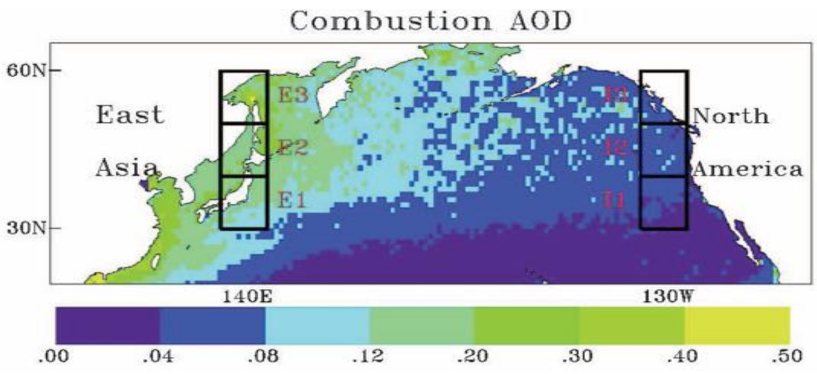
Chapter 8

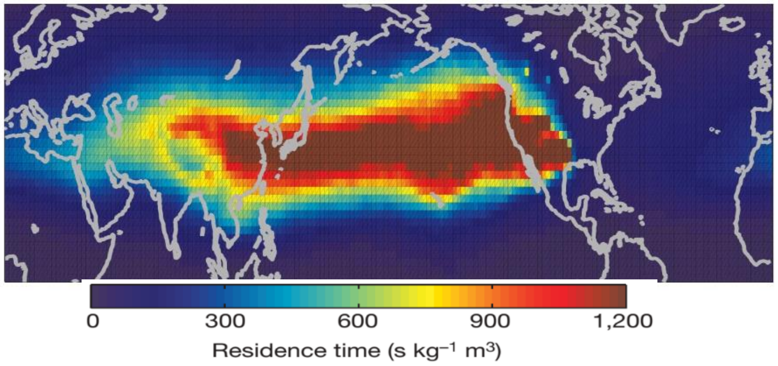
Economic Globalization, Trade and Pollution Transfer

Atmospheric Transport of Chinese Pollution

Yu et al., 2012, Science:

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



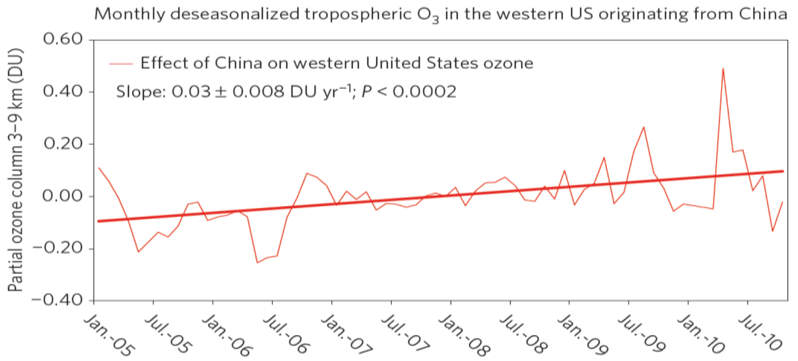


Cooper et al., 2010, Nature:

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

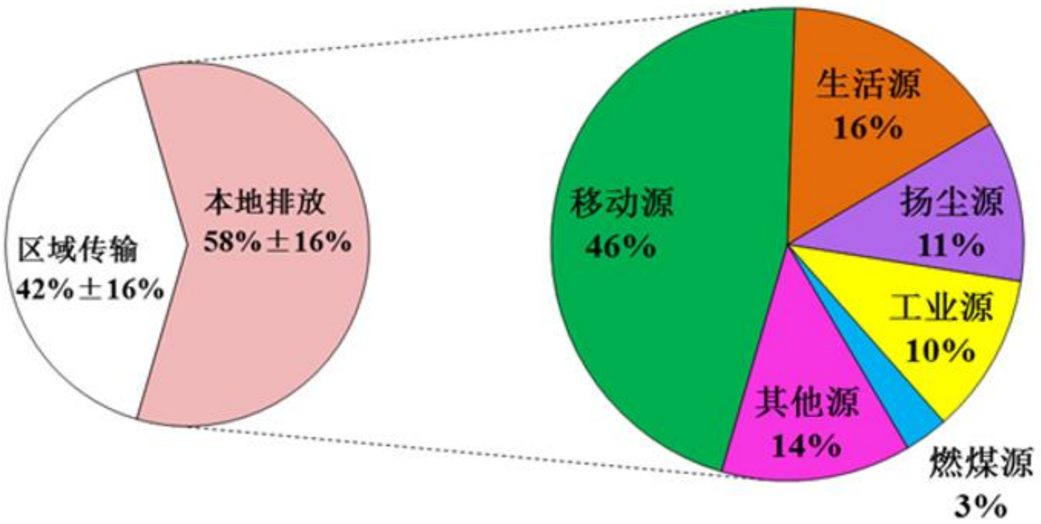
Verstraeten et al., 2015, Nat. Geos.:

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

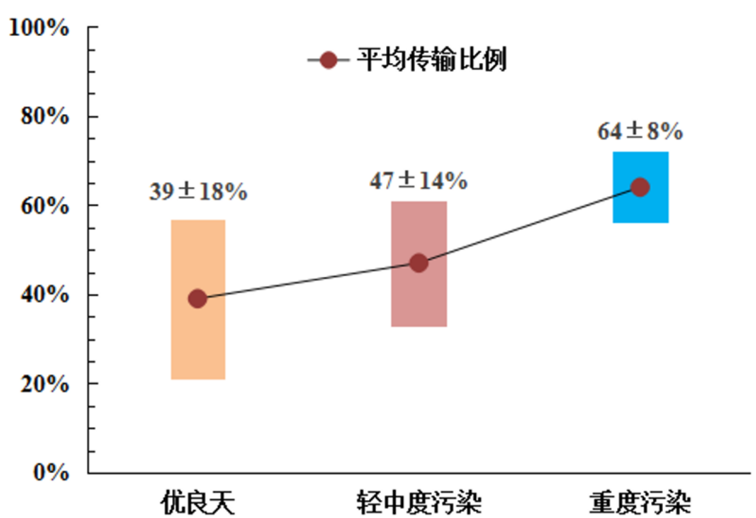


Increasing Role of Atmospheric Transport to Beijing's $PM_{2.5}$

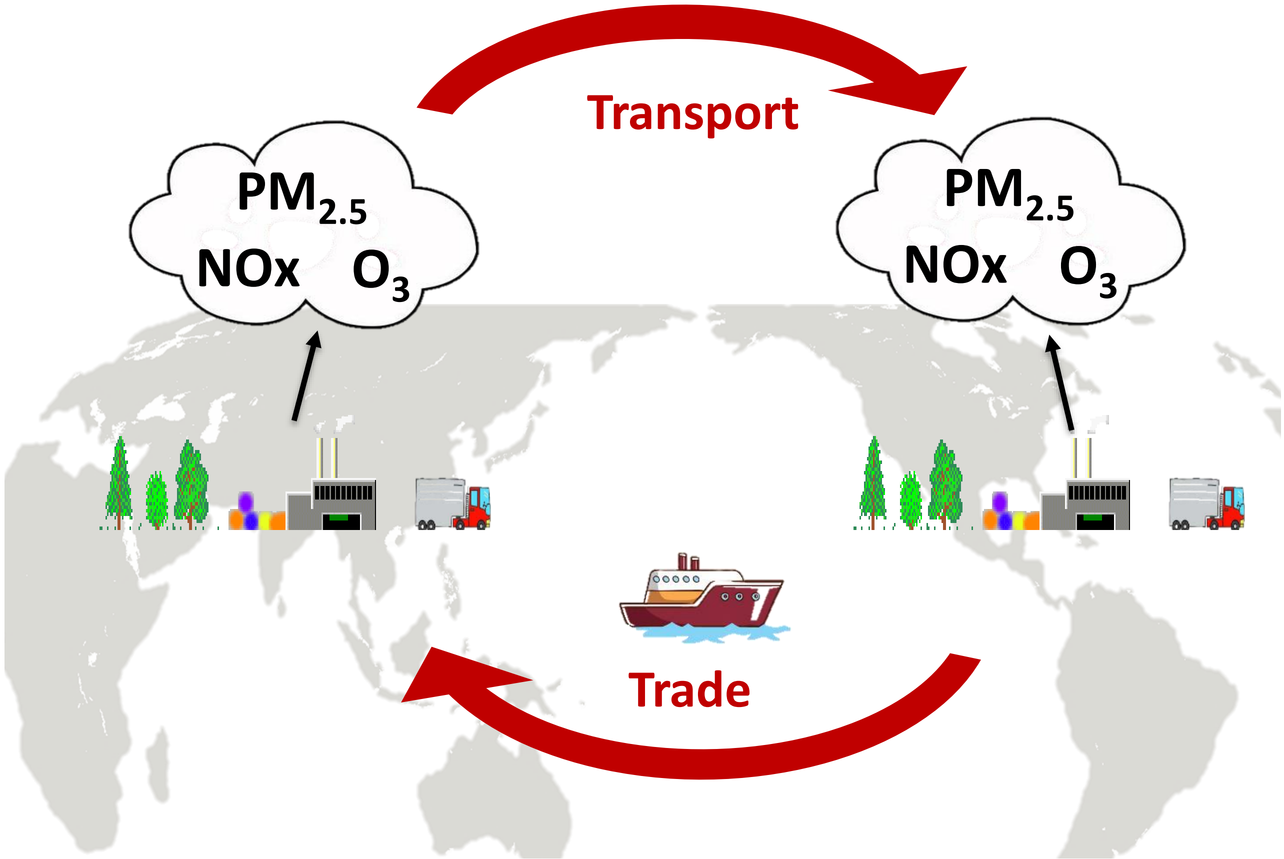
Sources of Beijing's $PM_{2.5}$ (北京市生态环境局，2021)



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

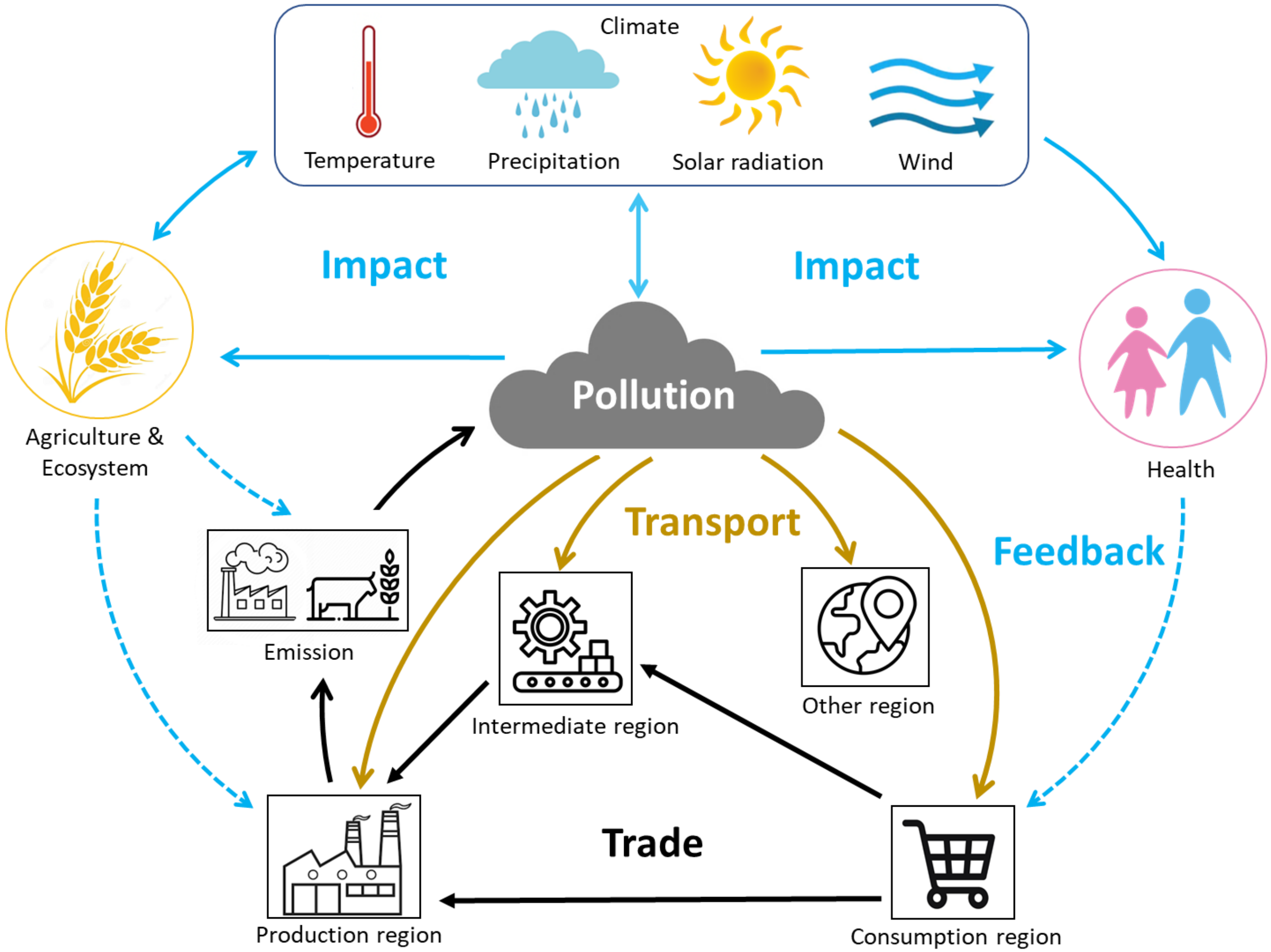


Globalizing Air Pollution
via Atmospheric Transport, Economic Trade and Their Synergy



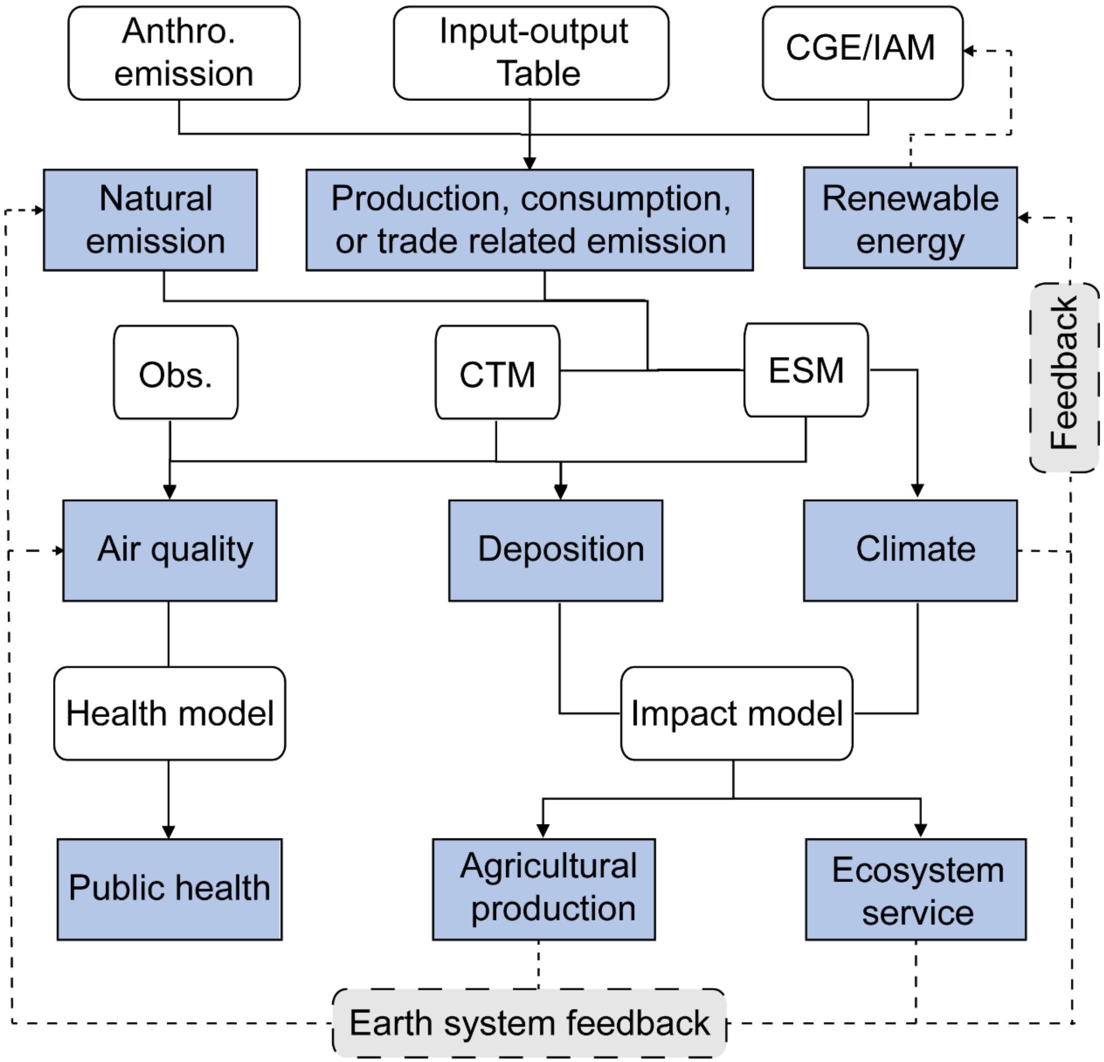
Lin JT et al., PNAS 2014; Lin JT et al., Nature Geoscience 2016
Zhang Q et al., Nature 2017; Lin JT et al., Nature Comm. 2019
Wang JX et al., Science Bulletin, 2019; Lin JT et al., Nature Geoscience, 2022
Chen LL et al., Science Bulletin, 2022; Xu JW et al., ACP, 2023, Highlight Paper
Kong H et al.,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

