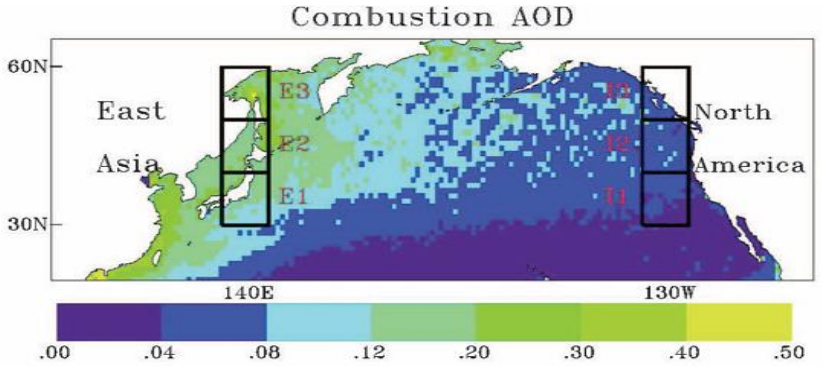
Chapter 8

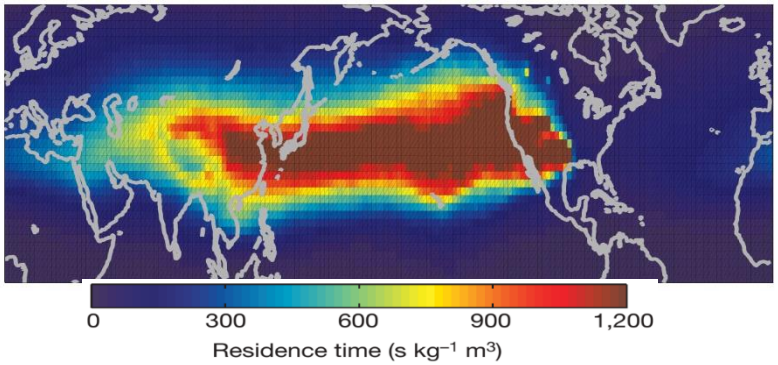
Economic Globalization, Trade and Pollution Transfer

Atmospheric Transport of Chinese Pollution

Yu et al., 2012, Science:

- E. Asian anthropogenic PM causes 6% of N.A. DRE



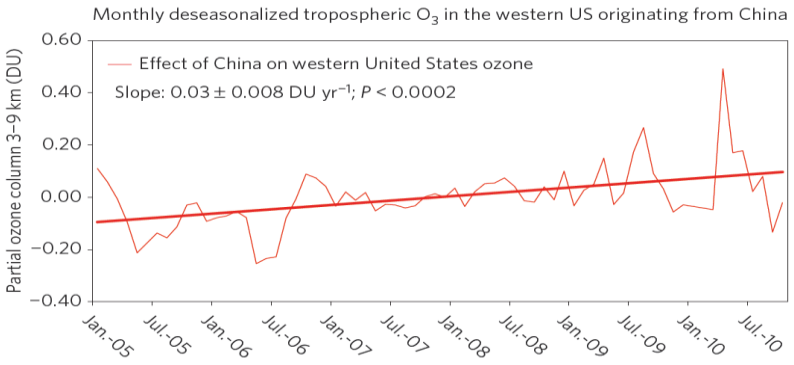


Cooper et al., 2010, Nature:

- Air transported from Asia to W. US contains greatest increasing O_3

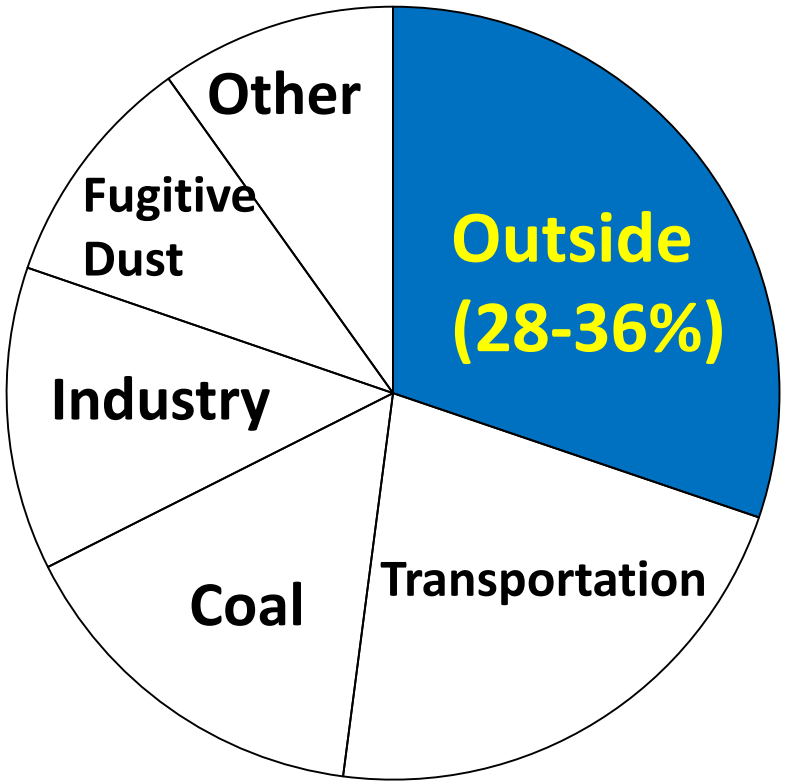
Verstraeten et al., 2015, Nat. Geos.:

- Rising Chinese emissions offset 43% of FT O_3 reduction over W. US.



Atmospheric $PM_{2.5}$ Transport Affects Beijing

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



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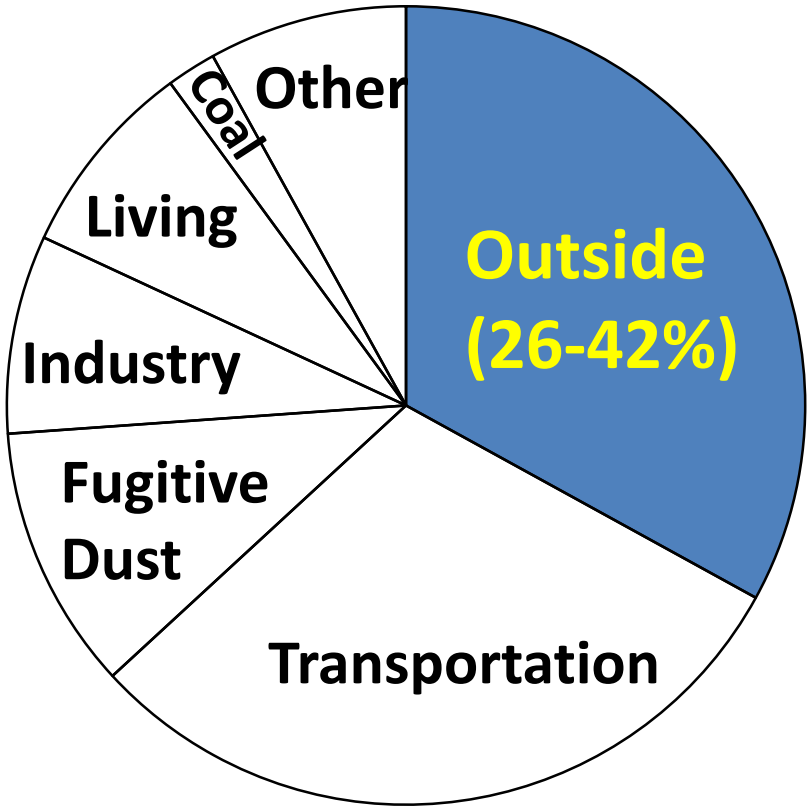
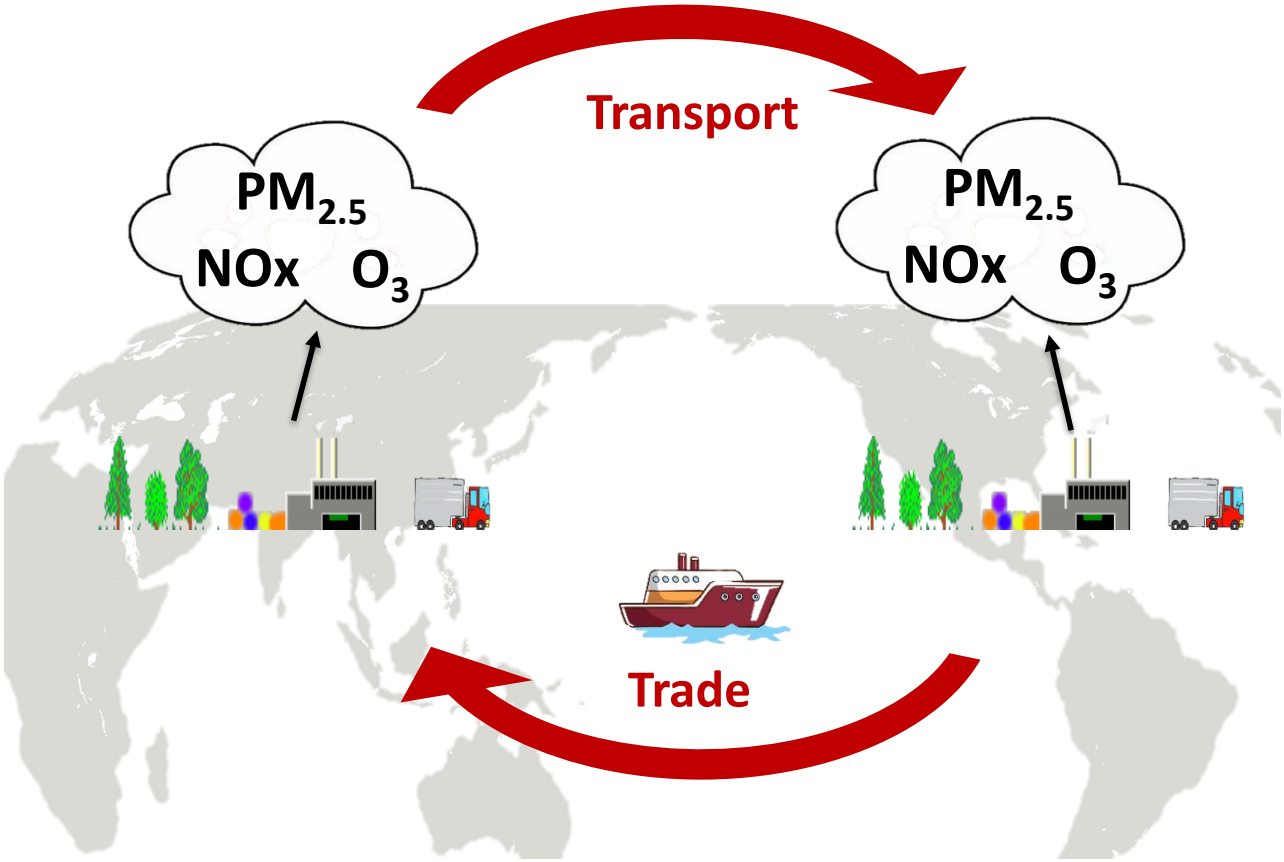


区域输送贡献：

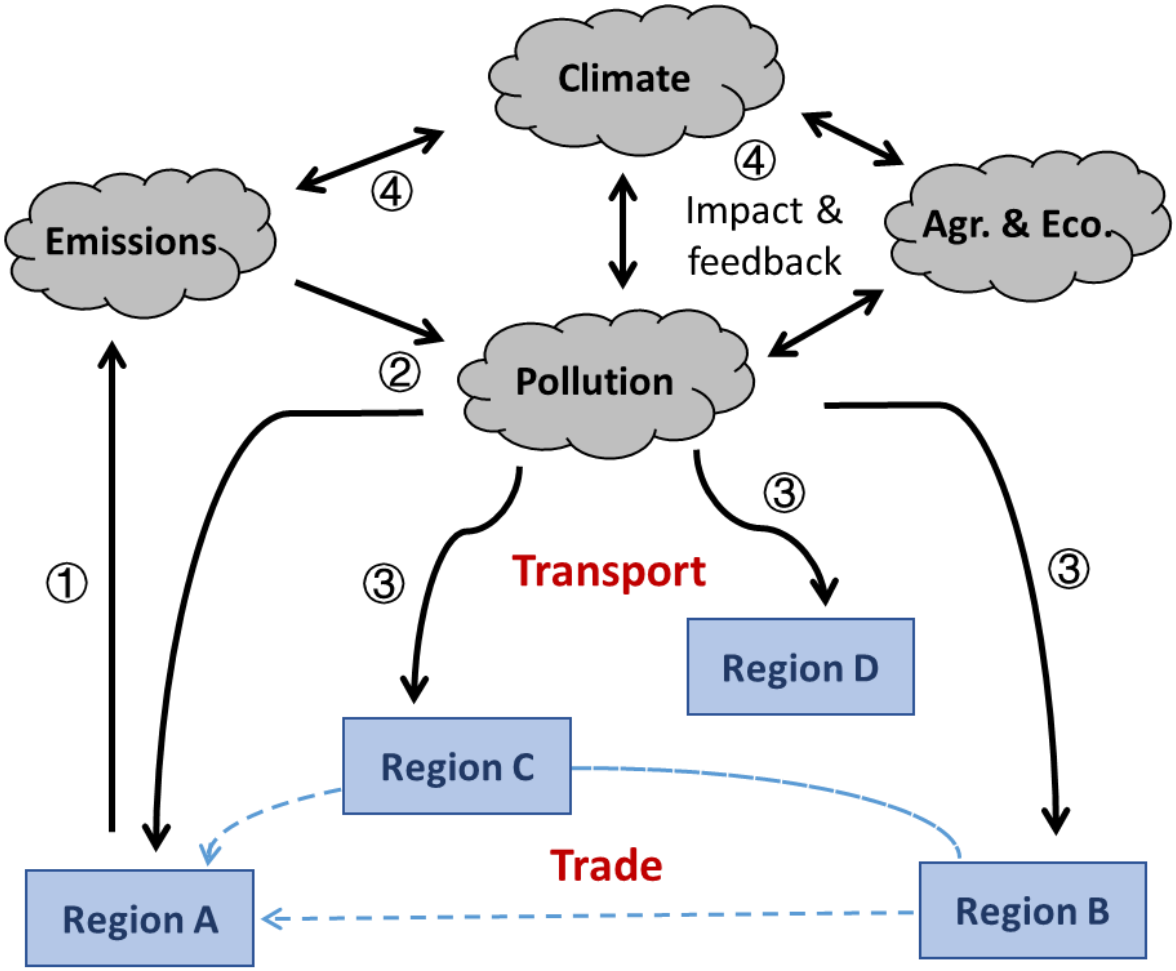
- 年平均：26%-42%
- 中度污染（115-150 μg/m³）：34%-50%
- 重污染日（＞150 μg/m³）：55%-75%

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



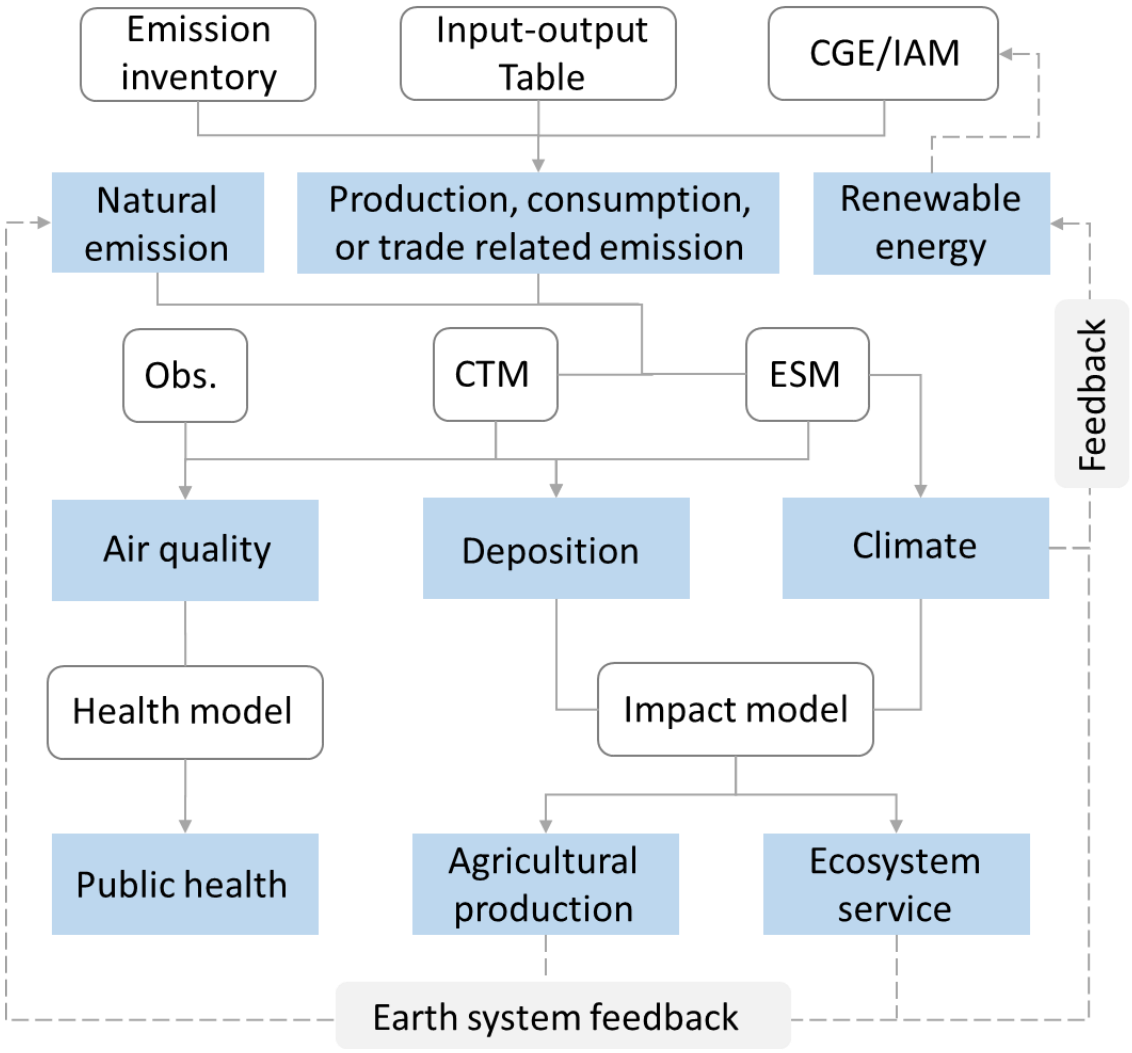
Lin JT et al., PNAS 2014; Lin JT et al., Nature Geoscience 2016
Zhang Q et al., Nature 2017; Lin JT et al., Nature Comm. 2019
Wang JX et al., Science Bulletin, 2019; Lin JT et al., Nature Geoscience, 2022
Chen LL et al., Science Bulletin, 2022; Xu JW et al., ACP, 2023, Highlight Paper
Kong H et al.,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

Synergistic Effects of Trade and Atmospheric Transport



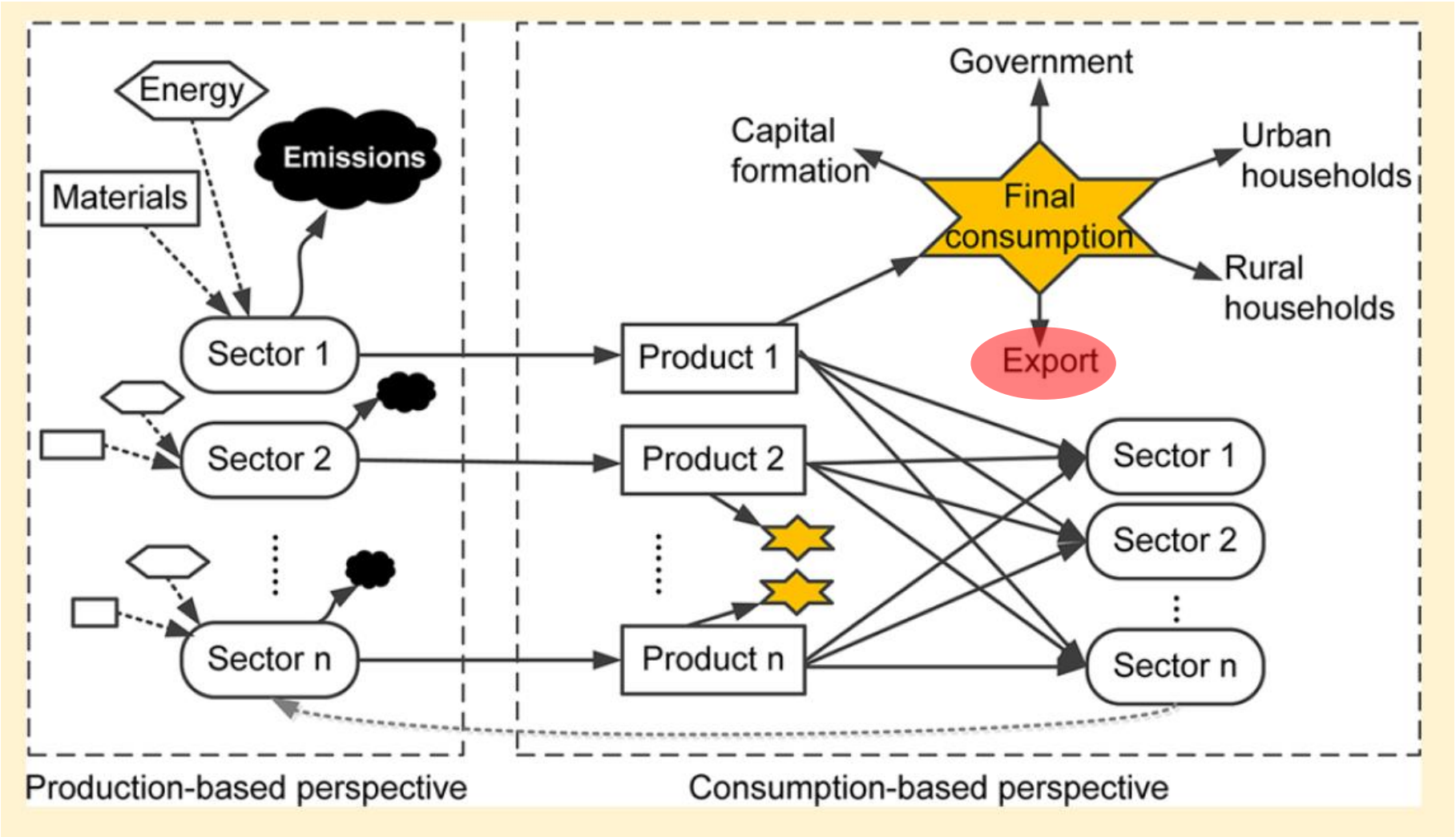
Lin et al., in prep

An Interdisciplinary Approach to Calculating Globalizing Air Pollution



Lin et al., in prep

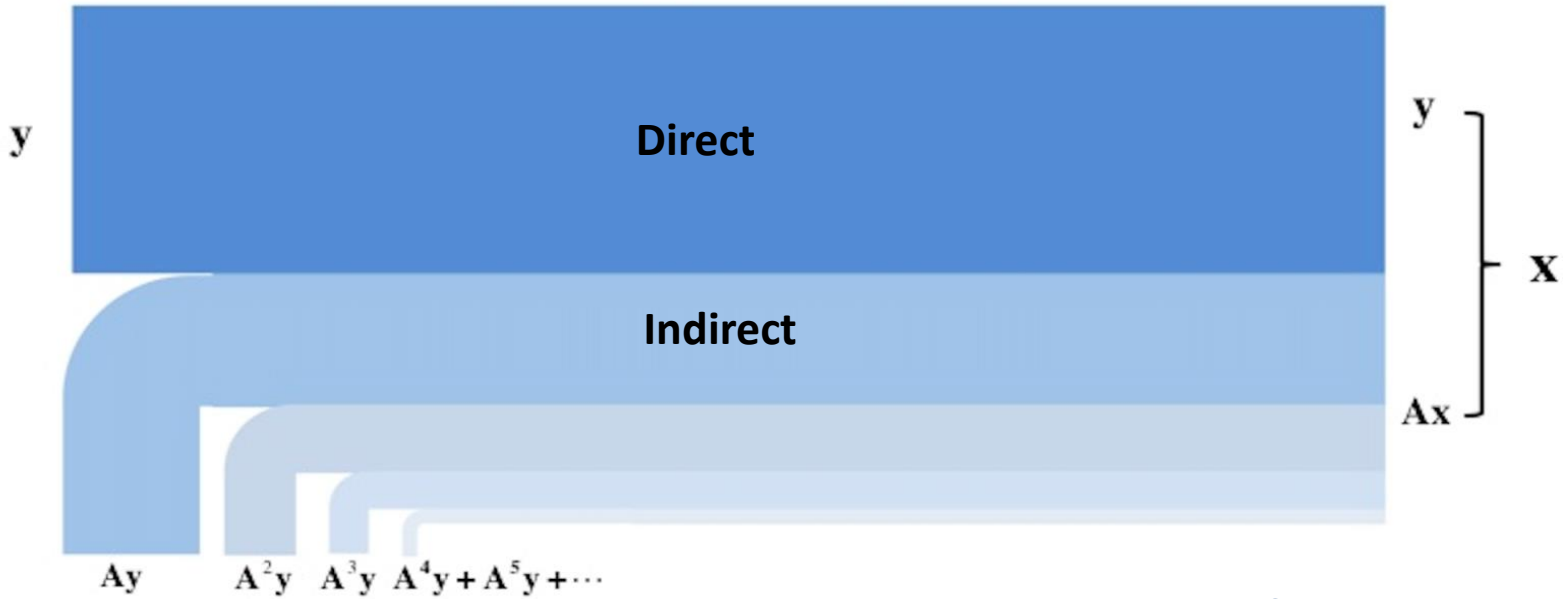
Emissions Associated with Production, Consumption & Trade



Huo et al., 2014

Production, Final Consumption, Intermediate Consumption

Structure Path Analysis



Sources: Da Pan

$$X = \underline{Y} + \underline{AY} + \underline{A^2Y} + \underline{A^3Y} + \underline{A^4Y} + \underline{A^5Y} + \ldots\ldots$$

(1) (2) (3) (4) (5) (6)

$$= (I + A + A^2 + A^3 + A^4 + A^5 + \ldots\ldots)Y$$

$$= (I - A)^{-1}Y$$

1, 2, 3, 4, … are # of transactions along the supply chains (Layers/Tiers)

$$\boldsymbol{X = (I - A)^{-1}Y}$$

Input-Output Analysis Based on Bilateral Trade

Single Region Input-Output Table

	Intermediate use			Final demand			Export	Import	Total output
	Sector 1	…….	Sector n	Sector 1	…….	Sector m			
Intermediate input	z_{11}	…….	z_{1n}	c_{11}	…….	c_{1m}	e_1	m_1	x_1
	…….	…….	…….	…….	…….	…….	…….	…….	…….
	z_{n1}	…….	z_{nn}	C_{n1}	…….	c_{nm}	e_n	m_n	x_n
Value added	v_1	…….	v_n						
Total inputs	x_1	…….	x_n						

$$a_{ij} = z_{ij}/x_j$$

$$x_i = \sum_{j=1}^{n} z_{ij} + \sum_{k=1}^{m} c_{ik} + e_i - m_i$$

$$\boldsymbol{Z = AX}$$

$$\boldsymbol{X = AX + C + E - M}$$

Export

Import

Domestic output

Intermediate output (domestic + import)

Final cons. (domestic + import)

Input-Output Analysis Based on Bilateral Trade

Direct requirement coefficient matrix: $\mathbf{A} = \mathbf{A}^{\mathrm{d}} + \mathbf{A}^{\mathrm{m}}$

Final demand: $\boldsymbol{C} = \boldsymbol{C}^{\mathrm{d}} + \boldsymbol{C}^{\mathrm{m}}$

Import: $\boldsymbol{M} = \mathbf{A}^{\mathrm{m}}\boldsymbol{X} + \boldsymbol{C}^{\mathrm{m}}$

Thus:

$$\begin{aligned}\boldsymbol{X} &= \mathbf{A}\boldsymbol{X} + \boldsymbol{C} + \boldsymbol{E} - \boldsymbol{M} \\ &= \left(\mathbf{A}^{\mathrm{d}} + \mathbf{A}^{\mathrm{m}}\right)\boldsymbol{X} + \left(\boldsymbol{C}^{\mathrm{d}} + \boldsymbol{C}^{\mathrm{m}}\right) + \boldsymbol{E} - \boldsymbol{M} \\ &= \mathbf{A}^{\mathrm{d}}\boldsymbol{X} + \boldsymbol{C}^{\mathrm{d}} + \boldsymbol{E} \\ &= \left(\mathbf{I} - \mathbf{A}^{\mathrm{d}}\right)^{-1}\boldsymbol{C}^{\mathrm{d}} + \left(\mathbf{I} - \mathbf{A}^{\mathrm{d}}\right)^{-1}\boldsymbol{E}\end{aligned}$$

Domestic output for domestic cons.

