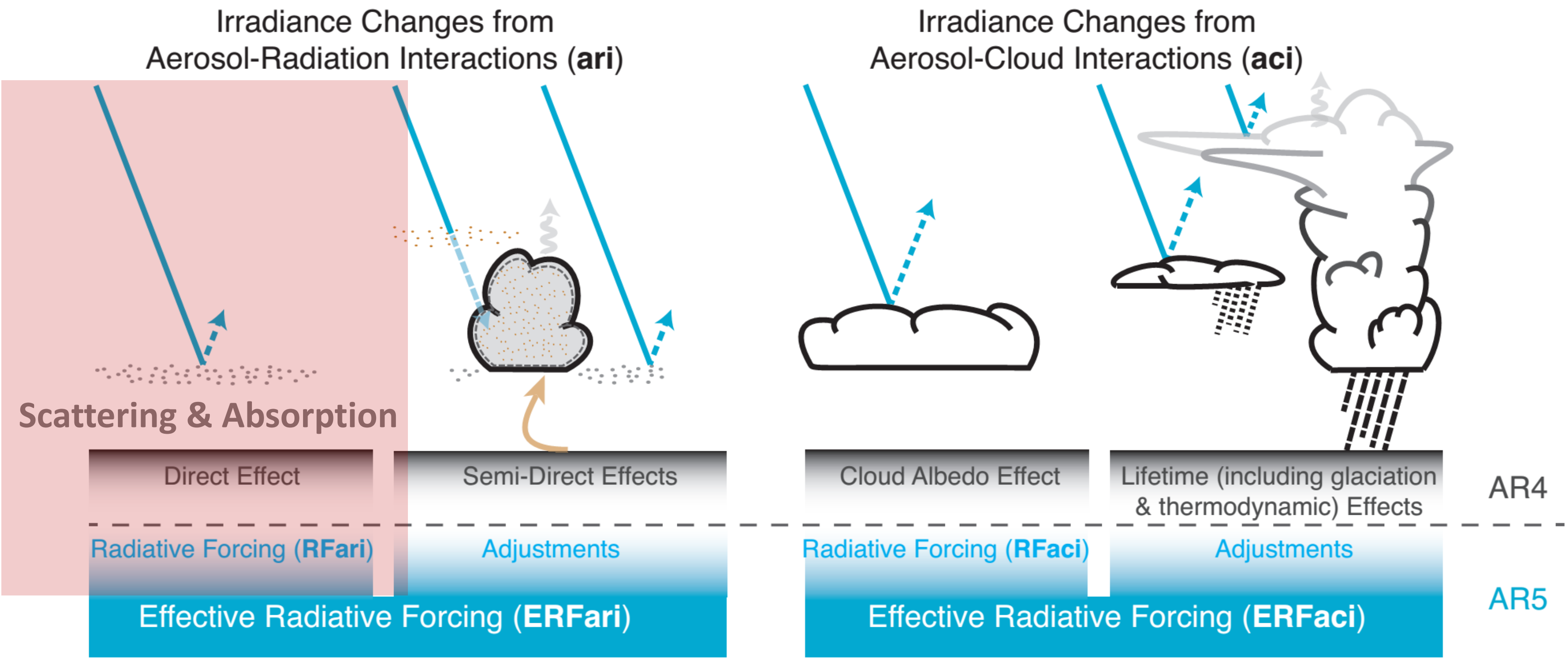
Lin et al., 2016, Nature Geoscience

Transboundary $PM_{2.5}$ Due to Trade-Transport Synergy



Lin et al., under review

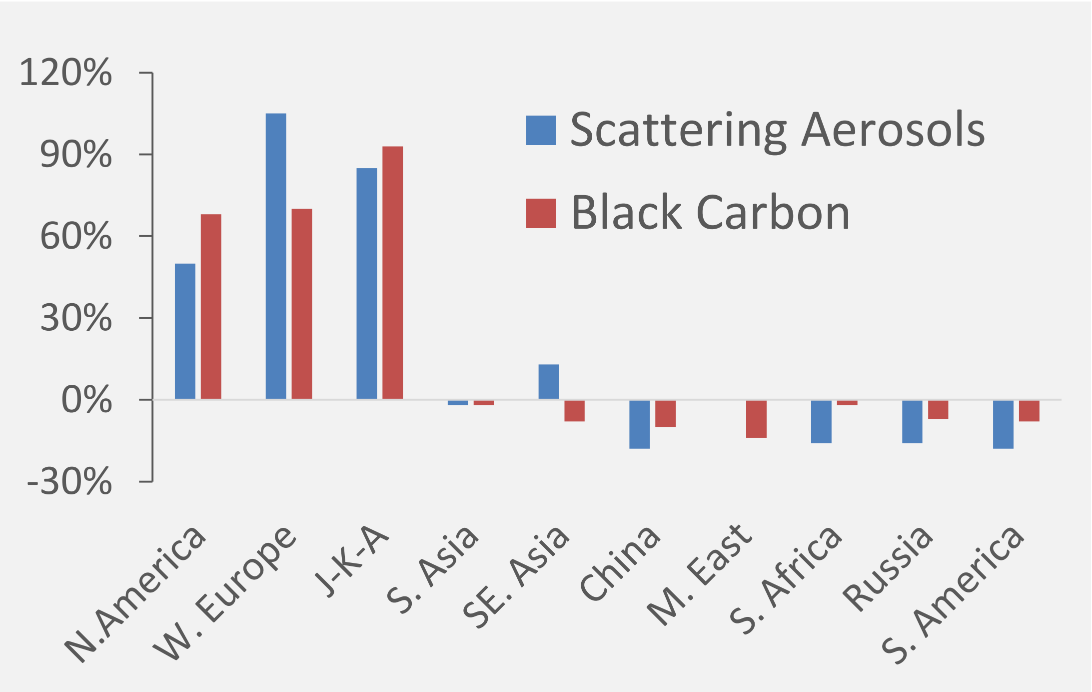
Radiative Forcing of Aerosols



IPCC, 2013