Globalizing Air Pollution



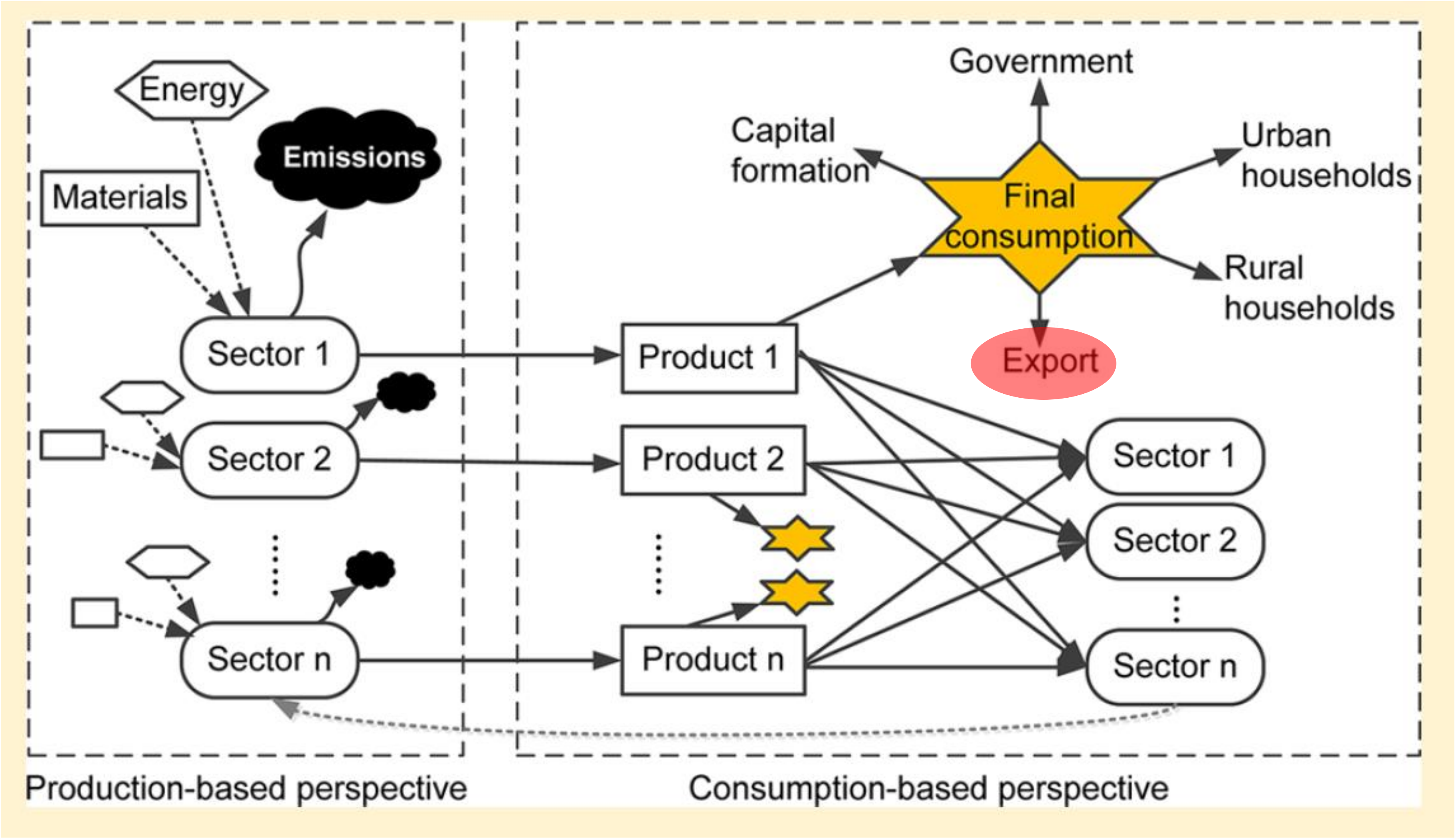
Lin et al., under review

An Interdisciplinary Approach to Calculating Globalizing Air Pollution



Lin et al., under review

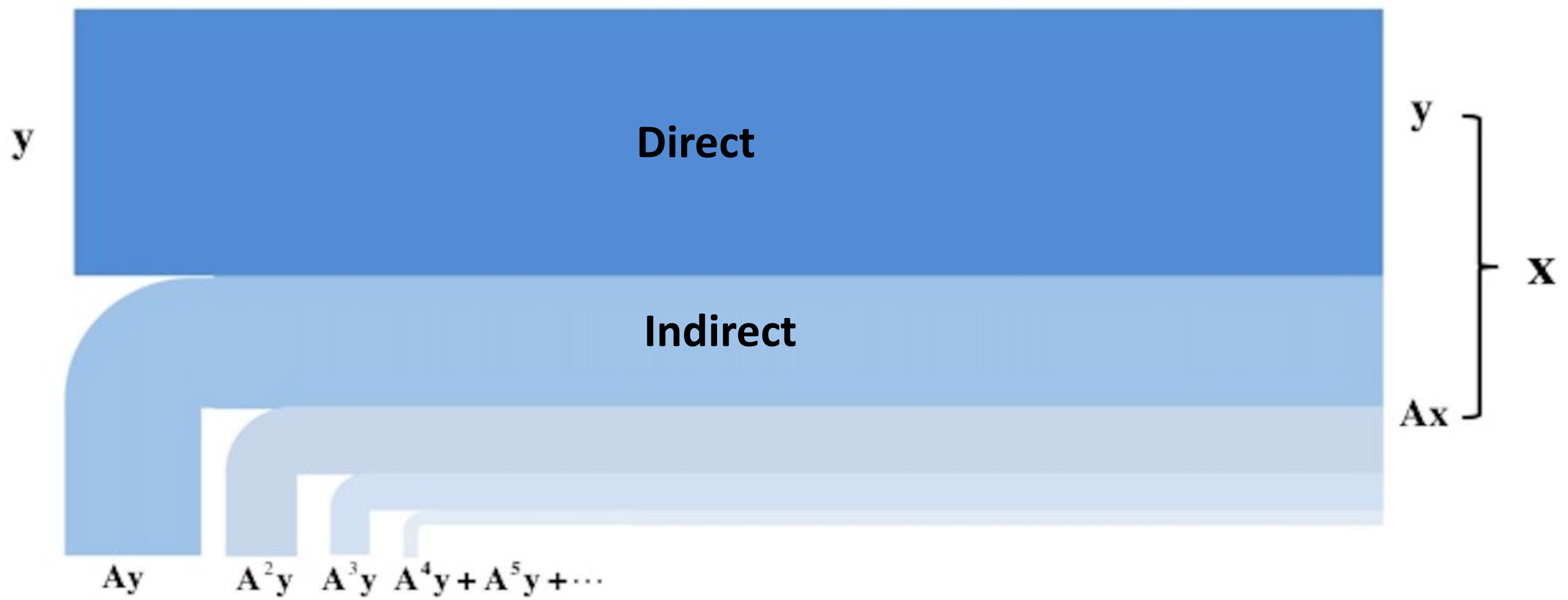
Emissions Associated with Production, Consumption & Trade



Huo et al., 2014

Production, Final Consumption, Intermediate Consumption

Structure Path Analysis



$$\begin{aligned} \boldsymbol{X} &= \overset{1}{\boldsymbol{Y}} + \overset{2}{\mathbf{A}\boldsymbol{Y}} + \overset{3}{\mathbf{A}^2\boldsymbol{Y}} + \overset{4}{\mathbf{A}^3\boldsymbol{Y}} + \overset{5}{\mathbf{A}^4\boldsymbol{Y}} + \cdots \\ &= \left(\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \mathbf{A}^4 + \cdots\right)\boldsymbol{Y} \\ &= (\mathbf{I} - \mathbf{A})^{-1}\boldsymbol{Y} \end{aligned}$$

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

Source: Da Pan

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 input	x_1	....	x_n						

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

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

n x n matrix

$$\mathbf{Z} = \mathbf{A} \circ [\boldsymbol{X}, \boldsymbol{X}, \dots, \boldsymbol{X}]^{\mathbf{T}}$$

Export

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

Import

Domestic output

For intermediate use (domestic + import)

For 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:

$$
\begin{aligned}
\boldsymbol{X} &= \mathbf{A}\boldsymbol{X} + \boldsymbol{C} + \boldsymbol{E} - \boldsymbol{M} \\
&= \left(\mathbf{A}^{\mathrm{d}} + \mathbf{A}^{\mathrm{m}}\right)\boldsymbol{X} + \left(\boldsymbol{C}^{\mathrm{d}} + \boldsymbol{C}^{\mathrm{m}}\right) + \boldsymbol{E} - \boldsymbol{M} \\
&= \mathbf{A}^{\mathrm{d}}\boldsymbol{X} + \boldsymbol{C}^{\mathrm{d}} + \boldsymbol{E} \\
&= \underbrace{\left(\mathbf{I} - \mathbf{A}^{\mathrm{d}}\right)^{-1}\boldsymbol{C}^{\mathrm{d}}}_{\text{Domestic output for domestic cons.}} + \underbrace{\left(\mathbf{I} - \mathbf{A}^{\mathrm{d}}\right)^{-1}\boldsymbol{E}}_{\text{Domestic output for export}}
\end{aligned}
$$

Emissions Embodied in Export Based on Bilateral Trade

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

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

Total output: $\boldsymbol{X}$

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

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:

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

Emissions avoided by import:

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

Emissions embedded in import:

Rough approximation

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

Emissions embedded in net trade:

$$EET = EEE - EEI$$

Lin et al., 2014, PNAS

Multi-Regional Input-Output Analysis

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

$$\begin{bmatrix} \boldsymbol{x}^1 \\ \boldsymbol{x}^2 \\ \boldsymbol{x}^3 \\ \vdots \\ \boldsymbol{x}^m \end{bmatrix} = \begin{bmatrix} \mathbf{A}^{1,1} & \mathbf{A}^{1,2} & \mathbf{A}^{1,3} & \dots & \mathbf{A}^{1,m} \\ \mathbf{A}^{2,1} & \mathbf{A}^{2,2} & \mathbf{A}^{2,3} & \dots & \mathbf{A}^{2,m} \\ \mathbf{A}^{3,1} & \mathbf{A}^{3,2} & \mathbf{A}^{3,3} & \dots & \mathbf{A}^{3,m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}^{m,1} & \mathbf{A}^{m,2} & \mathbf{A}^{m,3} & \dots & \mathbf{A}^{m,m} \end{bmatrix} \begin{bmatrix} \boldsymbol{x}^1 \\ \boldsymbol{x}^2 \\ \boldsymbol{x}^3 \\ \vdots \\ \boldsymbol{x}^m \end{bmatrix} + \begin{bmatrix} \Sigma_s \boldsymbol{y}^{1,s} \\ \Sigma_s \boldsymbol{y}^{2,s} \\ \Sigma_s \boldsymbol{y}^{3,s} \\ \vdots \\ \Sigma_s \boldsymbol{y}^{m,s} \end{bmatrix}$$

$$\boldsymbol{x}^r = \mathbf{A}^{r,r}\boldsymbol{x}^r + \boldsymbol{y}^{r,r} + \sum_{s \neq r} (\mathbf{A}^{r,s}\boldsymbol{x}^s + \boldsymbol{y}^{r,s})$$

$$x_i^r = \sum_j \left(\mathrm{A}_{i,j}^{r,r} x_j^r + y_j^{r,r}\right) + \sum_{s \neq r} \sum_j \left(\mathrm{A}_{i,j}^{r,s} x_j^s + y_j^{r,s}\right)$$

- **An example of global supply chain:**
  - Country: China: 1, Japan: 2, US: 3
  - Sector: crude oil: 1; gasoline: 2; transportation: 3
  - $\boldsymbol{y}^{r,s}$: final demand (consumption)

Multi-Regional Input-Output Analysis

Multi-Regional Input-Output Table (2 regions and n sectors)

		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	$z^{1,1}_{1,1}$	....	$z^{1,1}_{1,n}$	$z^{1,2}_{1,1}$	....	$z^{1,2}_{1,n}$	$y^{1,1}_{1}$	$y^{1,2}_{1}$	x^{1}_{1}
		....	....	....	....	....	....	....	....	....
		$z^{1,1}_{n,1}$	....	$z^{1,1}_{n,n}$	$z^{1,2}_{n,1}$	....	$z^{1,2}_{n,n}$	$y^{1,1}_{n}$	$y^{1,2}_{n}$	x^{1}_{n}
	Region 2	$z^{2,1}_{1,1}$	....	$z^{2,1}_{1,n}$	$z^{22}_{1,1}$	....	$z^{2,2}_{1,n}$	$y^{2,1}_{1}$	$y^{2,2}_{1}$	x^{2}_{1}
		....	....	....	....	....	....	....	....	....
		$z^{2,1}_{n,1}$	....	$z^{2,1}_{n,n}$	$z^{2,2}_{n,1}$	....	$z^{2,2}_{n,n}$	$y^{2,1}_{n}$	$y^{2,2}_{n}$	x^{2}_{n}
Value added		v^{1}_{1}	....	v^{1}_{n}	v^{2}_{1}	....	v^{2}_{n}			
Total input		x^{1}_{1}	....	x^{1}_{n}	x^{2}_{1}	....	x^{2}_{n}			