Domestic output for export

Calculating Emissions Embodied in Exports Based on Bilateral Trade

Emissions embedded in export: $EEE = \boldsymbol{F} \cdot \boldsymbol{X^e}$

Total emissions: $\boldsymbol{P} = \boldsymbol{F} \cdot \boldsymbol{X}$

Total output: $\boldsymbol{X}$

Total output for export (based on IOA): $\boldsymbol{X^e} = \left(\mathbf{I} - \mathbf{A}^{\mathrm{d}}\right)^{-1} \boldsymbol{E}$

Emission intensity: $\boldsymbol{F}$ where $F_i = \frac{P_i}{X_i}$

Domestic direct requirement coefficient matrix: $\mathbf{A}^{\mathrm{d}}$

Lin et al., 2014, PNAS

Emissions Embodied in Bilateral Trade

Emissions embedded in export:

$$EEE = \boldsymbol{F} \cdot \boldsymbol{X^e} = \boldsymbol{F} \cdot \left(\mathbf{I} - \mathbf{A}^{\mathrm{d}}\right)^{-1} \boldsymbol{E}$$

Emissions avoided by import:

$$EAI = \boldsymbol{F} \cdot \boldsymbol{X^m} = \boldsymbol{F} \cdot \left(\mathbf{I} - \mathbf{A}^{\mathrm{d}}\right)^{-1} \boldsymbol{M}$$

Emissions embedded in import:

$$EEI = EAI \cdot \frac{(CO_2/GDP)_i}{(CO_2/GDP)_0}$$

Emissions embedded in net trade:

$$EET = EEE - EEI$$

Lin et al., 2014, PNAS

Multi-Regional Input-Output Analysis

- **A bigger matrix to describe global supply chain**

$$\begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \mathbf{x}^3 \\ \vdots \\ \mathbf{x}^m \end{pmatrix} = \begin{pmatrix} \mathbf{A}^{11} & \mathbf{A}^{12} & \mathbf{A}^{13} & \cdots & \mathbf{A}^{1m} \\ \mathbf{A}^{21} & \mathbf{A}^{22} & \mathbf{A}^{23} & \cdots & \mathbf{A}^{2m} \\ \mathbf{A}^{31} & \mathbf{A}^{32} & \mathbf{A}^{33} & \cdots & \mathbf{A}^{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}^{m1} & \mathbf{A}^{m2} & \mathbf{A}^{m3} & \cdots & \mathbf{A}^{mm} \end{pmatrix} \begin{pmatrix} \mathbf{x}^1 \\ \mathbf{x}^2 \\ \mathbf{x}^3 \\ \vdots \\ \mathbf{x}^m \end{pmatrix} + \begin{pmatrix} \sum_s \mathbf{y}^{1s} \\ \sum_s \mathbf{y}^{2s} \\ \sum_s \mathbf{y}^{3s} \\ \vdots \\ \sum_s \mathbf{y}^{ms} \end{pmatrix}$$

$$x^r = A^{rr}x^r + y^{rr} + \sum_{s \neq r} A^{rs}x^s + \sum_{s \neq r} y^{rs}$$

- **Example:**
- **Country: China: 1, Japan: 2, US: 3**
- **Sector: crude oil: 1; gasoline: 2; transportation: 3**
- **y^{rs}: final demand (consumption)**

Multi-Regional Input-Output Analysis

Multi-Regional Input-Output Table

		Intermediate use						Final demand		Total output
		Region 1			Region 2			Region 1	Region 2	
		Sector 1	.....	Sector n	Sector 1	.....	Sector n			
Intermediate input	Region 1	z_{11}^{11}	.....	z_{1n}^{11}	z_{11}^{12}	.....	z_{1n}^{12}	y_1^{11}	y_1^{12}	x_1^1
		.....	.....	.....	.....	.....	.....	.....	.....	.....
		z_{n1}^{11}	.....	z_{nn}^{11}	z_{n1}^{12}	.....	z_{11}^{12}	y_n^{11}	y_n^{12}	x_n^1
	Region 2	z_{11}^{21}	.....	z_{11}^{21}	z_{11}^{22}	.....	z_{1n}^{22}	y_1^{21}	y_1^{22}	x_1^2
		.....	.....	.....	.....	.....	.....	.....	.....	.....
		z_{n1}^{21}	.....	z_{n1}^{21}	z_{n1}^{22}	.....	z_{nn}^{22}	y_n^{21}	y_n^{22}	x_n^2
Value added		v_1^1	.....	v_n^1	v_1^2	.....	v_n^2			
Total input		x_1^1	.....	x_n^1	x_1^2	.....	x_n^2			

$$x_i^R = \sum_{S=1}^{m} \sum_{j=1}^{n} z_{ij}^{RS} + \sum_{S=1}^{m} y_i^{RS}$$

$$A_{ij}^{RS} = z_{ij}^{RS} / x_j^S$$

Multi-Regional Input-Output Analysis of Emissions

$$x^r = \sum_{s=1}^{m} z^{rs} + \sum_{s=1}^{m} y^{rs} \qquad A^{rs} = z^{rs}/x^s \qquad (1)$$

Regions and sectors lumped

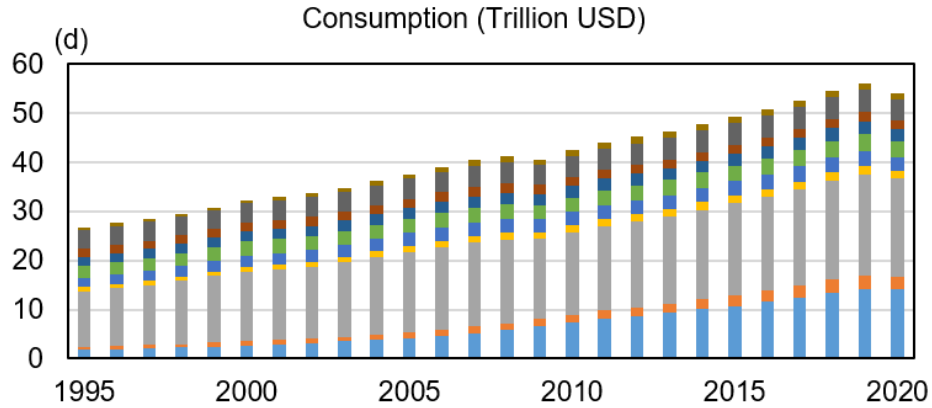
$$\begin{pmatrix} x^1 \\ x^2 \\ \vdots \\ x^m \end{pmatrix} = \begin{pmatrix} A^{11} & A^{12} & \cdots & A^{1m} \\ A^{21} & A^{22} & \cdots & A^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A^{m1} & A^{m2} & \cdots & A^{mm} \end{pmatrix} \begin{pmatrix} x^1 \\ x^2 \\ \vdots \\ x^m \end{pmatrix} + \begin{pmatrix} \sum_s y^{1s} \\ \sum_s y^{2s} \\ \vdots \\ \sum_s y^{ms} \end{pmatrix} \qquad (2)$$

$$\begin{pmatrix} x^1 \\ x^2 \\ \vdots \\ x^m \end{pmatrix} = \left[I - \begin{pmatrix} A^{11} & A^{12} & \cdots & A^{1m} \\ A^{21} & A^{22} & \cdots & A^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A^{m1} & A^{m2} & \cdots & A^{mm} \end{pmatrix} \right]^{-1} \begin{pmatrix} \sum_s y^{1s} \\ \sum_s y^{2s} \\ \vdots \\ \sum_s y^{ms} \end{pmatrix} \qquad (3)$$

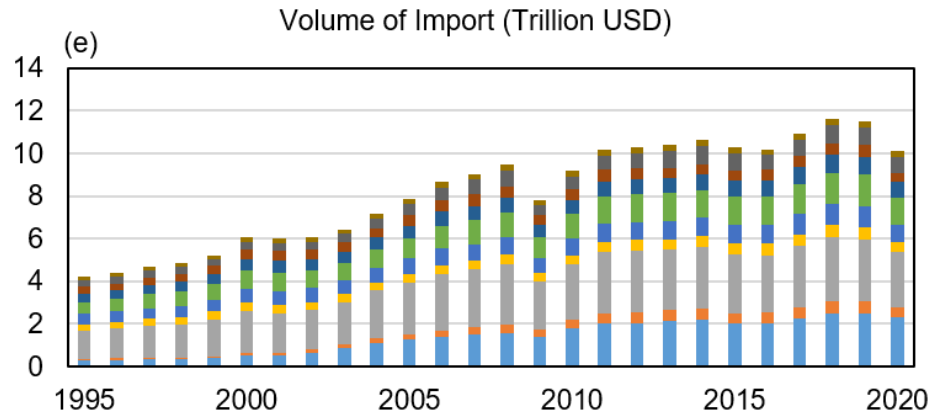
$$F = \begin{pmatrix} F^1 & 0 & \cdots & 0 \\ 0 & F^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & F^m \end{pmatrix}$$

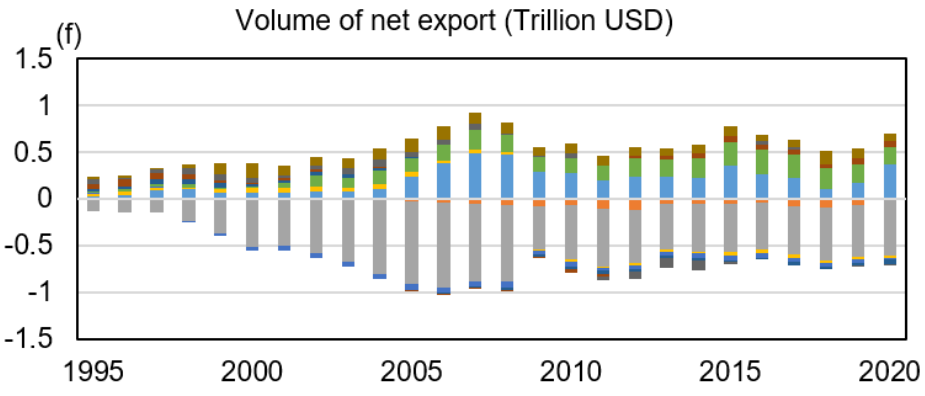
$$E = F \times \begin{pmatrix} x^1 \\ x^2 \\ \vdots \\ x^m \end{pmatrix} = \begin{pmatrix} F^1 & 0 & \cdots & 0 \\ 0 & F^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & F^m \end{pmatrix} \times \left[I - \begin{pmatrix} A^{11} & A^{12} & \cdots & A^{1m} \\ A^{21} & A^{22} & \cdots & A^{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A^{m1} & A^{m2} & \cdots & A^{mm} \end{pmatrix} \right]^{-1} \begin{pmatrix} \sum_s y^{1s} \\ \sum_s y^{2s} \\ \vdots \\ \sum_s y^{ms} \end{pmatrix} \qquad (4)$$

Rapid Changes in Trade and Outsourcing



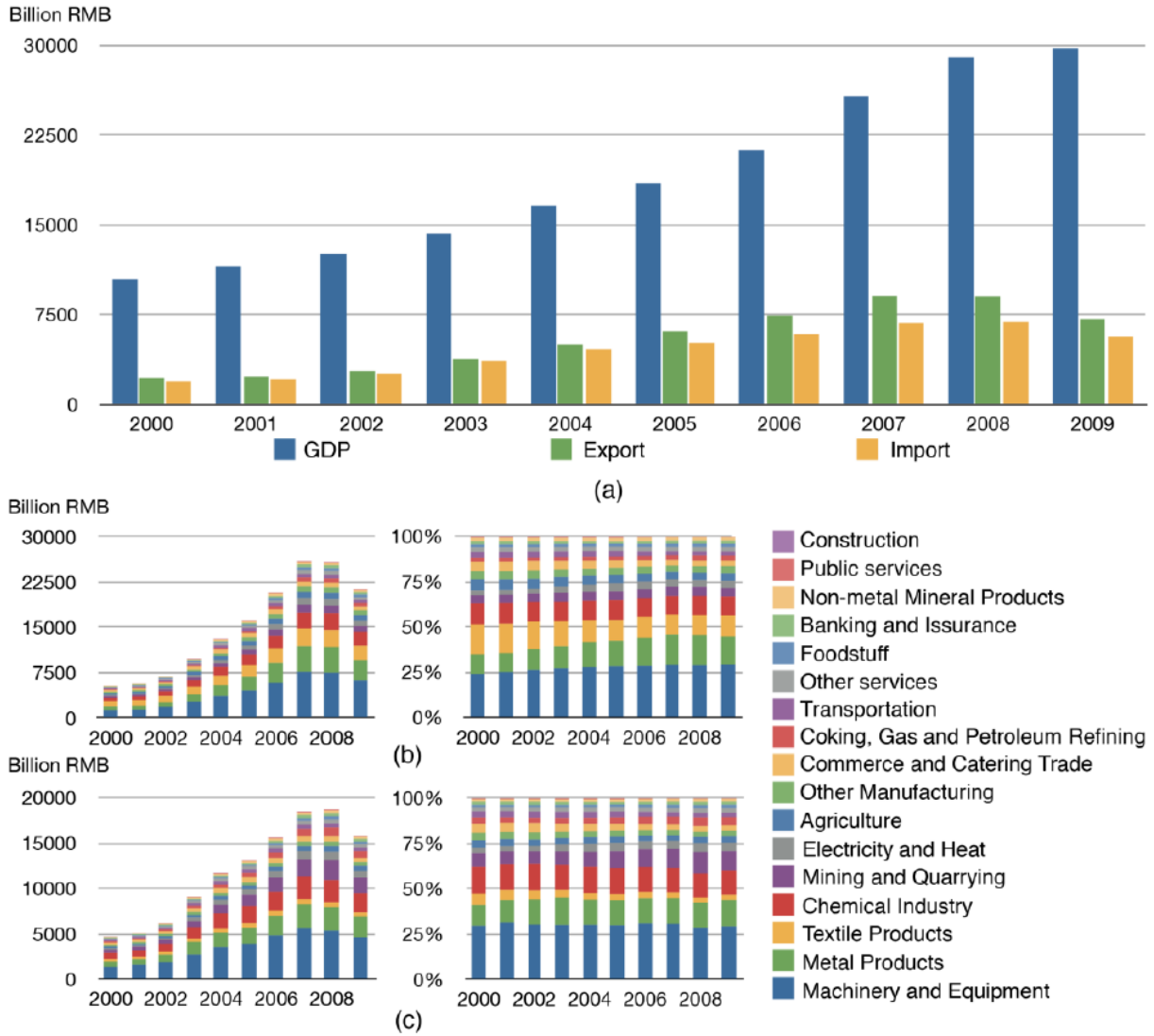
Data source: World Bank





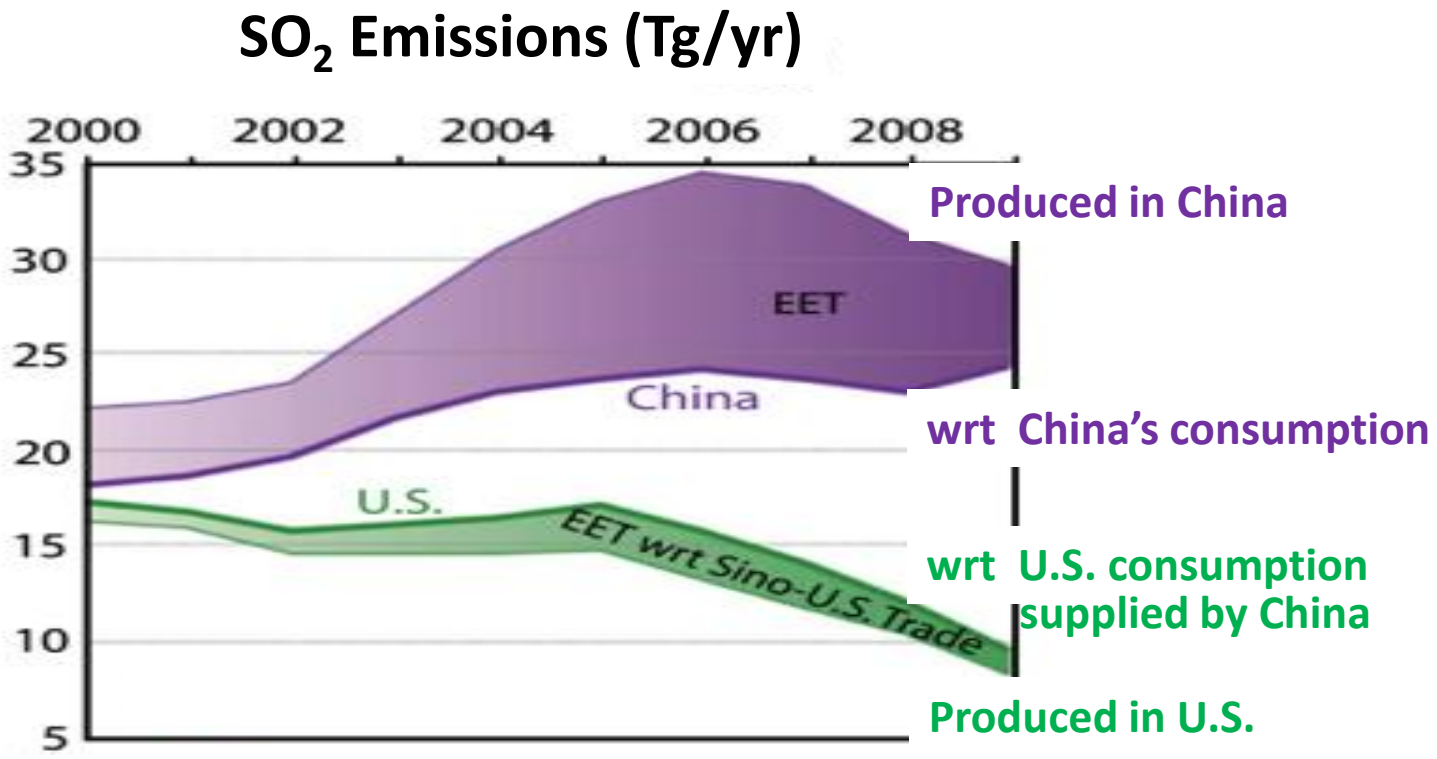
China India United States Canada United Kingdom Germany France Italy Japan Russian Federation

Export and Total GDP of China



Lin et al., 2014, PNAS

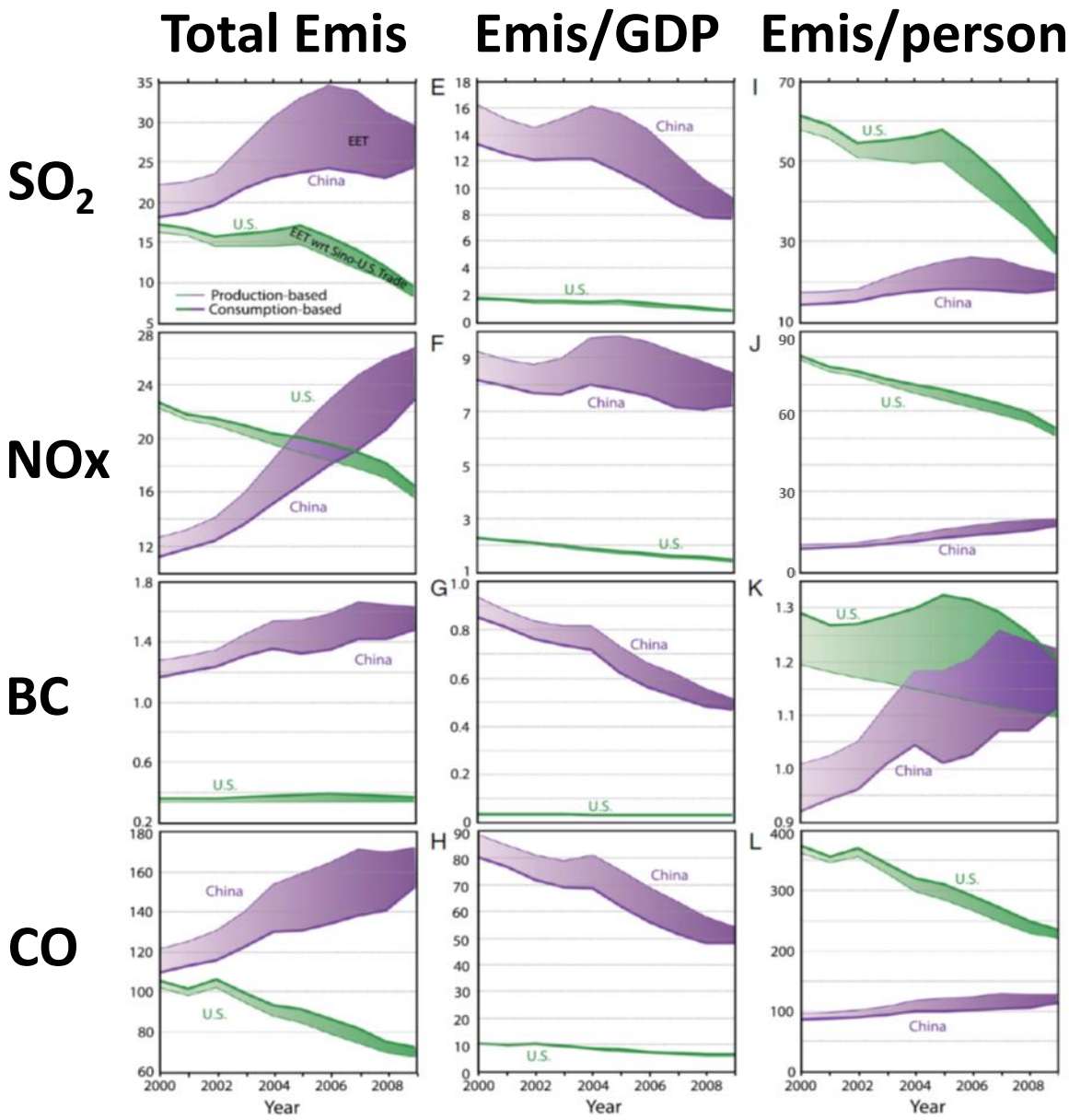
Trade Redefines Chinese and U.S. Emissions



- 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

Trade Redefines Chinese and U.S. Emissions

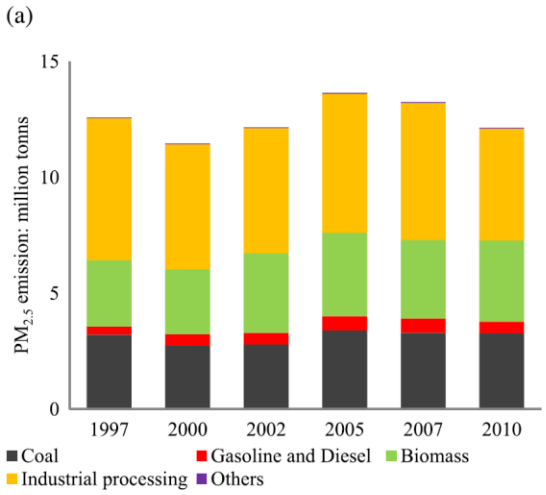


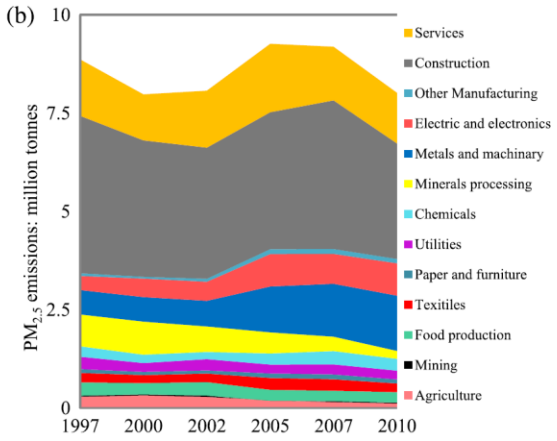
China v.s. US:

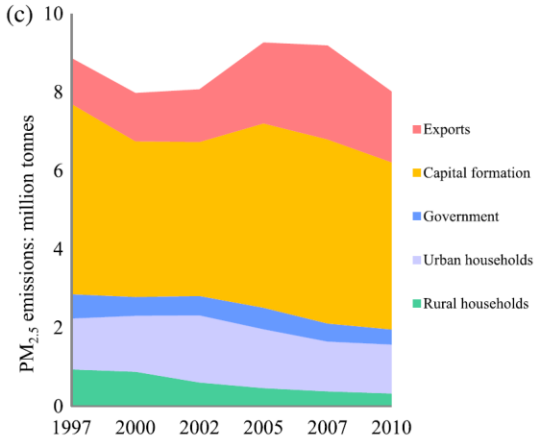
- **Higher emis**
- **Higher intensity**
- **Lower emis/person**
- **Net emis due to exports**

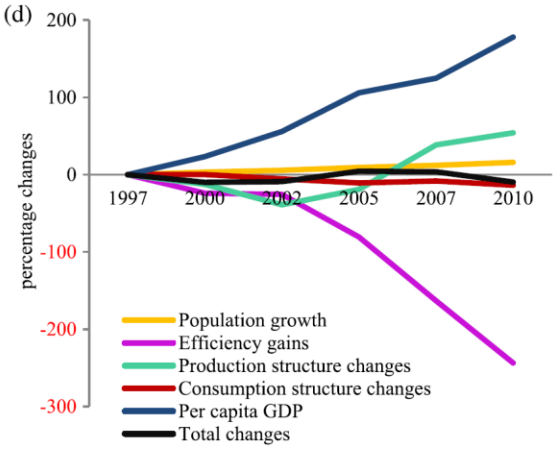
Lin et al., 2014, PNAS

Decomposed Drivers of China's $PM_{2.5}$ Emission Growth









Structural Decomposition Analysis

$$PM_{2.5} = p \cdot \mathbf{F} \cdot \mathbf{L} \cdot \mathbf{y_s} \cdot \mathbf{y_v}$$

$$\begin{aligned}
\Delta PM_{2.5} &= \Delta PM_{2.5(t)} - \Delta PM_{2.5(t-1)} \\
&= p_{(t)}\mathbf{F}_{(t)}\mathbf{L}_{(t)}\mathbf{y_s}_{(t)}\mathbf{y_v}_{(t)} \\
&\quad - p_{(t-1)}\mathbf{F}_{(t-1)}\mathbf{L}_{(t-1)}\mathbf{y_s}_{(t-1)}\mathbf{y_v}_{(t-1)} \\
&= \Delta p\mathbf{F}_{(t)}\mathbf{L}_{(t)}\mathbf{y_s}_{(t)}\mathbf{y_v}_{(t)} + p_{(t-1)}\Delta\mathbf{F}\mathbf{L}_{(t)}\mathbf{y_s}_{(t)}\mathbf{y_v}_{(t)} \\
&\quad + p_{(t-1)}\mathbf{F}_{(t-1)}\Delta\mathbf{L}\mathbf{y_s}_{(t)}\mathbf{y_v}_{(t)} \\
&\quad + p_{(t-1)}\mathbf{F}_{(t-1)}\mathbf{L}_{(t-1)}\Delta\mathbf{y_s}\mathbf{y_v}_{(t)} \\
&\quad + p_{(t-1)}\mathbf{F}_{(t-1)}\mathbf{L}_{(t-1)}\mathbf{y_s}_{(t-1)}\Delta\mathbf{y_v}.
\end{aligned}$$

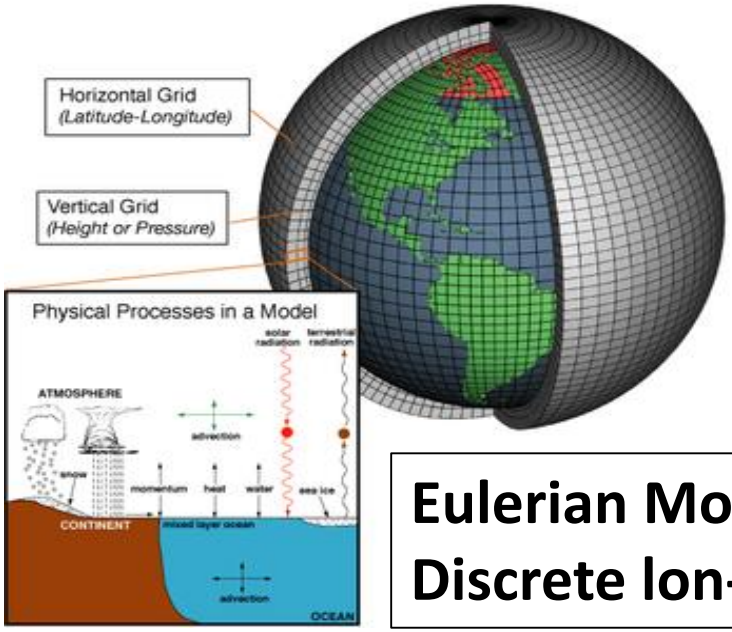
Guan et al., 2014, ERL

Atmospheric Chemical Transport Modeling

Emis Dep Transport & Mixing Chemistry

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

Grid-resolved Unresolved



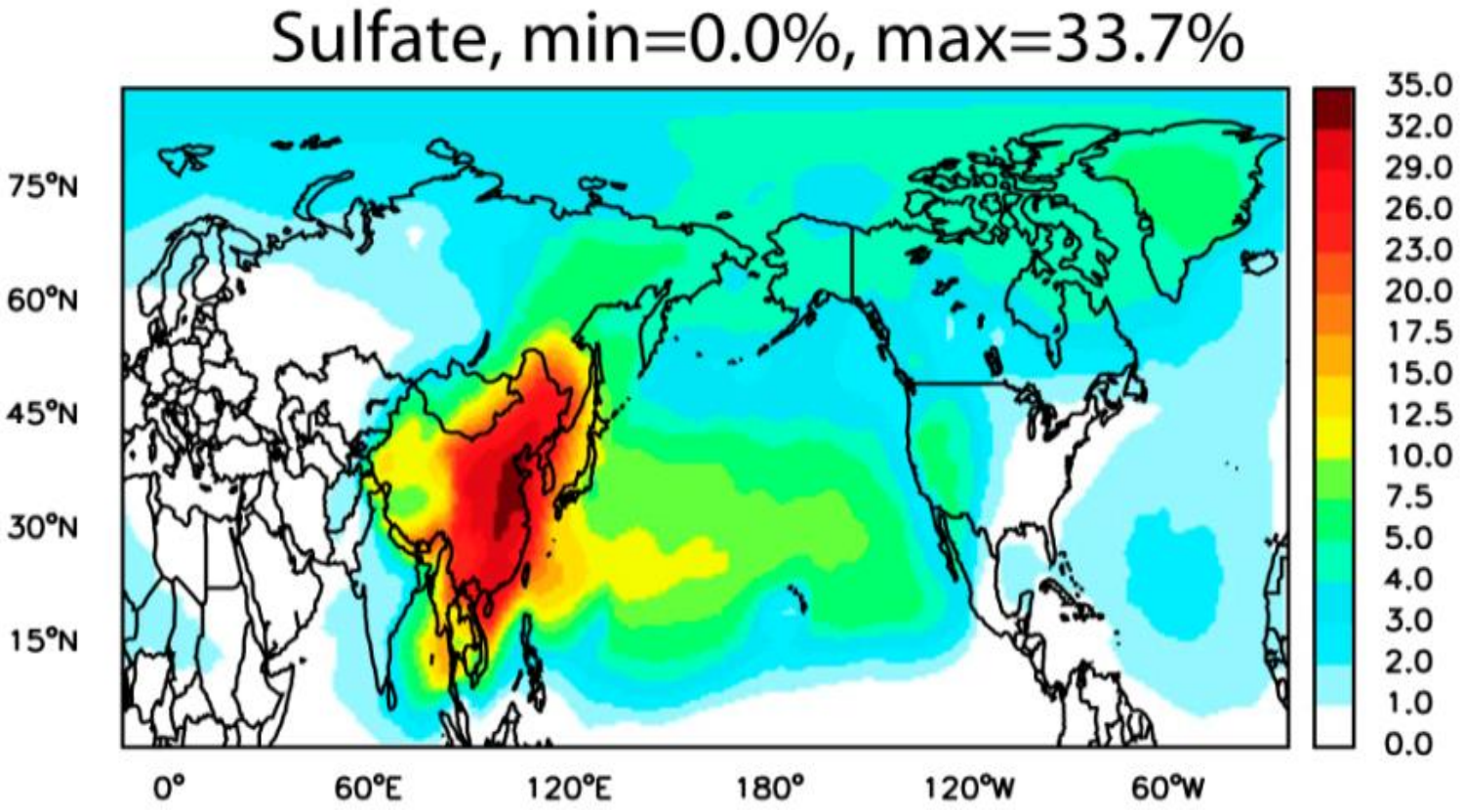
Eulerian Model:
Discrete lon-lat grid

Atmospheric chemical transport models:

- **Simulating spatiotemporal variations of trace species after they or their precursors are emitted into the atmosphere**

Goods Export Contributes ~ 30% of China's Sulfate

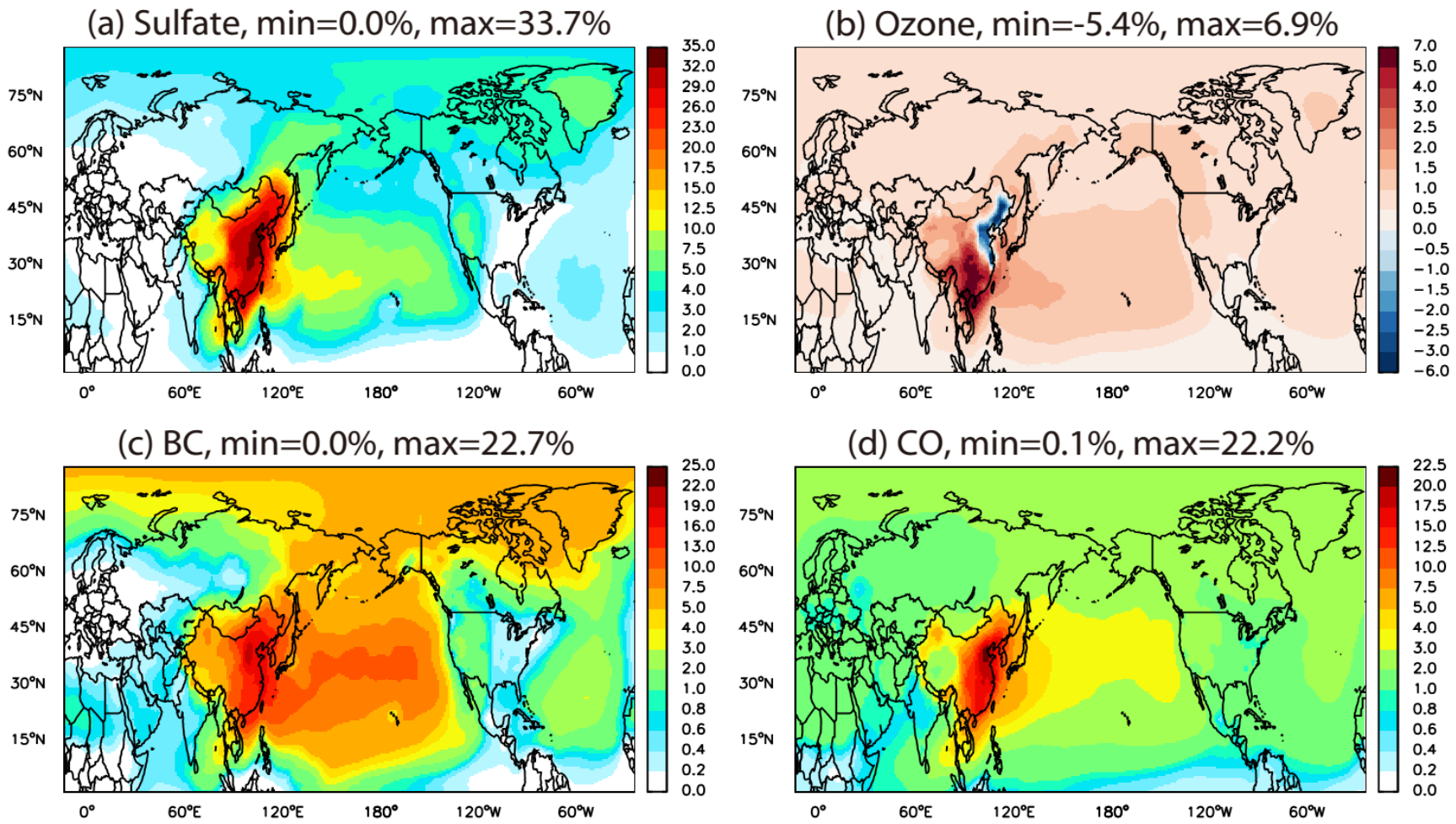
% contribution of China's export-related pollution to total pollution anywhere in the world