Aerosol Radiative Forcing Embedded in Trade: From Richer to Poorer Regions

Percent Difference between consumption- and production-based RF in 2007

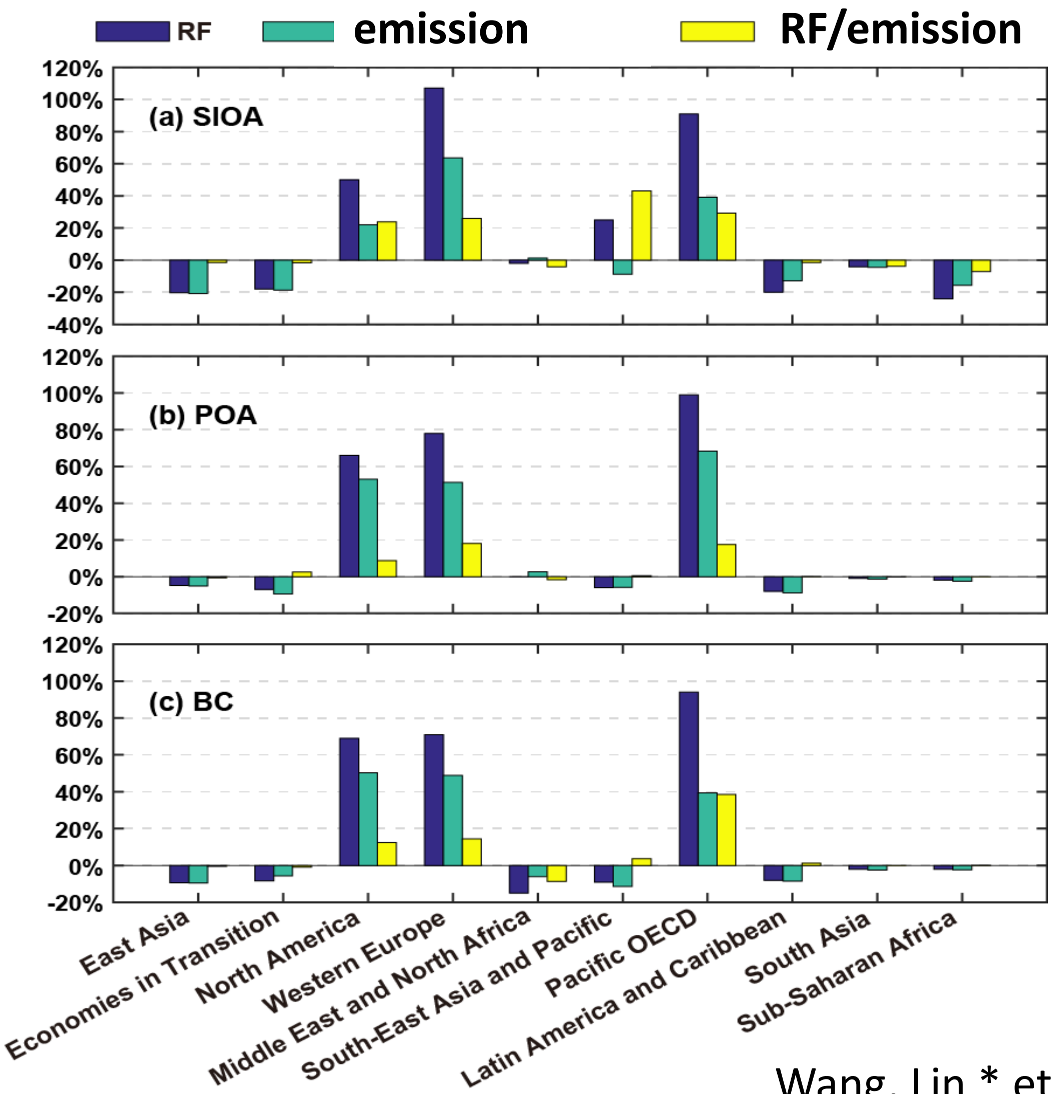


Method:
Emission inventory +
GTAP MRIO table +
GEOSChem + RRTMG

What is a region's contribution to climate change ???