For a total of m regions and n sectors:

$$x_i^r = \sum_{s=1}^{m} \sum_{j=1}^{n} z_{i,j}^{r,s} + \sum_{s=1}^{m} y_i^{r,s}$$

$$A_{i,j}^{r,s} = z_{i,j}^{r,s} / x_j^s$$

Multi-Regional Input-Output Analysis of Emissions

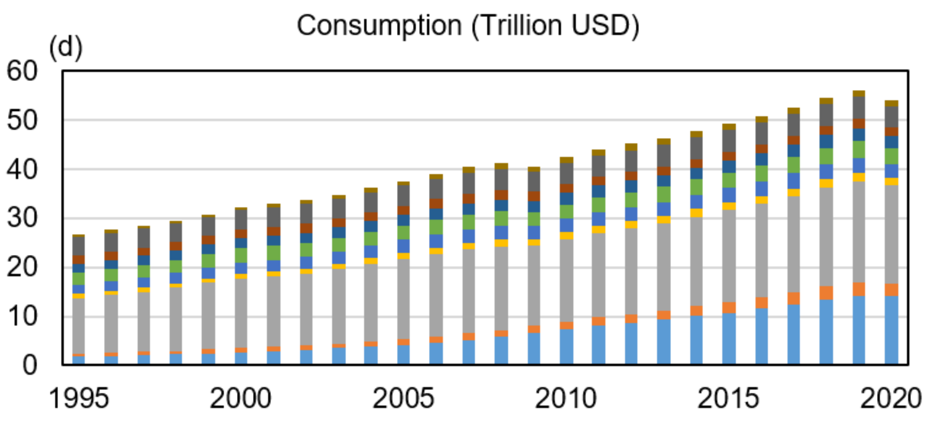
$$\boldsymbol{x} = \begin{bmatrix} \boldsymbol{x}^1 \\ \boldsymbol{x}^2 \\ \boldsymbol{x}^3 \\ \vdots \\ \boldsymbol{x}^m \end{bmatrix} = \begin{bmatrix} \mathbf{A}^{1,1} & \mathbf{A}^{1,2} & \mathbf{A}^{1,3} & \dots & \mathbf{A}^{1,m} \\ \mathbf{A}^{2,1} & \mathbf{A}^{2,2} & \mathbf{A}^{2,3} & \dots & \mathbf{A}^{2,m} \\ \mathbf{A}^{3,1} & \mathbf{A}^{3,2} & \mathbf{A}^{3,3} & \dots & \mathbf{A}^{3,m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}^{m,1} & \mathbf{A}^{m,2} & \mathbf{A}^{m,3} & \dots & \mathbf{A}^{m,m} \end{bmatrix} \begin{bmatrix} \boldsymbol{x}^1 \\ \boldsymbol{x}^2 \\ \boldsymbol{x}^3 \\ \vdots \\ \boldsymbol{x}^m \end{bmatrix} + \begin{bmatrix} \boldsymbol{\Sigma}_s \boldsymbol{y}^{1,s} \\ \boldsymbol{\Sigma}_s \boldsymbol{y}^{2,s} \\ \boldsymbol{\Sigma}_s \boldsymbol{y}^{3,s} \\ \vdots \\ \boldsymbol{\Sigma}_s \boldsymbol{y}^{m,s} \end{bmatrix}$$

$$= \left(\mathbf{I} - \begin{bmatrix} \mathbf{A}^{1,1} & \mathbf{A}^{1,2} & \mathbf{A}^{1,3} & \dots & \mathbf{A}^{1,m} \\ \mathbf{A}^{2,1} & \mathbf{A}^{2,2} & \mathbf{A}^{2,3} & \dots & \mathbf{A}^{2,m} \\ \mathbf{A}^{3,1} & \mathbf{A}^{3,2} & \mathbf{A}^{3,3} & \dots & \mathbf{A}^{3,m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}^{m,1} & \mathbf{A}^{m,2} & \mathbf{A}^{m,3} & \dots & \mathbf{A}^{m,m} \end{bmatrix} \right)^{-1} \times \begin{bmatrix} \boldsymbol{\Sigma}_s \boldsymbol{y}^{1,s} \\ \boldsymbol{\Sigma}_s \boldsymbol{y}^{2,s} \\ \boldsymbol{\Sigma}_s \boldsymbol{y}^{3,s} \\ \vdots \\ \boldsymbol{\Sigma}_s \boldsymbol{y}^{m,s} \end{bmatrix}$$

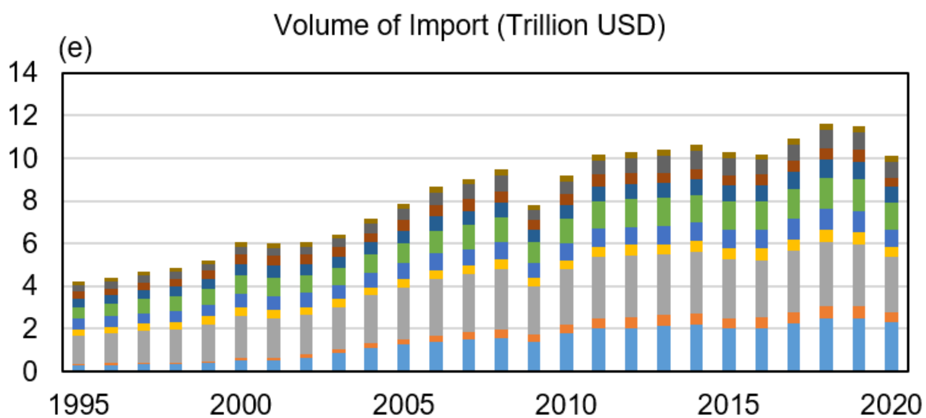
$$\mathbf{F} = \begin{bmatrix} \boldsymbol{F}^1 & 0 & 0 & \dots & 0 \\ 0 & \boldsymbol{F}^2 & 0 & \dots & 0 \\ 0 & 0 & \boldsymbol{F}^3 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & \boldsymbol{F}^m \end{bmatrix} \Rightarrow \boldsymbol{E} = \begin{bmatrix} \boldsymbol{E}^1 \\ \boldsymbol{E}^2 \\ \boldsymbol{E}^3 \\ \vdots \\ \boldsymbol{E}^m \end{bmatrix} = \mathbf{F} \times \boldsymbol{x}$$

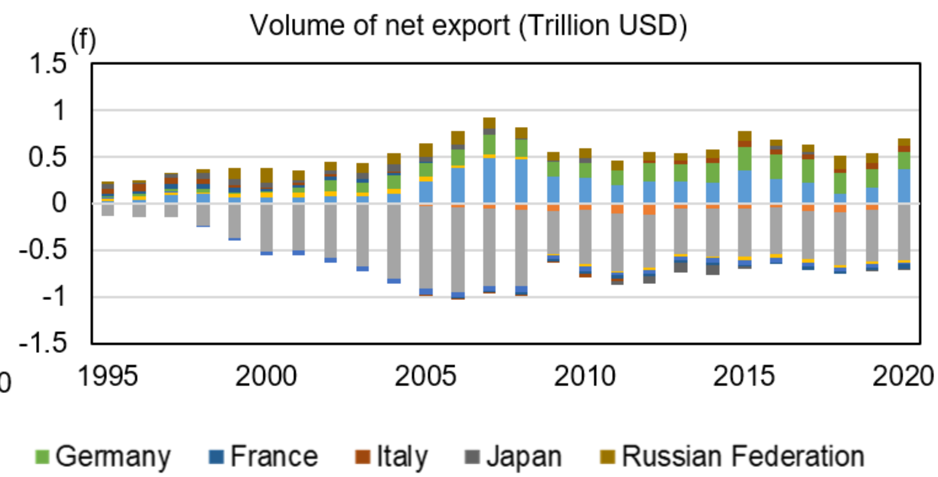
Here, $\boldsymbol{x}^r$, $\boldsymbol{y}^r$, $\boldsymbol{F}^r$ and $\boldsymbol{E}^r$ are vectors (of sectors), and $\mathbf{A}^{r,s}$ is a matrix

Rapid Changes in Trade and Outsourcing



Data source: World Bank



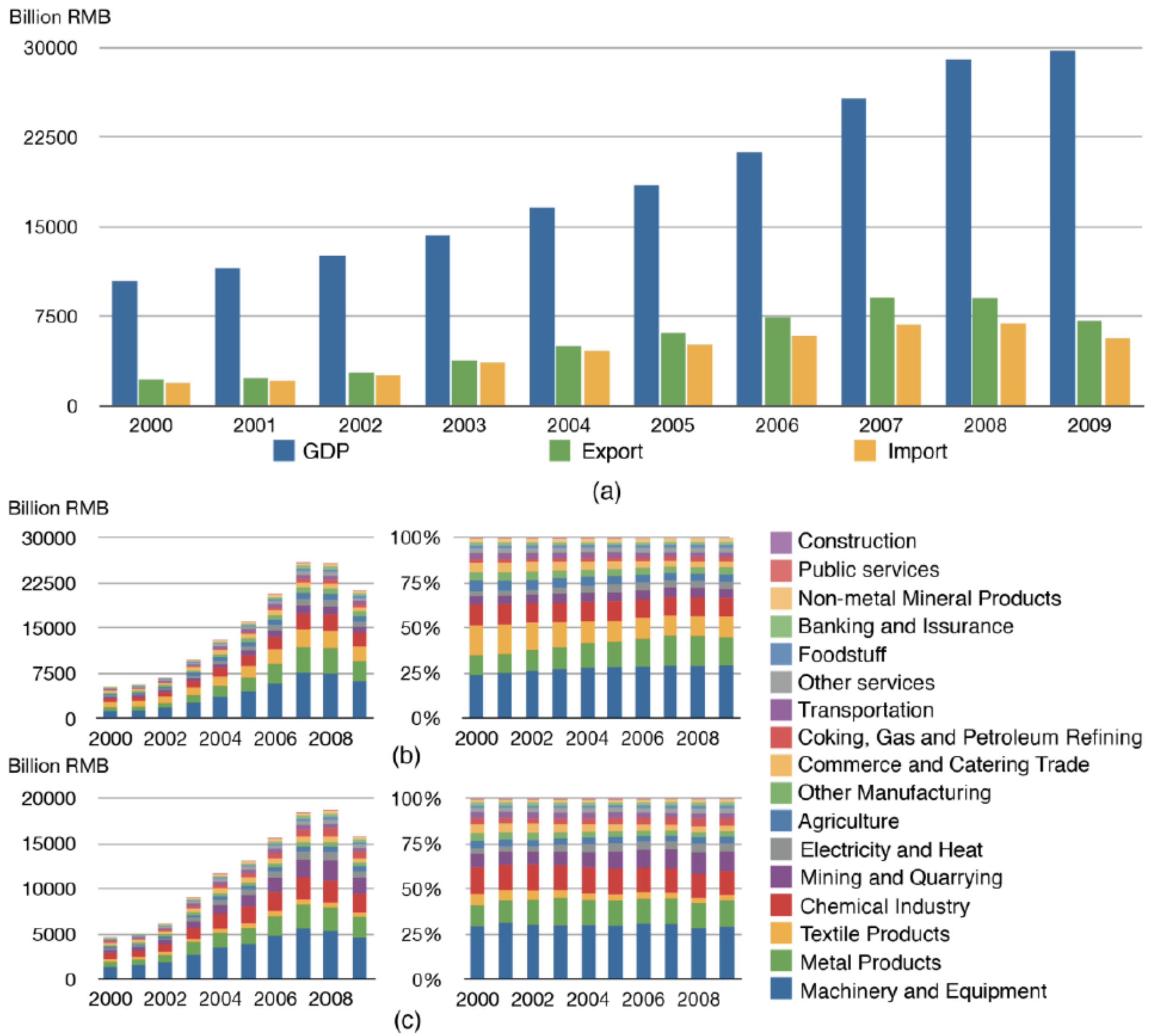


Export, Import and Total GDP of China

GDP
Export
Import

Exported production

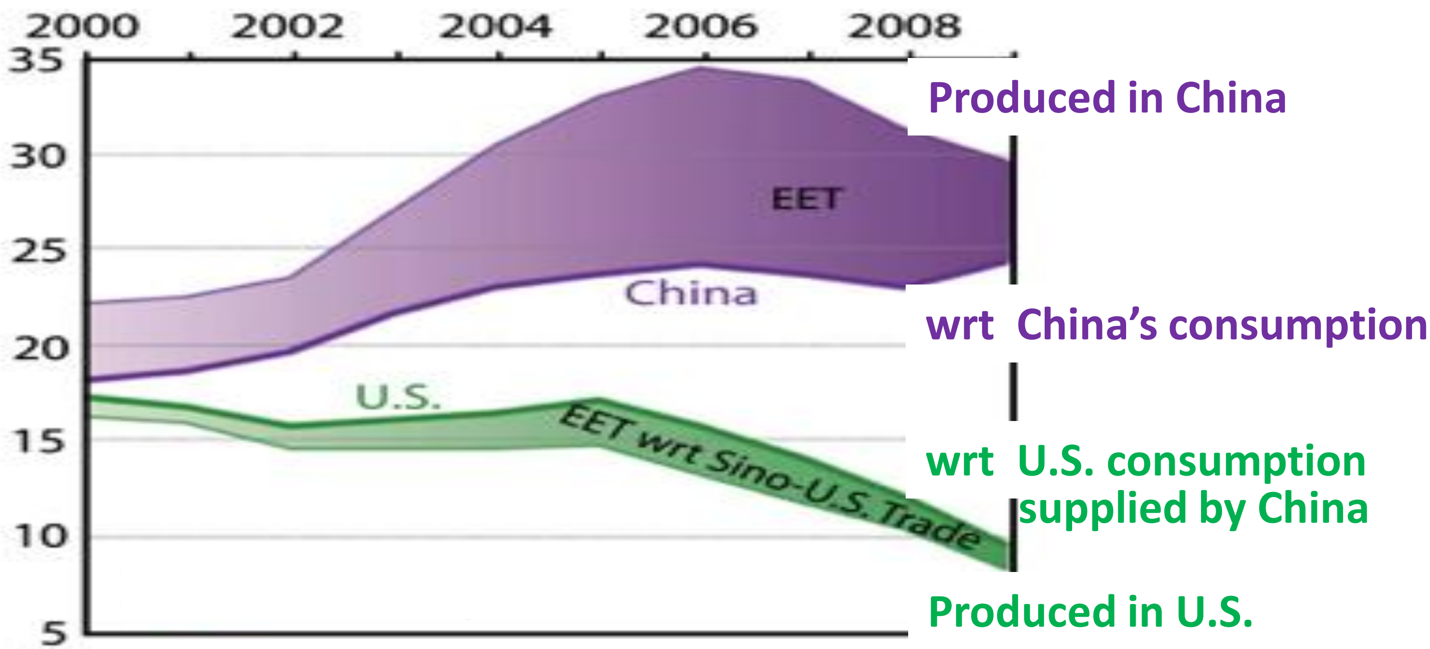
Imported production



Lin et al., 2014, PNAS

Trade Redefines Chinese and U.S. Emissions

SO_2 Emissions (Tg/yr)



- **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

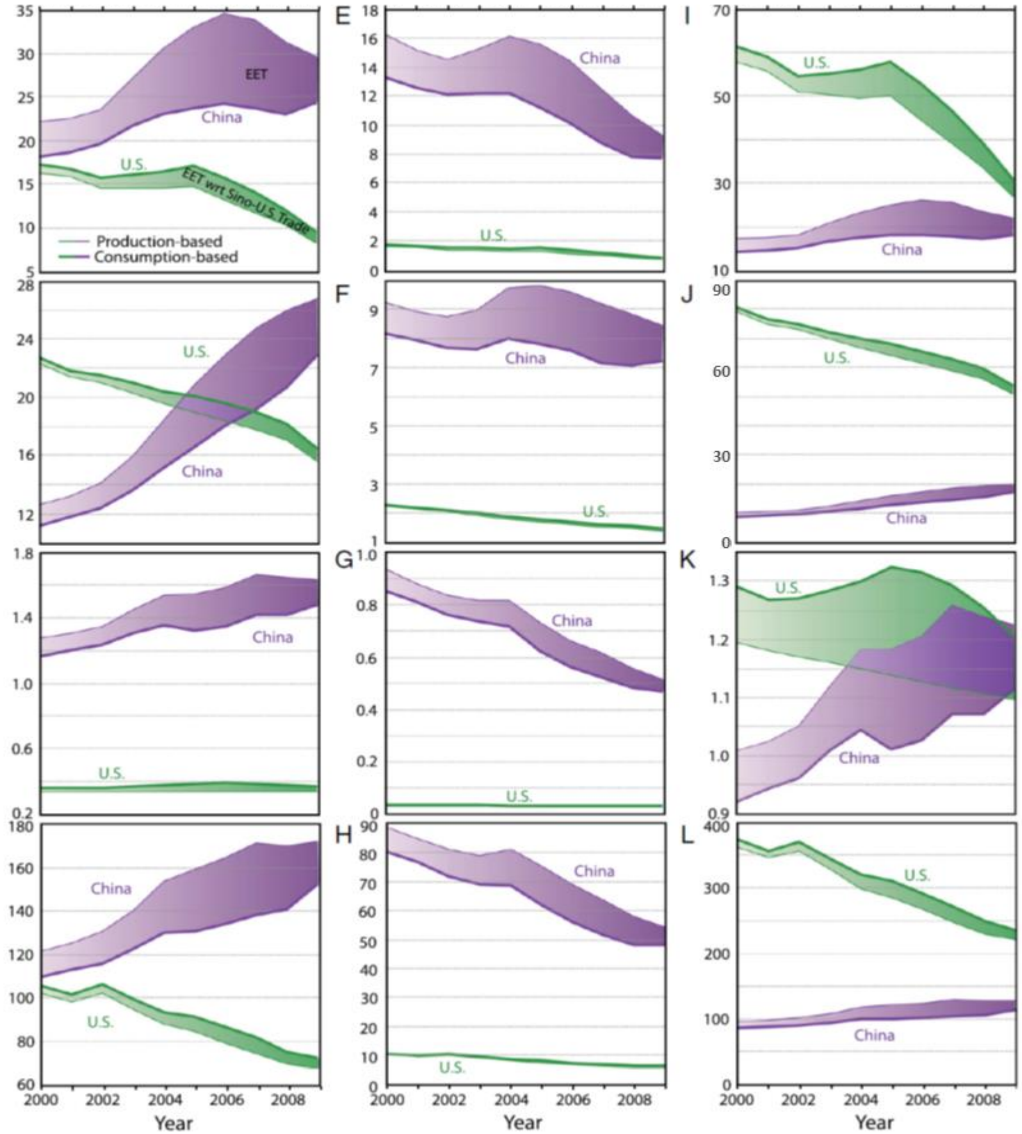
Total Emis **Emis/GDP** **Emis/person**

SO_2

NOx

BC

CO



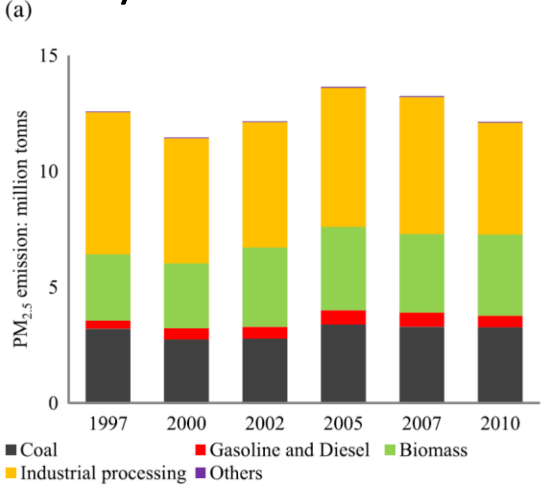
China v.s. US:

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

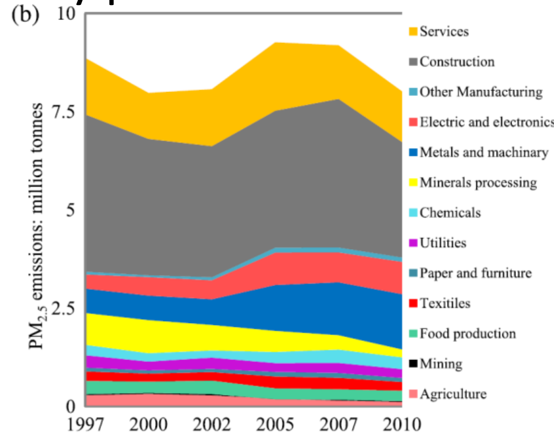
Lin et al., 2014, PNAS

Drivers of China’s $PM_{2.5}$ Emission Growth

By source

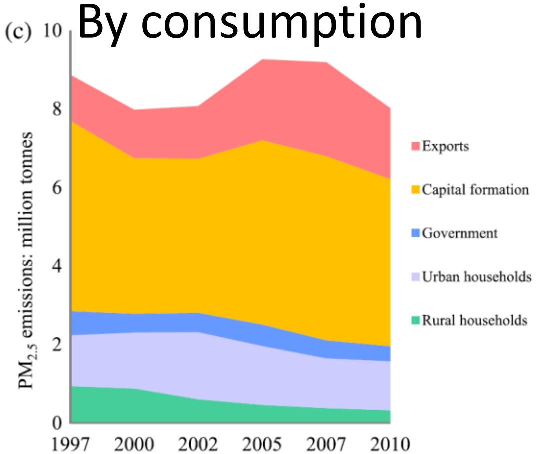


By production

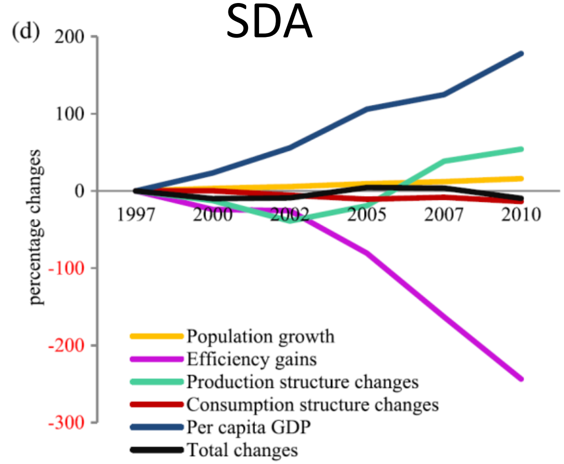


Structural Decomposition Analysis

By consumption



SDA



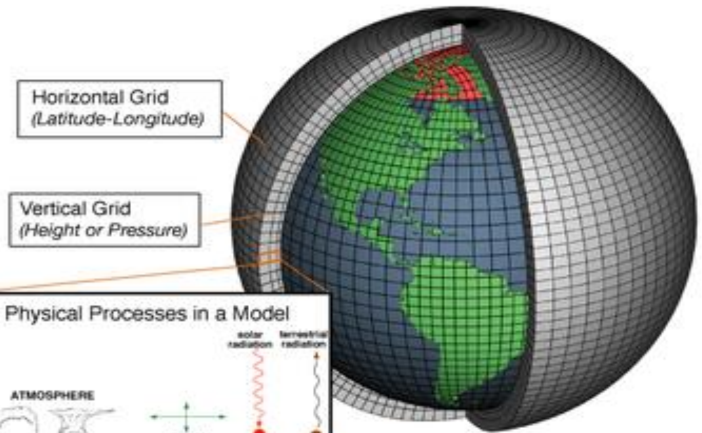
$$PM_{2.5} = p \cdot \mathbf{F} \cdot \mathbf{L} \cdot \mathbf{y_s} \cdot \mathbf{y_v}$$

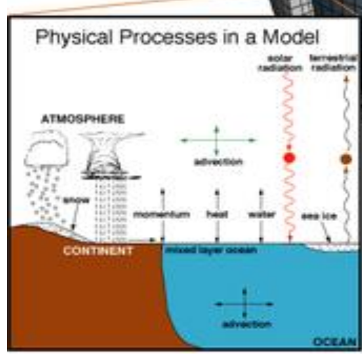
$$\begin{aligned}
\Delta PM_{2.5} &= \Delta PM_{2.5(t)} - \Delta PM_{2.5(t-1)} \\
&= p_{(t)}\mathbf{F}_{(t)}\mathbf{L}_{(t)}\mathbf{y}_{s(t)}\mathbf{y}_{v(t)} \\
&\quad - p_{(t-1)}\mathbf{F}_{(t-1)}\mathbf{L}_{(t-1)}\mathbf{y}_{s(t-1)}y_{v(t-1)} \\
&= \Delta p\mathbf{F}_{(t)}\mathbf{L}_{(t)}\mathbf{y}_{s(t)}y_{v(t)}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

Guan et al., 2014, ERL

Atmospheric Chemical Transport Modeling

$$\frac{\partial C}{\partial t} = \overbrace{E}^{\text{Emis}} - \overbrace{D}^{\text{Dep}} \overbrace{- \underbrace{\nabla \cdot C\boldsymbol{V}}_{\text{Grid-resolved}} - \underbrace{\nabla \cdot \overline{C'\boldsymbol{V}'}}_{\text{Unresolved}}}^{\text{Transport \& Mixing}} + \overbrace{(P - L)}^{\text{Chemistry}}$$





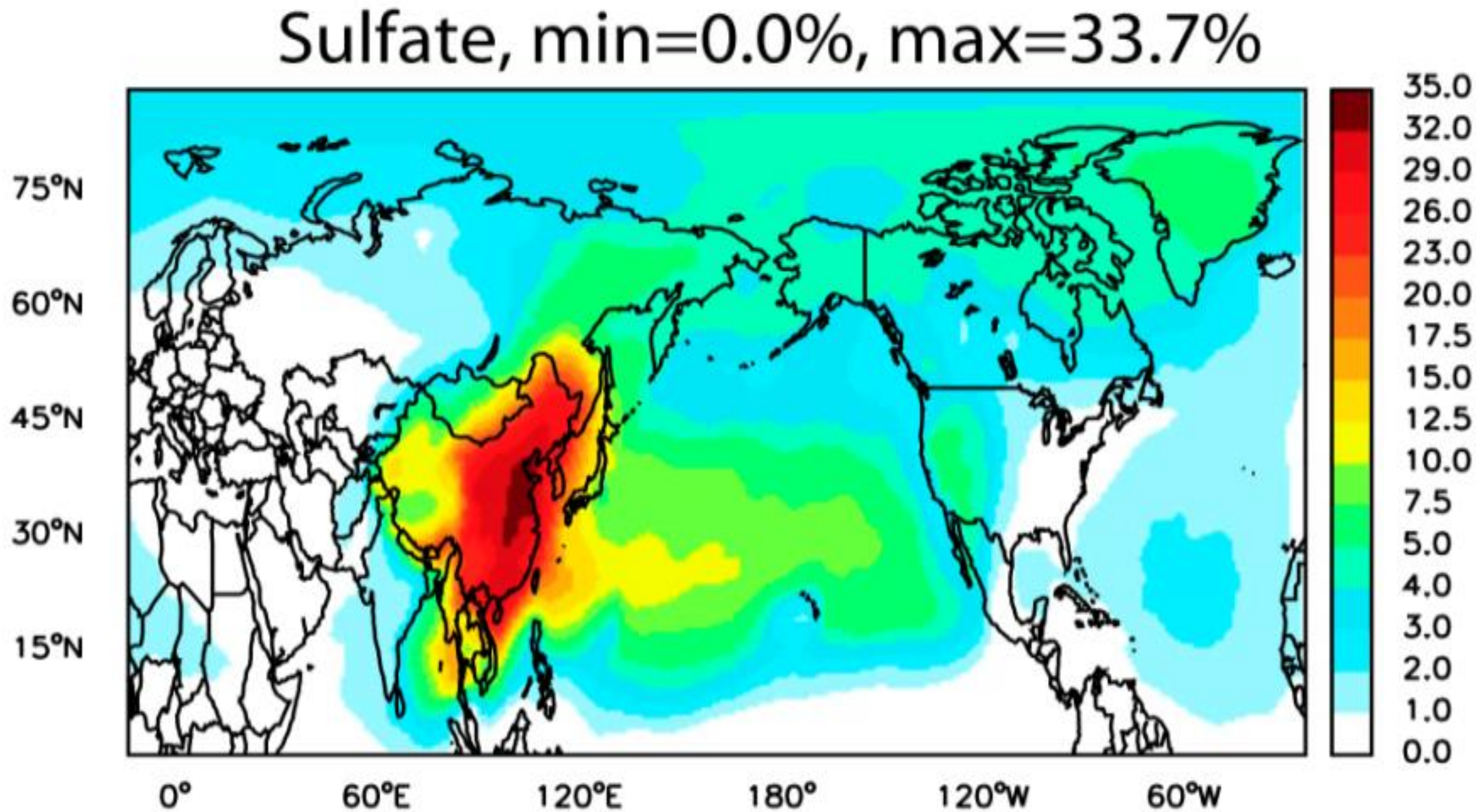
Eulerian Model:
Discrete lon-lat grid

Atmospheric chemical transport models:

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

Export of Goods Contributes to China's Sulfate

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



Lin et al., 2014, PNAS

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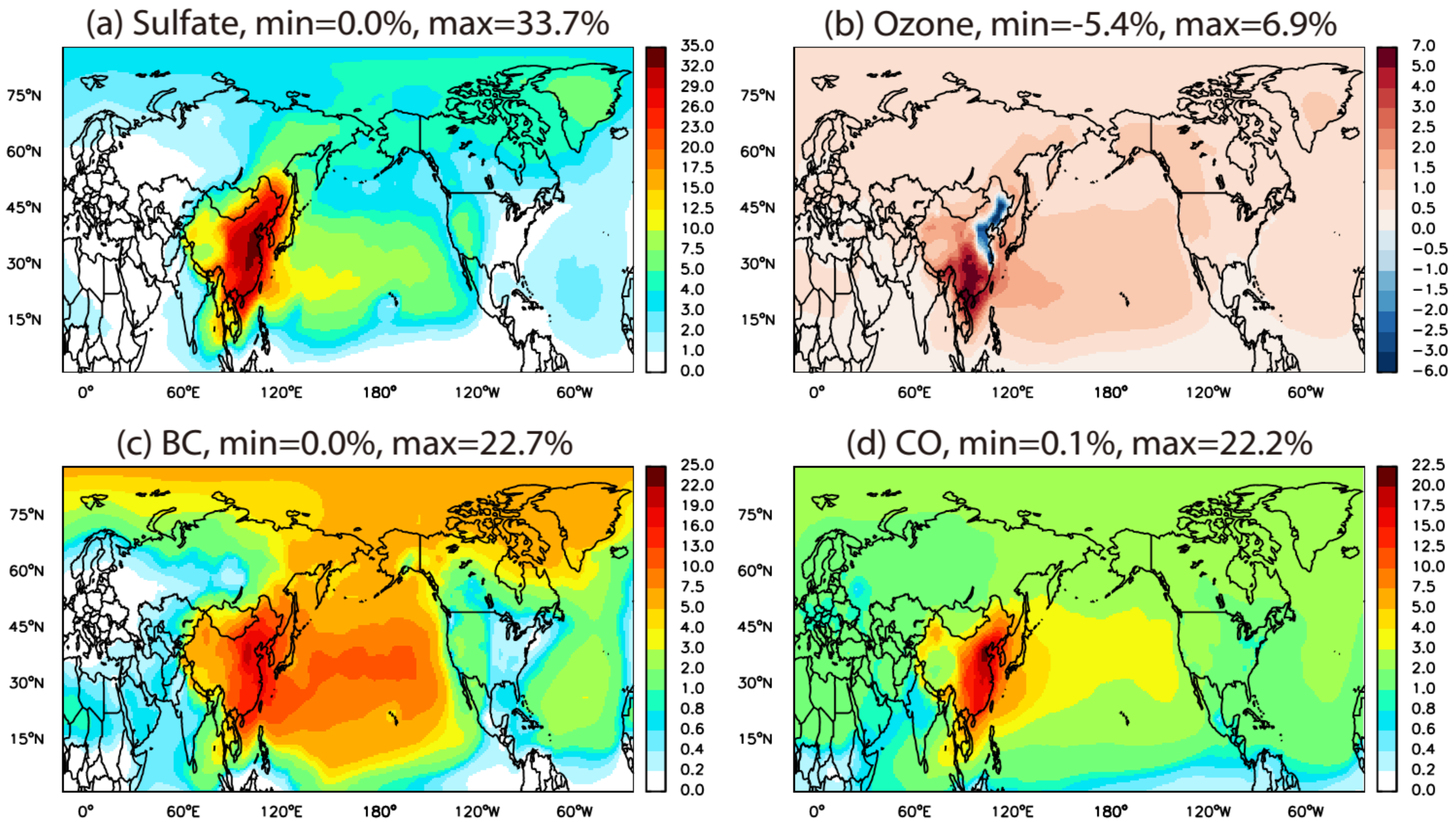
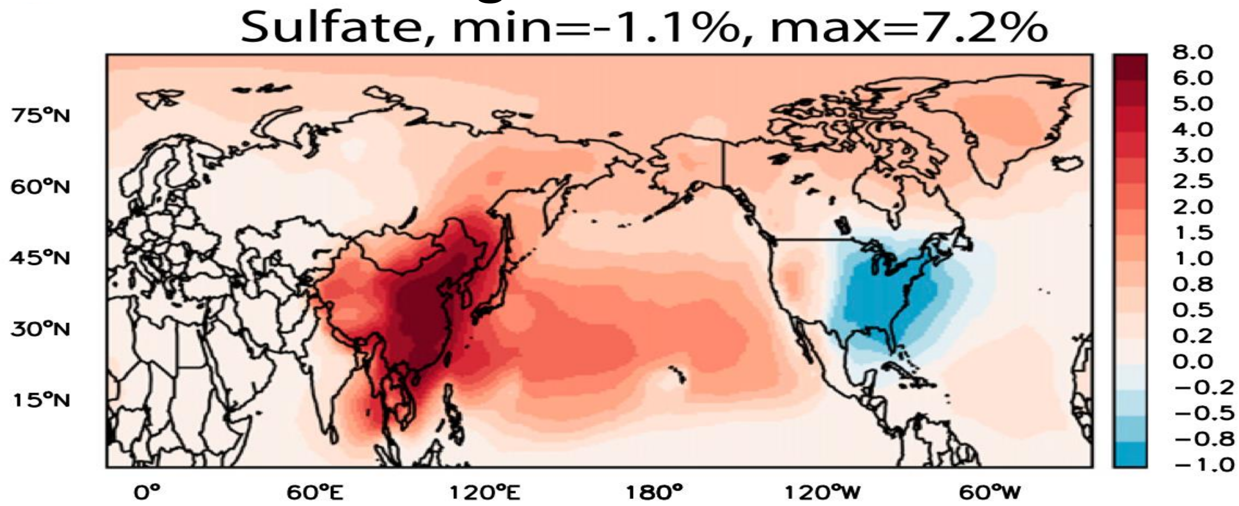