Lin et al., 2014, PNAS

Export of Goods Contributes to China's Pollution

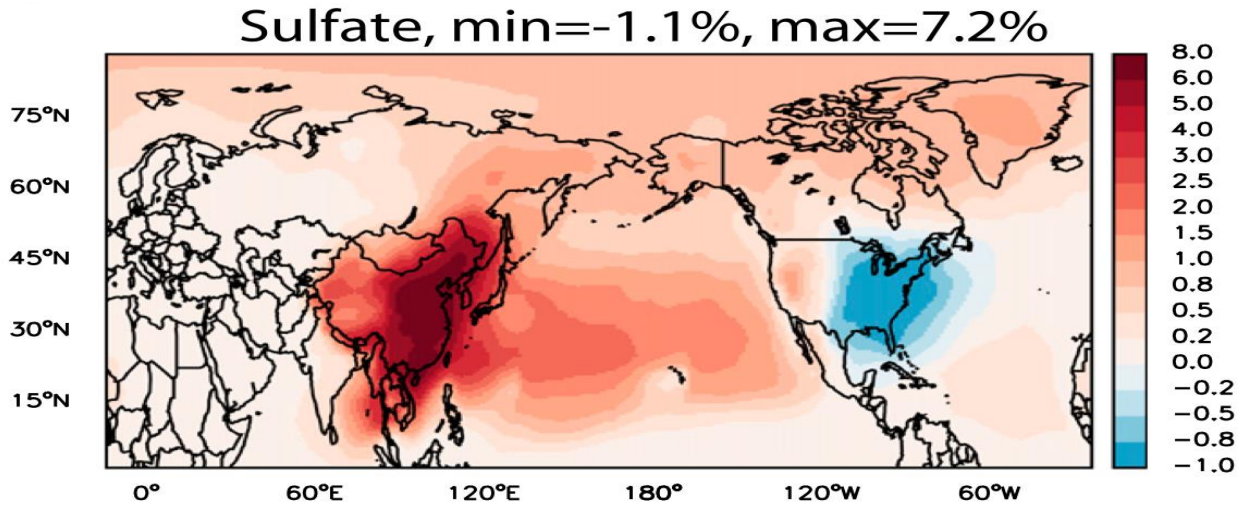
% contribution of China's export-related pollution to total pollution anywhere in the world



Lin et al., 2014, PNAS

USA Consumption Affects China's Sulfate Pollution

% change in sulfate



USA imports goods from China versus self-production:

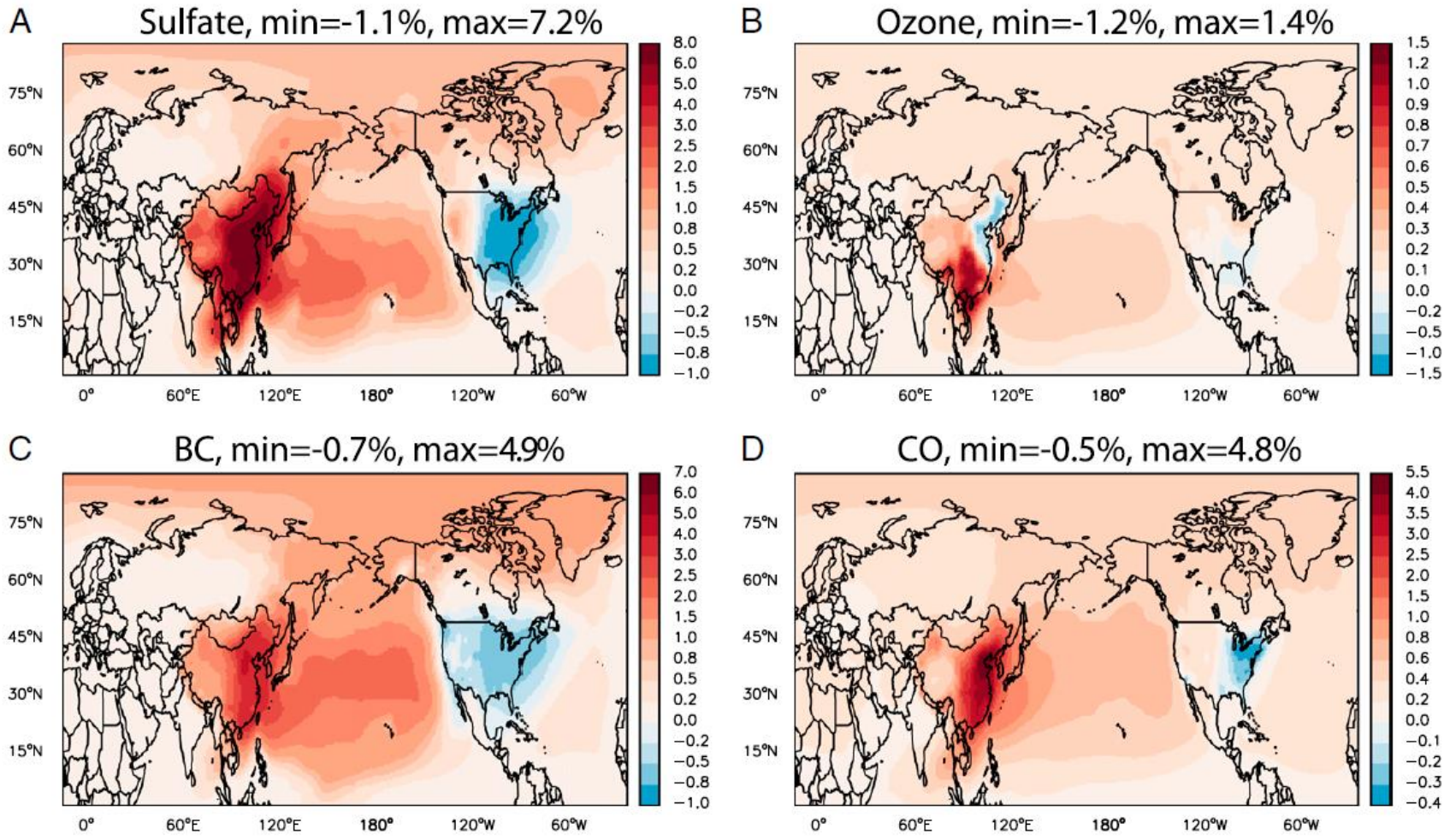
(accounting for differences in emission intensity)

- **Increase sulfate over China**
- **Decrease sulfate over E. USA with reduction over W. USA**

This is in contrast to traditional view that China reduces USA air quality via atmospheric transport !

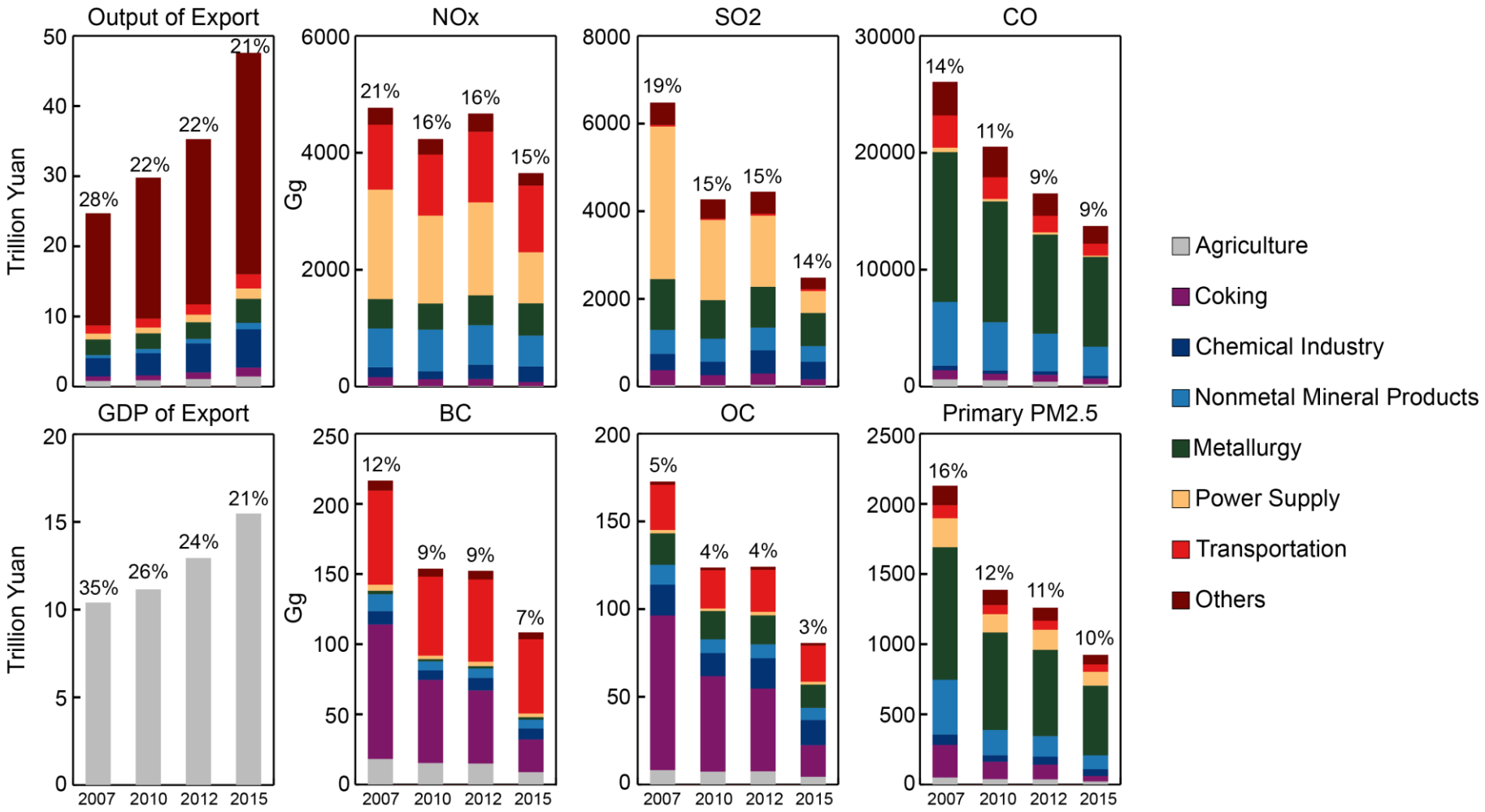
Lin et al., 2014, PNAS

USA Consumption Affects China's Pollution



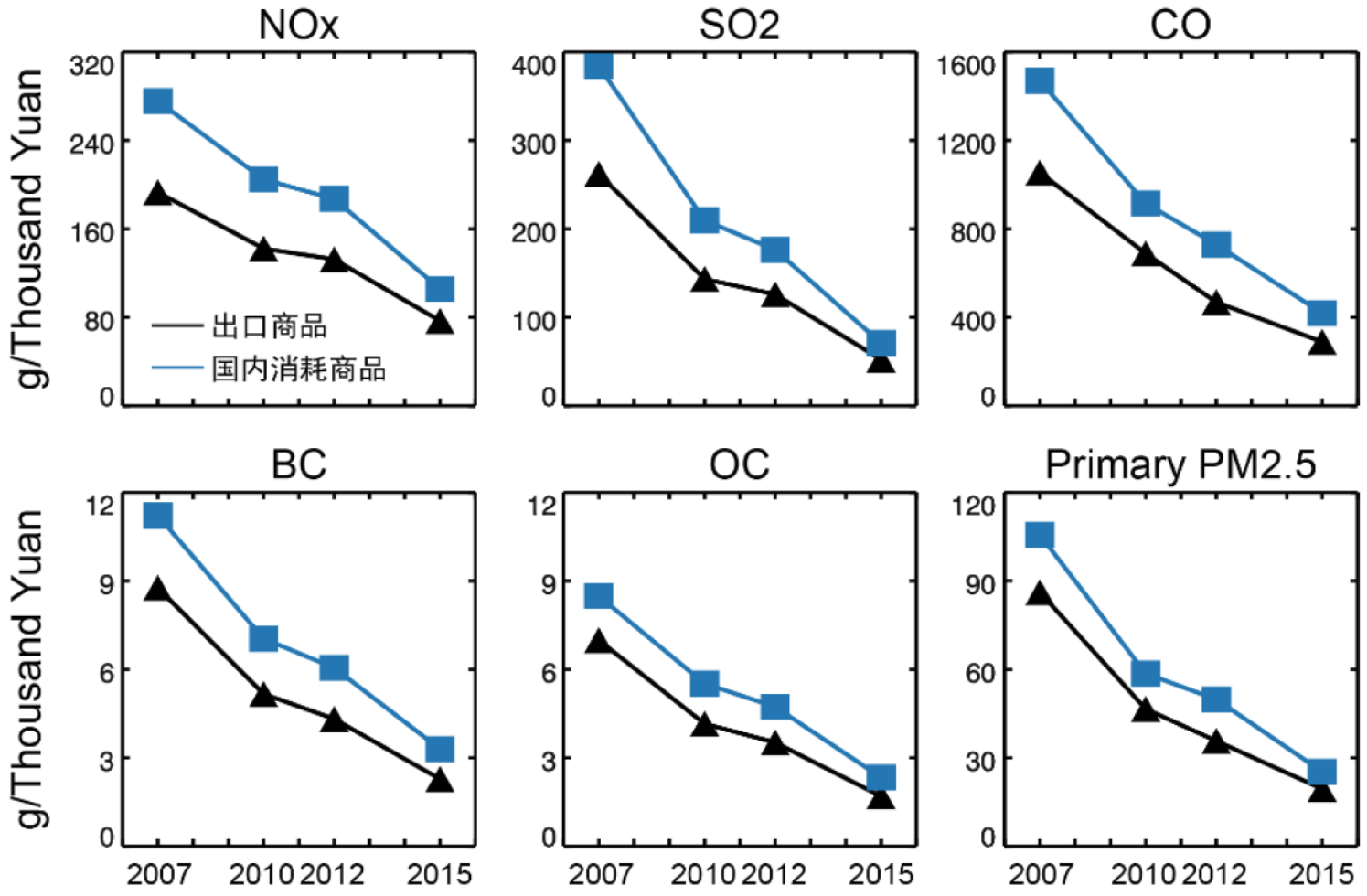
Lin et al., 2014, PNAS

Rapid Changes in China's Emissions Embedded in Export



Ni et al., in prep

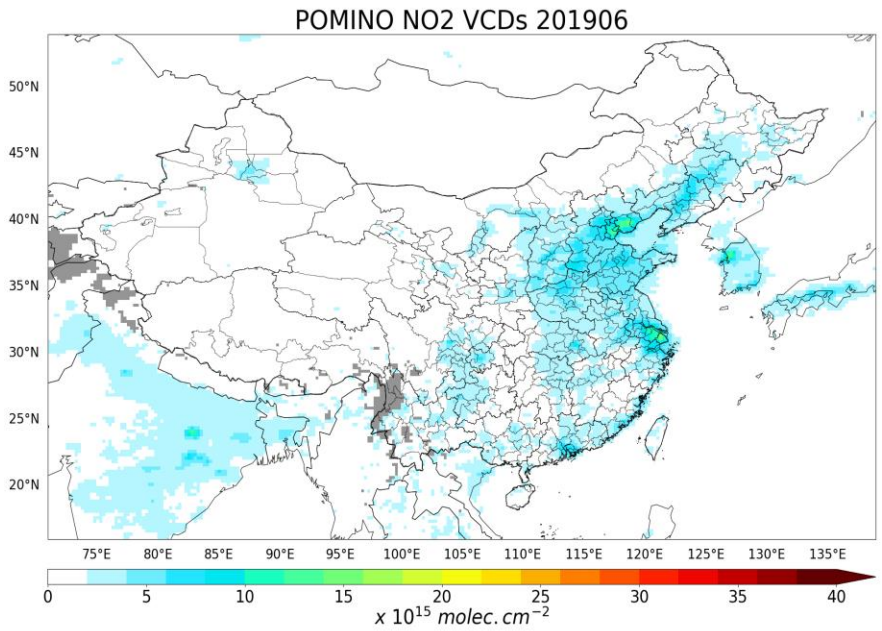
Rapid Decline in China's Emission Intensity



Ni et al., in prep

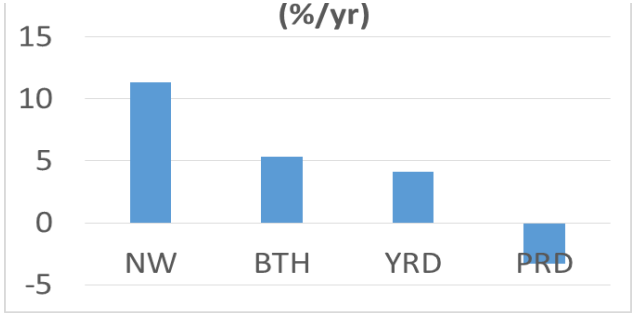
China's Cross-regional Pollution Embedded in Trade

POMINO – Peking U. OMI NO_2 Monthly Animation



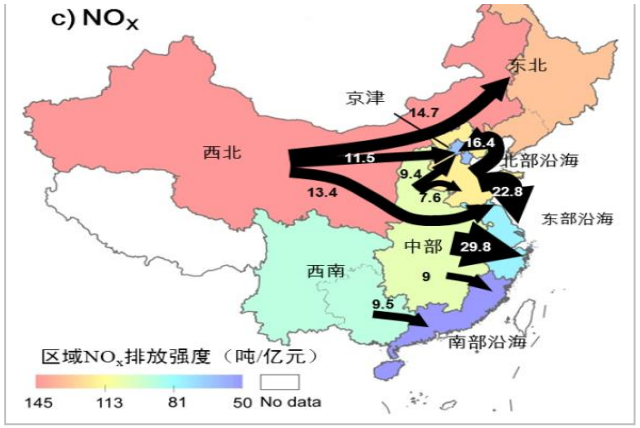
Lin et al., ACP, 2014; Lin et al., ACP, 2015; Liu et al., AMT, 2019; Zhang et al., NRSB, 2022
www.phy.pku.edu.cn/~acm/acmProduct.html#POMINO

Much stronger NO_2 growth over Northwest, 2005-2013



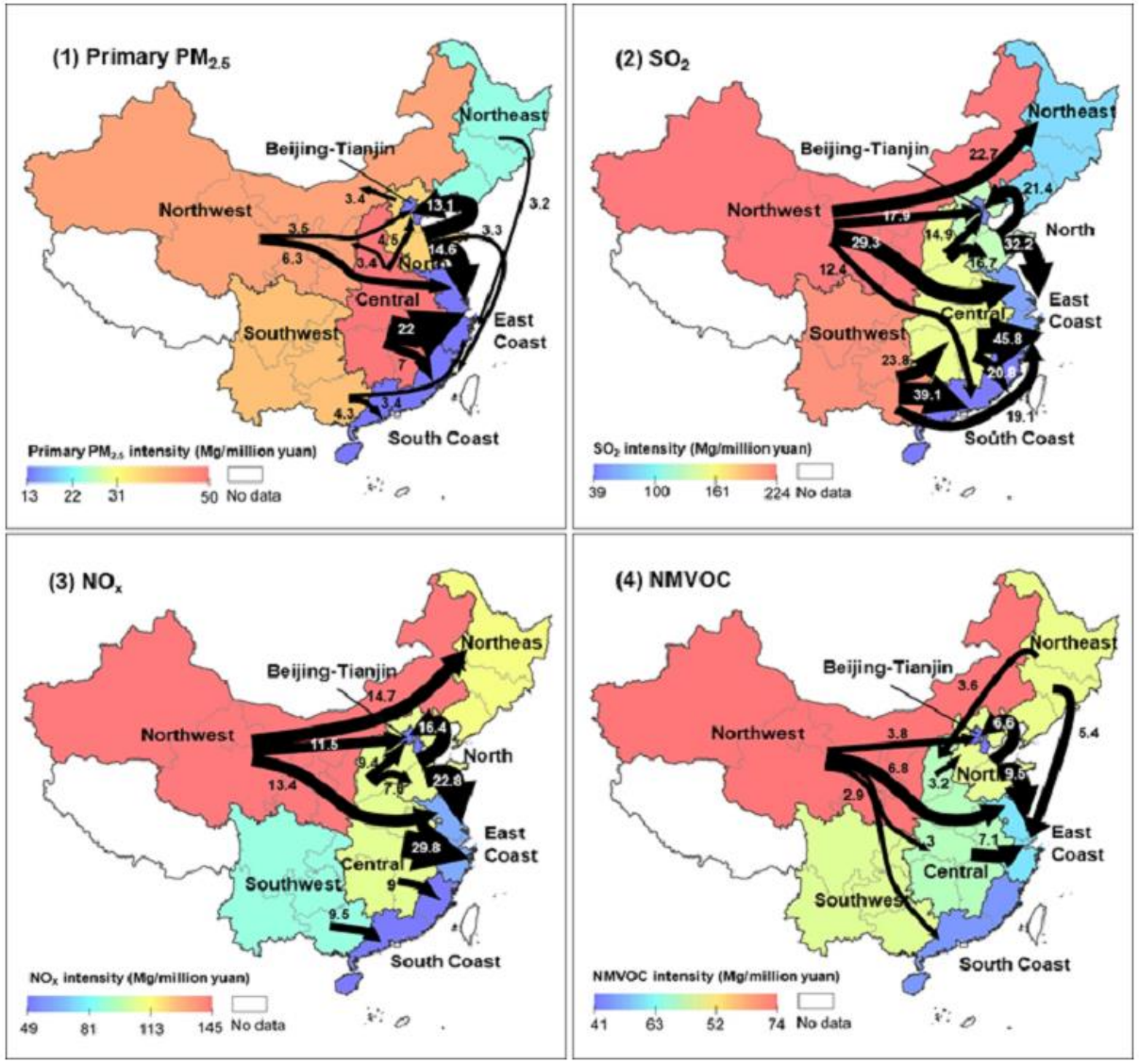
Cui et al., ACP, 2016

Large Westward Transfer of NOx Emissions via Trade



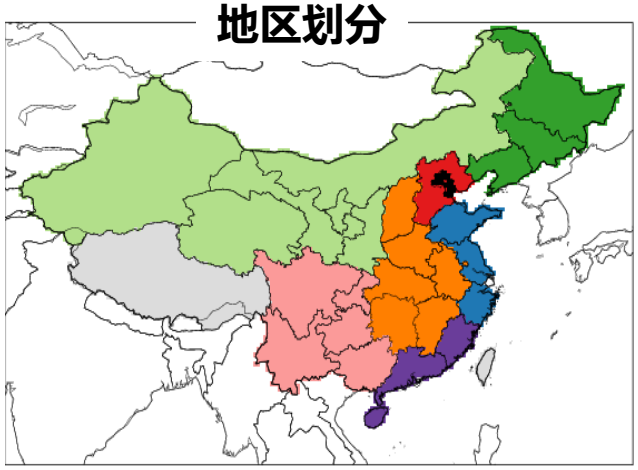
Zhao et al., ACP, 2015

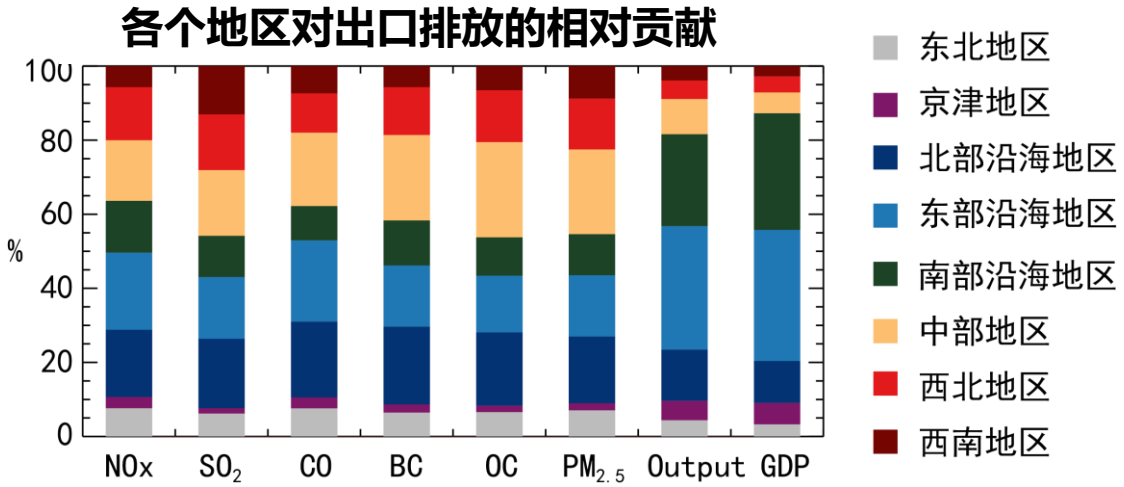
China's Inter-regional Pollution Transport Via Trade

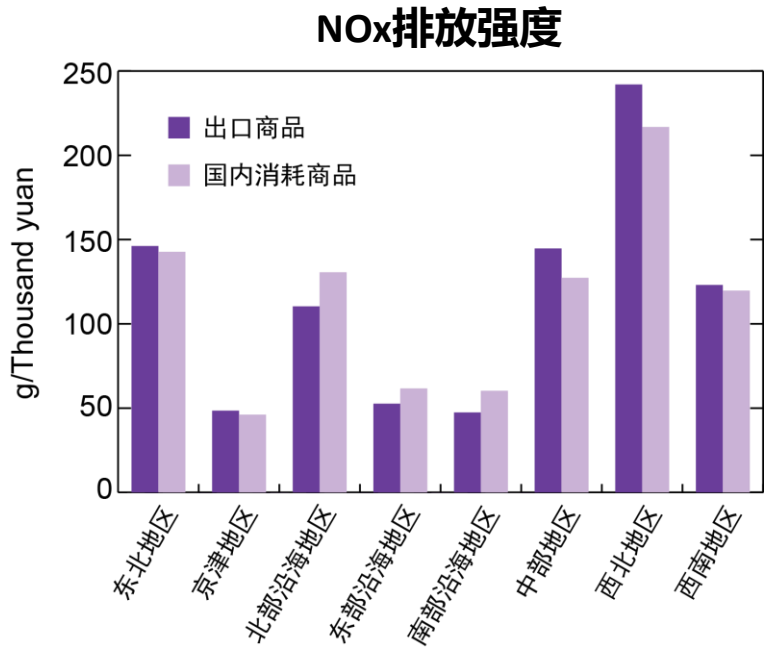


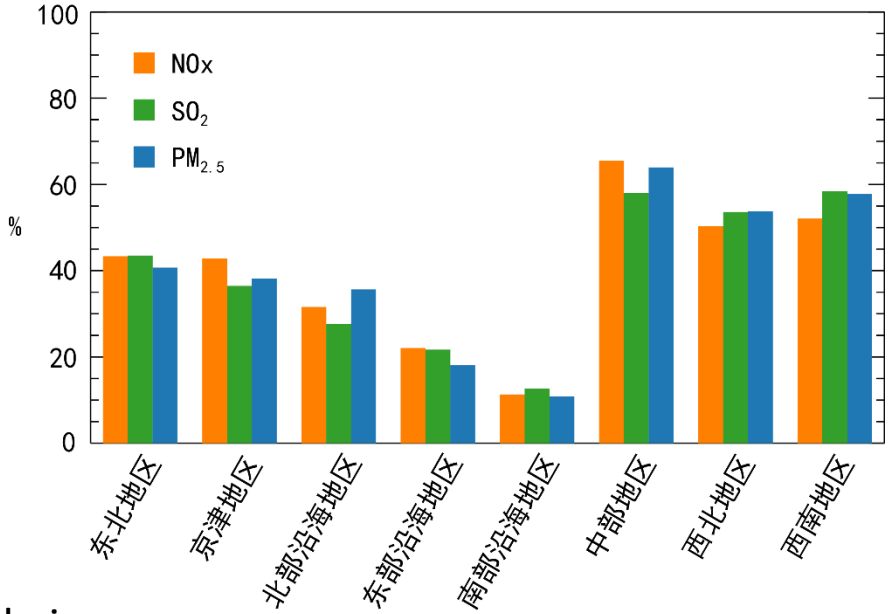
Zhao et al., ACP, 2015

2015年中国各个地区对出口相关排放的贡献



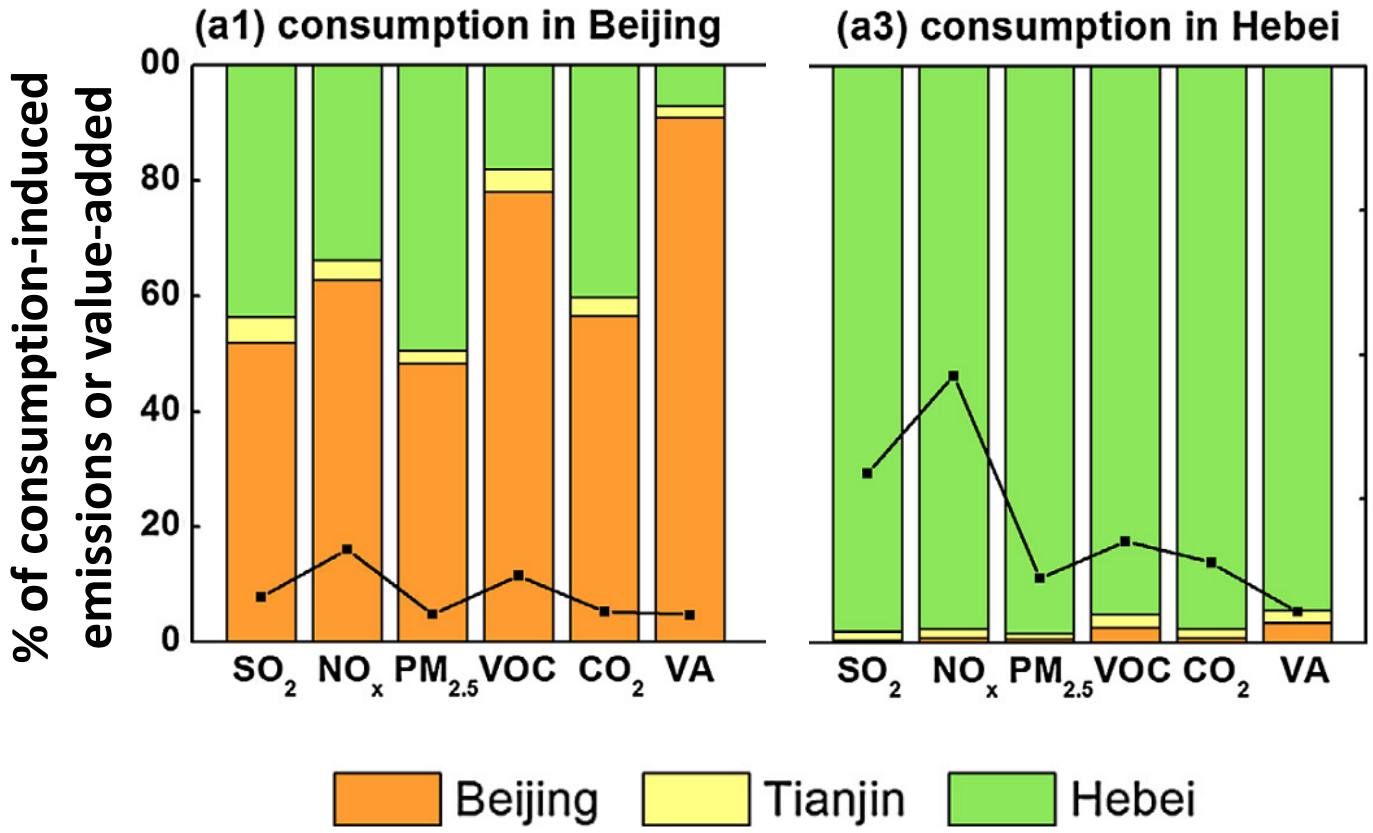






Ni et al., in prep

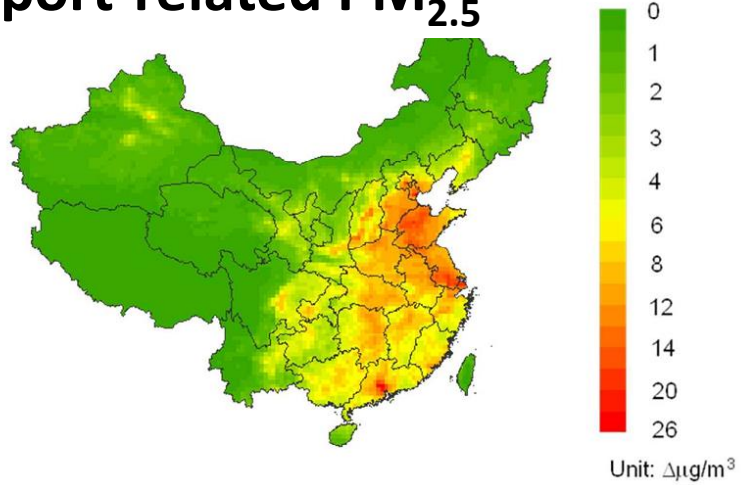
Pollution Transfer: Beijing → Hebei



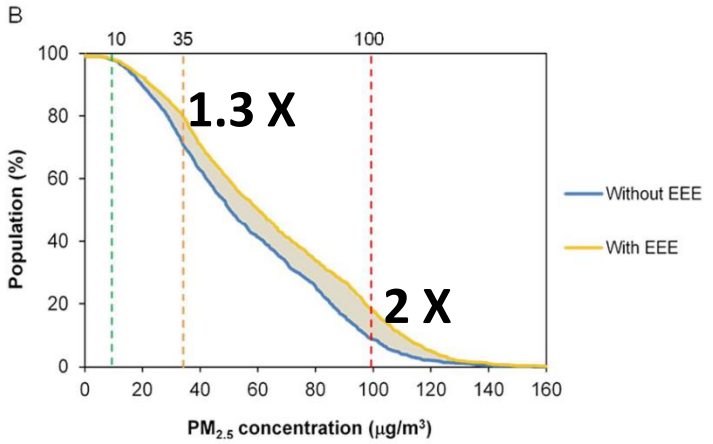
Zhao et al., Applied Energy, 2016

PM & Mortality from China's Inter-provincial Trade

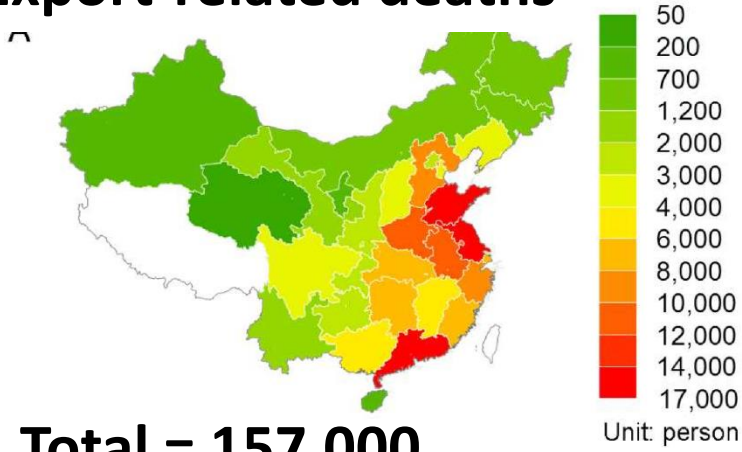
Export-related $PM_{2.5}$



Export-related $PM_{2.5}$ (CDF)



Export-related deaths

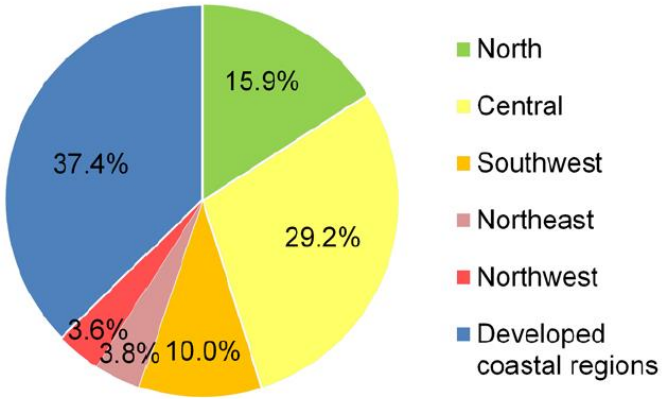


Total = 157,000

v.s.