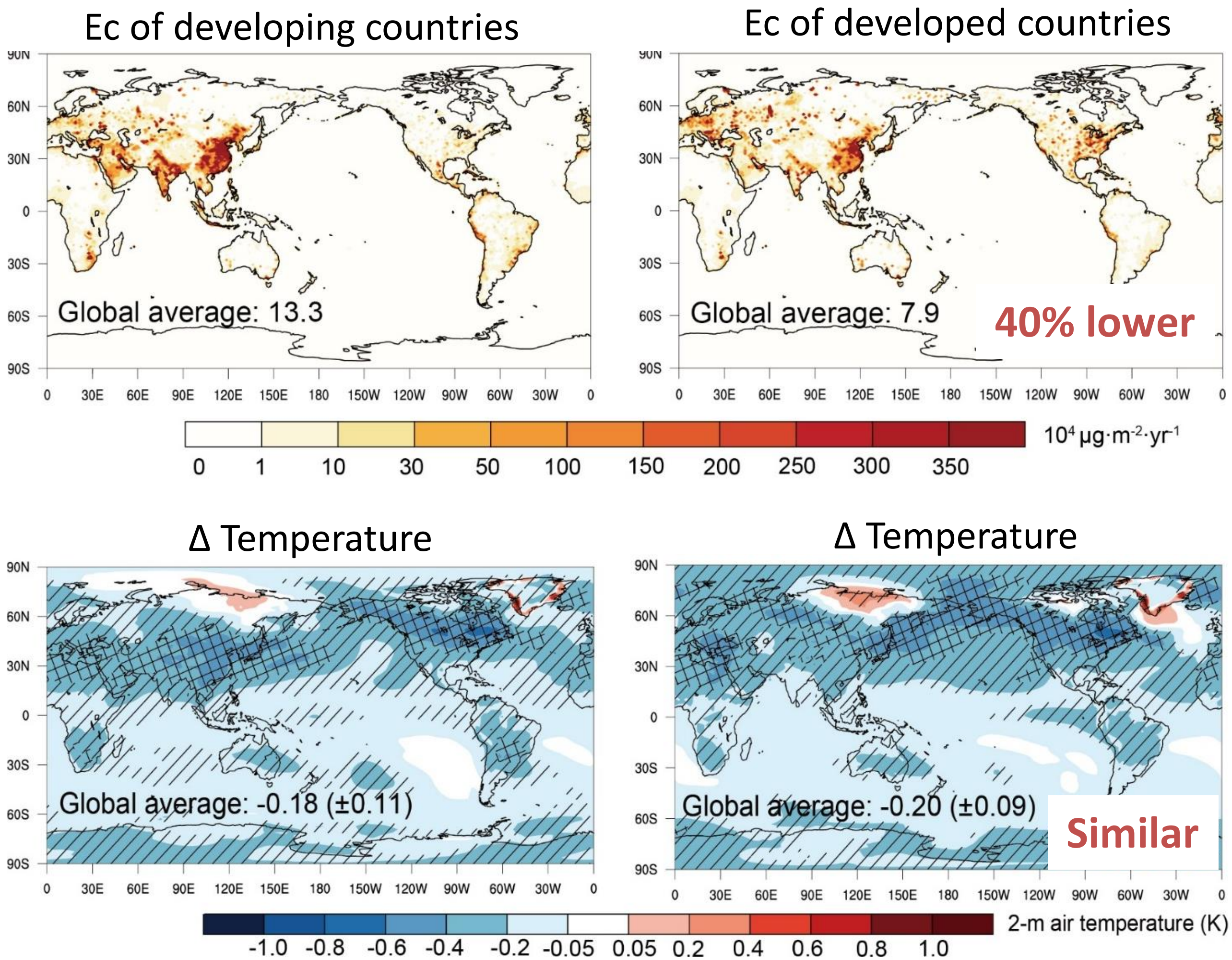
Lin et al., 2016, Nature Geoscience

Drivers of Difference Between Consumption- and Production-based Aerosol Radiative Forcing