Lin et al., 2014, PNAS

USA Consumption Affects China's Sulfate Pollution

% change in sulfate in 2006



USA imports goods from China versus self-production:

(accounting for differences in emission intensity)

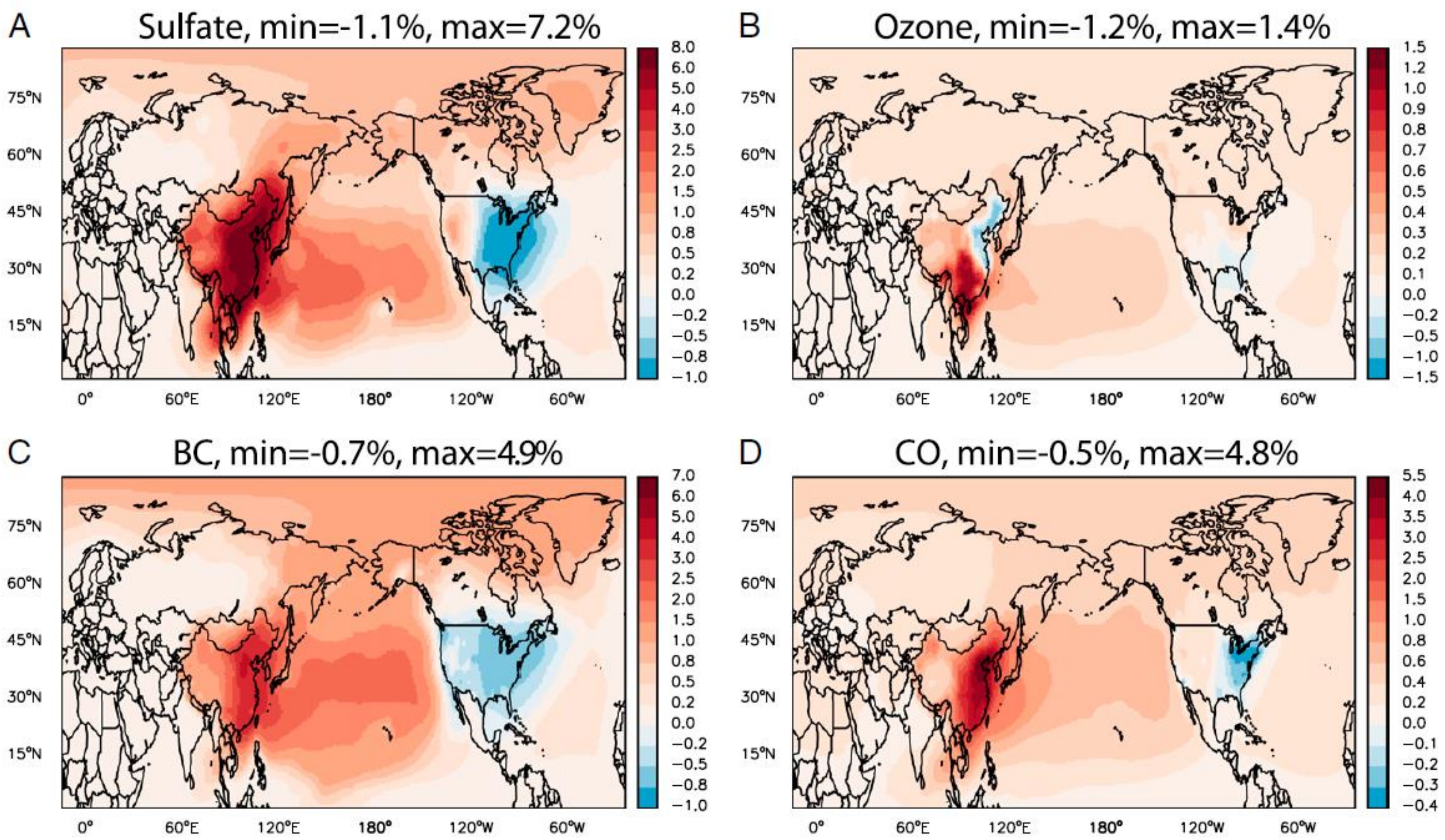
- **Increase sulfate over China**
- **Decrease sulfate over E. USA with reduction over W. USA**

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

Lin et al., 2014, PNAS

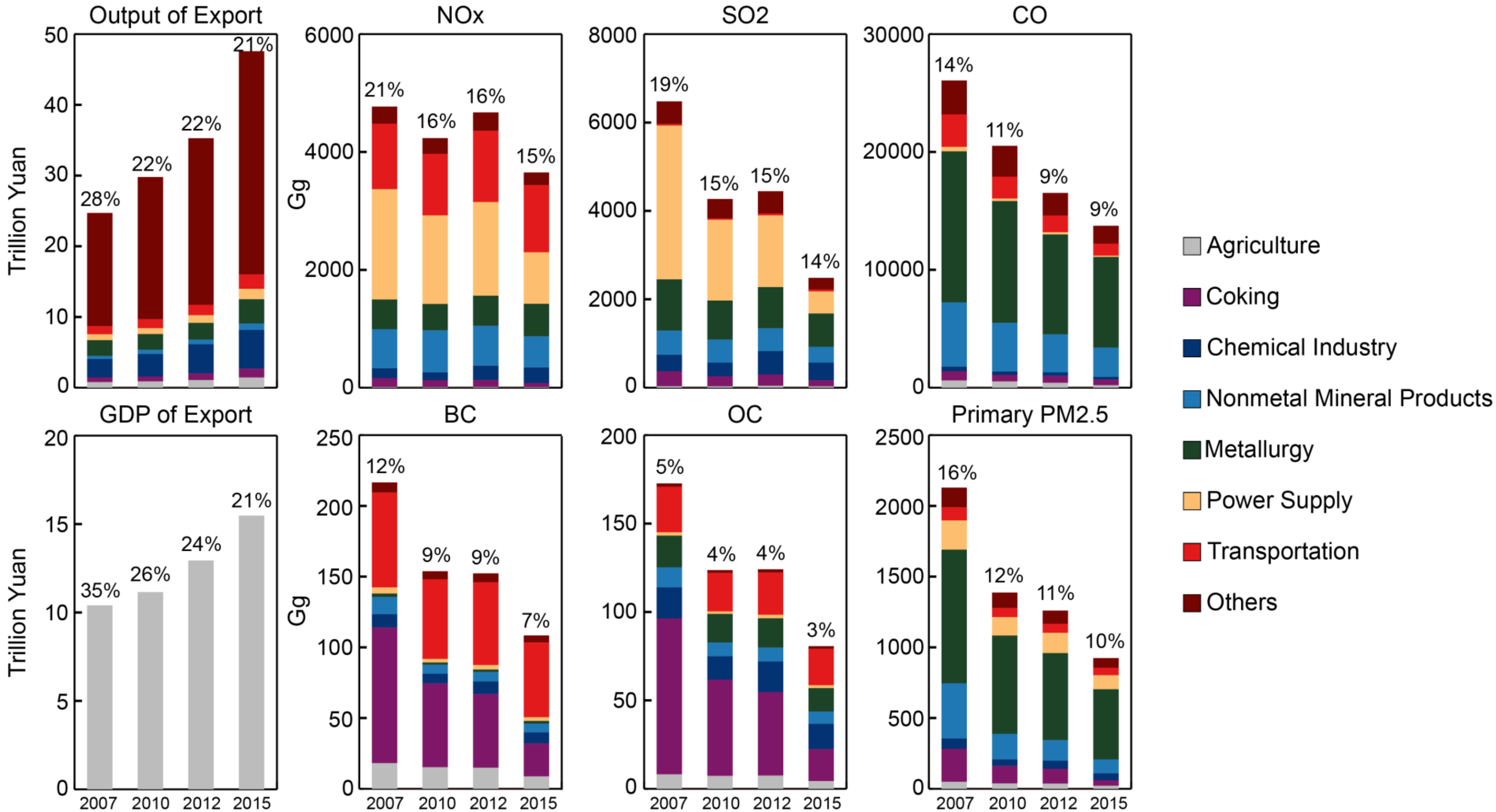
USA Consumption Affects China's Pollution

% change in pollution in 2006



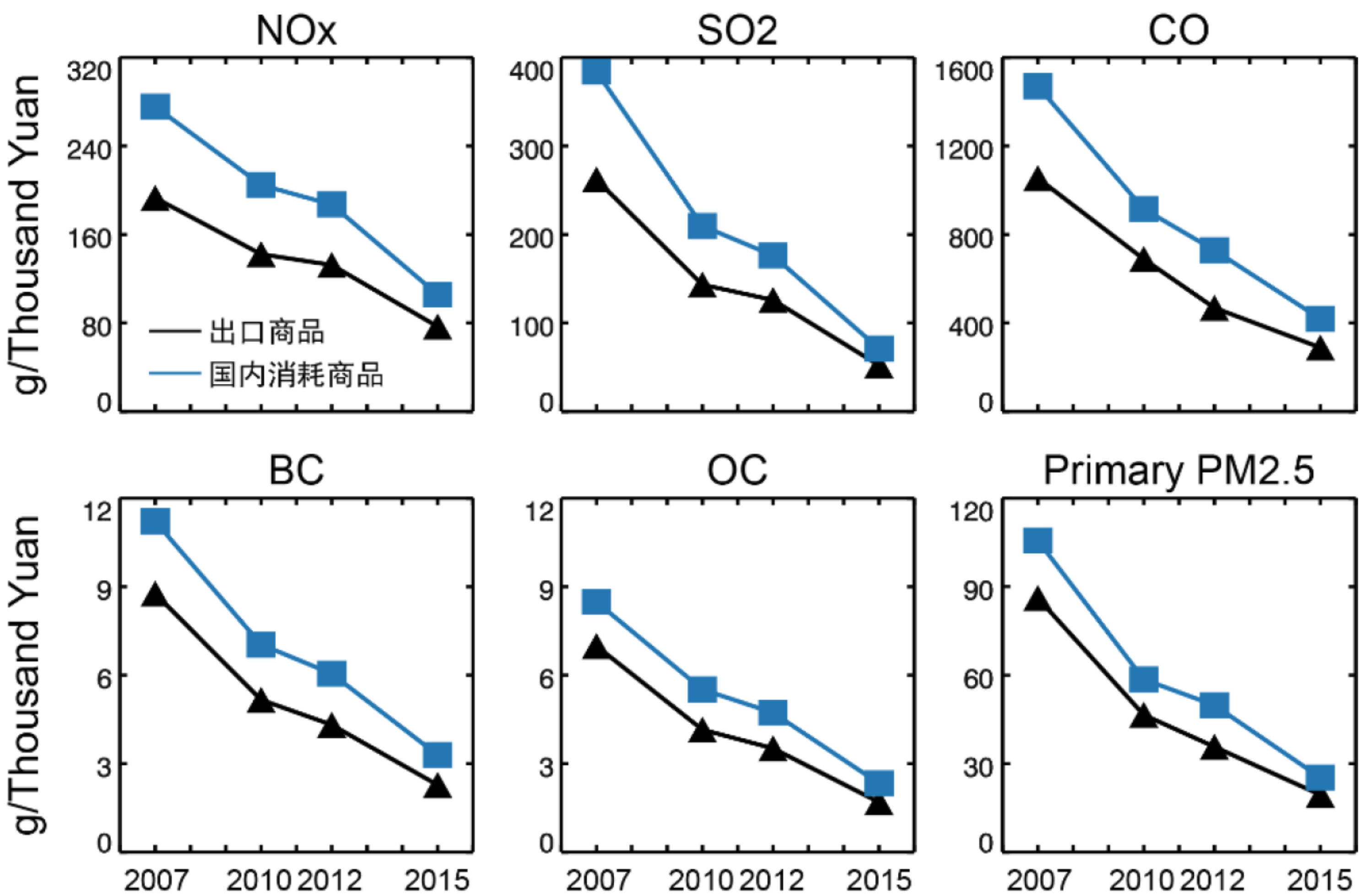
Lin et al., 2014, PNAS

Rapid Changes in China's Emissions Embedded in Export



Ni R.-J. dissertation

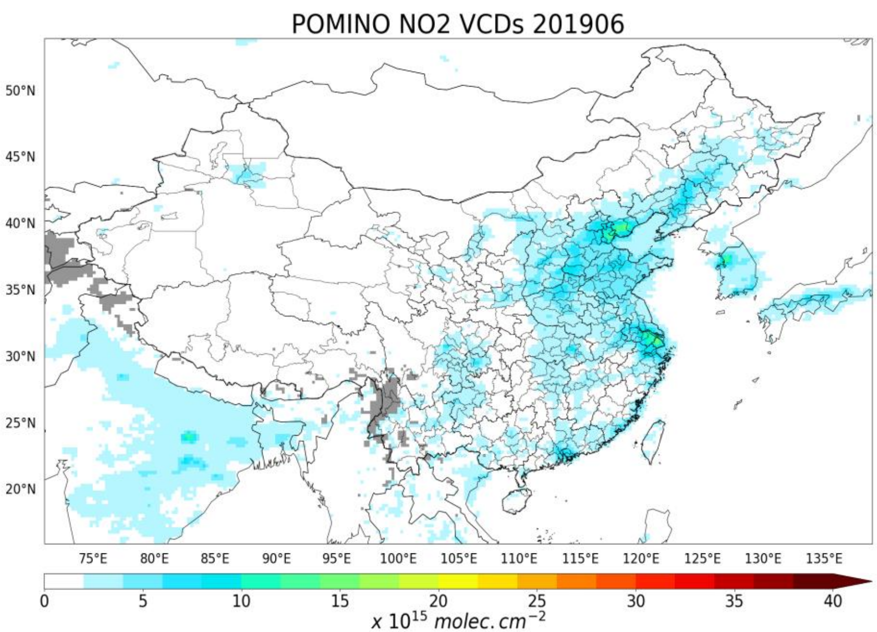
Rapid Decline in China's Emission Intensity



Ni R.-J. dissertation

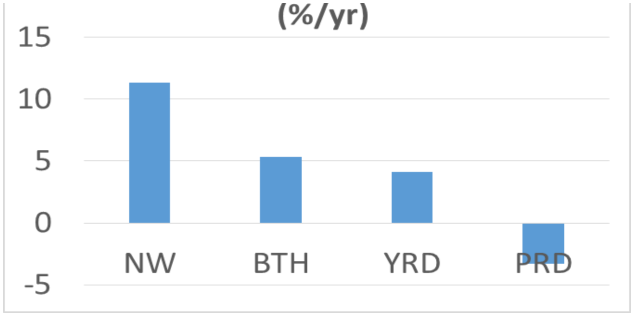
China's Cross-Regional Pollution Embedded in Trade

POMINO – Peking U. OMI NO_2 Monthly Animation



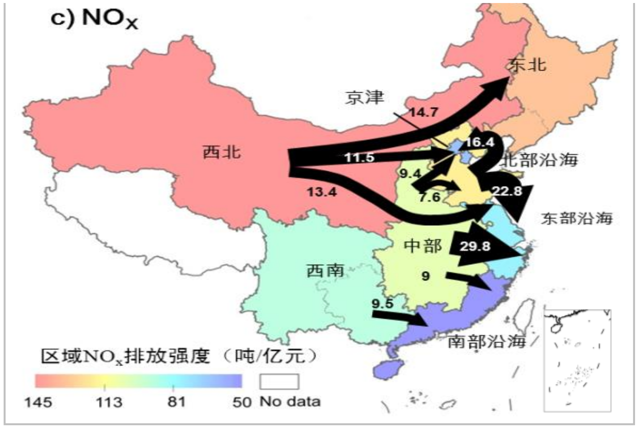
Lin et al., ACP, 2014; Lin et al., ACP, 2015; Liu et al., AMT, 2019; Zhang et al., NRSB, 2022
https://www.pku-atmos-acm.org/acmProduct.php