US death wrt O_3 = 5,000

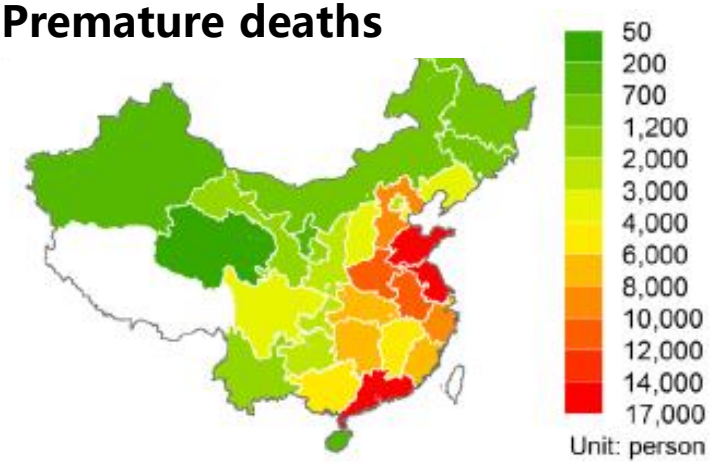
Export-related deaths



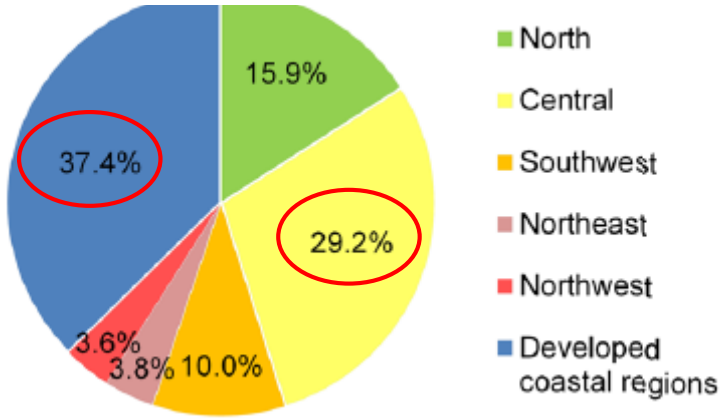
Jiang et al., EST, 2015

Inter-Provincial Disparity in Export-related Deaths

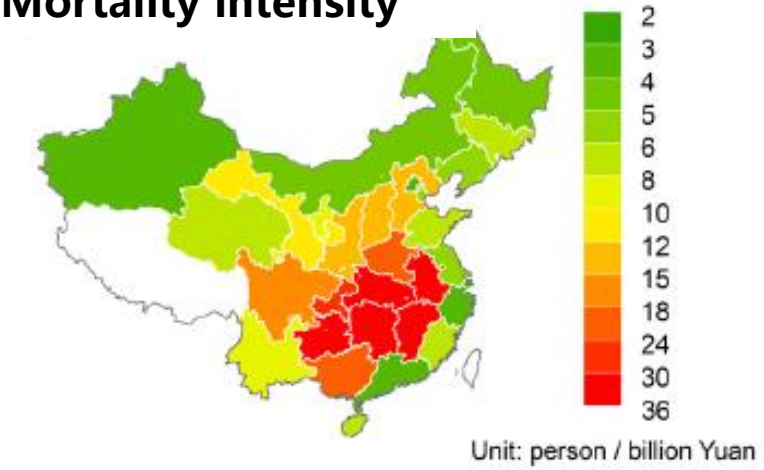
Premature deaths



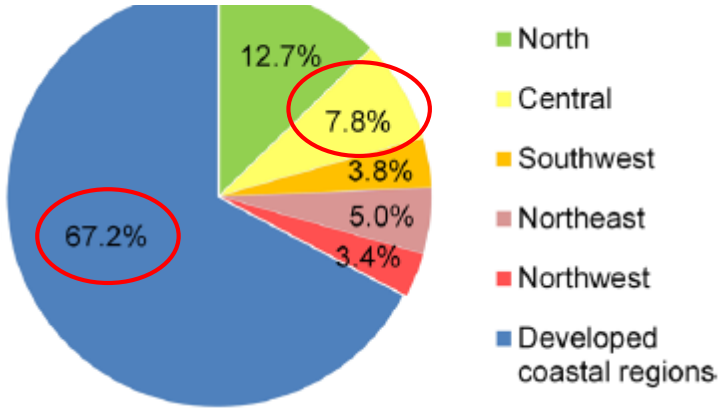
Premature deaths



Mortality intensity

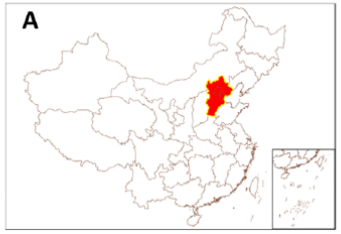


Economic gain



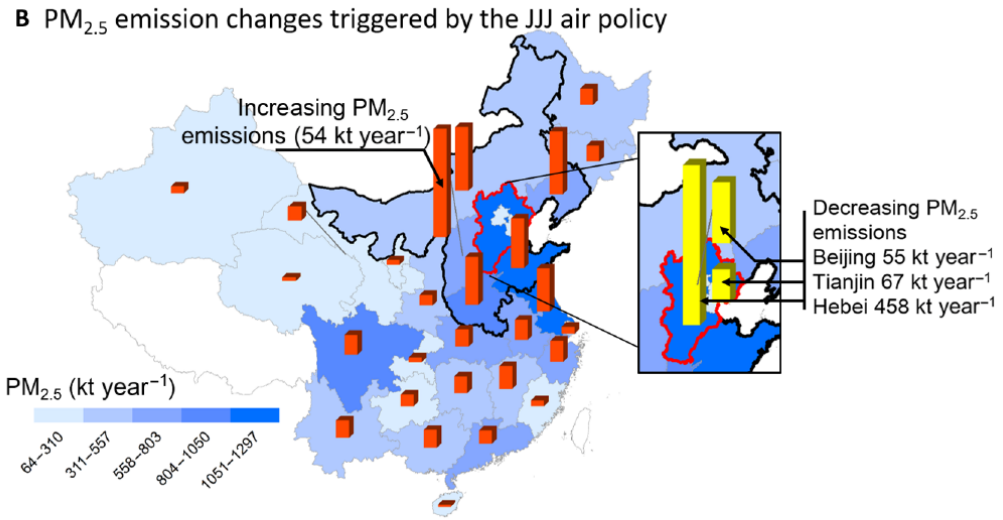
Jiang et al., EST, 2015

Potential Policy-Driven Outsourcing Within China

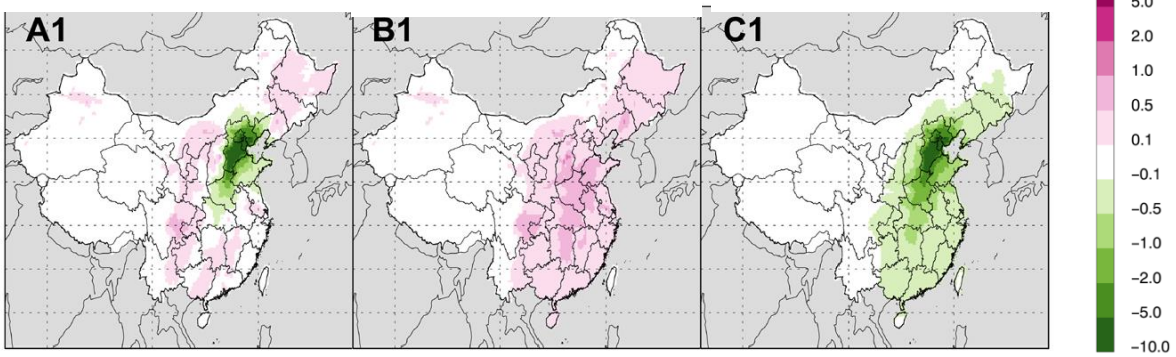


Regional environmental policy

- 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% ↓

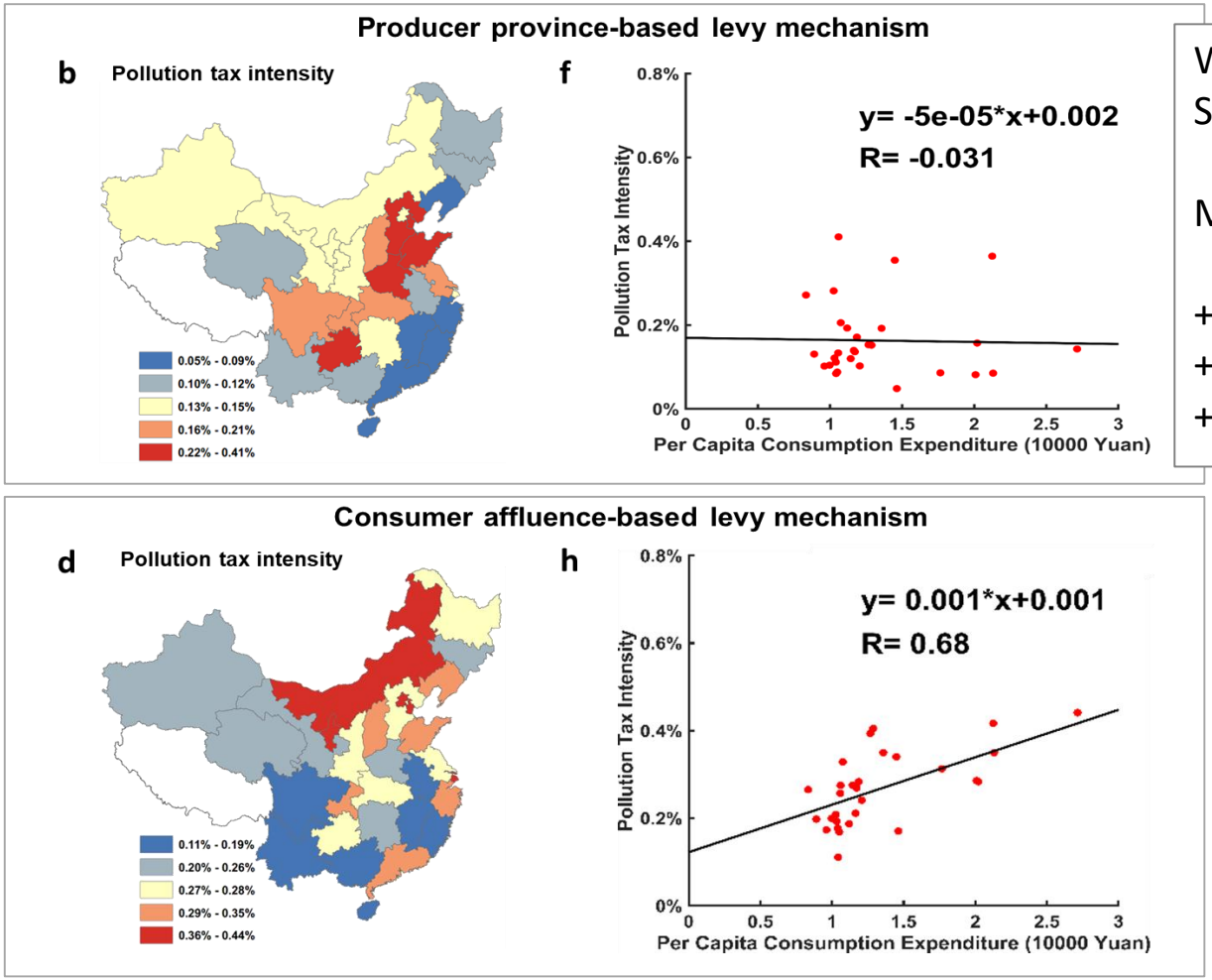


Local reduction + outsourcing | Outsourcing | Local reduction only



Fang et al., Science Advances, 2019

Shifted Economic Burden of Environmental Taxation Via Trade Within China



Wang et al., 2019
Science Bulletin

Method:

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

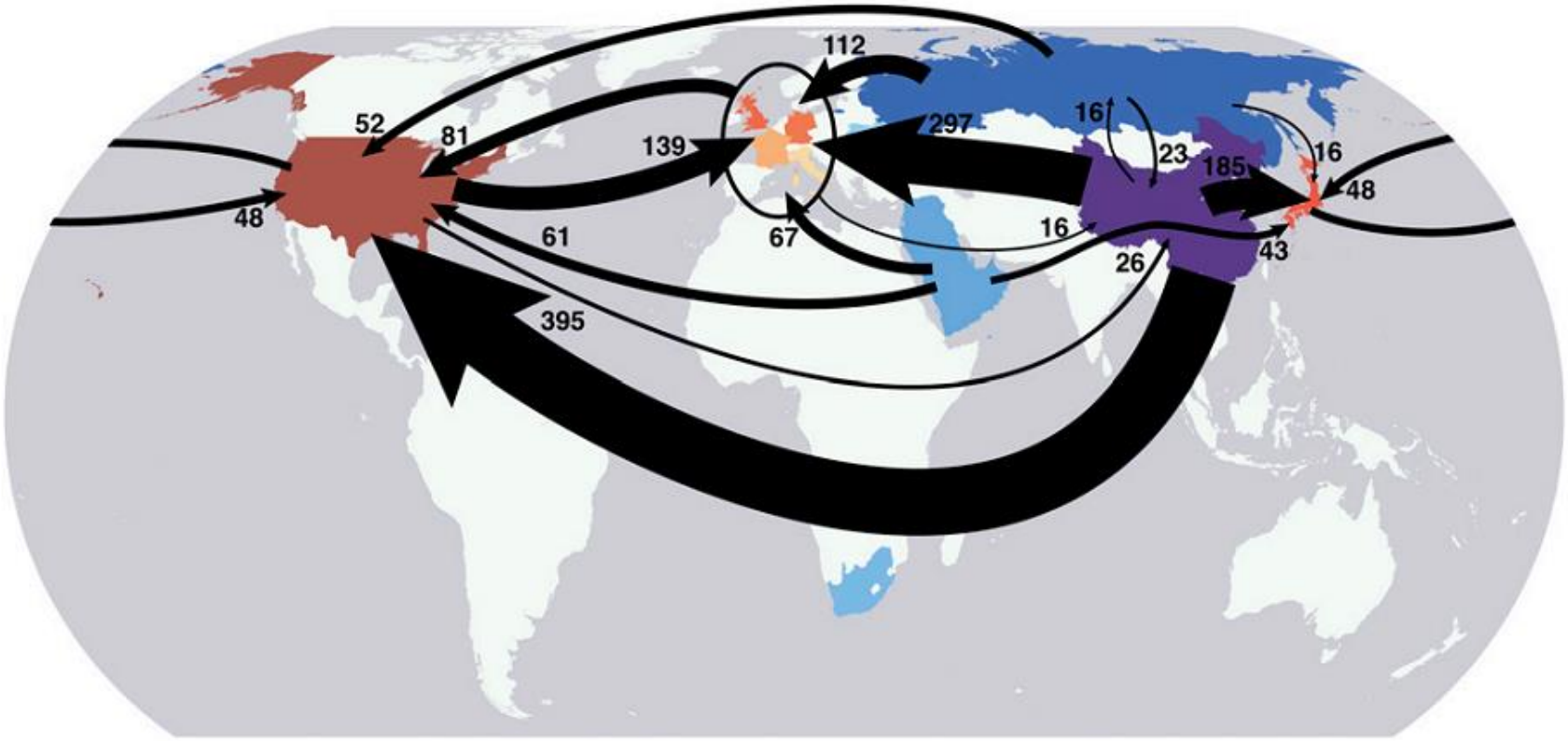
Trade-driven Pollution Transport: A Critical Issue in China's GO-WEST Movement

Pollution in Tenggeli Desert (2014/08/31)

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

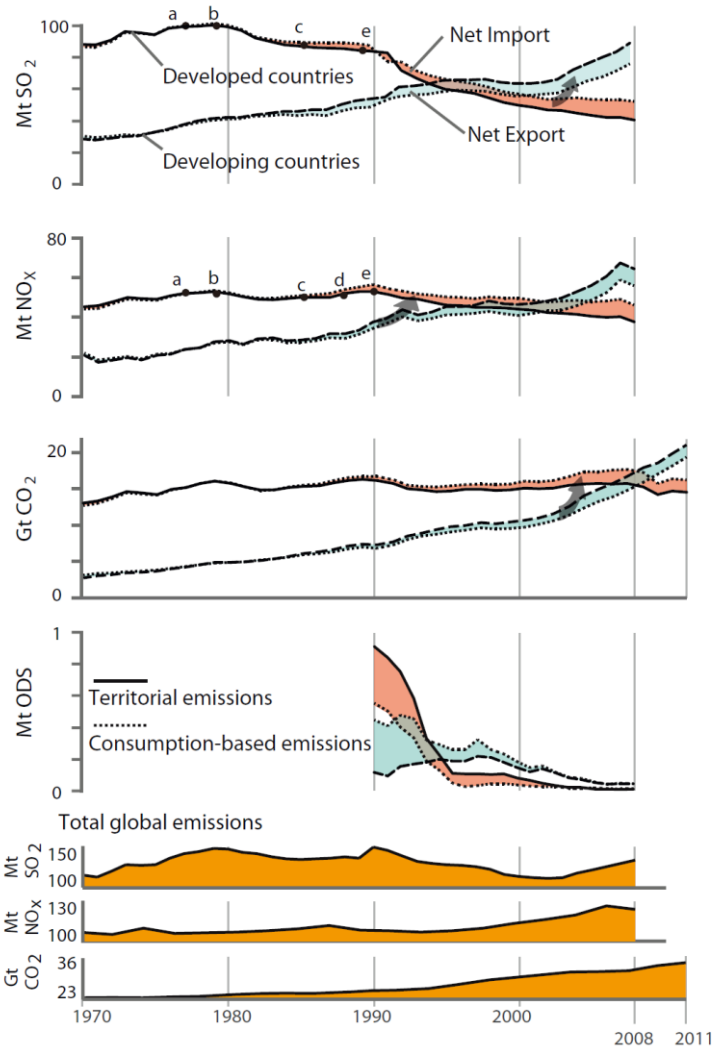
Global Trade Leads to Complex Emission Transfer

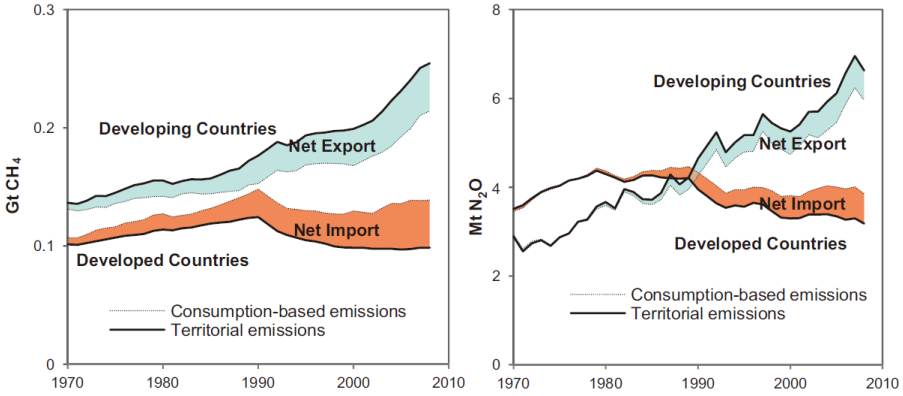
CO_2 emission transfer via trade



Davis and Caldaria, 2010, PNAS

Consumption and Trade Drives Emission Redistribution

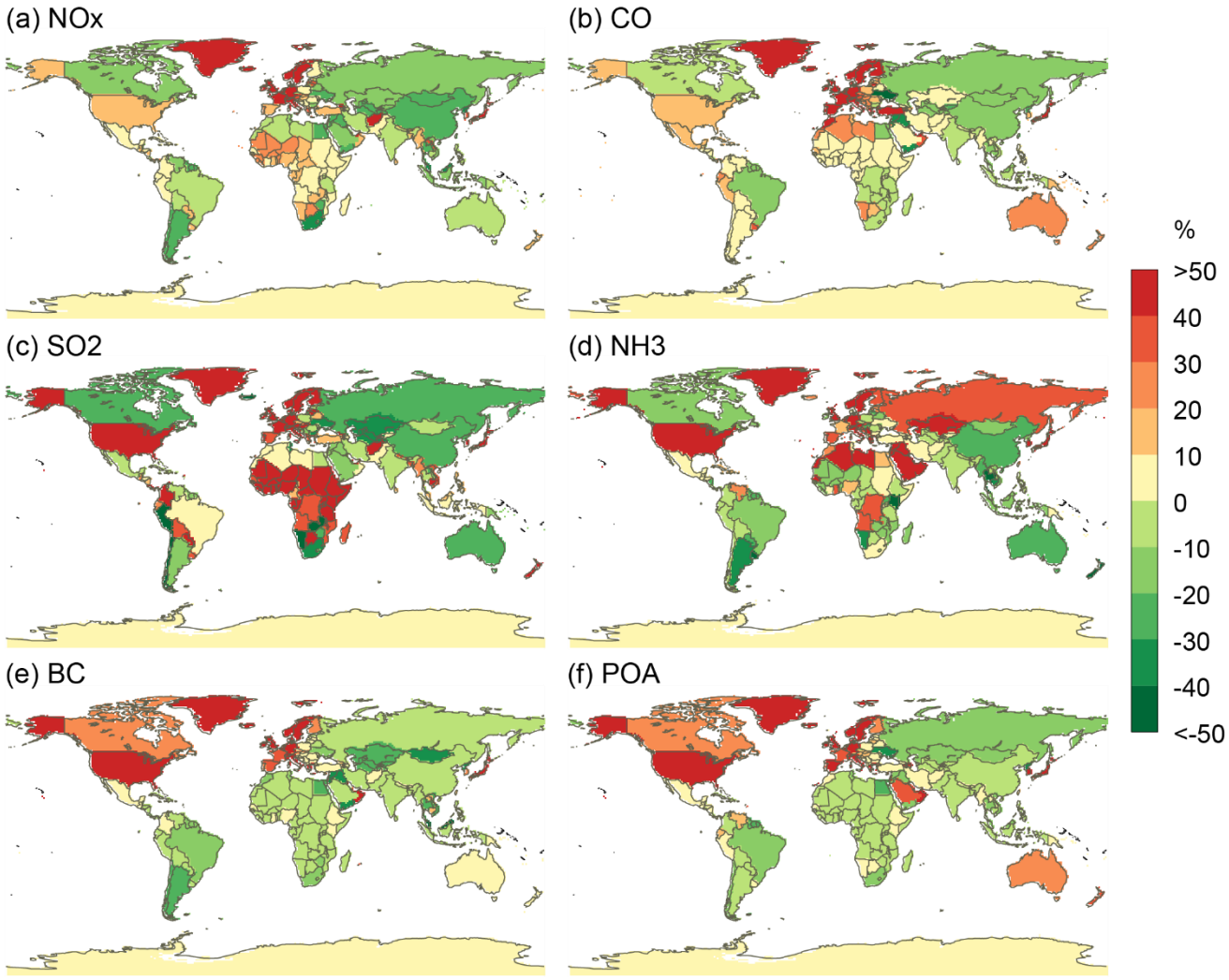




Kanemoto et al., 2014, GEC

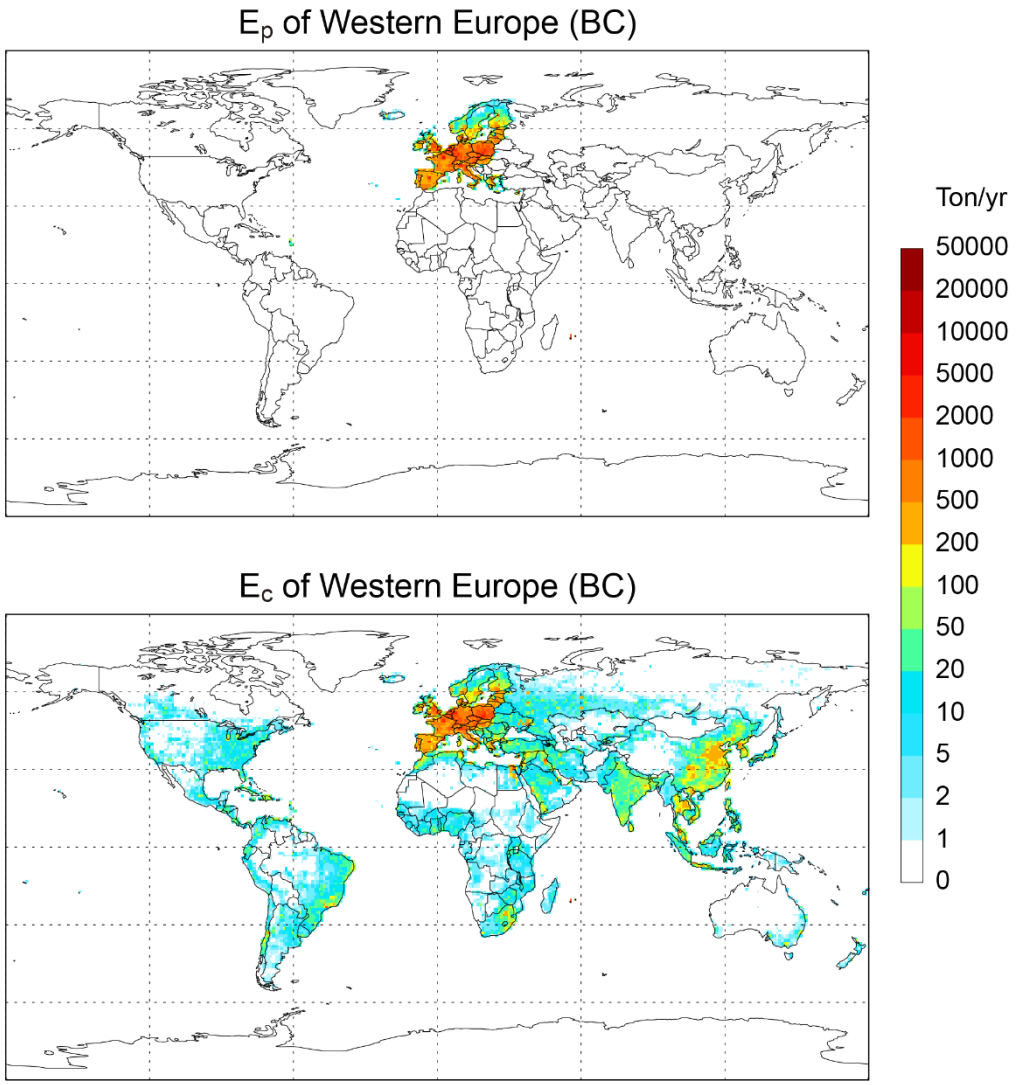
Trade Transfers Emissions from Rich to Poorer Regions