Wang, Lin * et al., 2019

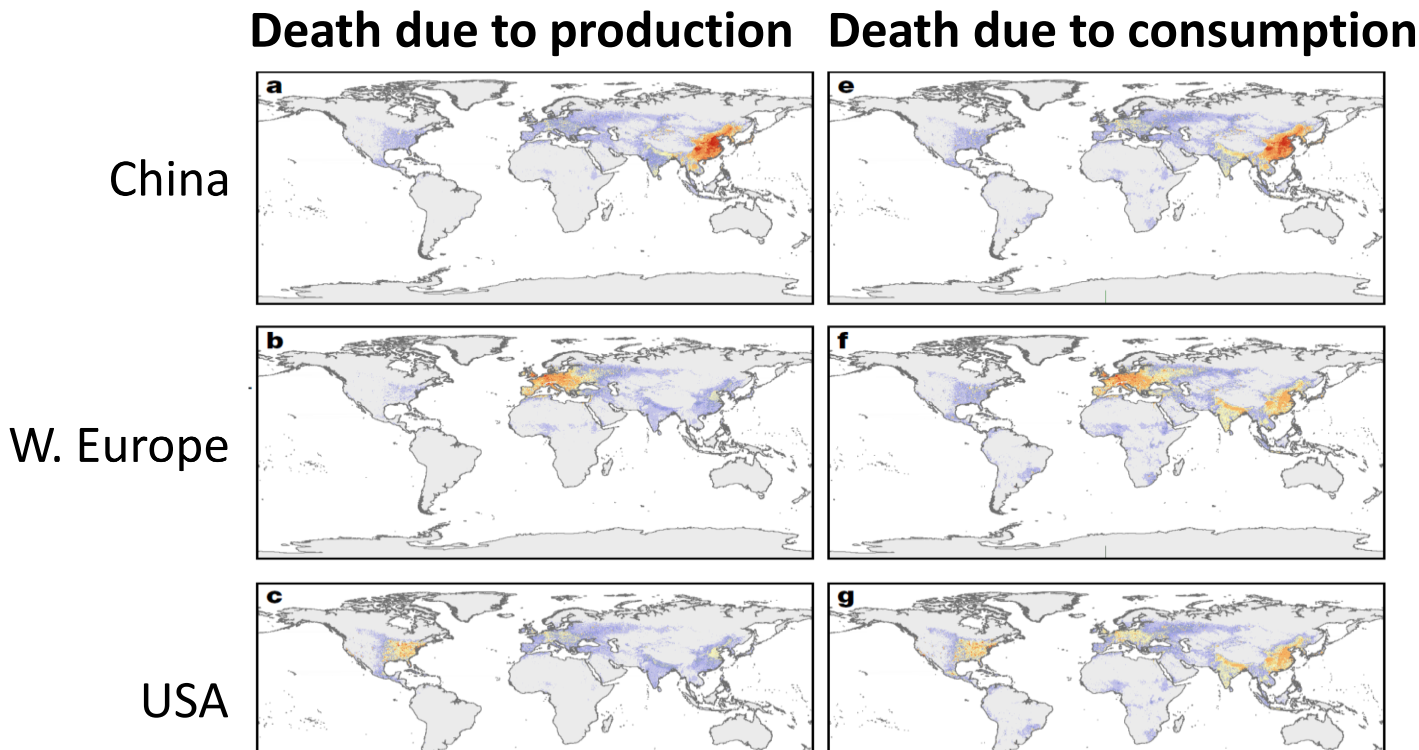
Sulfur Emissions from Consumption of Developing and Developing Countries Produce Comparable Climate Impacts



Method:
Emissions
+ GTAP
+ CESM2

Lin et al., Nature Geoscience, 2022

Transport & Trade are Related to Lots of $PM_{2.5}$ Mortality



Of 3,450,000 $PM_{2.5}$ related deaths in 2007:

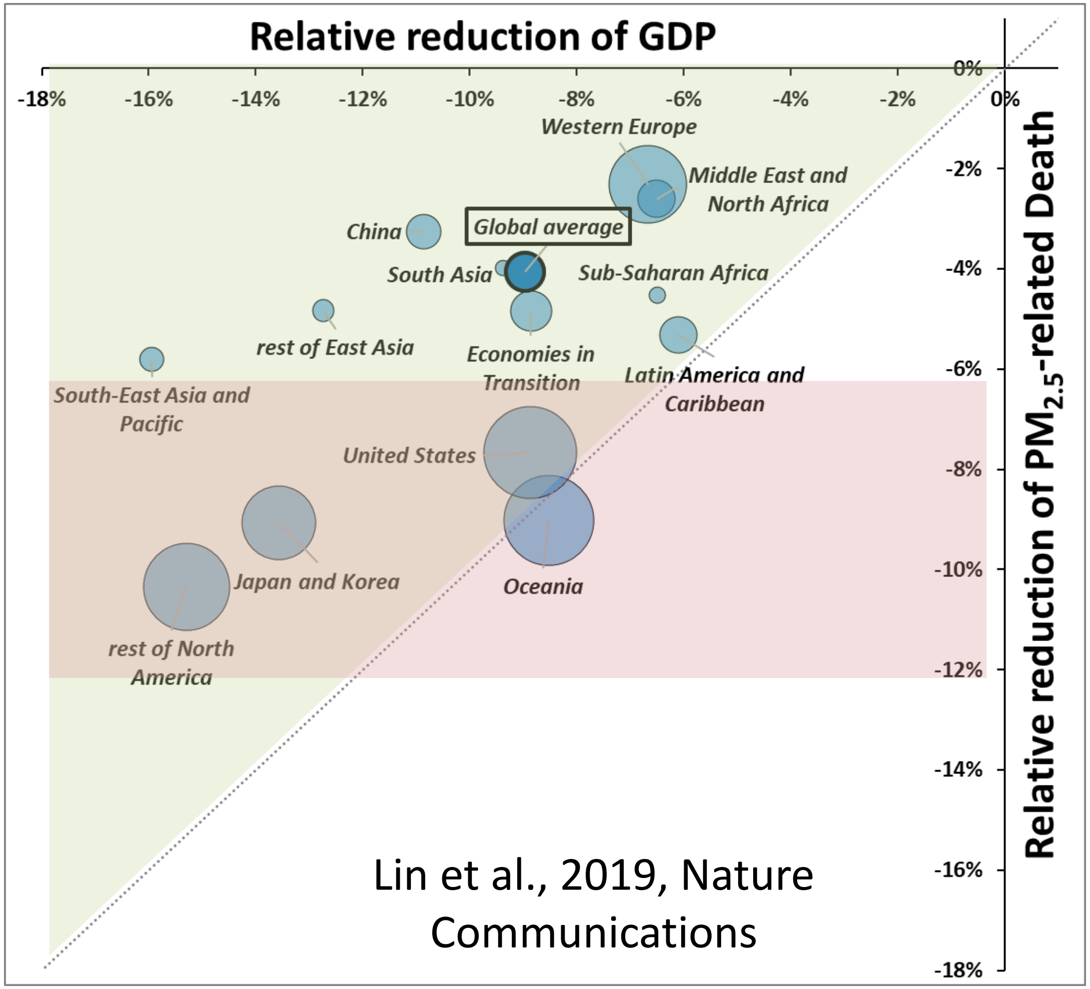
- **410,000 (12%) is due to atmospheric transboundary transport**
- **760,000 (22%) is due to consumption in a different region (trade + atmos)**