Much stronger NO_2 growth over Northwest, 2005-2013



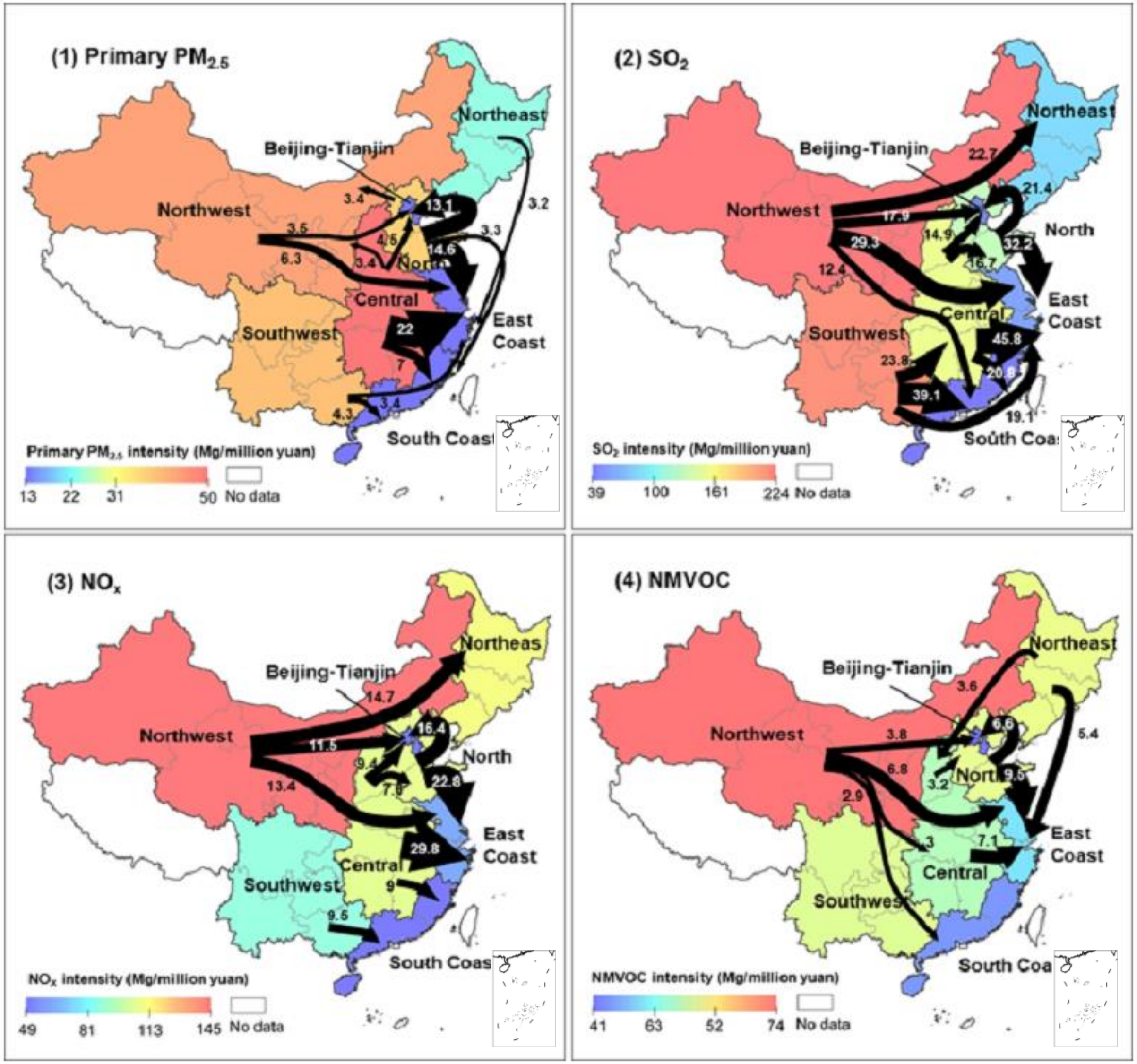
Cui et al., ACP, 2016

Large Westward Transfer of NOx Emissions via Trade



Zhao et al., ACP, 2015

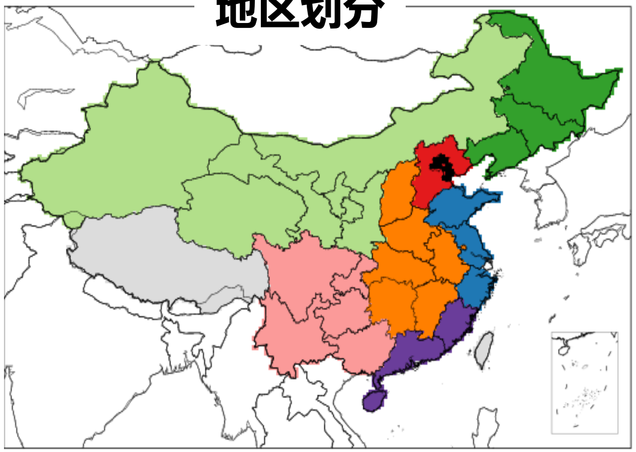
China's Inter-regional Pollution Transport Via Trade