Consumption-based minus Production-based Emissions in 2007



Lin et al., 2016, Nature Geoscience

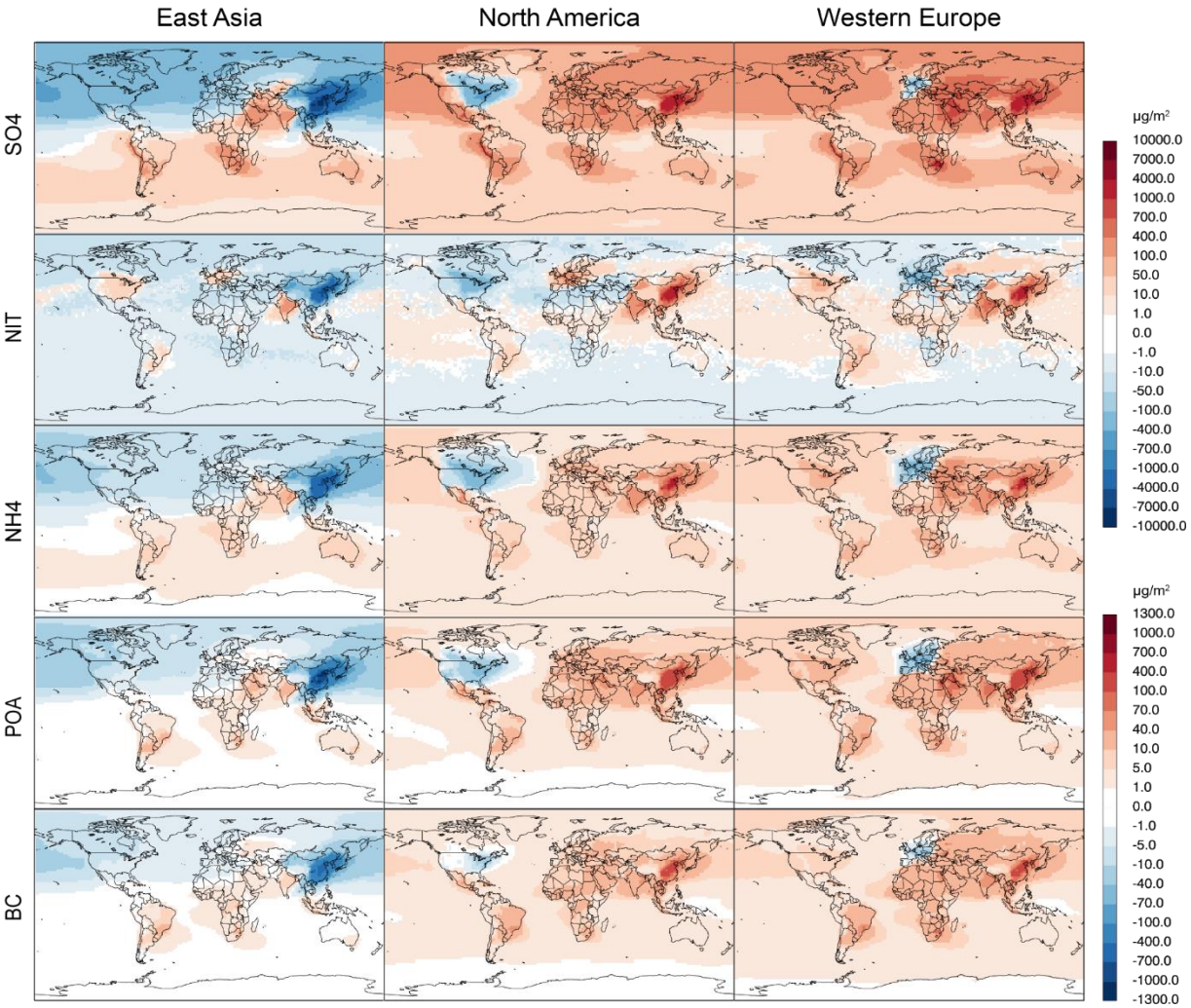
Trade Redistributes Emissions



Lin et al., 2016, Nature Geoscience

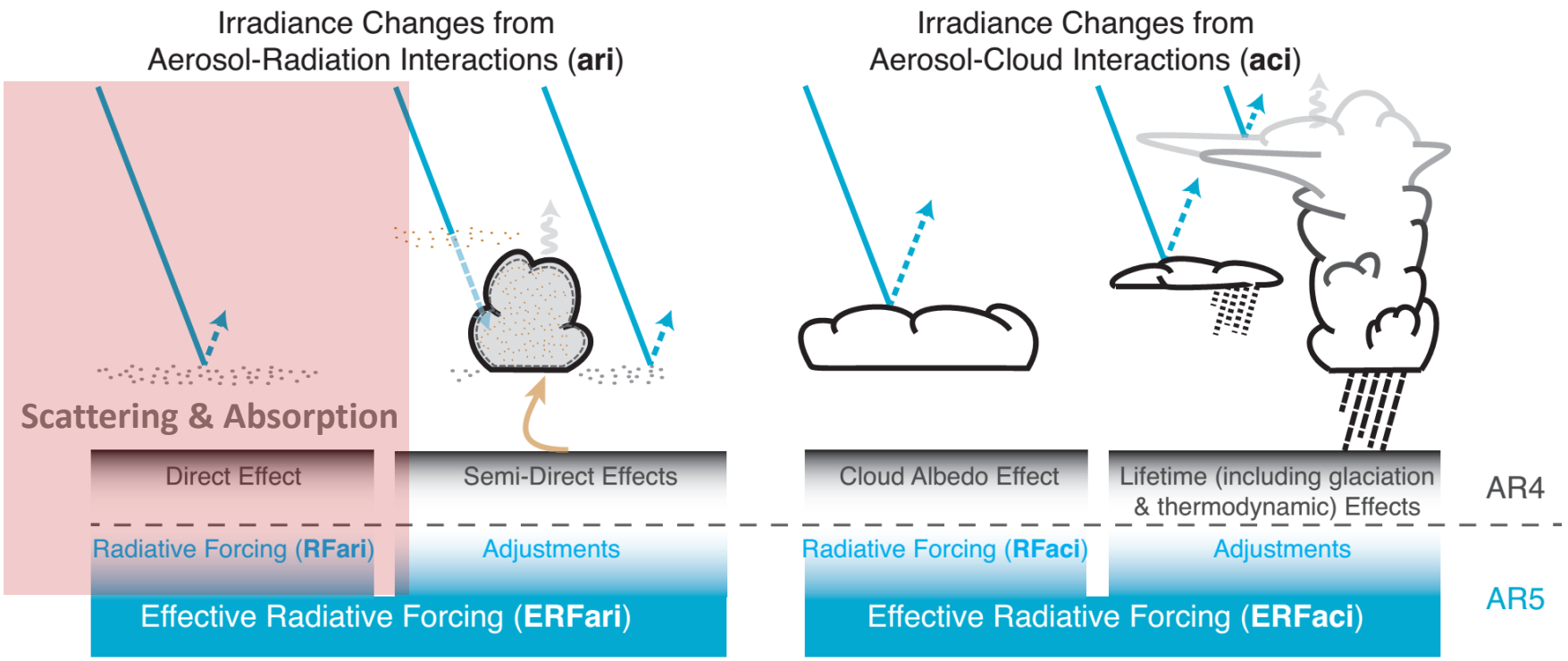
$PM_{2.5}$ Pollution Embedded in Trade: Rich → Poorer Regions

Consumption-based minus production-based PM in 2007



Lin et al., 2016, Nature Geoscience

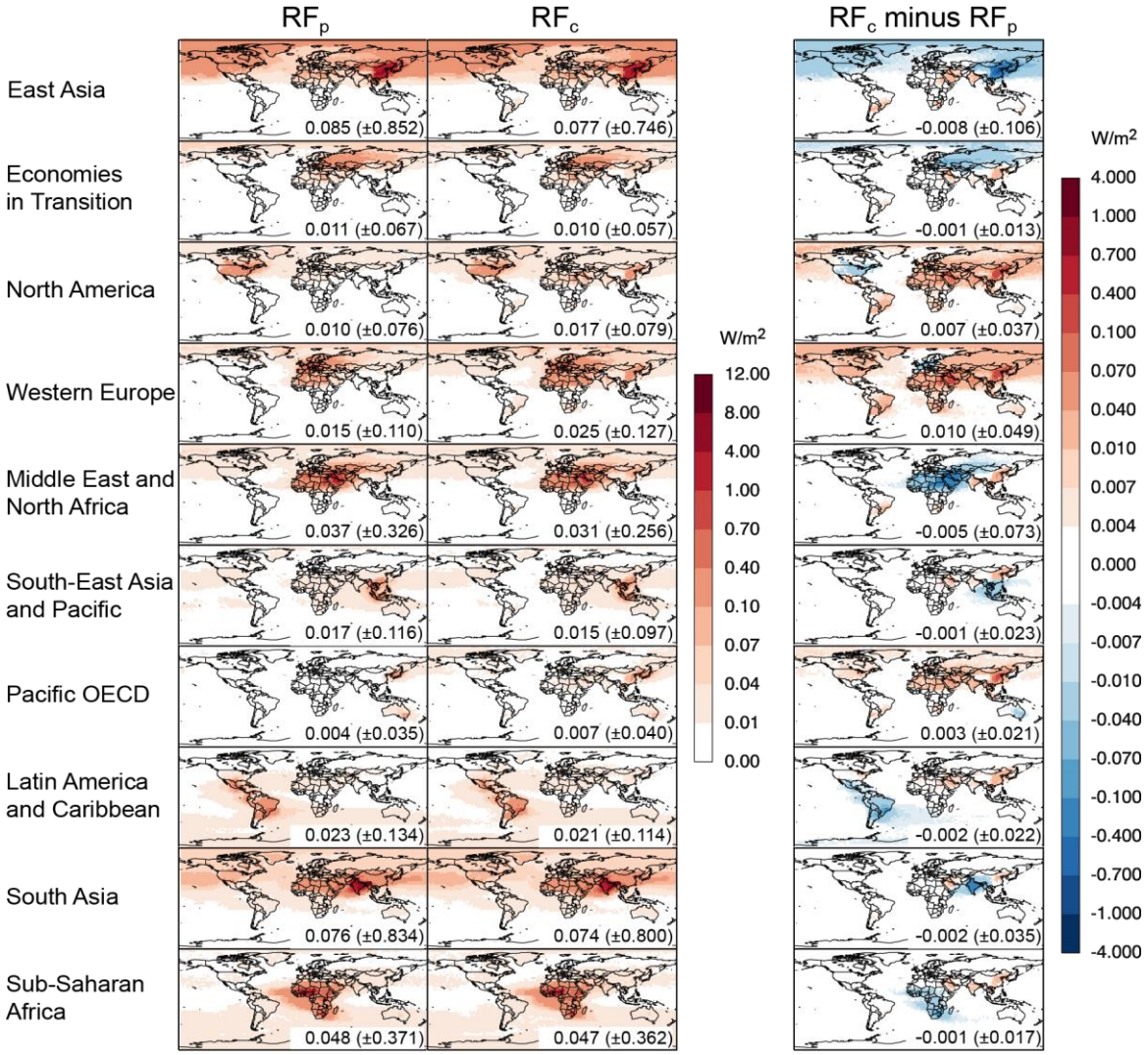
Radiative Forcing of Aerosols



IPCC, 2013

Trade Transfers RF from Rich to Poorer Regions

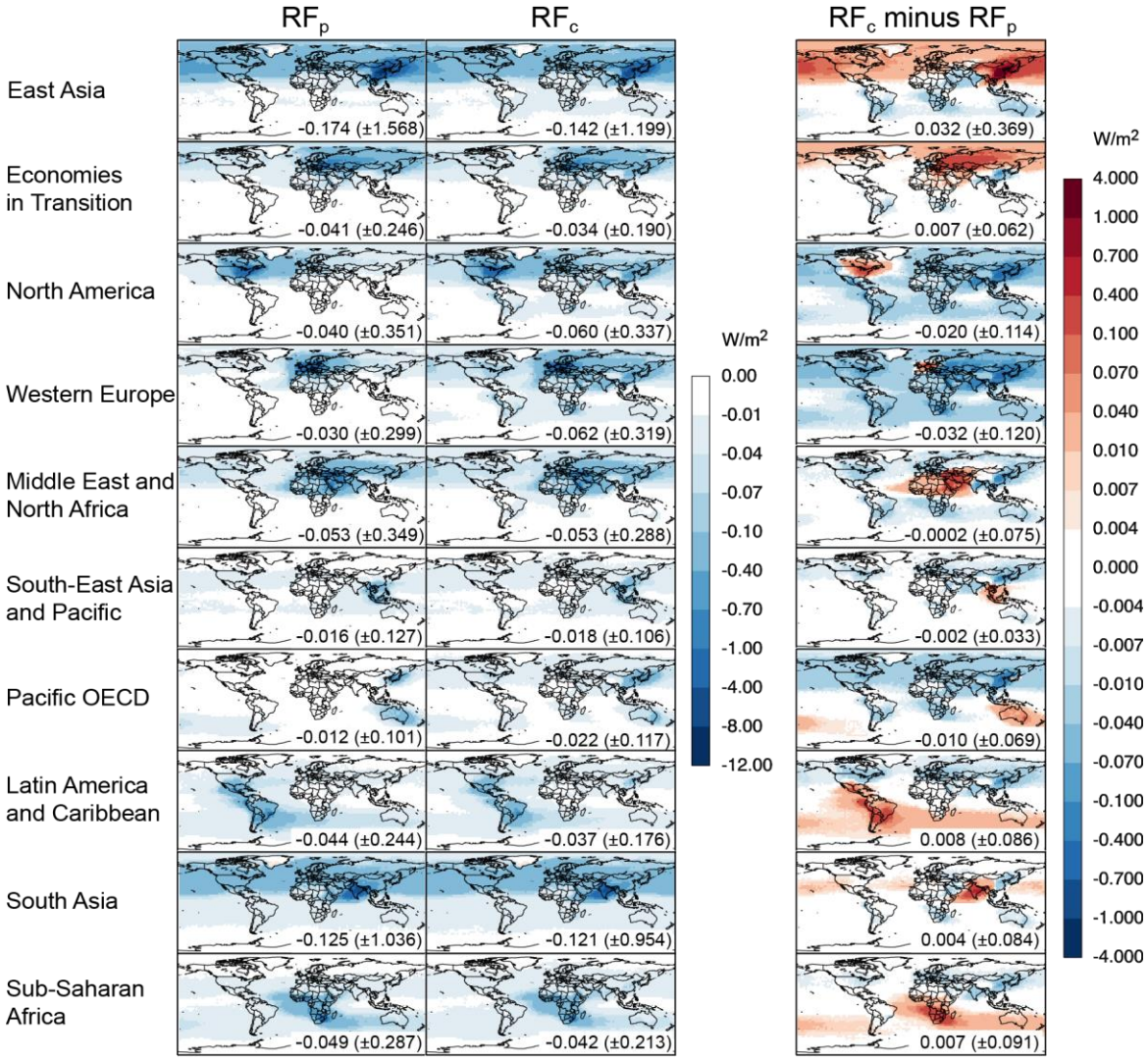
TOA direct RF of BC in 2007



Lin et al., 2016, Nature Geoscience

Trade Transfers RF from Rich to Poorer Regions

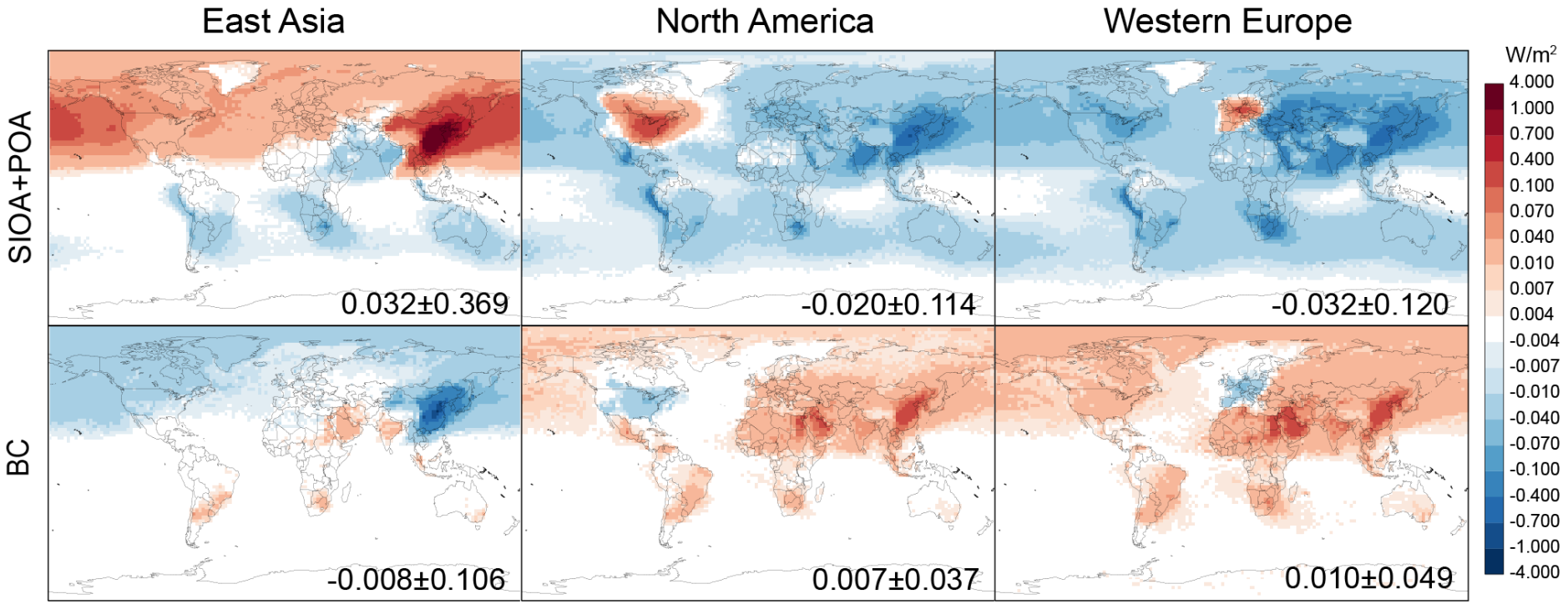
TOA direct RF of SO_4+NO_3+NH_4+POA in 2007



Lin et al., 2016, Nature Geoscience

Aerosol Radiative Forcing Embedded in Trade: Rich → Poorer Regions

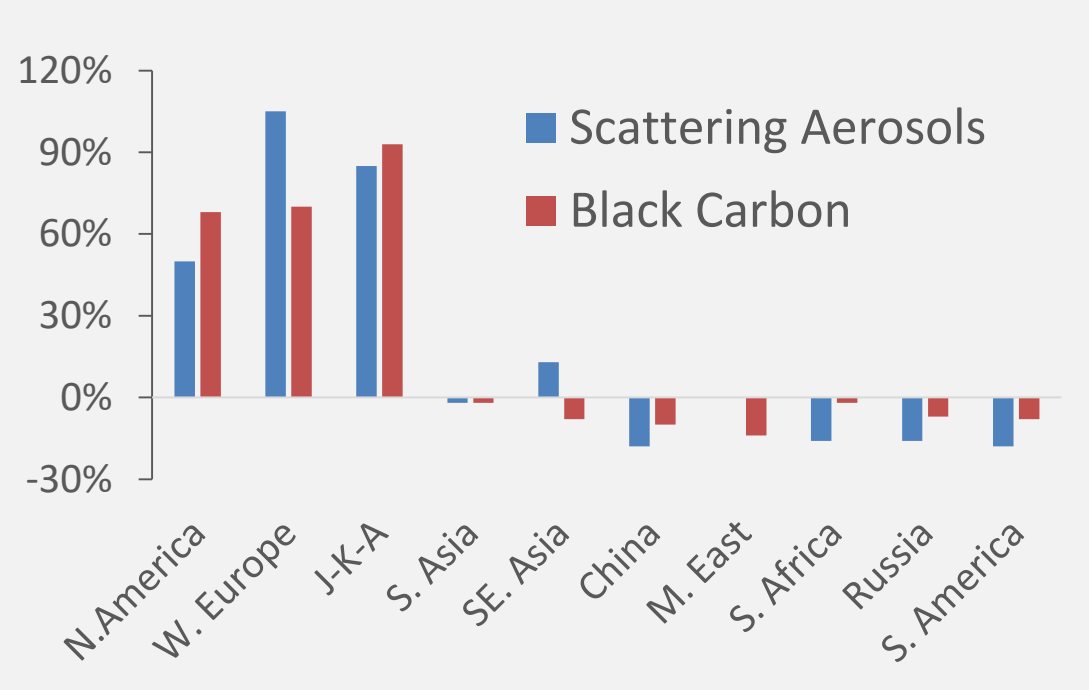
Consumption-based minus production-based TOA direct RF in 2007