Of 1,000,000 PM2.5 related deaths in 2007 in China:

- **35,000 (3.5%) is due to atmospheric transboundary transport**
- **240,000 (24%) is due to consumption in a different region (trade + atmos)**

Zhang, ..., Lin* et al., 2017, Nature

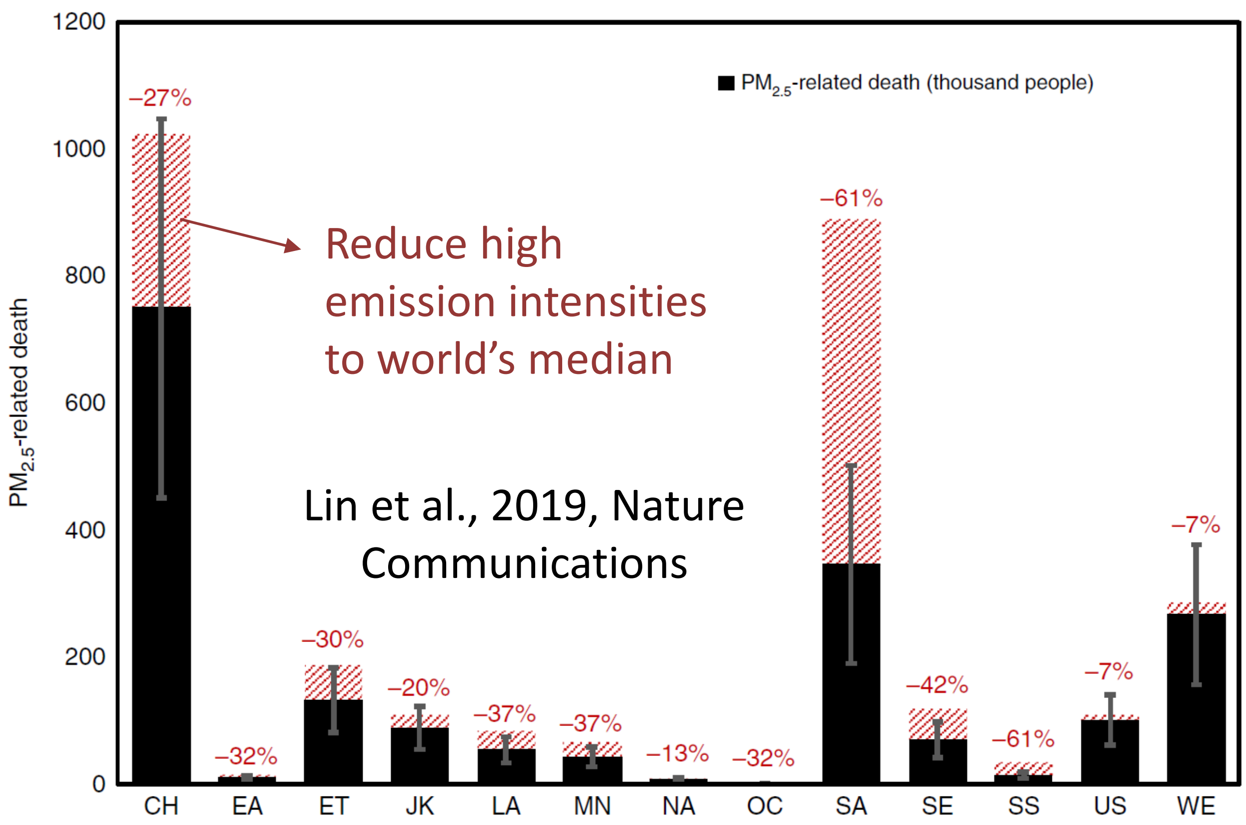
Distinctive Changes in Economy & $PM_{2.5}$ Mortality from *Free Trade* to *Current tariff plus an additional 25% tariff*



- With the trade restrictions, regional GDP, CO_2 emission and mortality **all decrease**.
- Relative reductions of **emissions and mortalities** are less significant than the reduction in **GDP**.
- **Developed regions** tend to have greater relative reductions in mortality than **developing regions**.