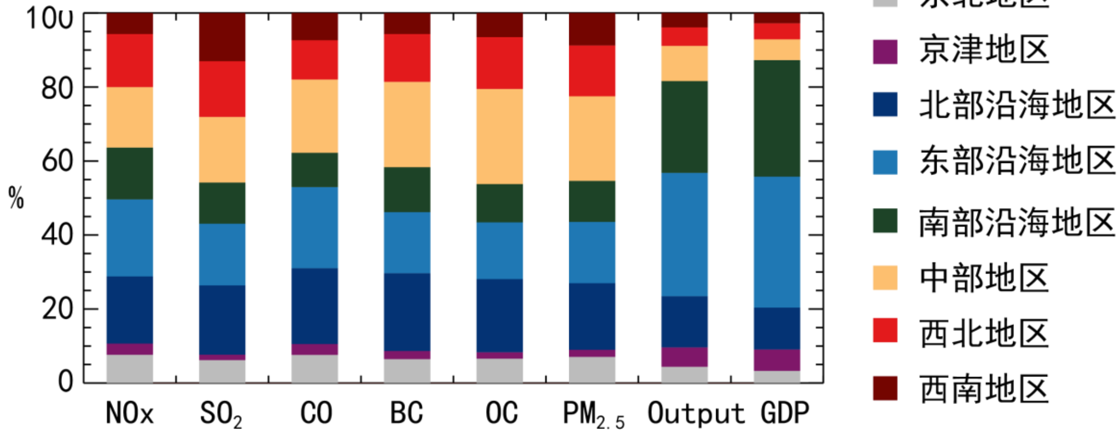
Zhao et al., ACP, 2015

Regional Contributions to China's Export & Embedded Emissions

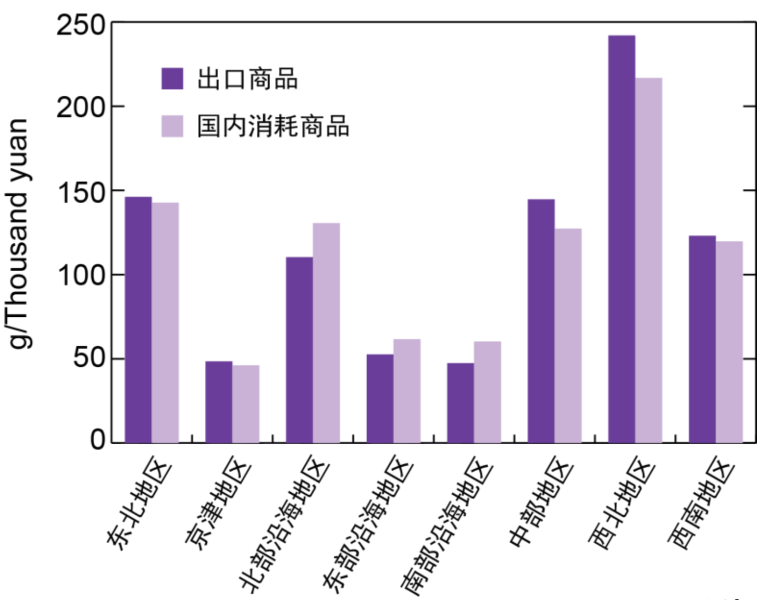
地区划分



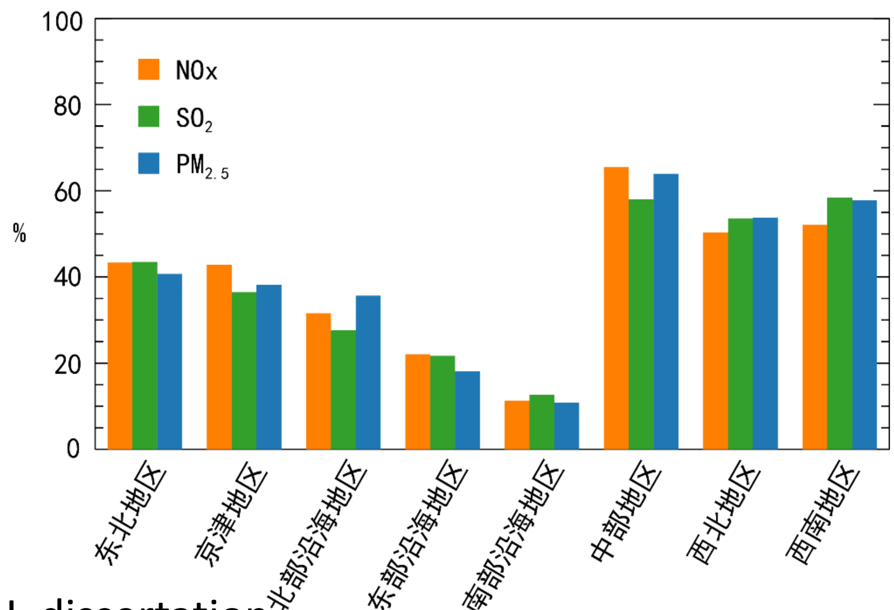
各个地区对出口排放的相对贡献



NOx排放强度

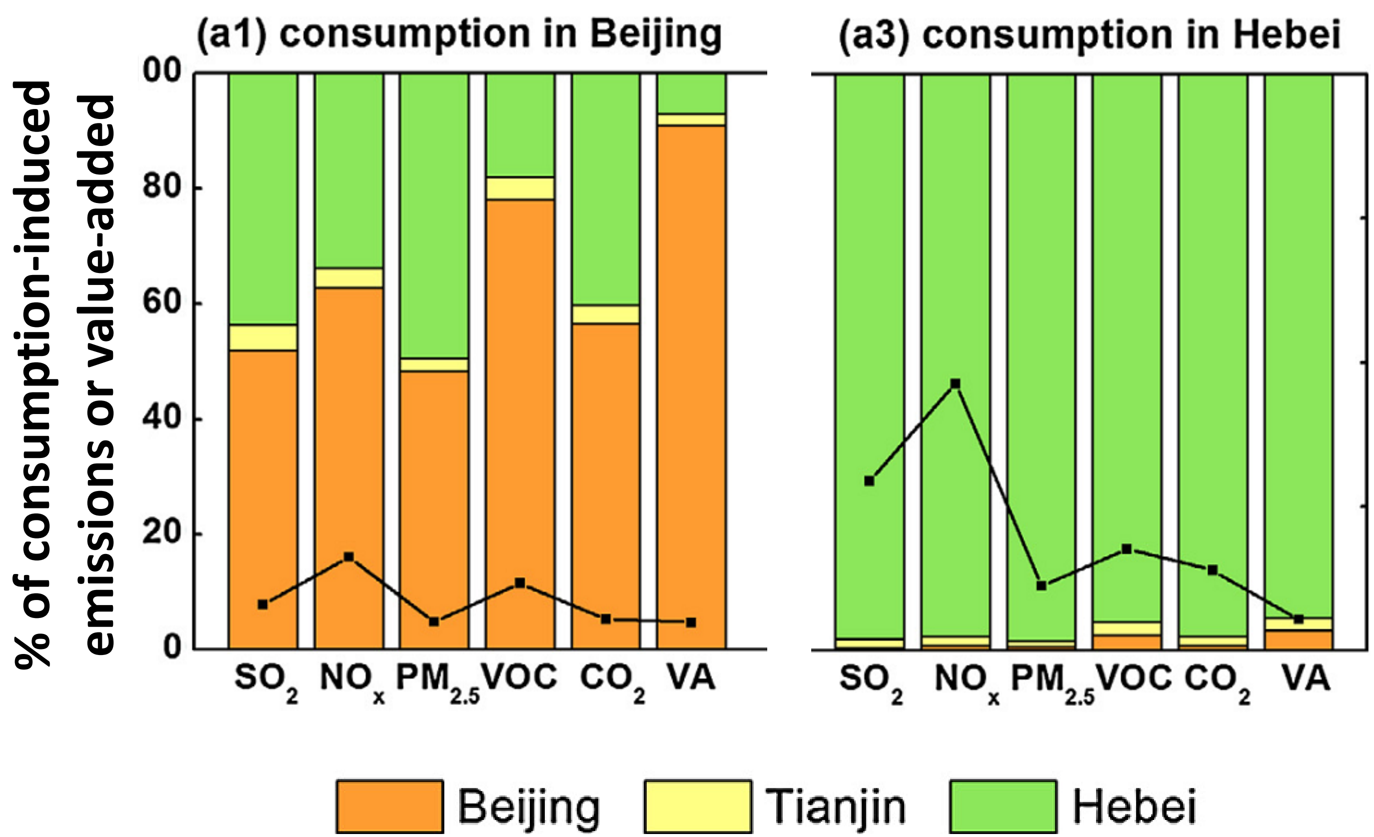


各个地区间接出口排放所占的比例



Ni R.-J. dissertation

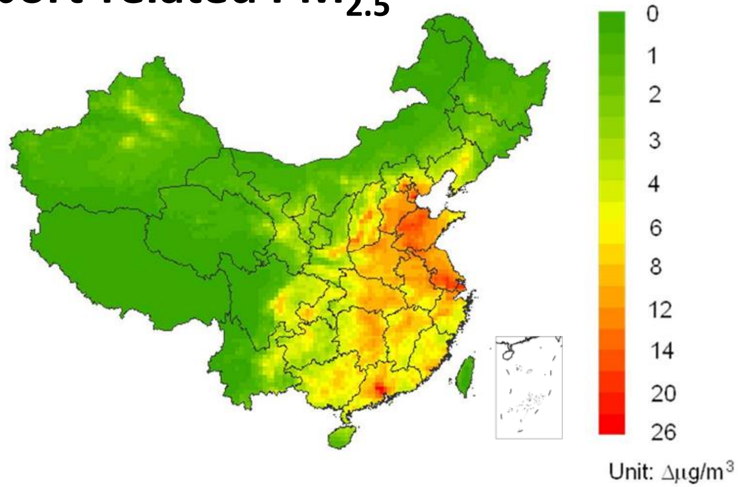
Pollution Transfer: Beijing → Hebei



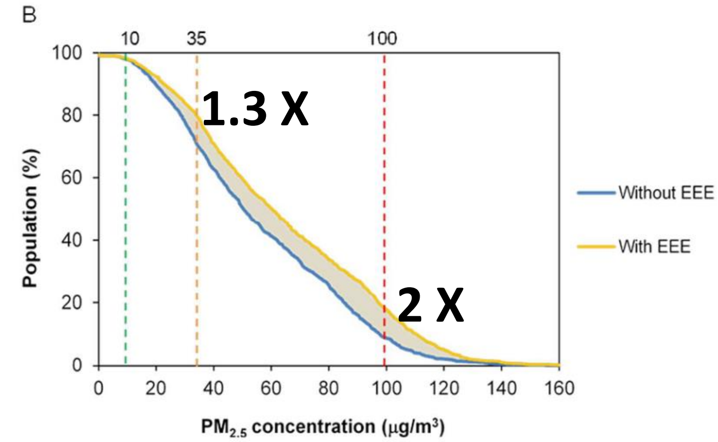
Zhao et al., Applied Energy, 2016

PM & Associated Mortality from China's Export

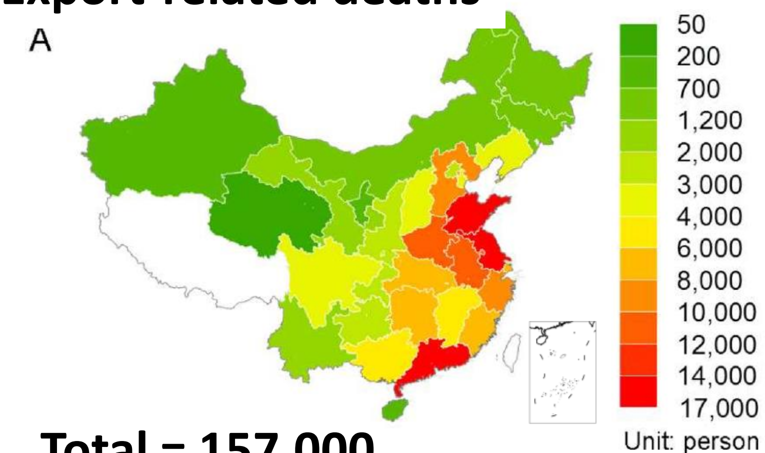
Export-related $PM_{2.5}$



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

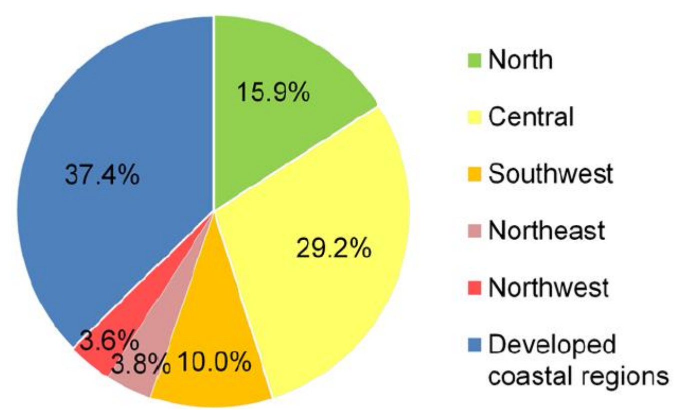


Export-related deaths



Total = 157,000

Export-related deaths



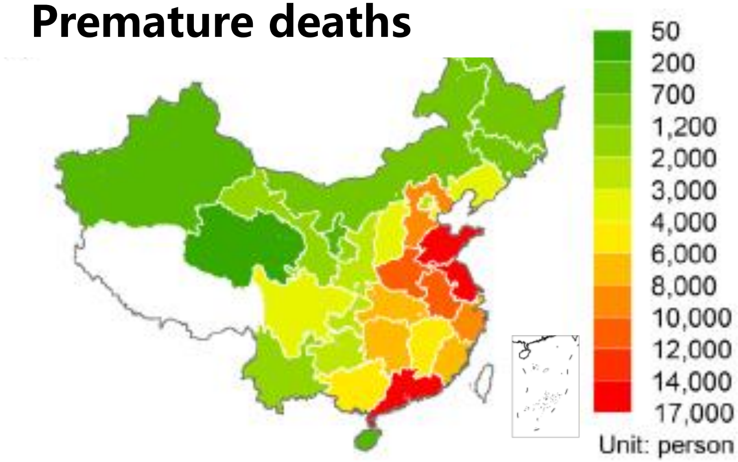
v.s.

US death wrt O_3 = 5,000

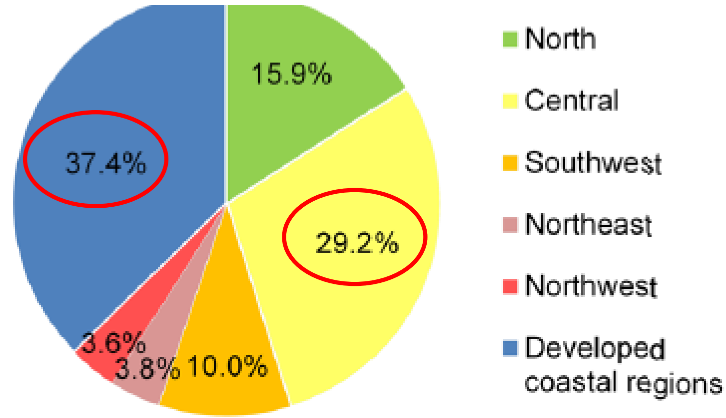
Jiang et al., EST, 2015

Inter-Provincial Disparity in Export-related Deaths

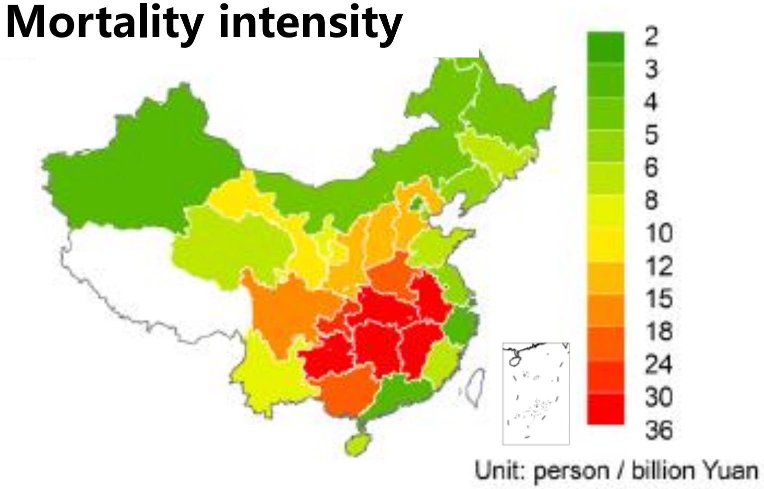
Premature deaths



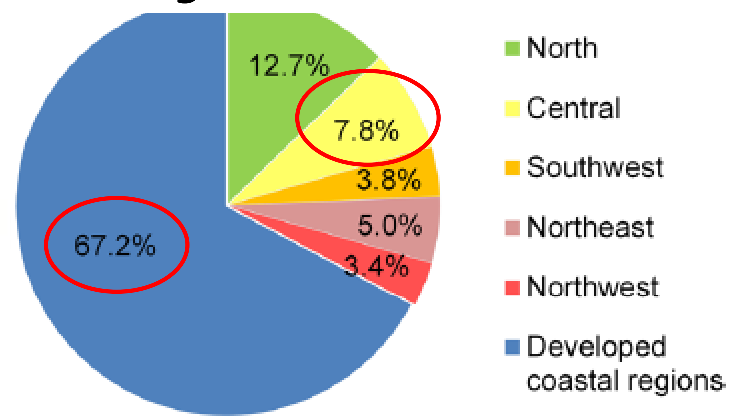
Premature deaths



Mortality intensity



Economic gain

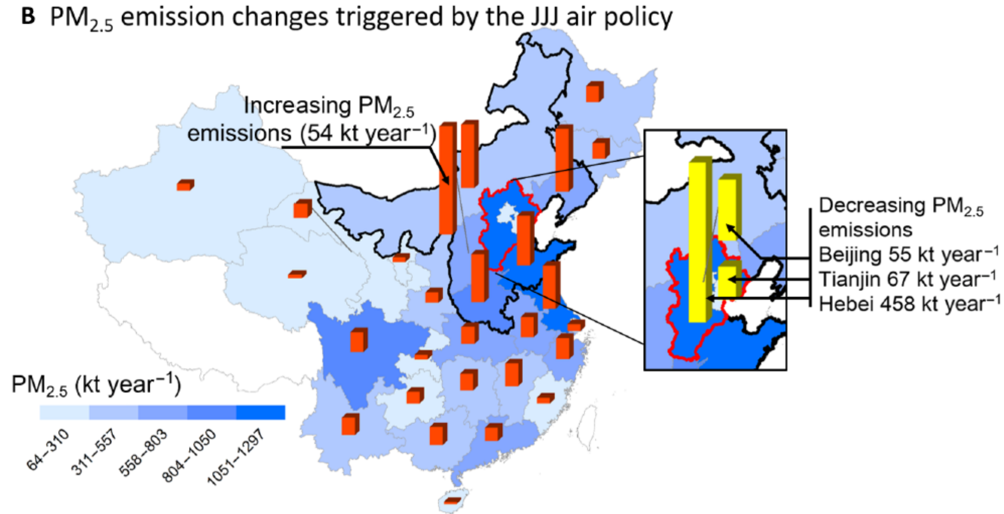


Jiang et al., EST, 2015

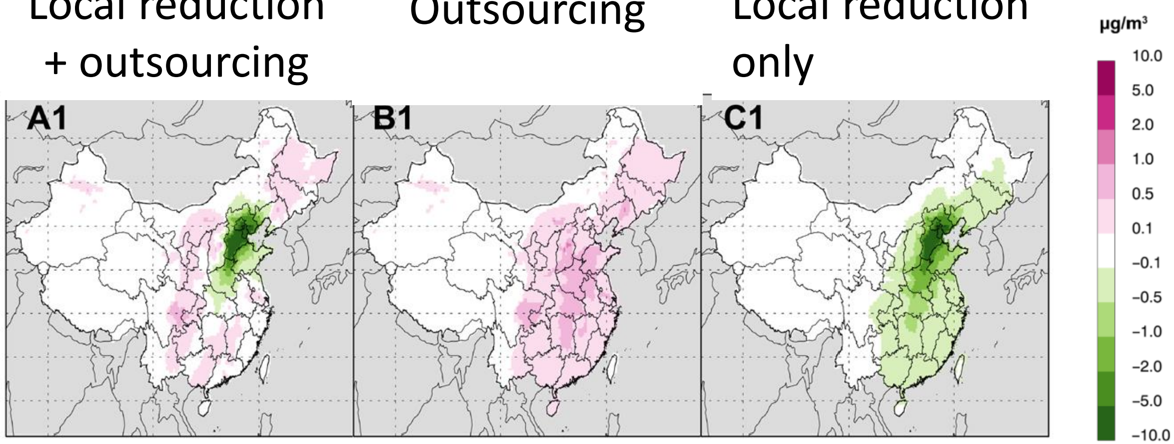
Potential Policy-Driven Outsourcing Within China

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



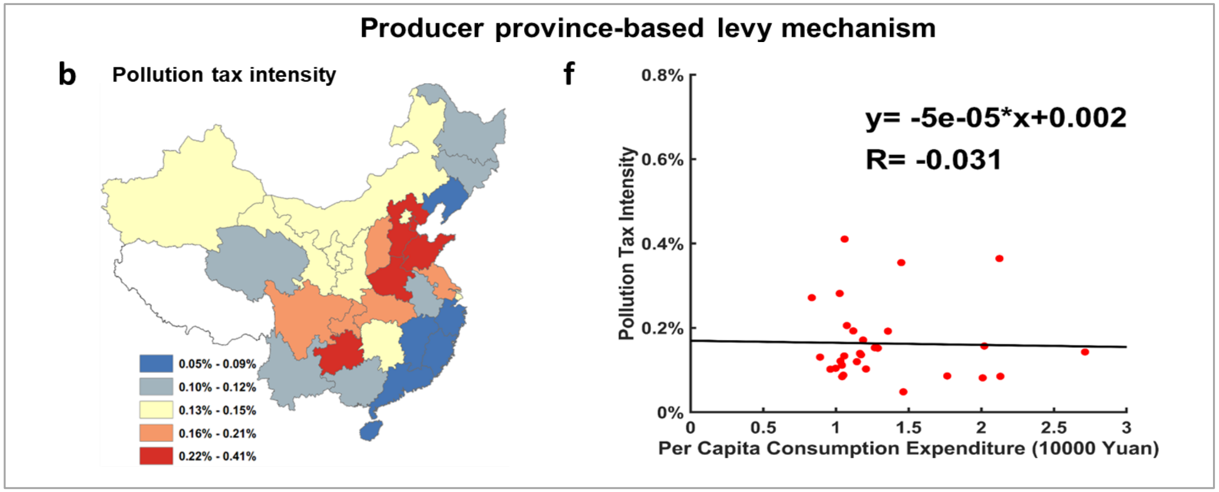
Fang et al., Science Advances, 2019

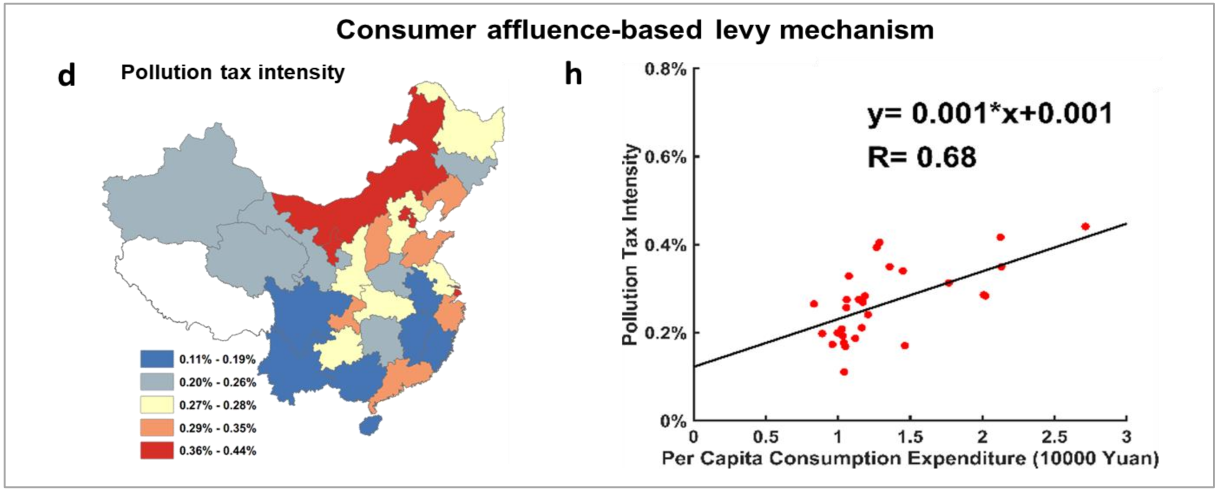
Trade-driven Pollution Transport: A Critical Issue in China's GO-WEST Movement

Pollution in Tenggeli Desert (2014/08/31)