Lin et al., 2016, Nature Geoscience

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

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

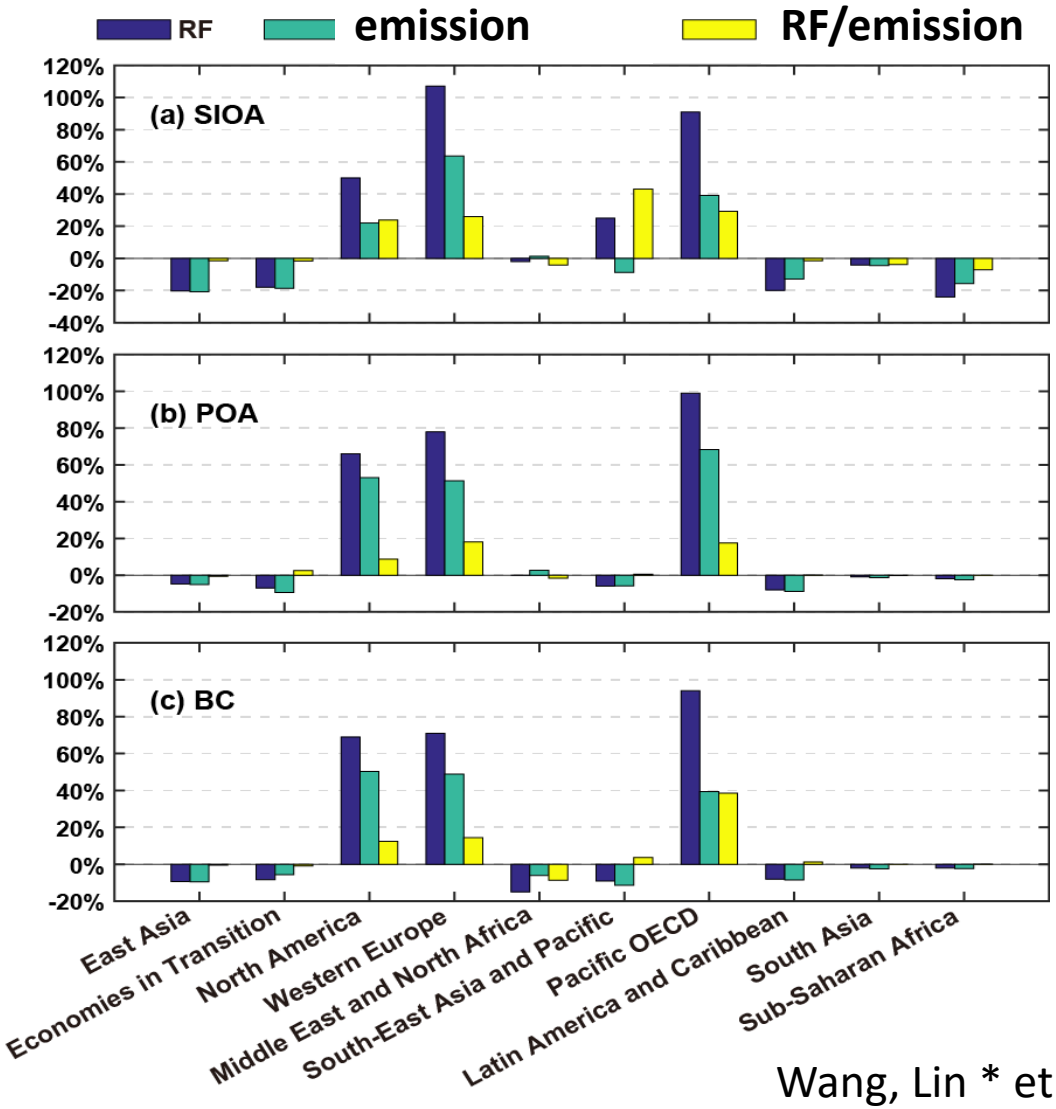


Method:
Emission inventory +
GTAP MRIO table +
GEOSChem + RRTMG

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

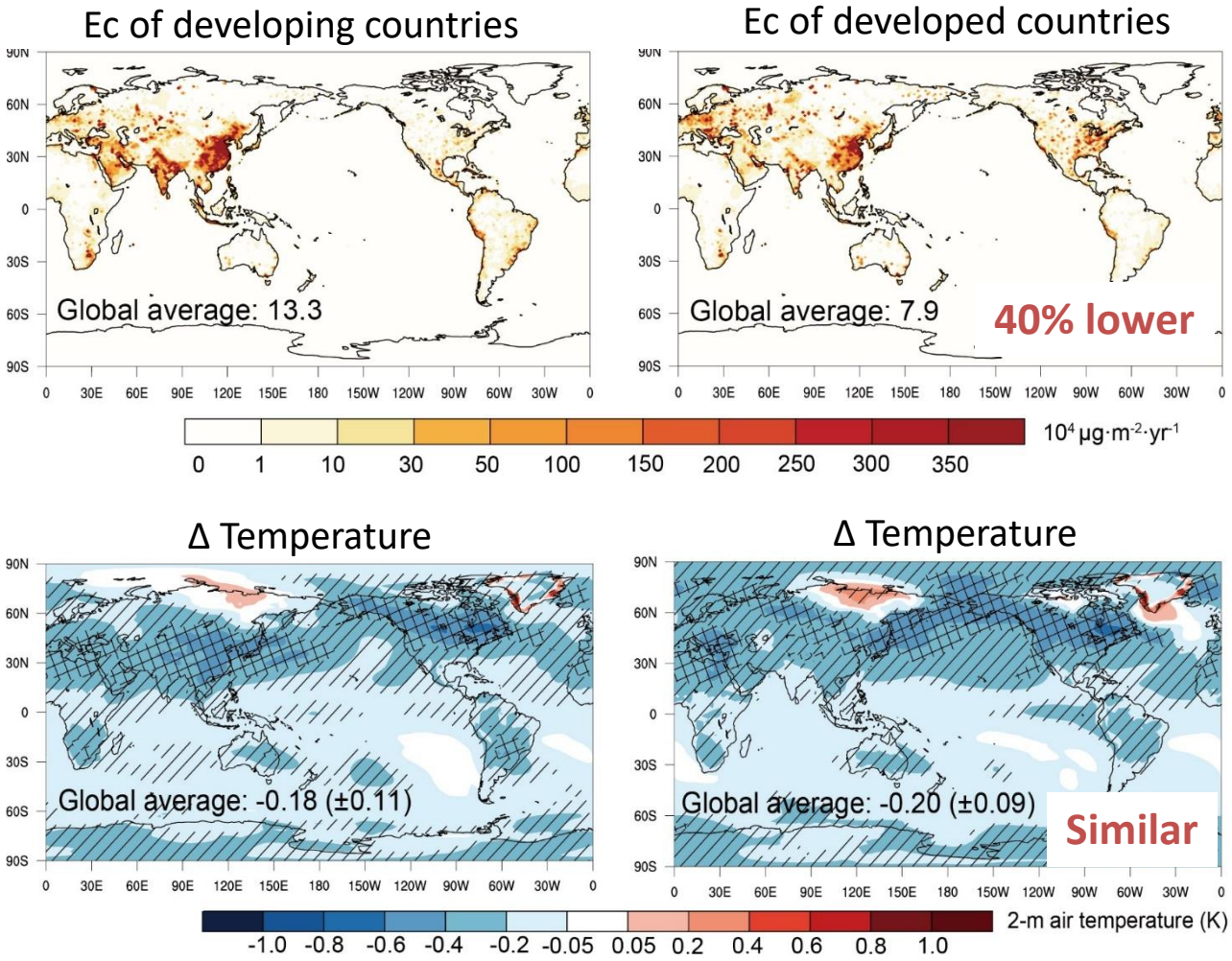
Lin et al., 2016, Nature Geoscience

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



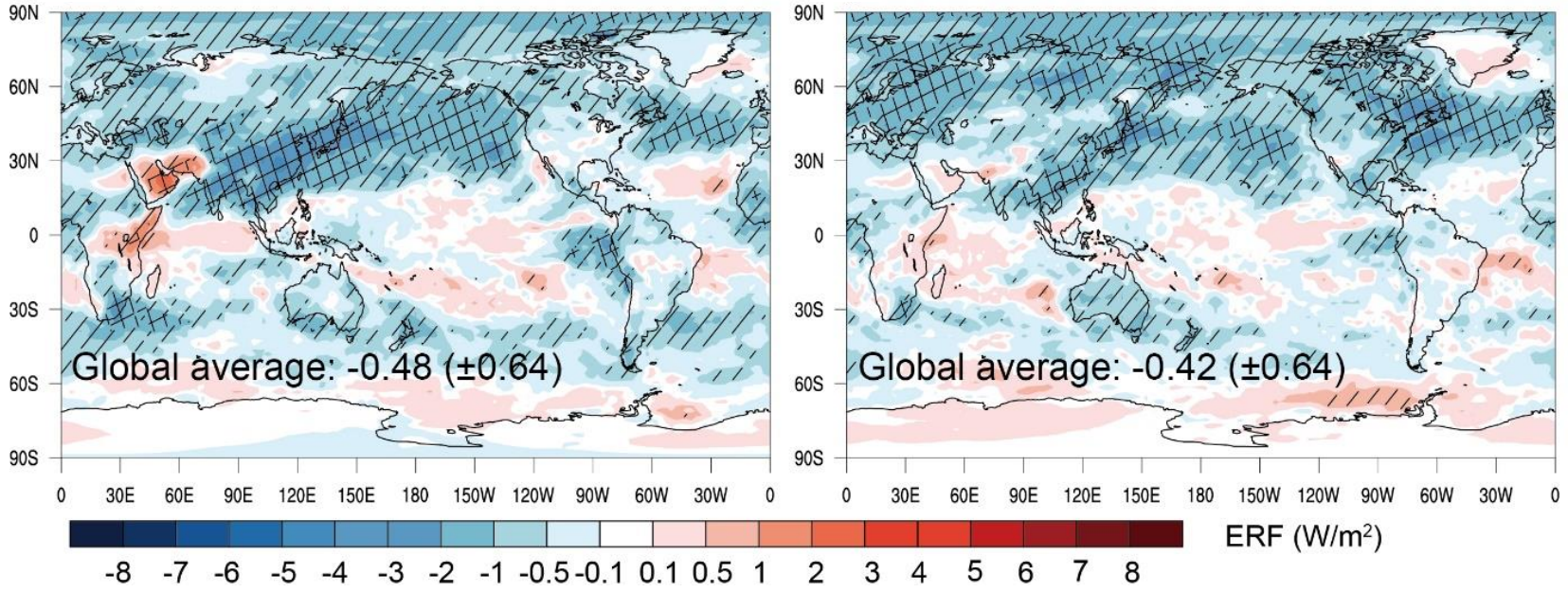
Method:
Emissions
+ GTAP
+ CESM2

Lin et al., Nature Geoscience, 2022

Effective Radiative Forcing of Ec

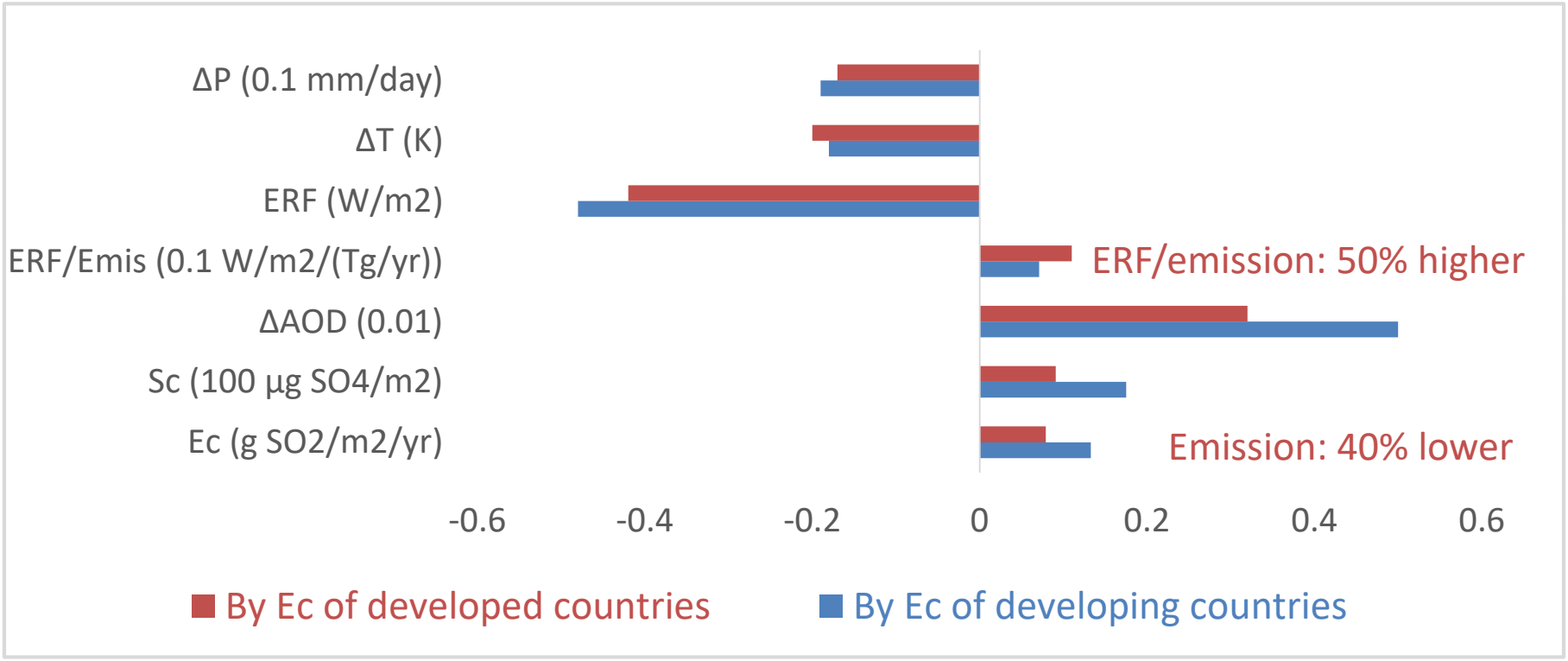
By Ec of developing countries

By Ec of developed countries



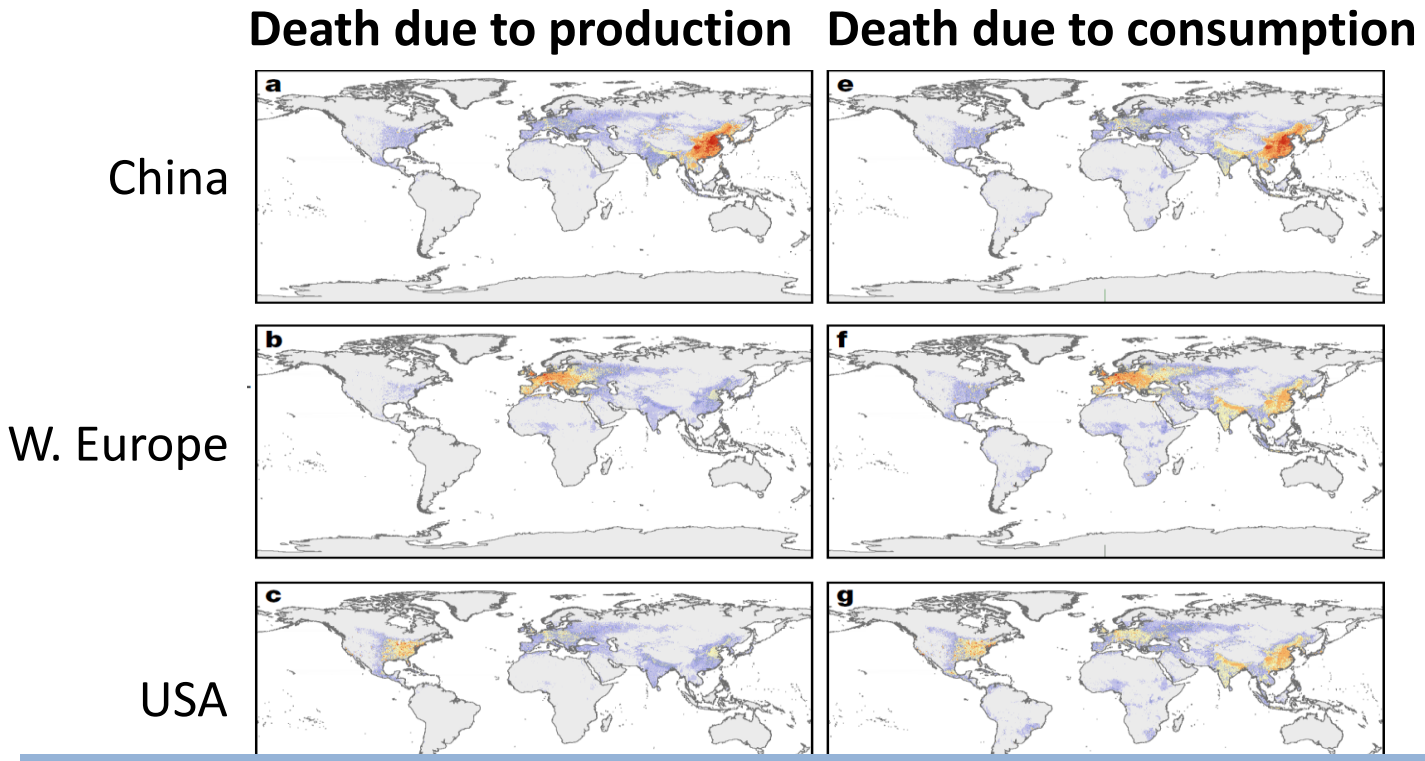
Lin et al., Nature Geoscience, 2022

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



Lin et al., Nature Geoscience, 2022

Global Transport and Trade Result In Large $PM_{2.5}$ Mortality



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

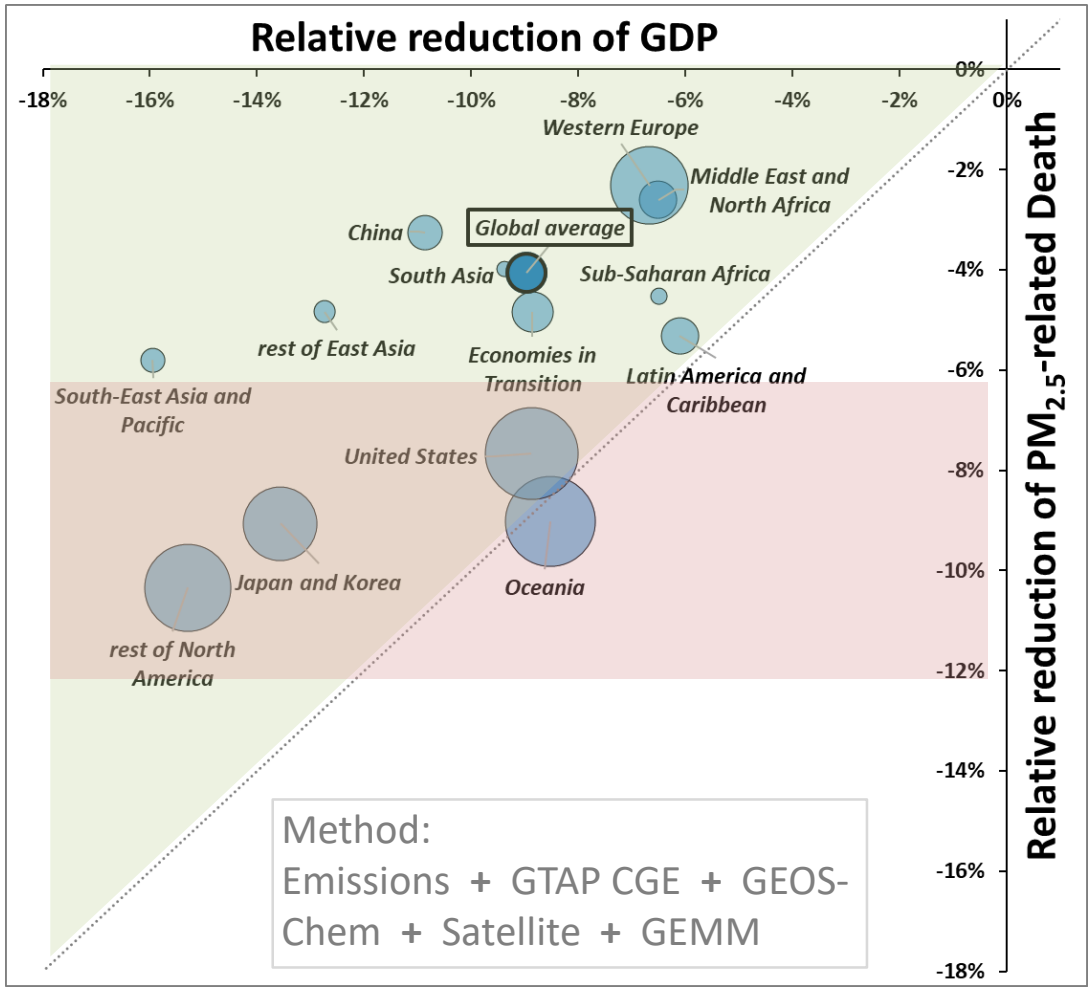
- 12% is due to atmospheric transboundary transport
- 22% is due to consumption in a different region (trade + transport)

Of 1,000,000 $PM_{2.5}$ related deaths in 2007 in China:

- 3.5% is due to atmospheric transboundary transport
- 24% is due to consumption in a different region (trade + transport)

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

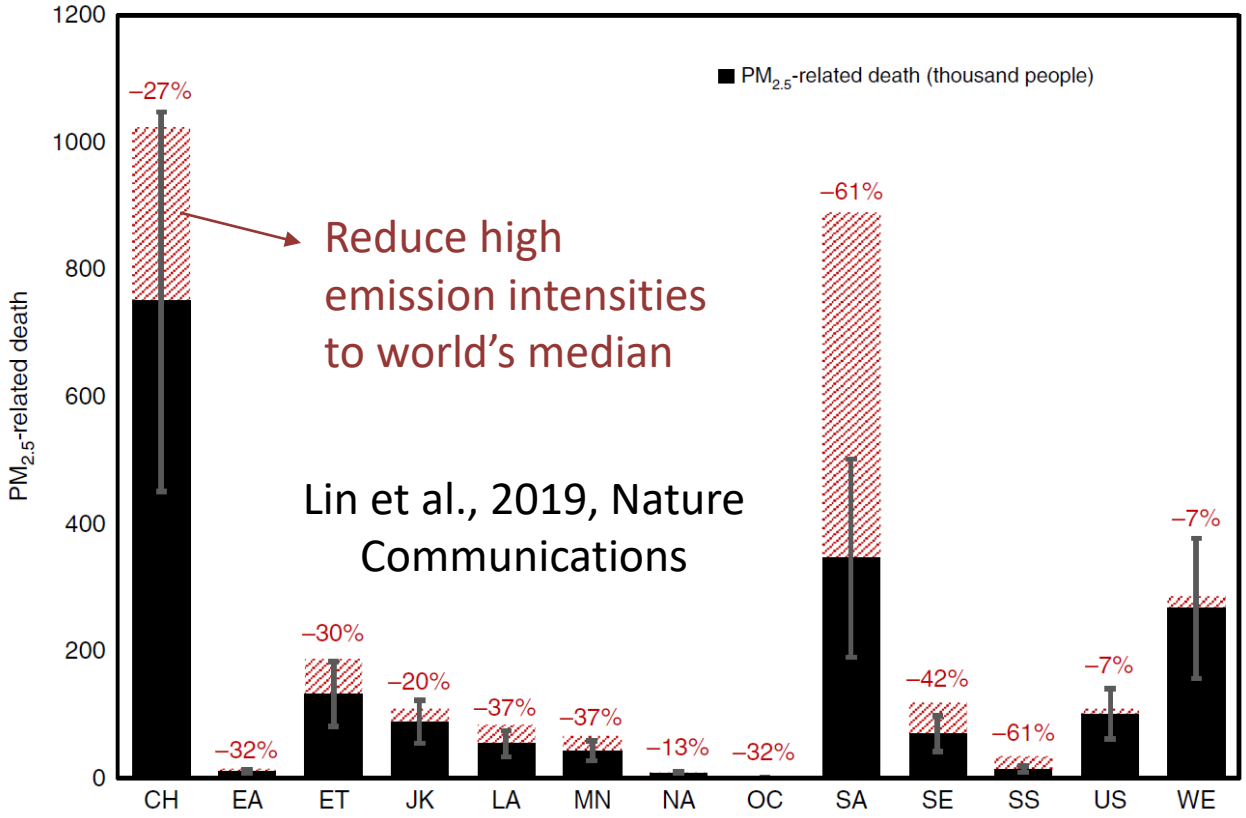
How Would Trade Development Affect Environment: Δ GDP and Δ $PM_{2.5}$ Mortality from *Free Trade* to *+25% tariff*



- 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**.

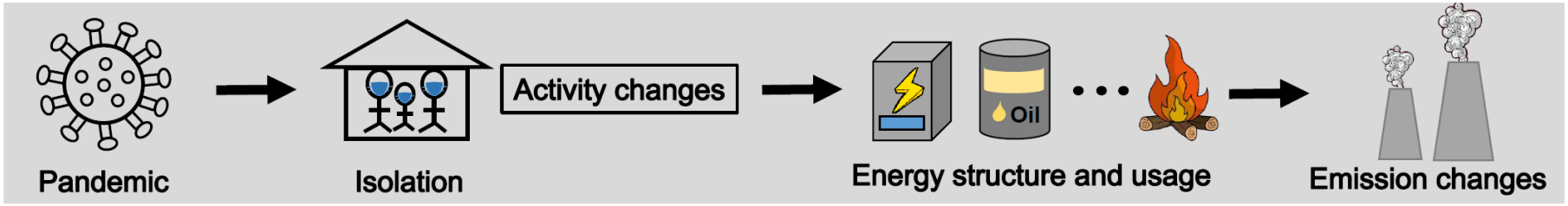
Lin et al., Nature Communications, 2019

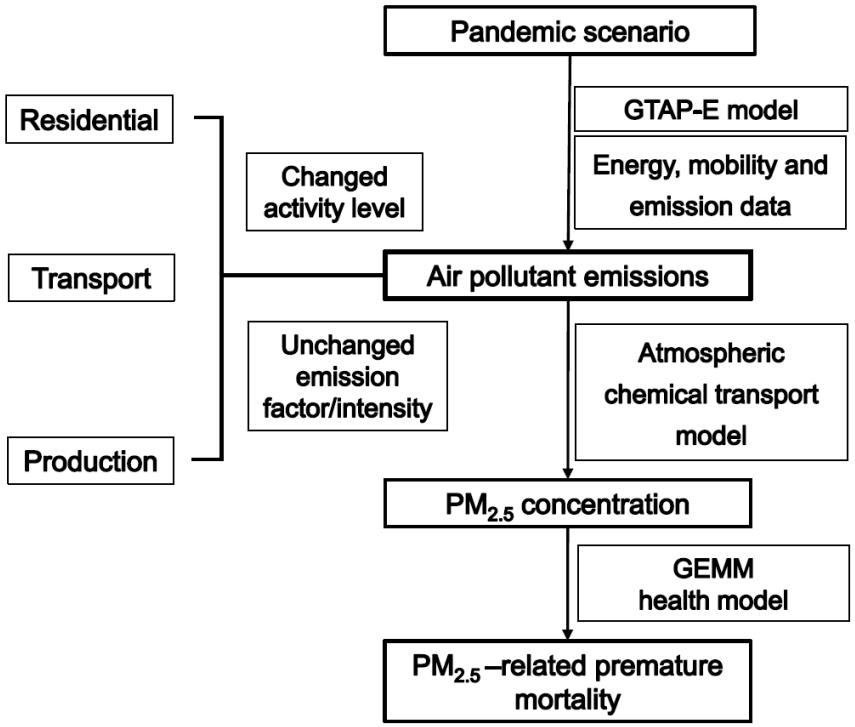
Global Concerted Actions to Cut Emission Intensities in Developing Regions to Ensure both Economic Growth & Environmental Protection

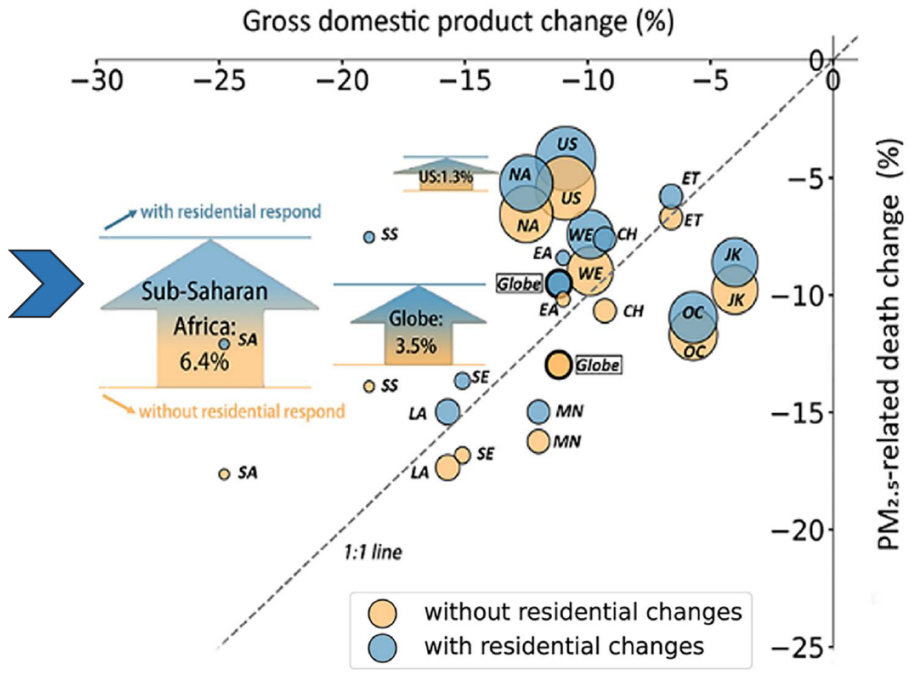


Method: Emissions + GTAP CGE + GEOS-Chem + Satellite + GEMM

Inter-regional Environmental Inequality under Lasting Pandemic Exacerbated by Residential Response

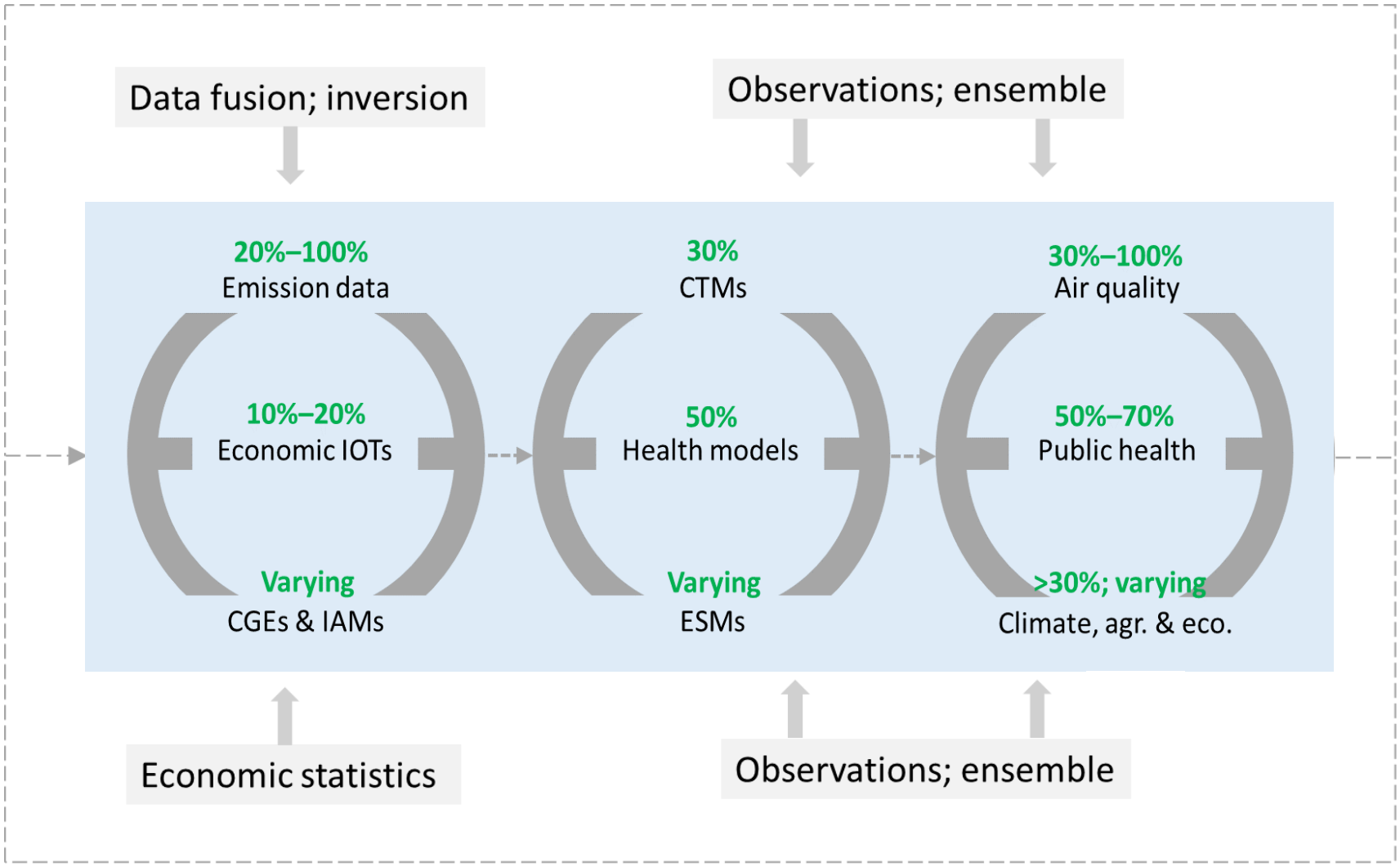






Li et al., SOTEN, 2023

Uncertainties in GAP Studies



Lin et al., in prep

From Production to Consumption Perspective

Trade

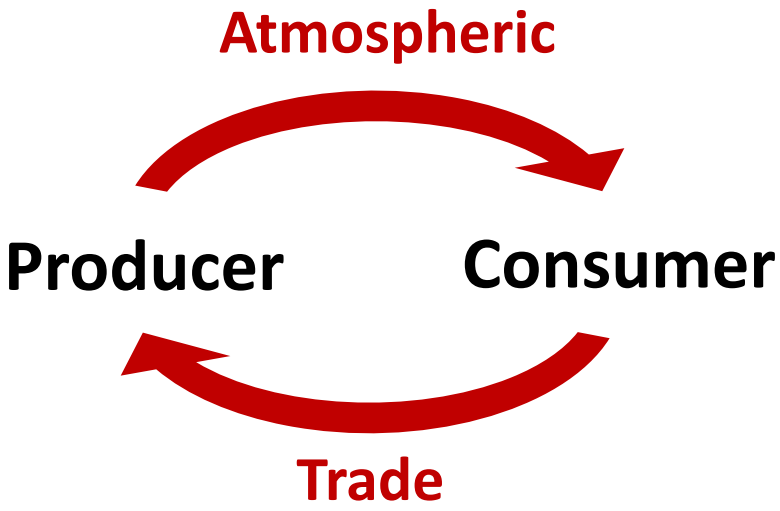
Production ➡ Impacts ⬅ Consumption

- Air Quality
- Climate
- Agriculture
- Ecosystems
- Sustainability

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

Summary

Globalization of Air Pollution



Given the looped mechanism of pollution transport :

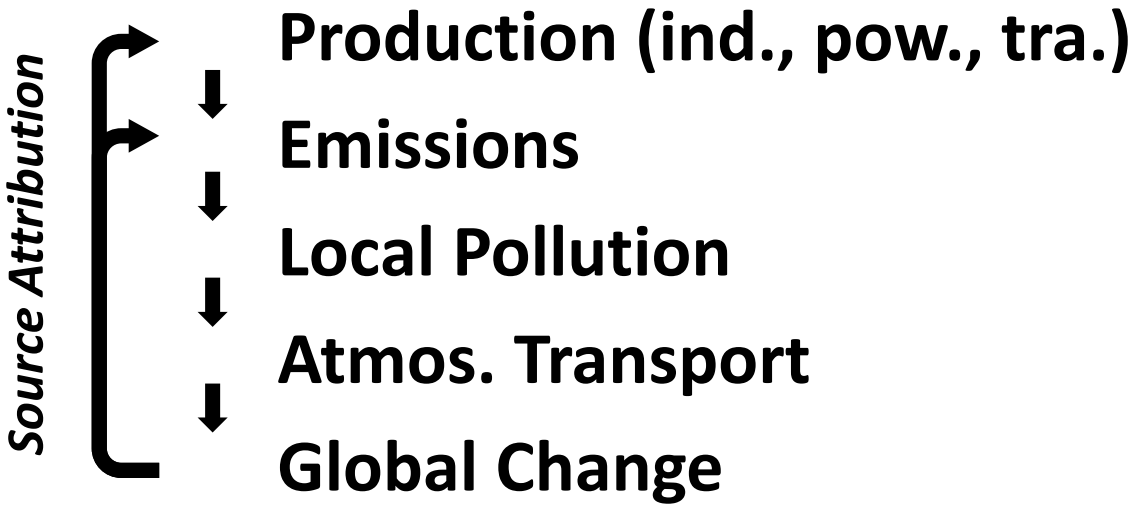
- **Domestic economic and environmental strategy ?**
- **International collaboration to reduce pollution transport ?**
- **Roles of consumers and producers ?**

Quiz

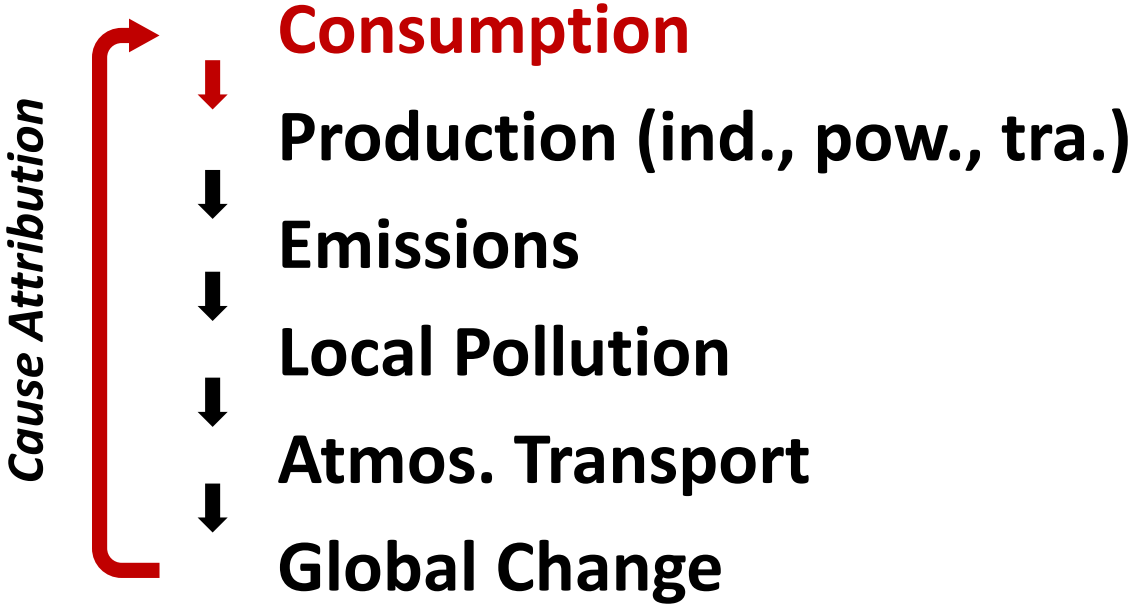
- **Challenges in calculating and verifying production-based emissions and consumption-based emissions. And solutions ?**
- **Uncertainties due to integration of multiple disciplines**
- **Roles of industries, sectors and individual consumers in pollution and mitigation**

How Is Air Pollution Globalized ???

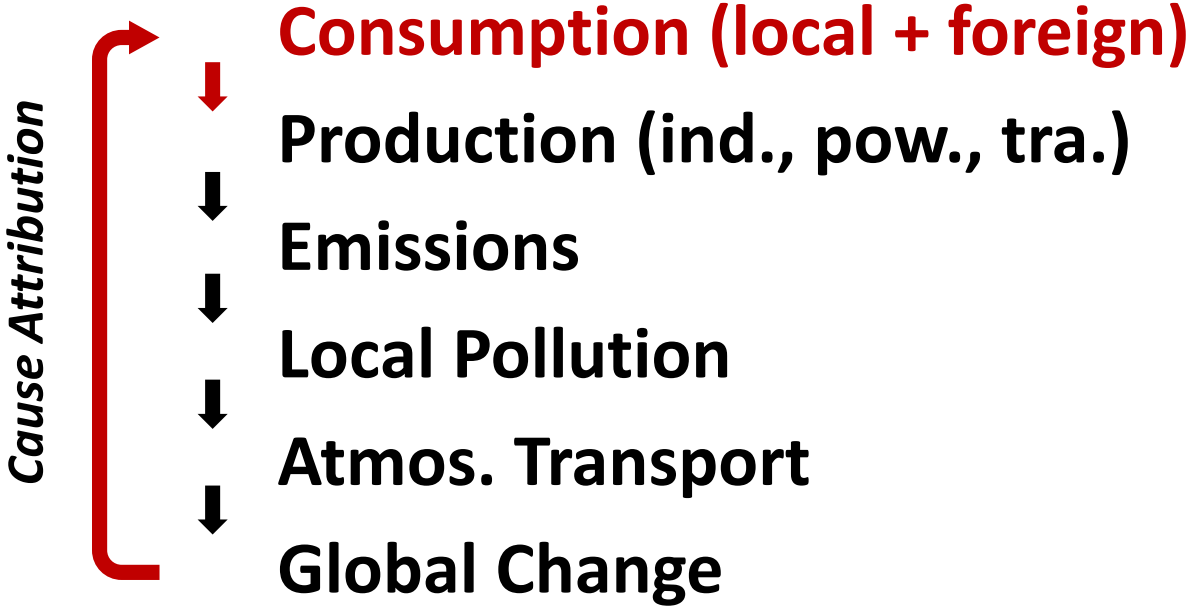
Traditional View



Consumption & Trade Drives Production and Pollution !



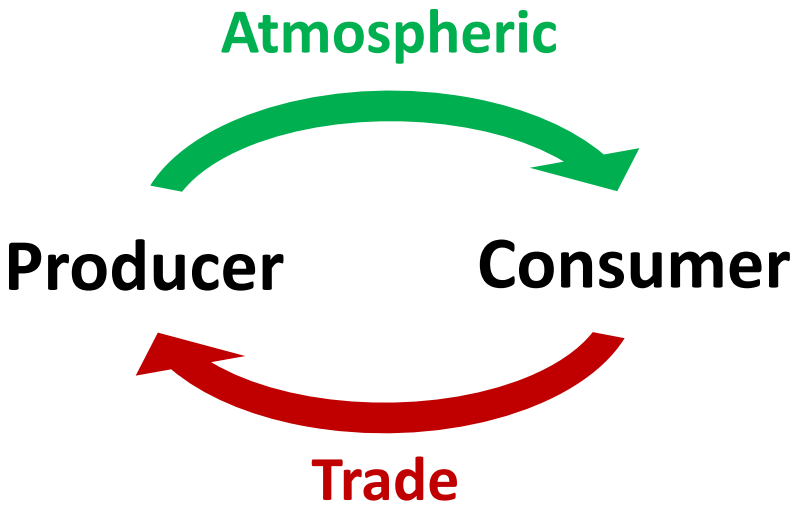
Consumption & Trade Drives Production and Pollution !