Method: Emissions + GTAP CGE + GEOS-Chem + Satellite + GEMM

Global Concerted Actions to Cut Emission Intensities in Developing Regions to Ensure both Economic Growth & Environmental Protection

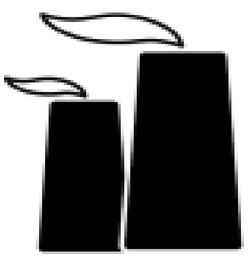


Method: Emissions + GTAP CGE + GEOS-Chem + Satellite + GEMM

From Production to Consumption Perspective

Trade

Production ➡ **Impacts** ⬅ **Consumption**



- **Air Quality**
- **Climate**
- **Agriculture**
- **Ecosystems**
- **Sustainability**

- **Socioeconomic-environmental integration**
- **Regionally consistent environmental standards ?**
- **Where and how to best invest ? Beijing v.s. Hebei ?**

Air Pollution Control

- **Local v.s. transboundary air pollution**
- **Long-term control strategies for sustainable development**
- **Short-term mitigation and implications**
- **How science is used to facilitate policy making?**

Quiz

1. Ozone production is normally VOC-limited in urban areas and NOx-limited in surrounding rural areas. To control urban ozone pollution, should we control NOx or VOC emissions?
2. How can ozone and PM pollution affect each other?
3. How can climate change affect ozone and PM pollution (local production and transport)?
4. What factors determine the transboundary transport of air pollutants?
5. How to better design pollution control strategies in light of trade-related transport?

How Is Air Pollution Globalized ???

Traditional View

Source Attribution

Production (ind., pow., tra.)
↓
Emissions
↓
Local Pollution
↓
Atmos. Transport
↓
Global Change

Consumption & Trade Drives Production and Pollution !

Cause Attribution

Consumption

↓

Production (ind., pow., tra.)

↓

Emissions

↓

Local Pollution

↓

Atmos. Transport

↓

Global Change

Consumption & Trade Drives Production and Pollution !

Cause Attribution

Consumption (local + foreign)

⬇

Production (ind., pow., tra.)

⬇

Emissions

⬇

Local Pollution

⬇

Atmos. Transport

⬇

Global Change

Consumption & trade re-locates pollution

from consumers to producers

Globalizing Air Pollution

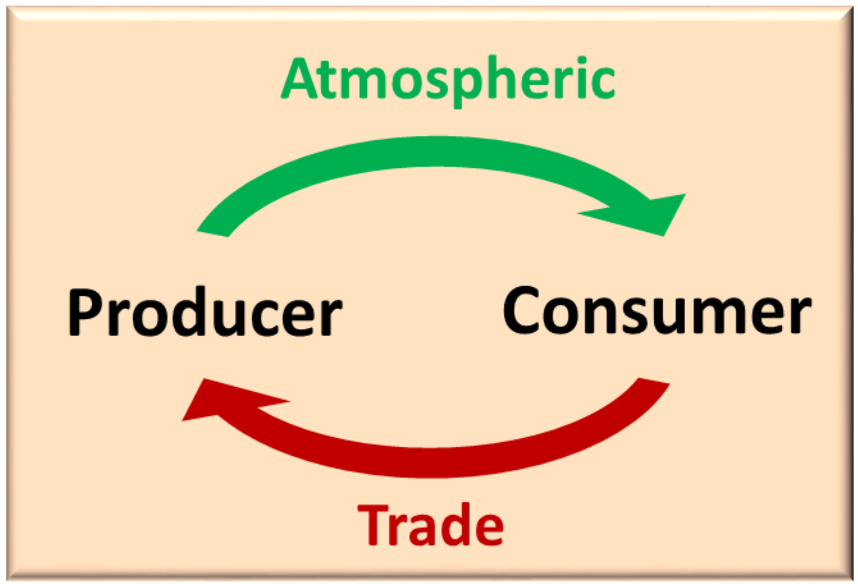
Advanced Satellite

High-Res Modeling

Pollution

Climate

Ecosystem



Regional

Historical

Future

Integrated Trade-Emission-Pollution Modeling

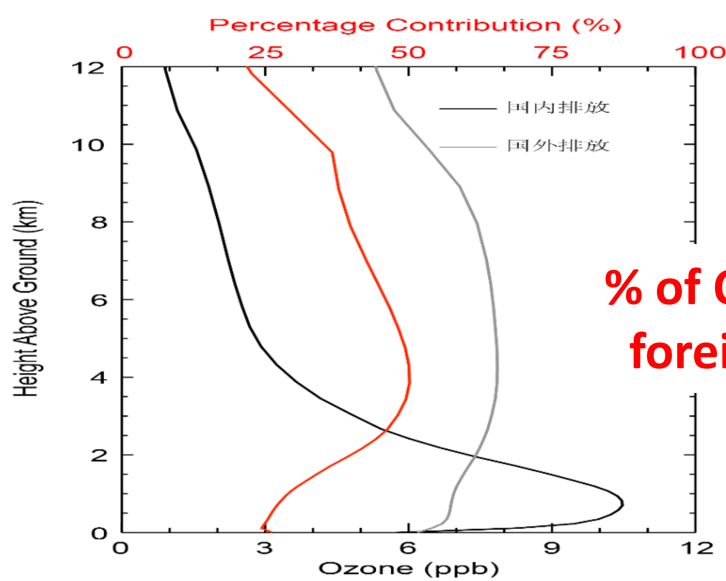
Long-range Transport

- Campaign observations
- Satellite observations
- Back trajectory modeling
- Chemical transport modeling
- Adjoint modeling of CTMs

- Episodic v.s. mean influences

- Trans-Pacific transport is most studied!

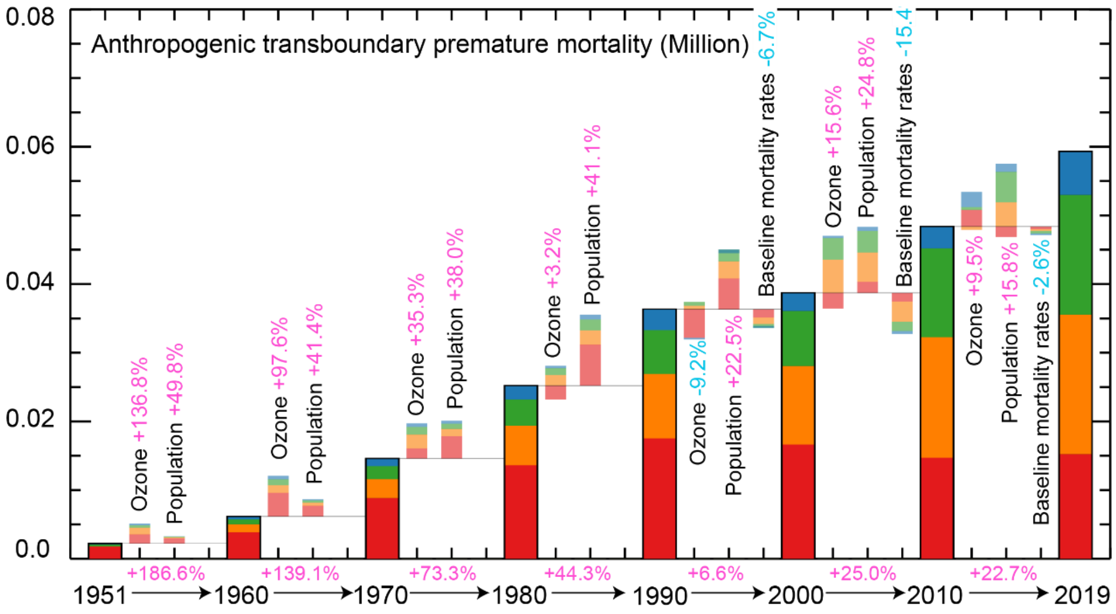
Two Chemistry Mechanisms of Ozone Transport



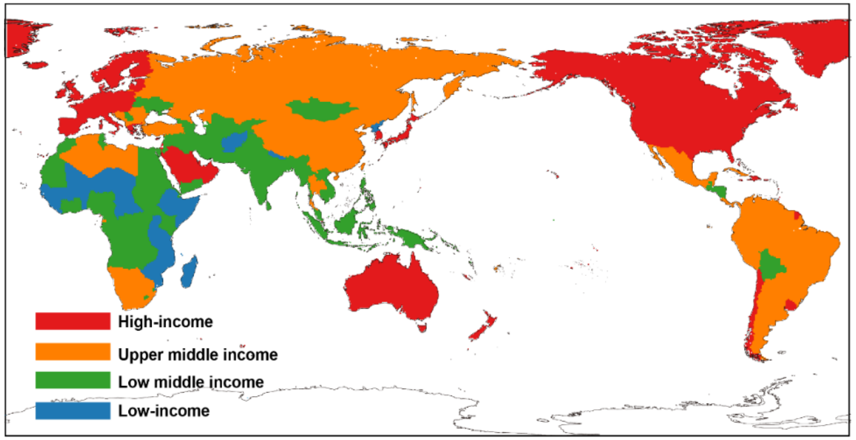
% of O_3 produced within foreign source regions