Consumption & trade re-locates pollution

from consumers to producers

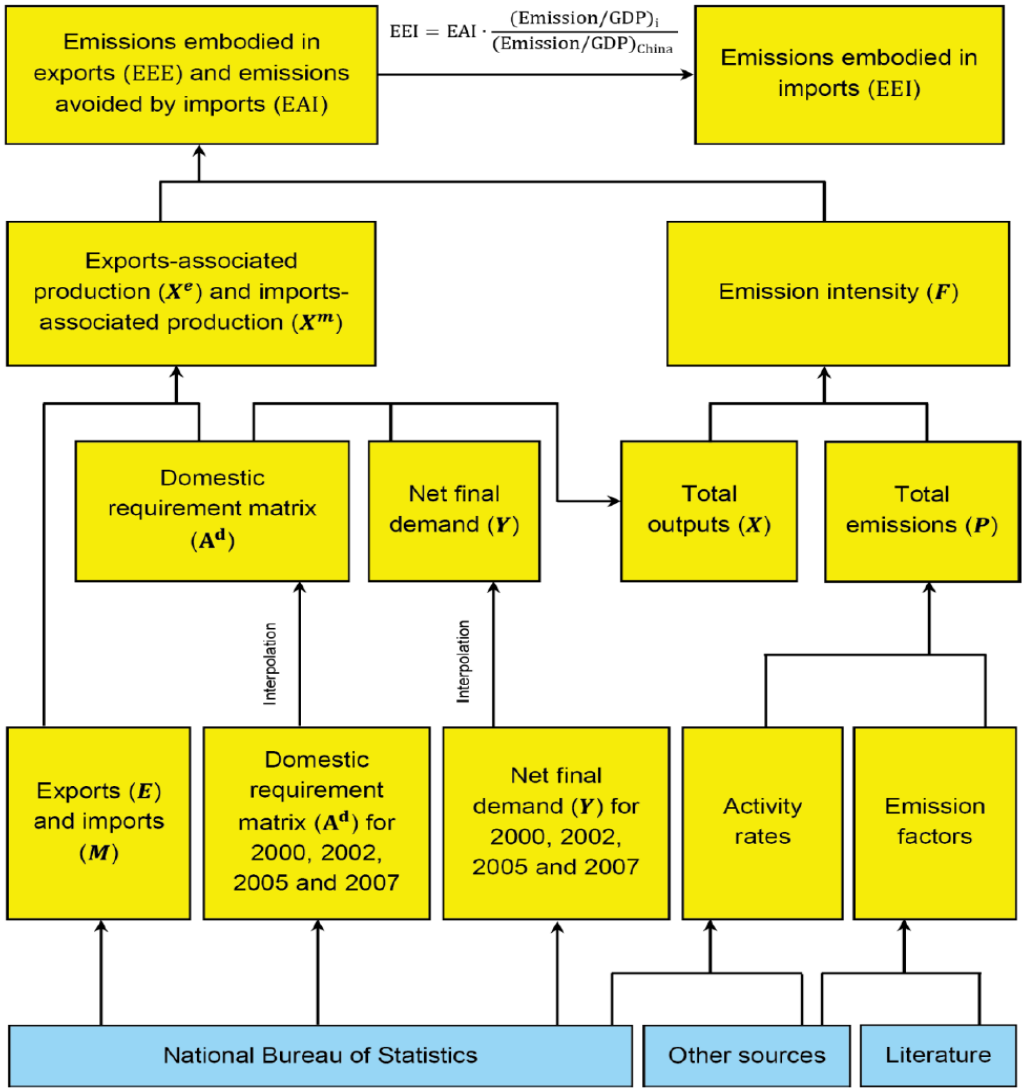
Globalizing Air Pollution



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

Lin et al., 2014, PNAS

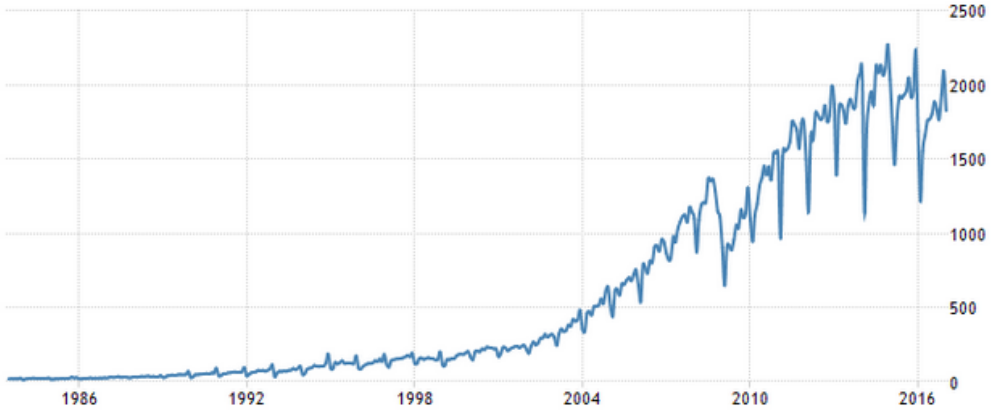
Calculating Emissions Embodied in Bilateral Trade of China Based on Bilateral Trade



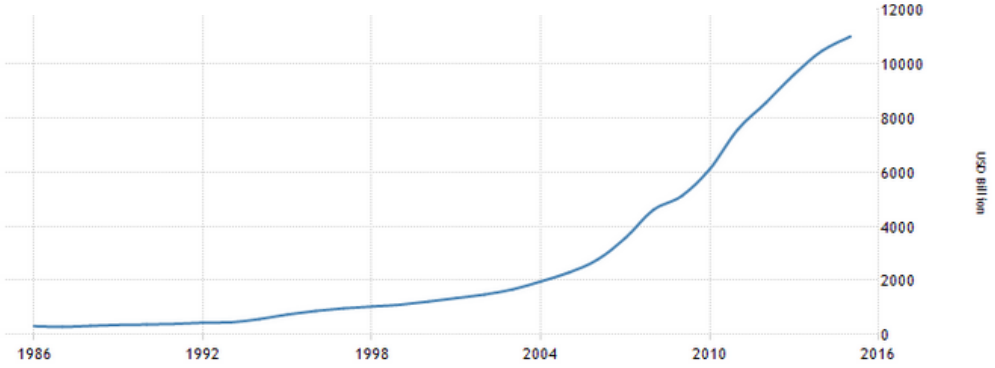
Lin et al., 2014, PNAS

Export and Total GDP of China

Export volume (Billion USD)



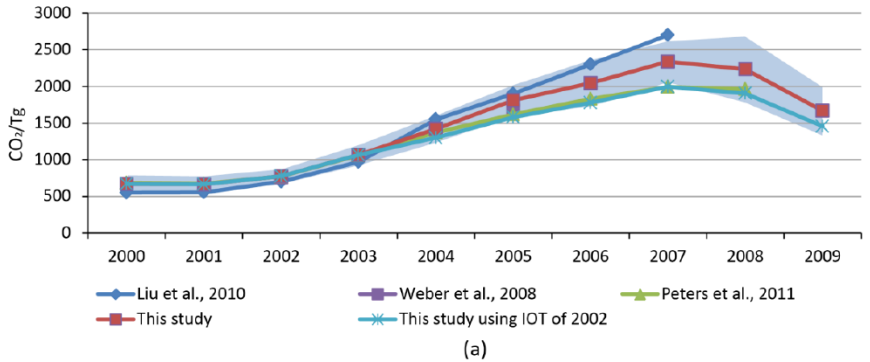
Total GDP (Billion USD)



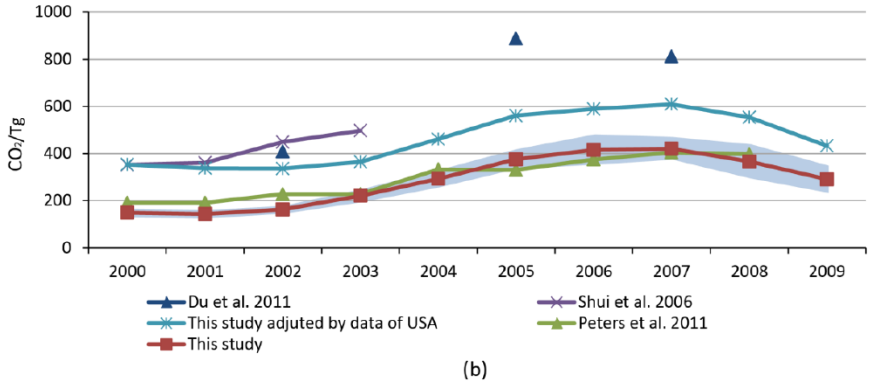
Source: Xujia Jiang

China's Export- and Import-related CO_2 Emissions

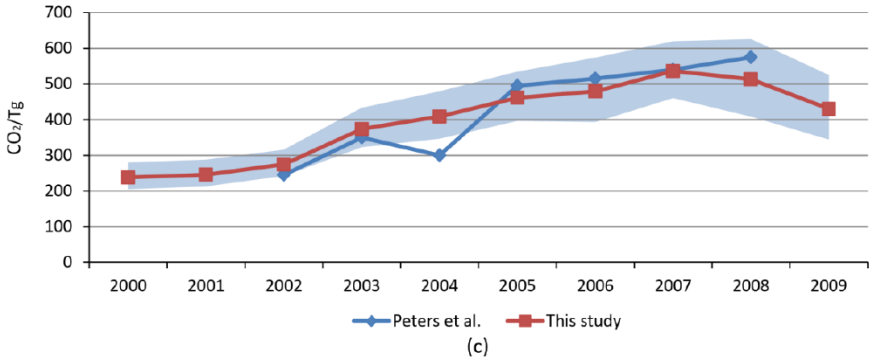
Export



Import

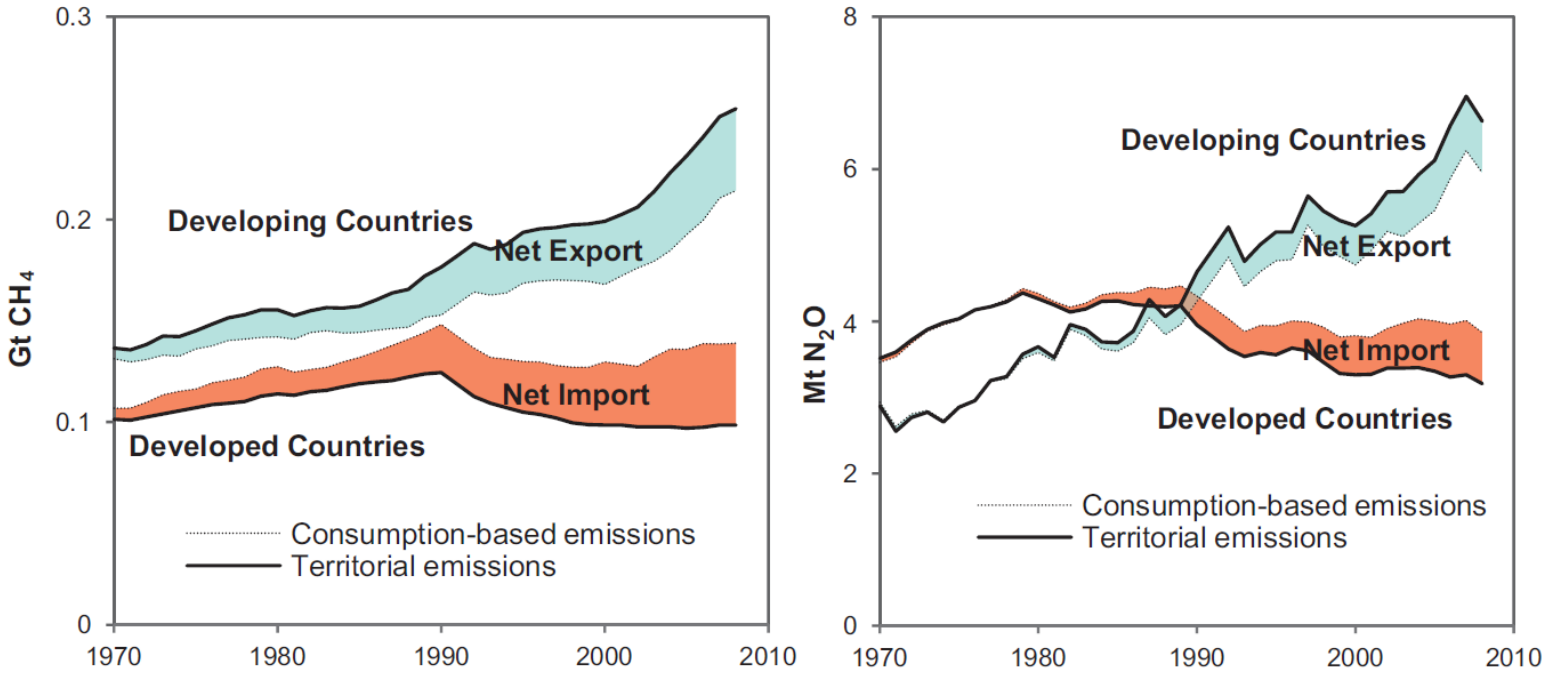


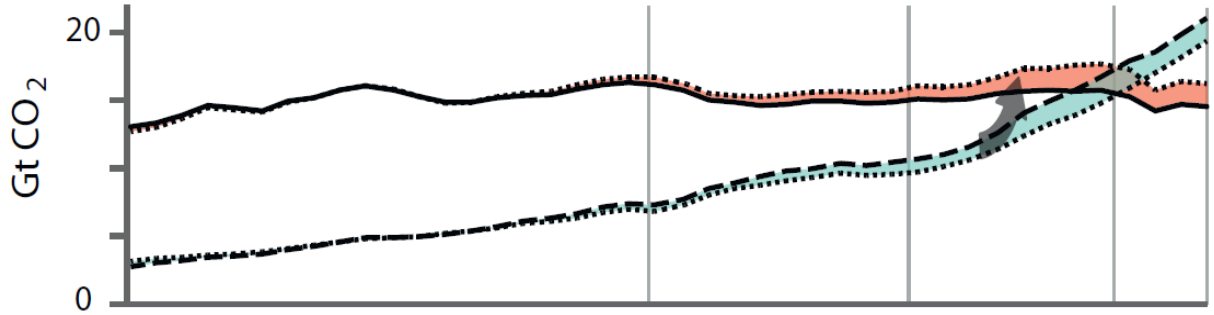
Net Export



Lin et al., 2014, PNAS

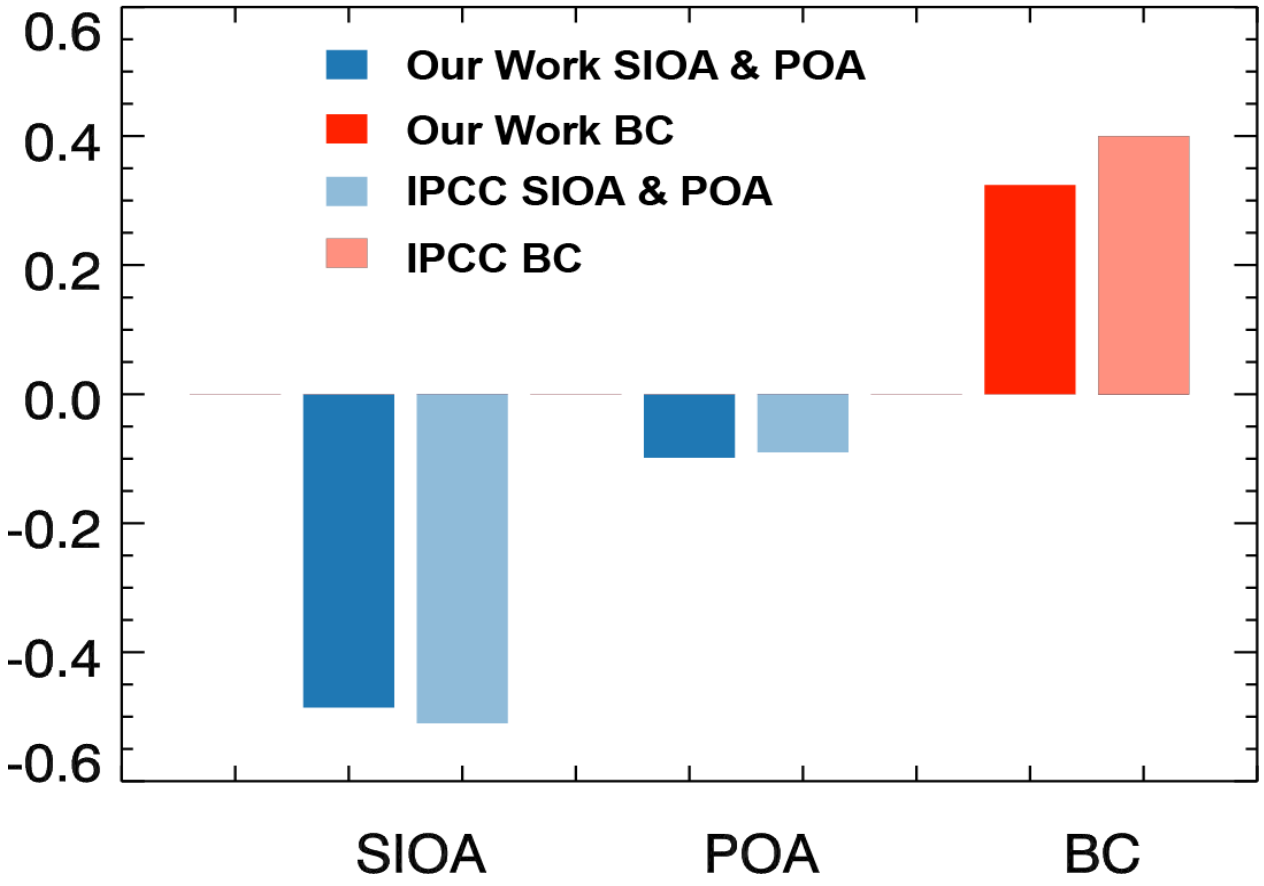
Consumption and Trade Drives Emission Redistribution





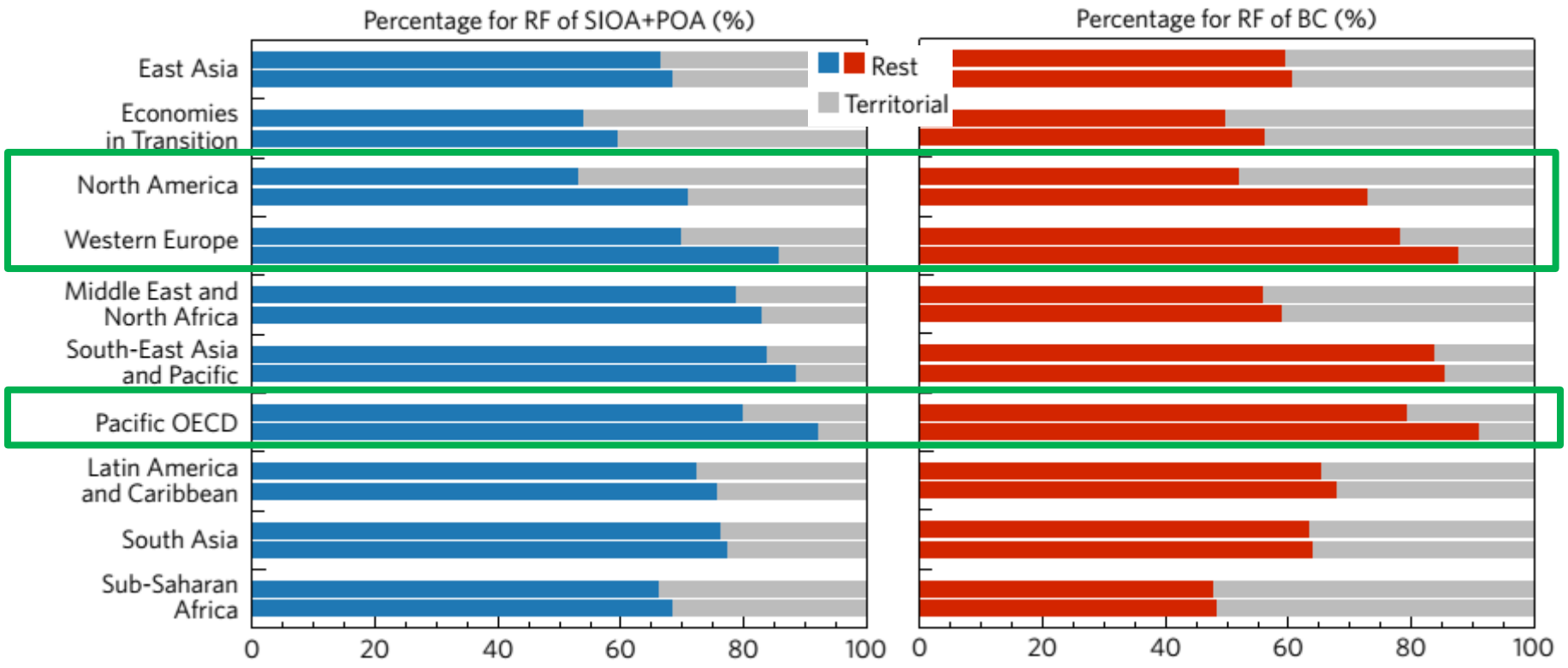
Kanemoto et al., 2014, GEC

TOA Direct RF of SIOA, POA, and BC



Lin et al., 2016, Nature Geoscience

Trade Transfers RF from Rich to Poorer Regions

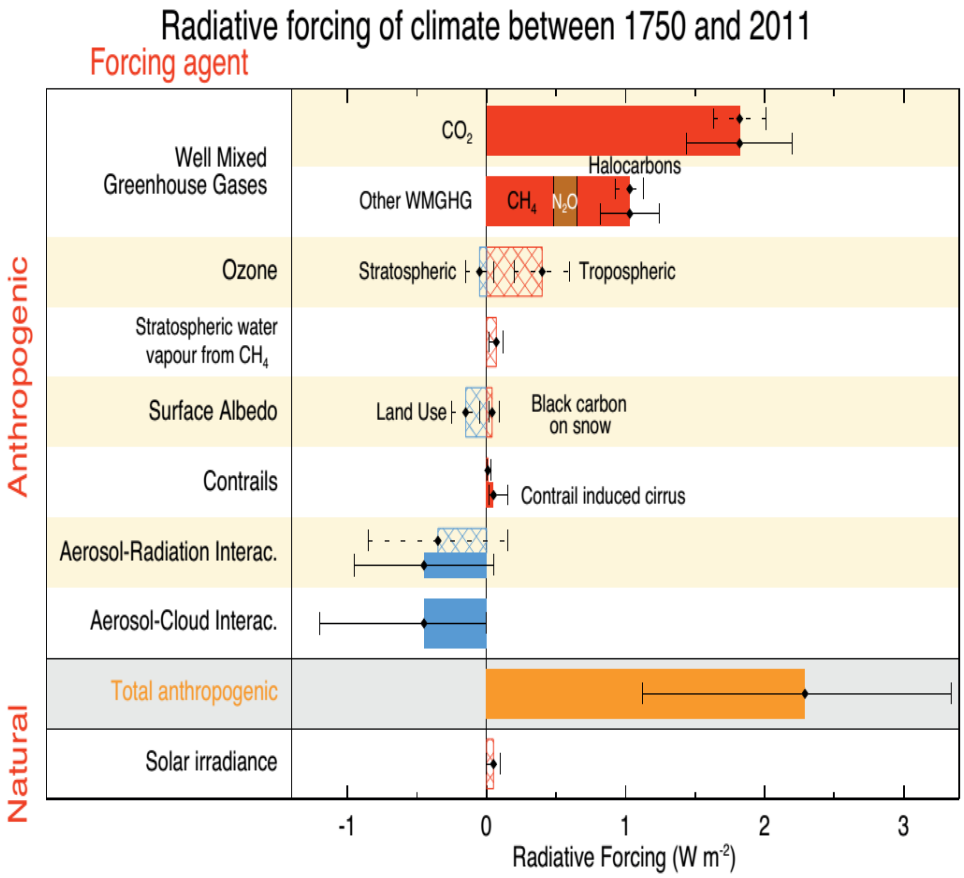


- Stronger *cumulated RF* outside than within the source region
- Terrestrial share is much reduced from RF_p to RF_c

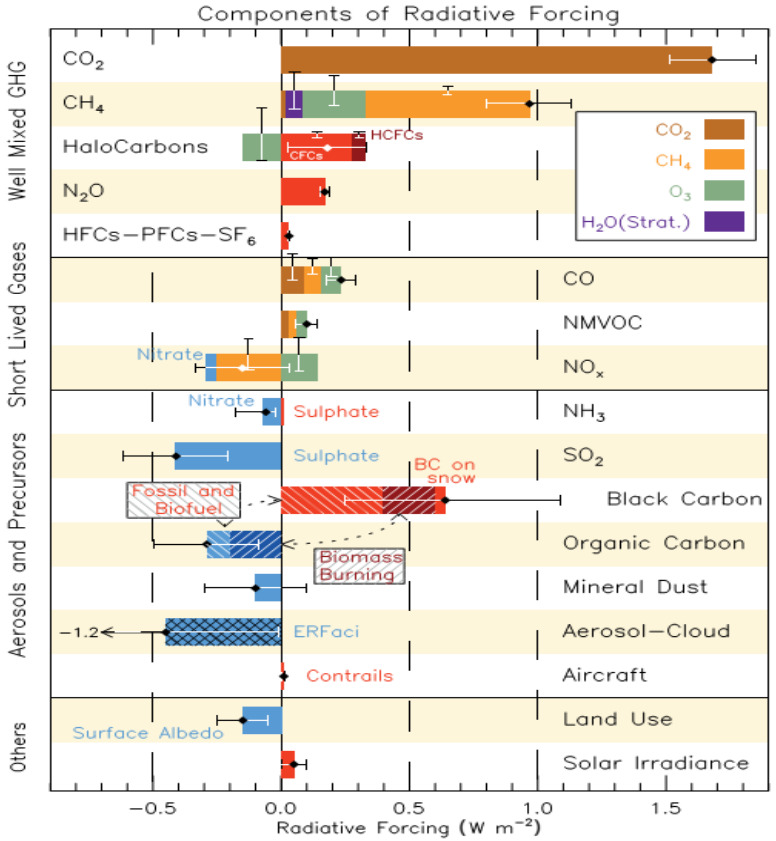
Lin et al., 2016, Nature Geoscience

Air Pollutants Exert Strong Radiative Forcing

Based on concentration change



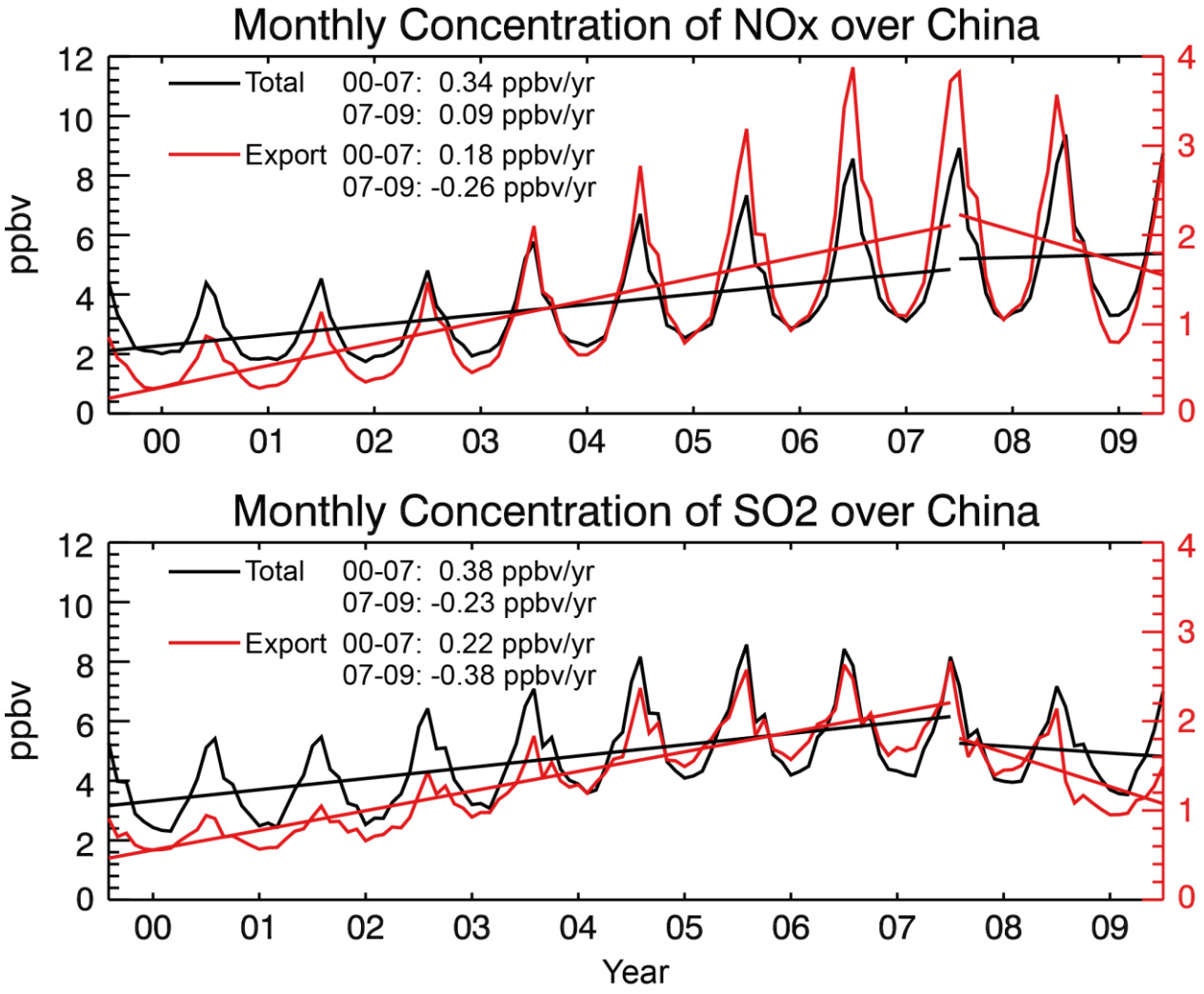
Based on emission change



1 w m^{-2} = 32 x world energy consumption in 2013

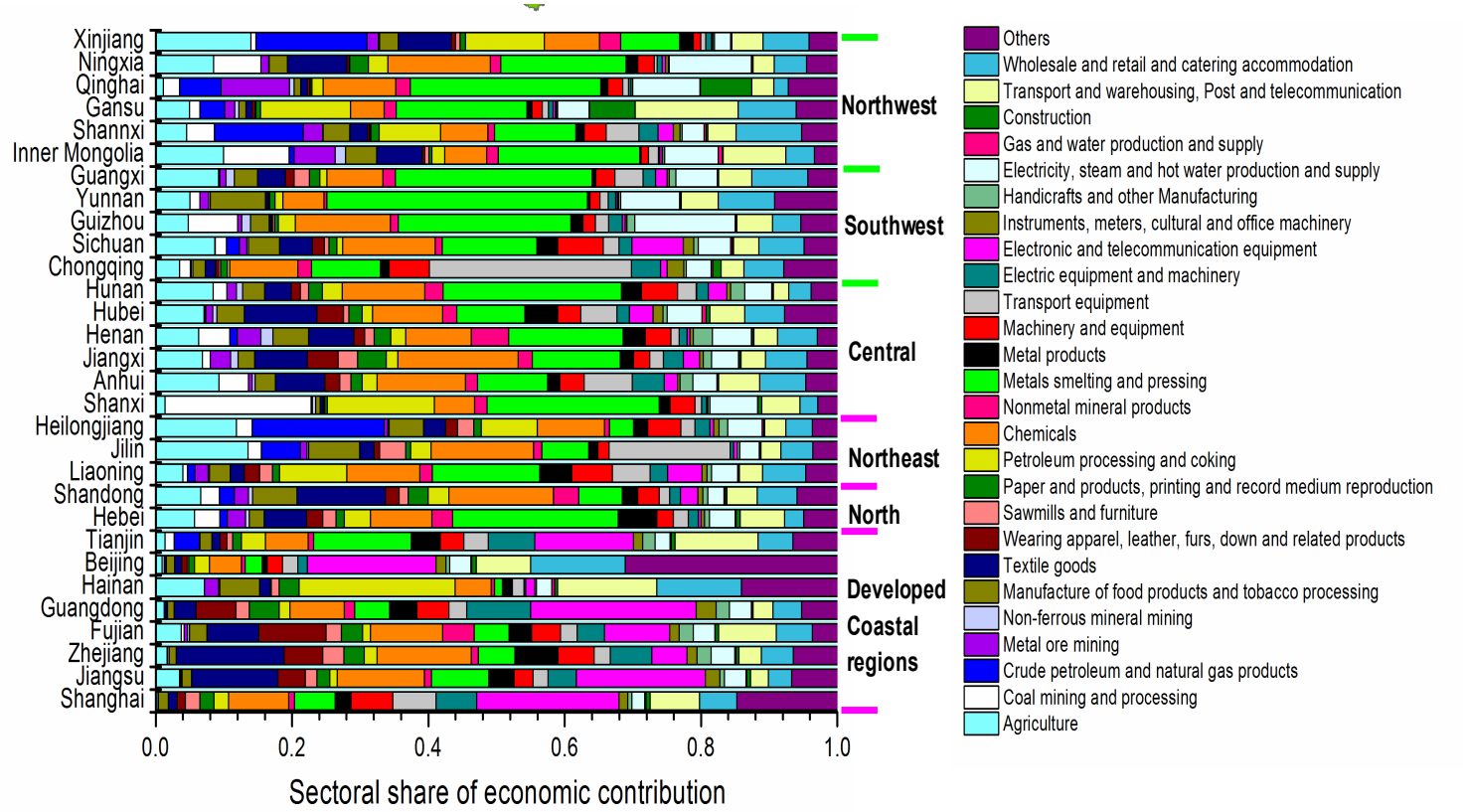
IPCC, 2013

Trend of Surface NOx and SO_2 over China



- **Export-related emissions contributed more than 50% of pollution growth in China over 2000-2007**