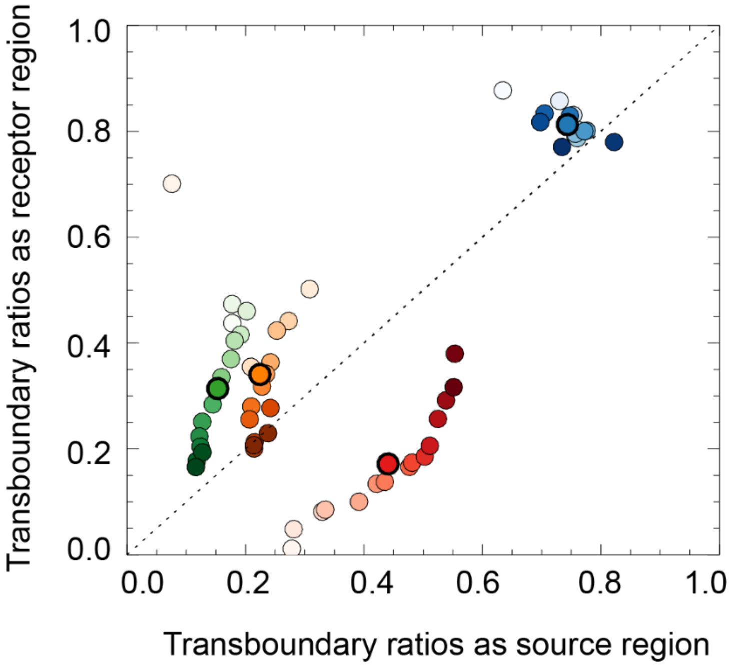
Ni et al., ACP, 2018

Historical Transboundary Ozone Mortality via Atmospheric Transport

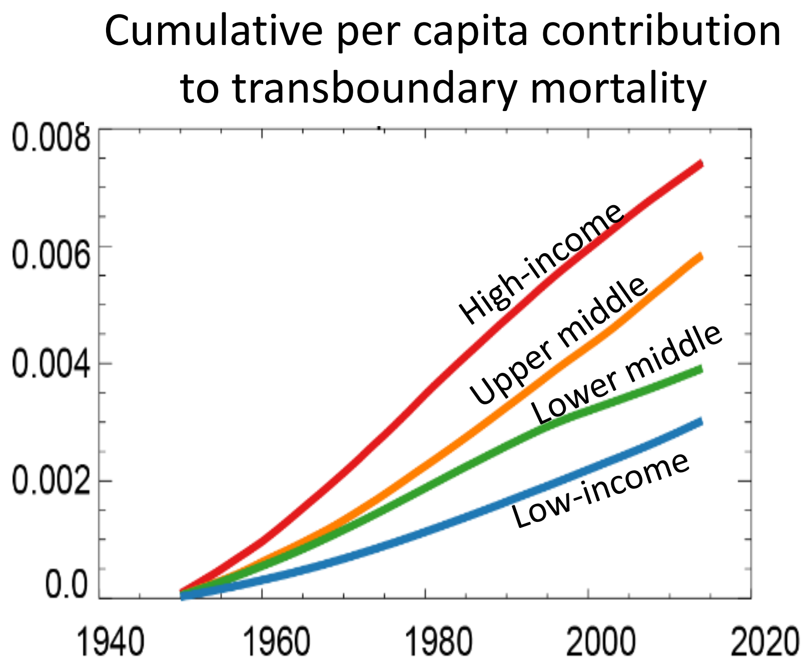


Chen et al., submitted

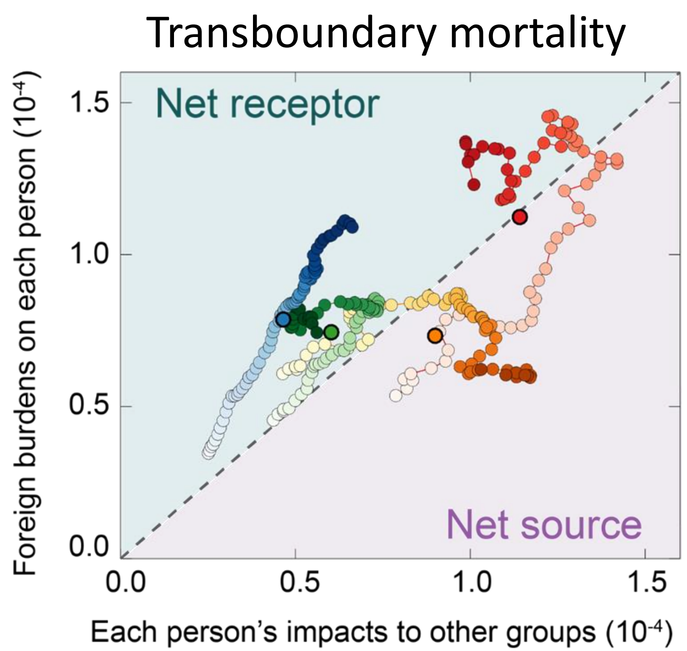




Historical Transboundary $PM_{2.5}$ Mortality via Atmospheric Transport



On a per capita contribution basis:
Richer group exerts larger cumulative transboundary mortality



On a per capita *net effect* basis:
Poorest suffers from heaviest *net* transboundary burden

Chen et al., Science Bulletin, 2021