Inter-Provincial Disparity in Export-related Sectors



EX-related sectors in inner provinces

- Metals, chemicals and other upstream products as intermediate goods

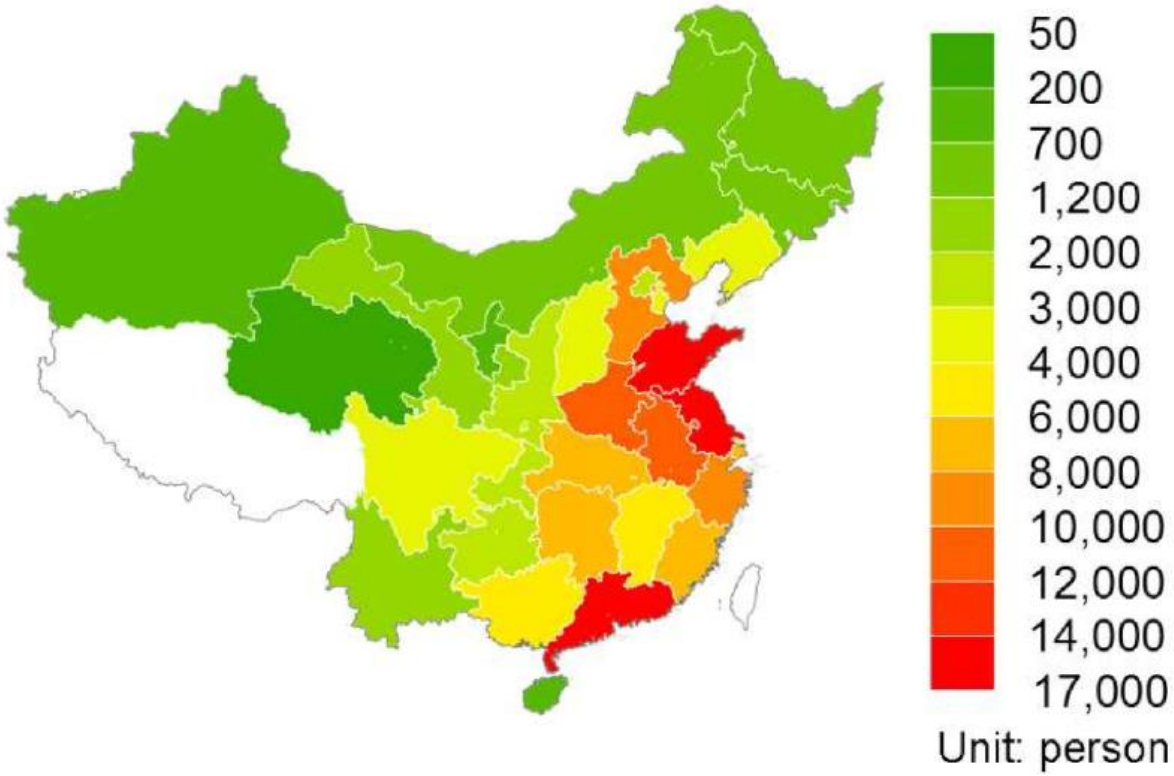
EX-related sectors in coastal provinces

- Electronics and other downstream (final) products

Zhao et al., 2015, ACP; Jiang et al., EST, 2015

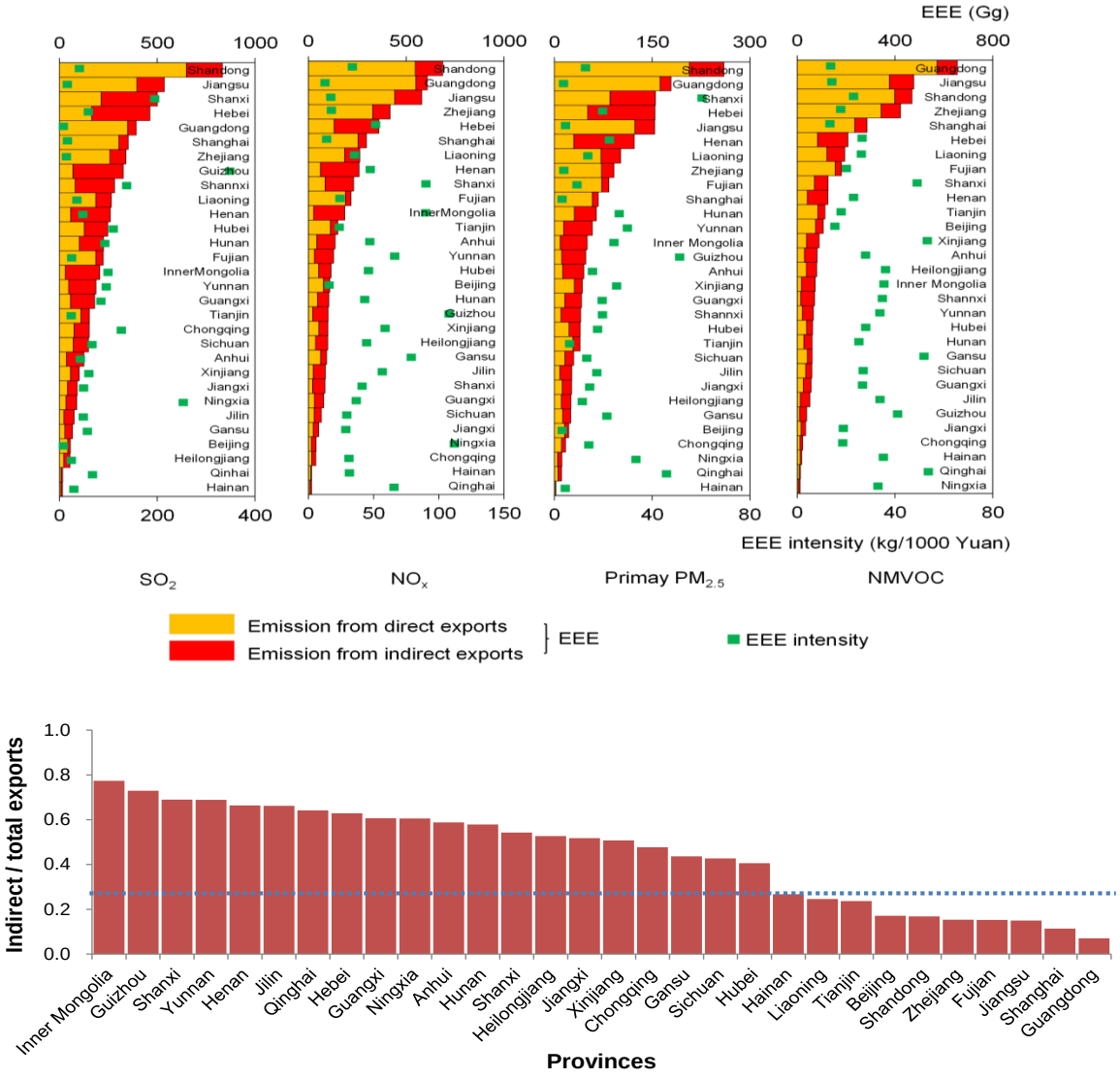
China's Inter-provincial Trade for Export Causes A Large Quantity of Deaths

China's export-related death toll in 2007 = 157,000, larger than all deaths in the US and the UK from ambient PM and O_3



Jiang et al., EST, 2015

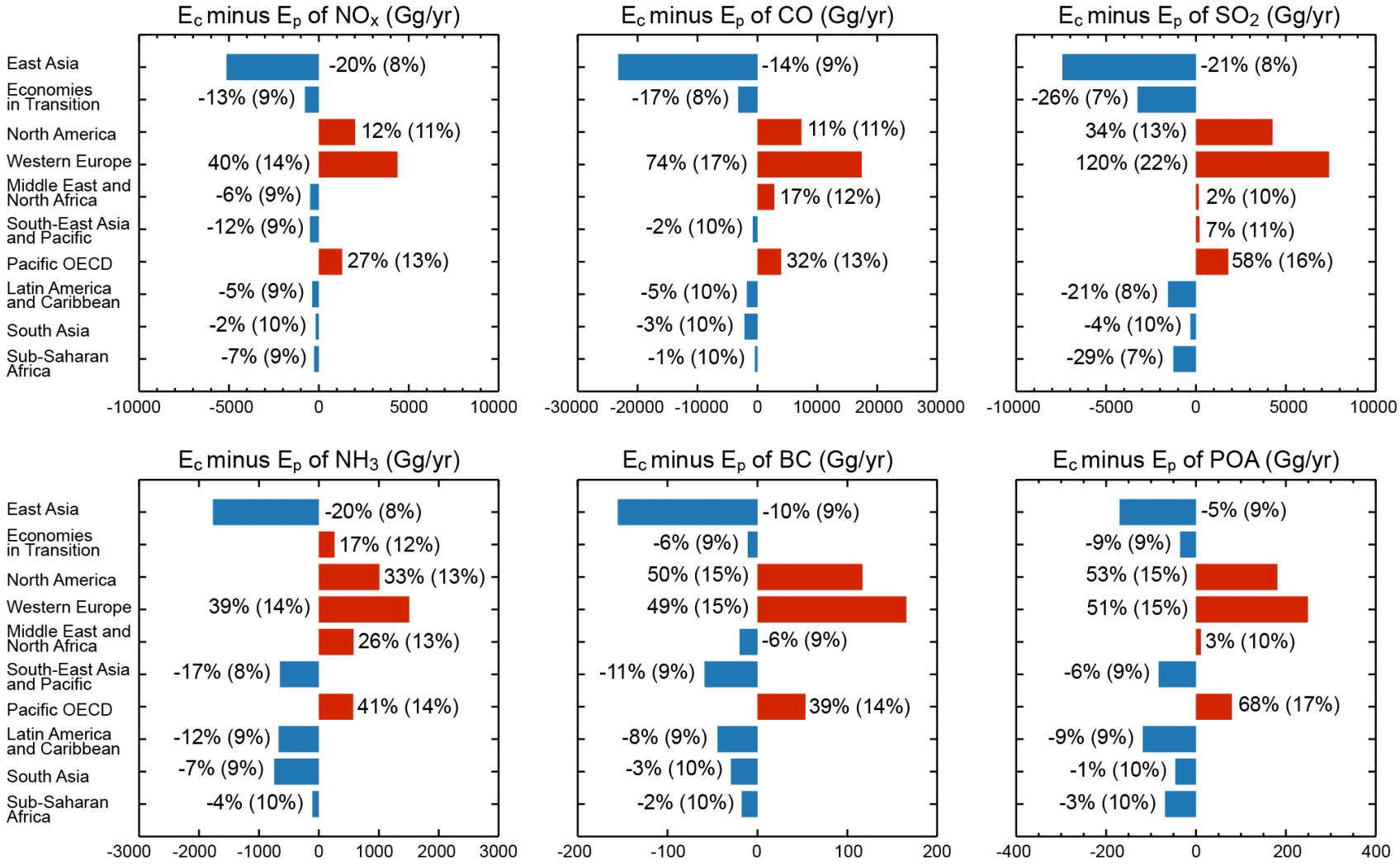
Inter-Provincial Disparity in Export-related Emissions



Zhao et al., 2015, ACP; Jiang et al., EST, 2015

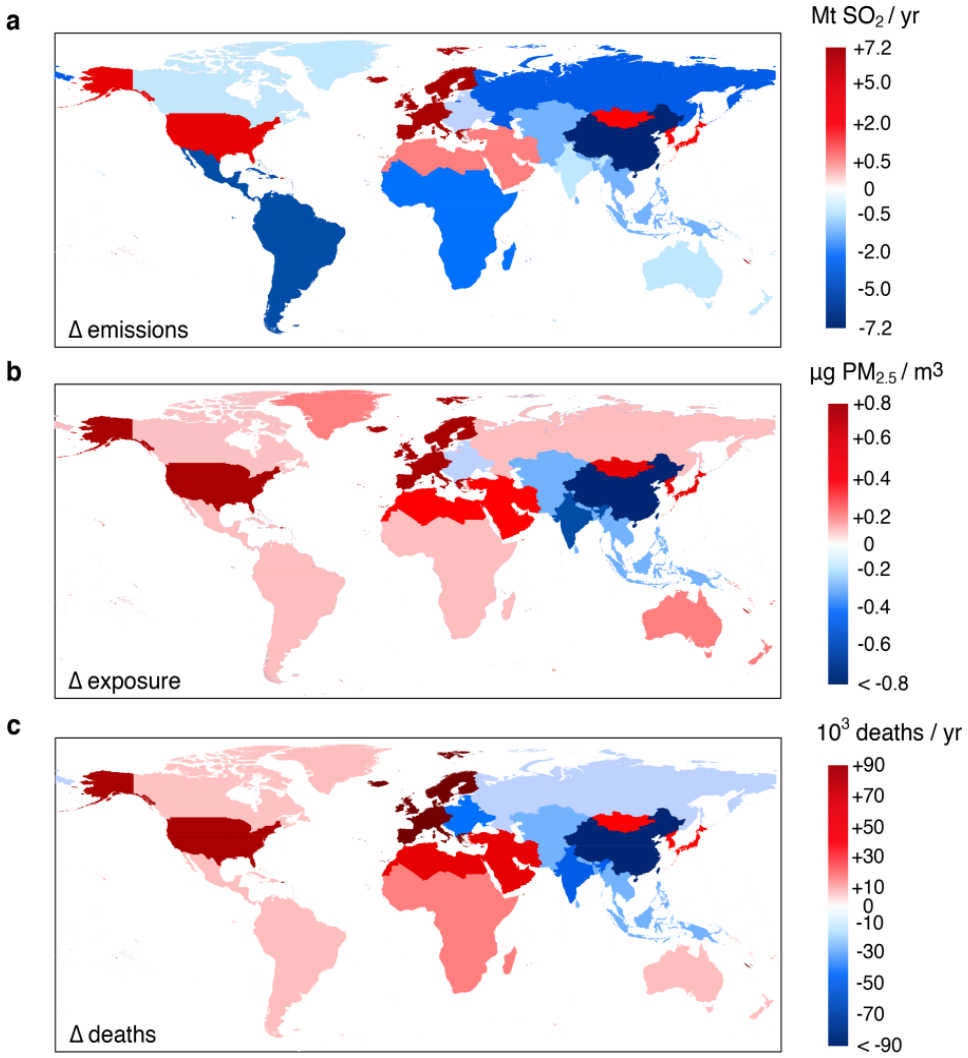
Trade Transfers Emissions from Rich to Poorer Regions

Consumption-based minus Production-based Emissions in 2007



Lin et al., 2016, Nature Geoscience

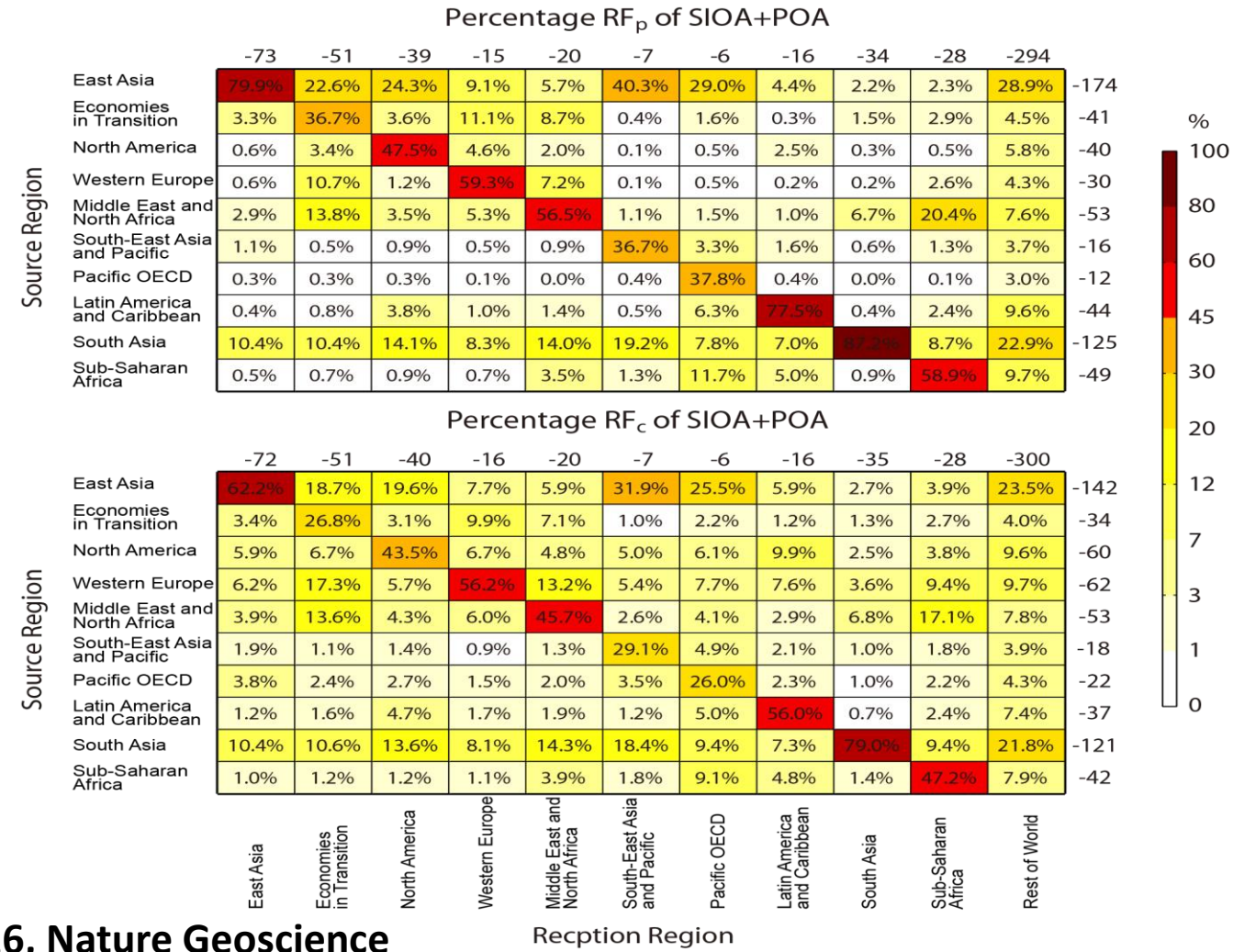
Transport and Trade are Related to Large Deaths



Zhang et al., 2017, Nature

Trade Transfers RF from Rich to Poorer Regions

- A region's RF is largely due to emissions in other regions
- A region's RF_c is much more spreaded spatially than RF_p



Lin et al., 2016, Nature Geoscience

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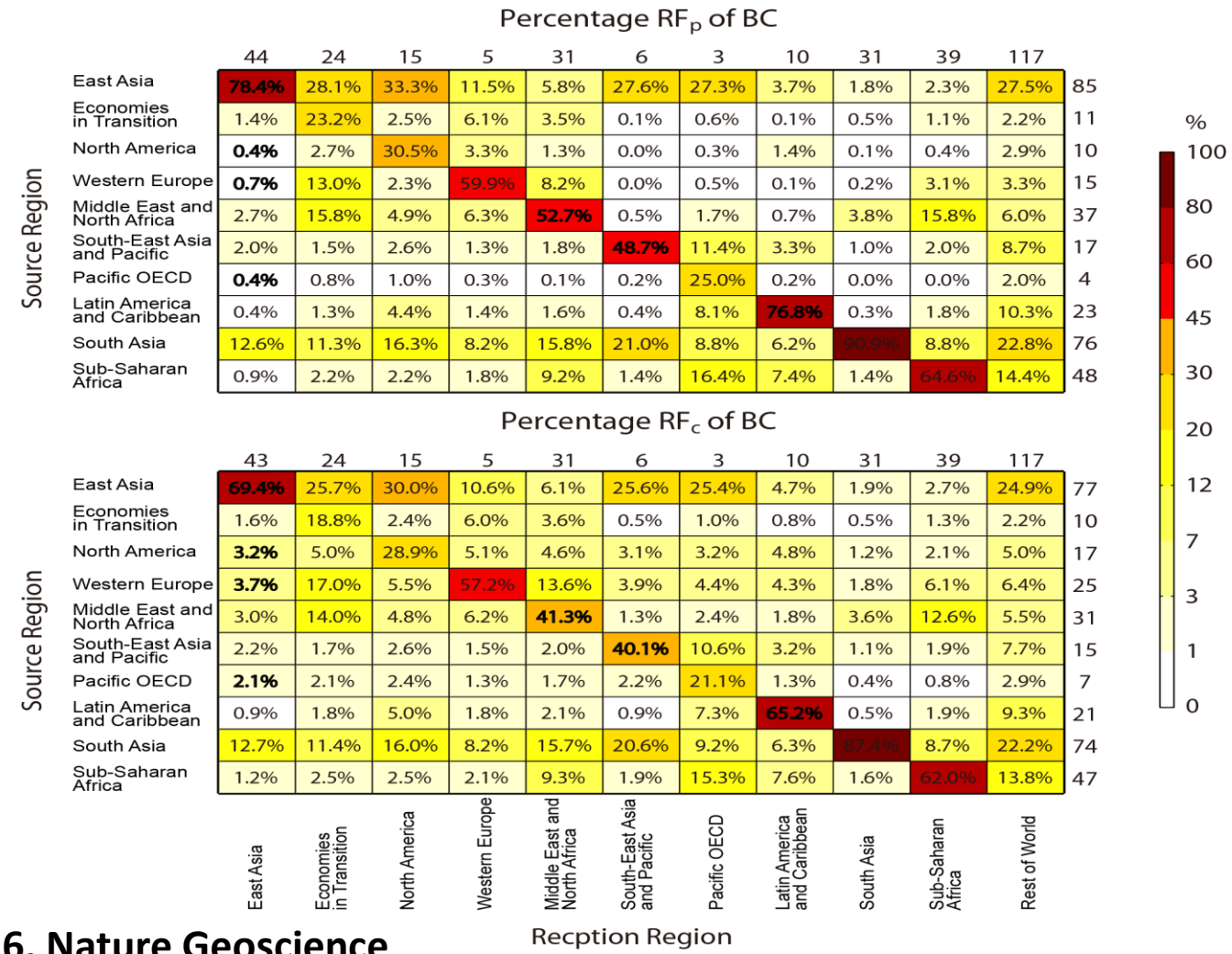
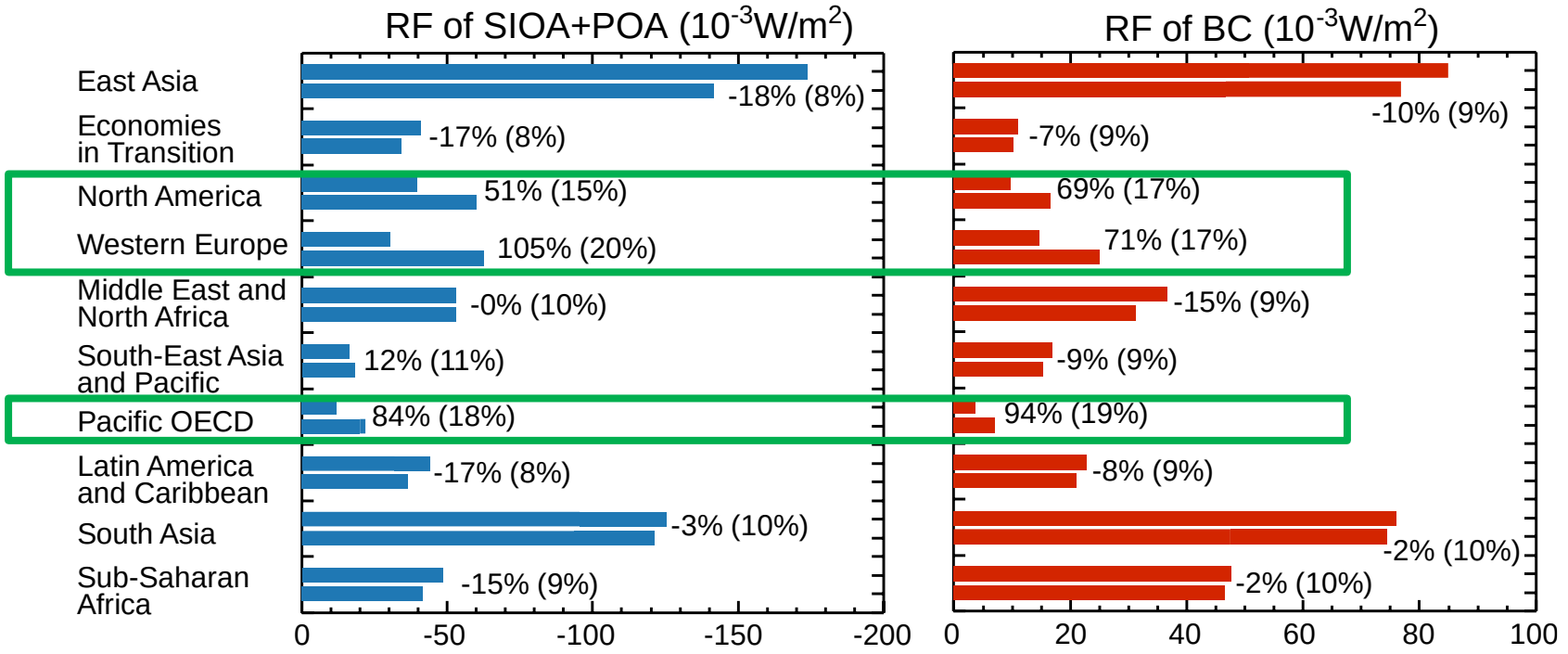


Lin et al., 2016, Nature Geoscience

Trade Transfers RF from Rich to Poorer Regions



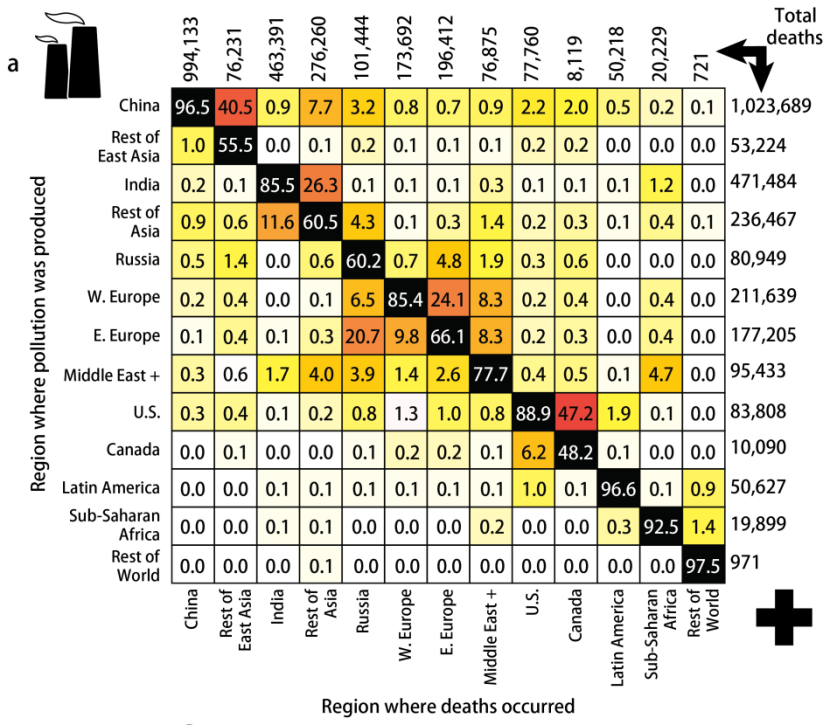
- **Developed regions: RF_c is higher than RF_p by 50–100%**
- **Developing regions: RF_c is smaller than RF_p**

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

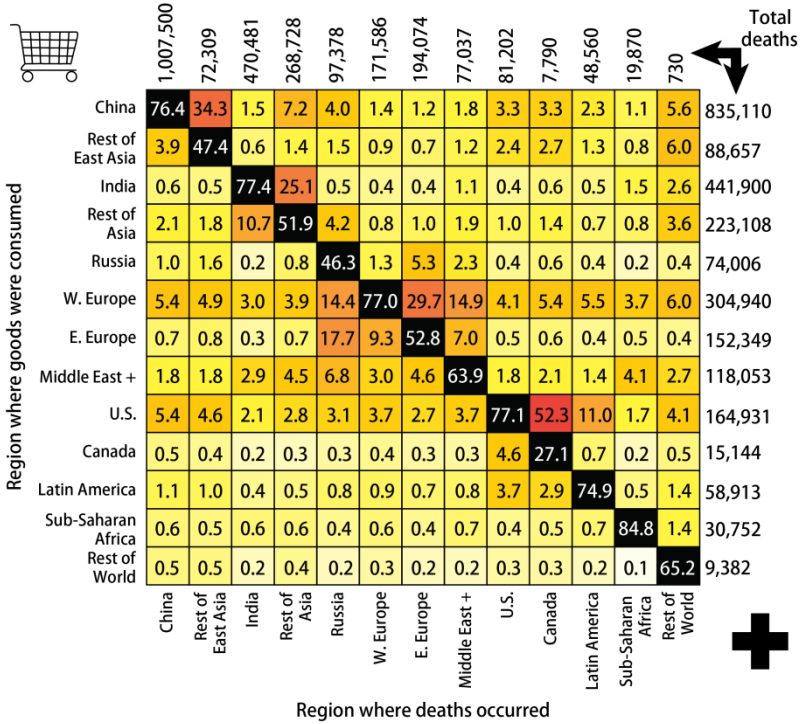
Lin et al., 2016, Nature Geoscience

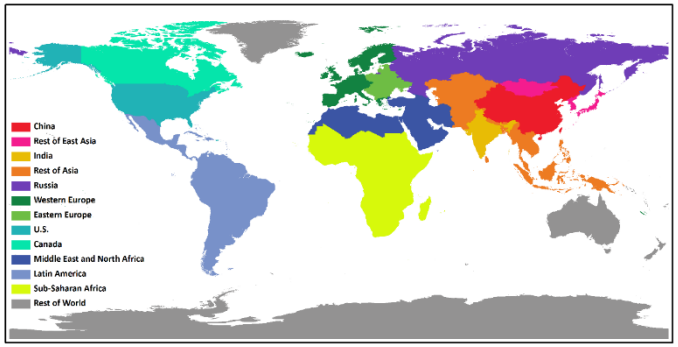
Transport and Trade are Related to Large Deaths

Production Perspective



Consumption Perspective



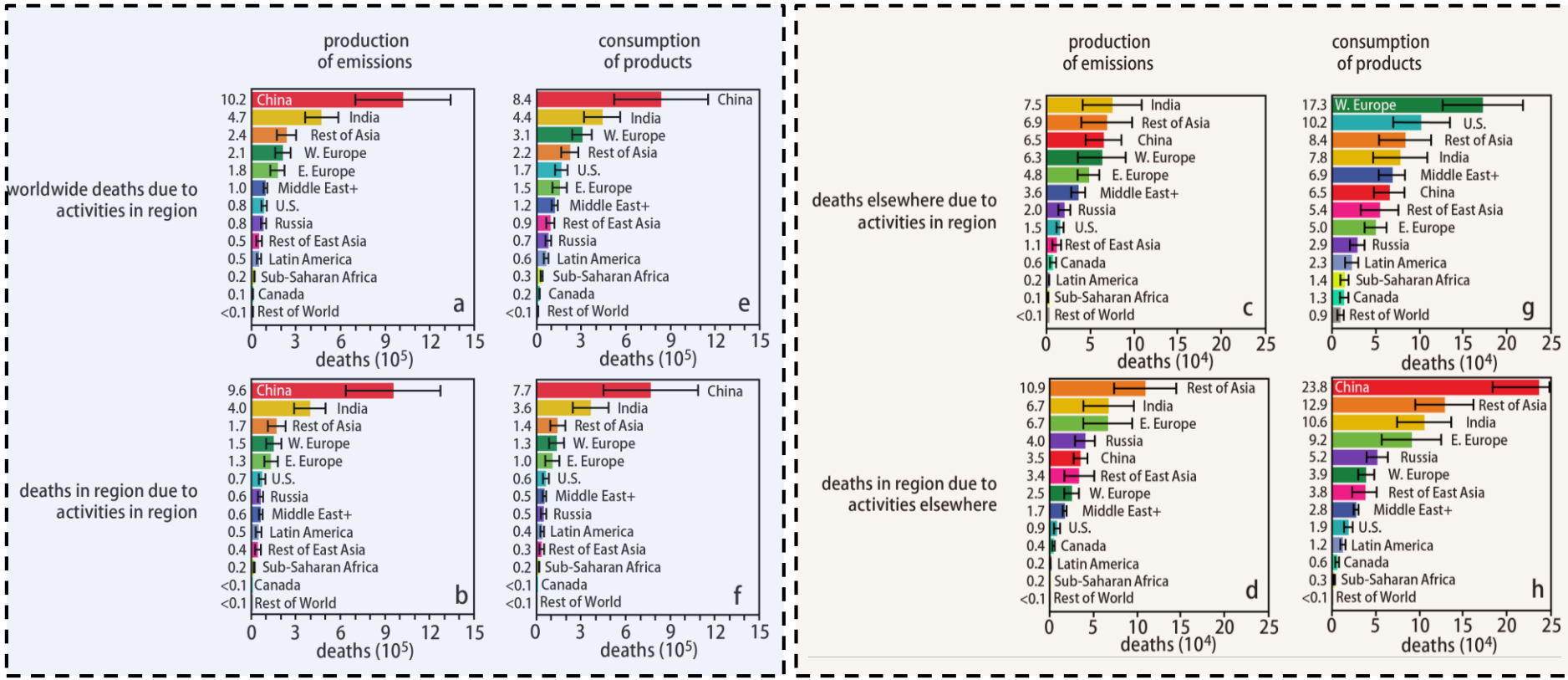


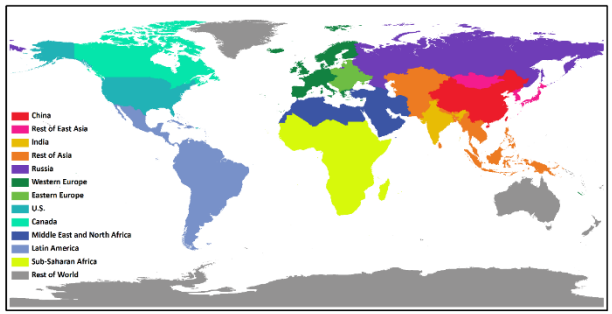
Zhang et al., 2017, Nature

Transport and Trade are Related to Large Deaths

Local as "source"

Local as "receptor"





Zhang et al., 2017, Nature