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

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



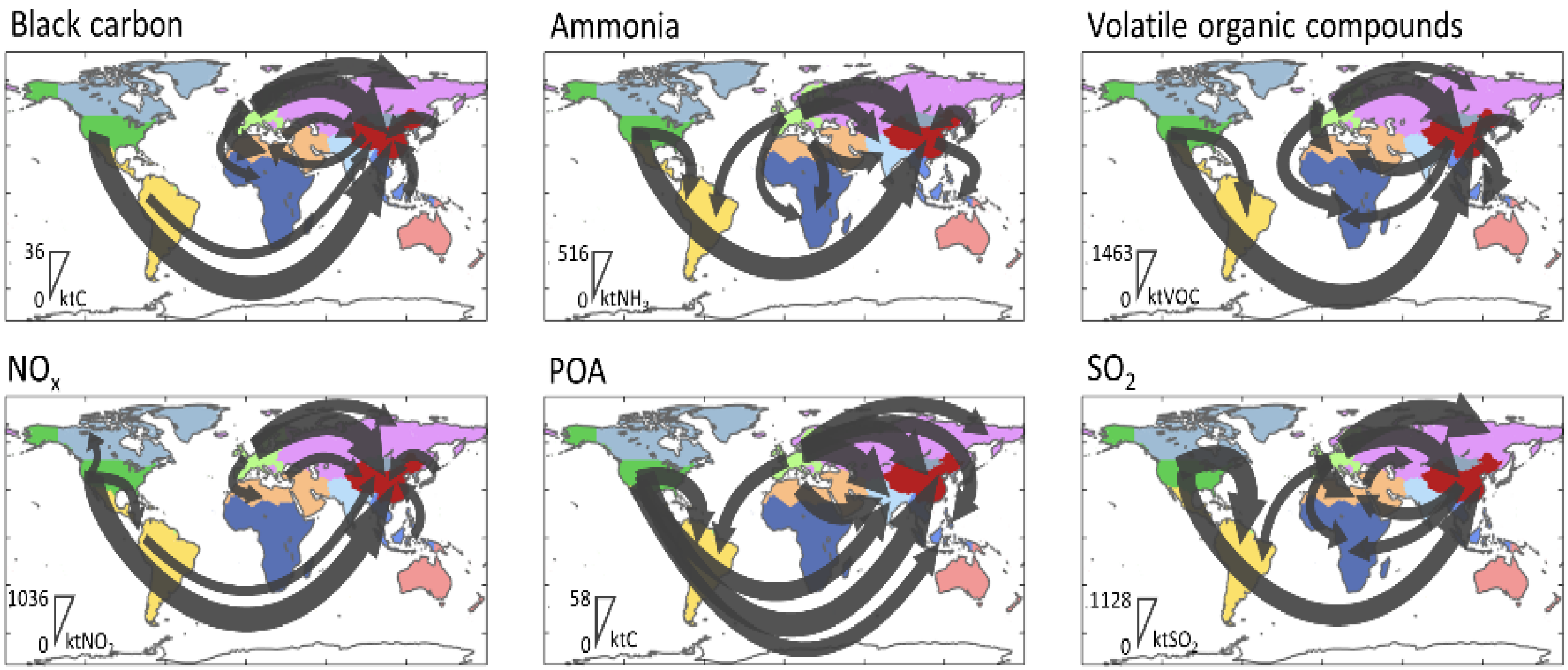


Wang et al., 2019
Science Bulletin

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

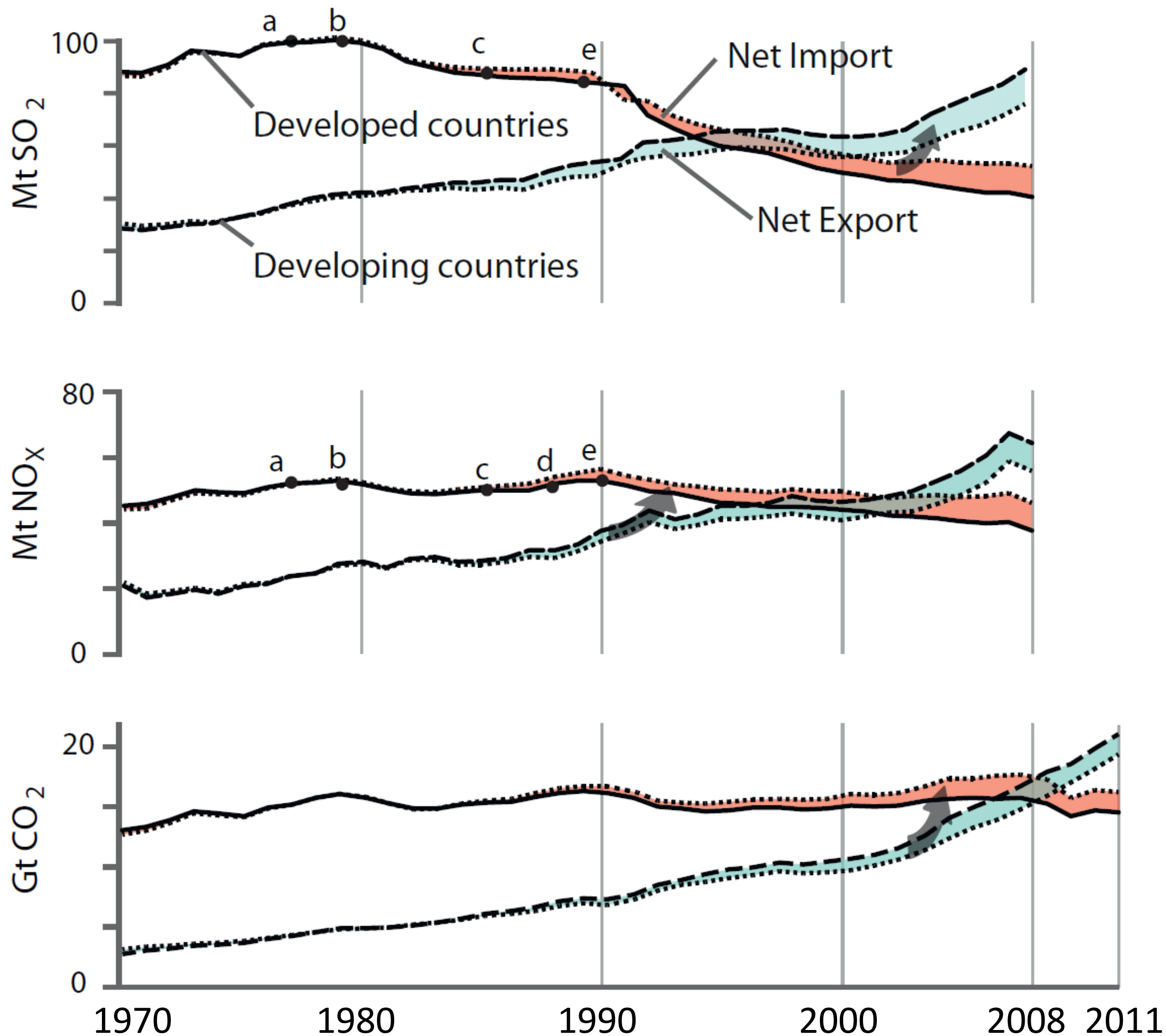
Global Trade Leads to Complex Emission Transfer

Top ten routes of emissions embedded in trade among 13 regions in 2014



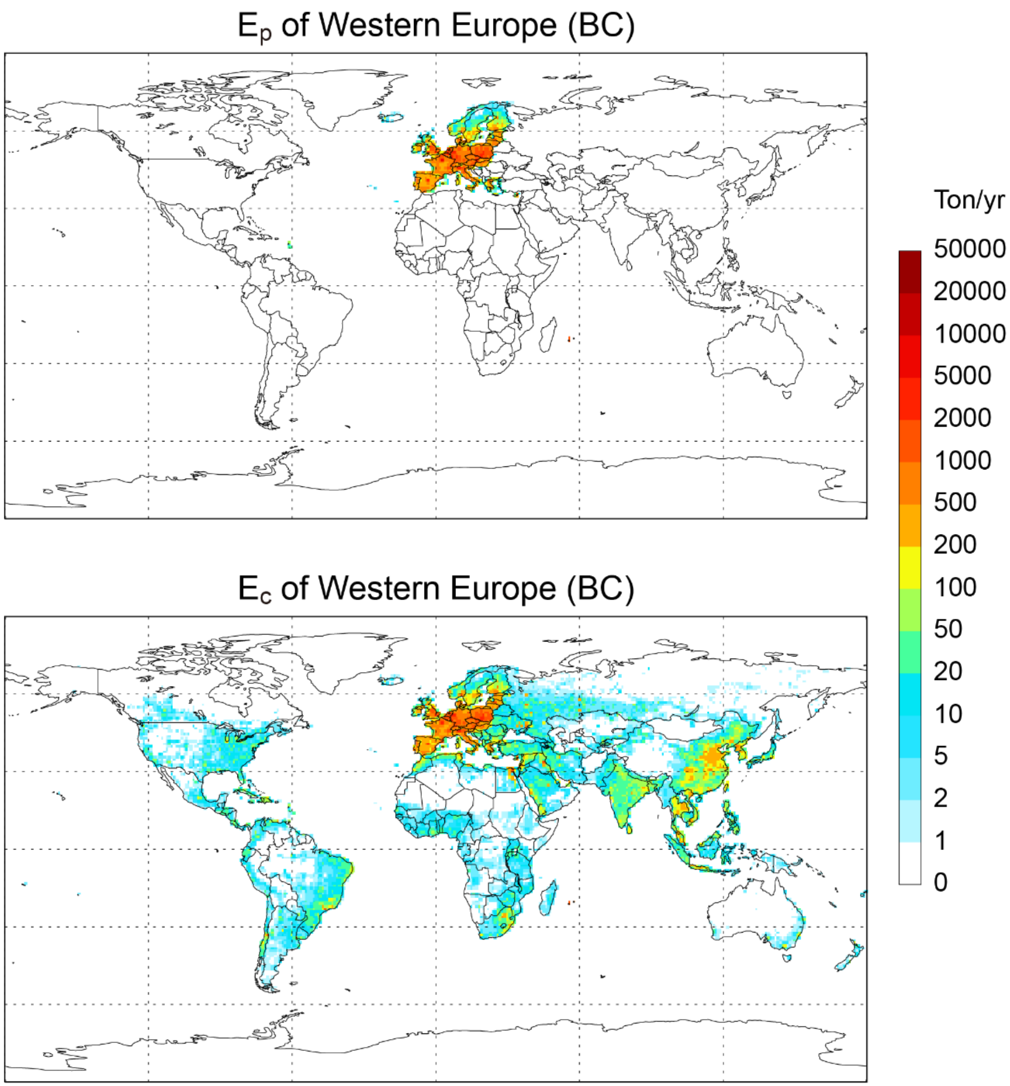
Lin et al., under review

Consumption & Trade Drive Emission Redistribution



Kanemoto et al., 2014, GEC

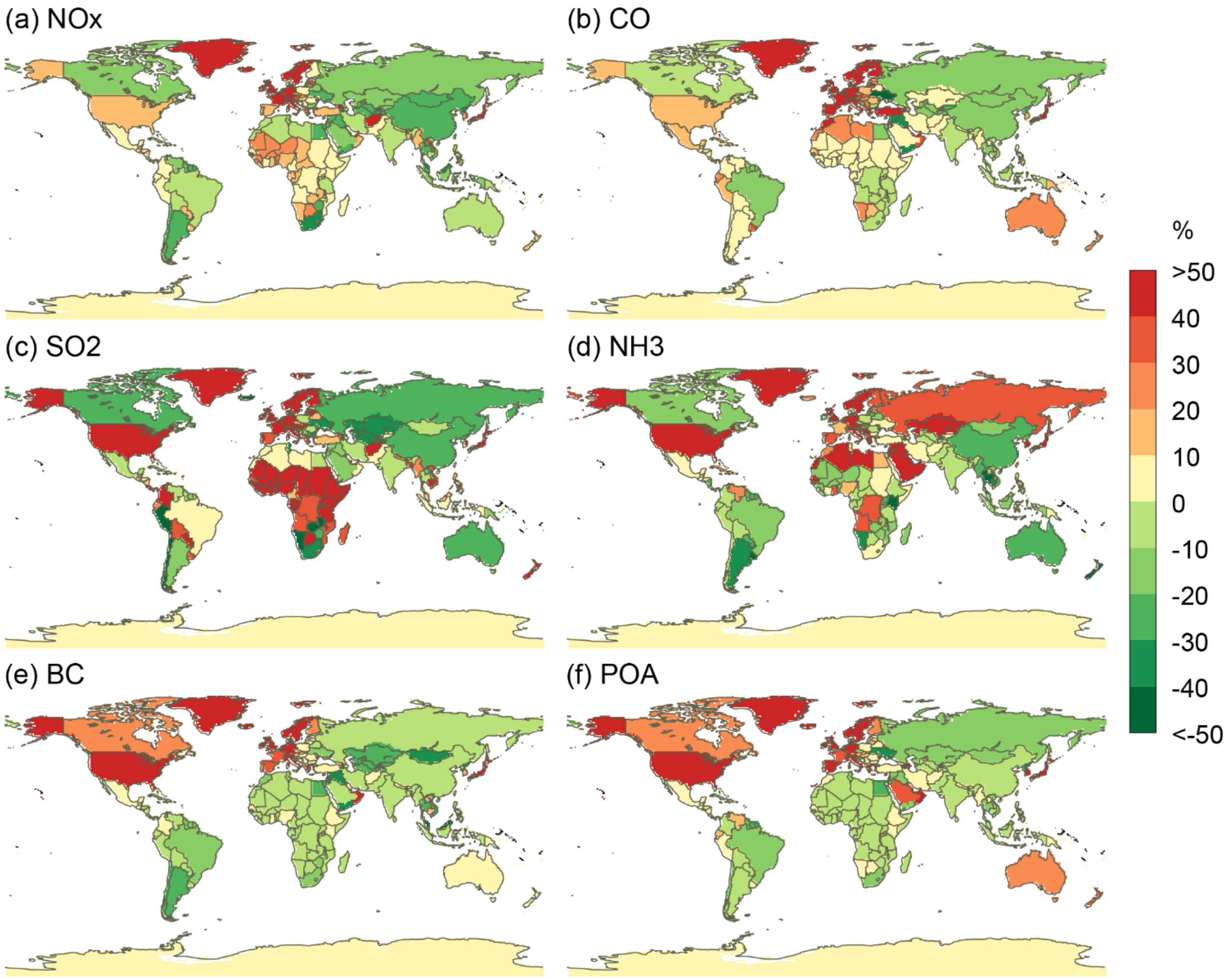
Trade Redistributes Emissions



Lin et al., 2016, Nature Geoscience

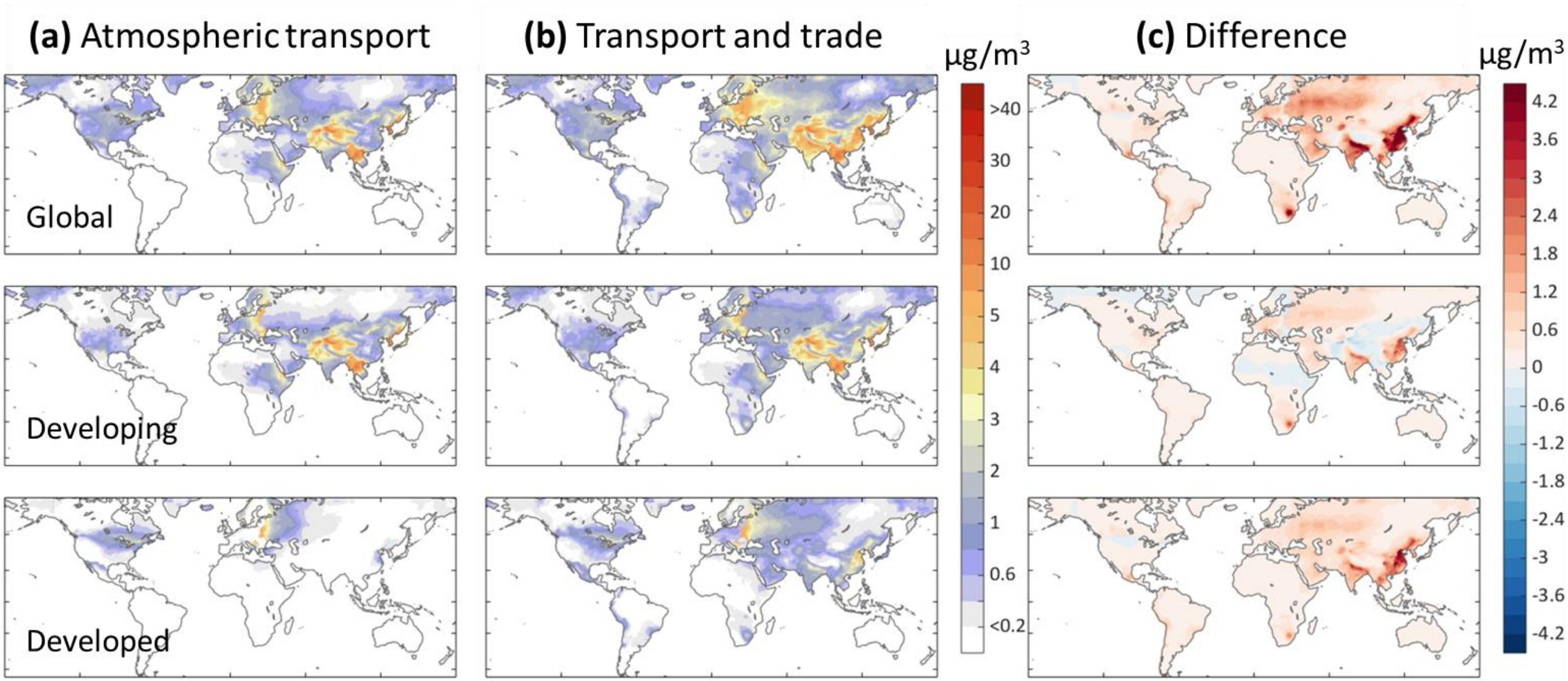
Trade Transfers Emissions from Rich to Poorer Regions

Consumption-based minus Production-based Emissions in 2007



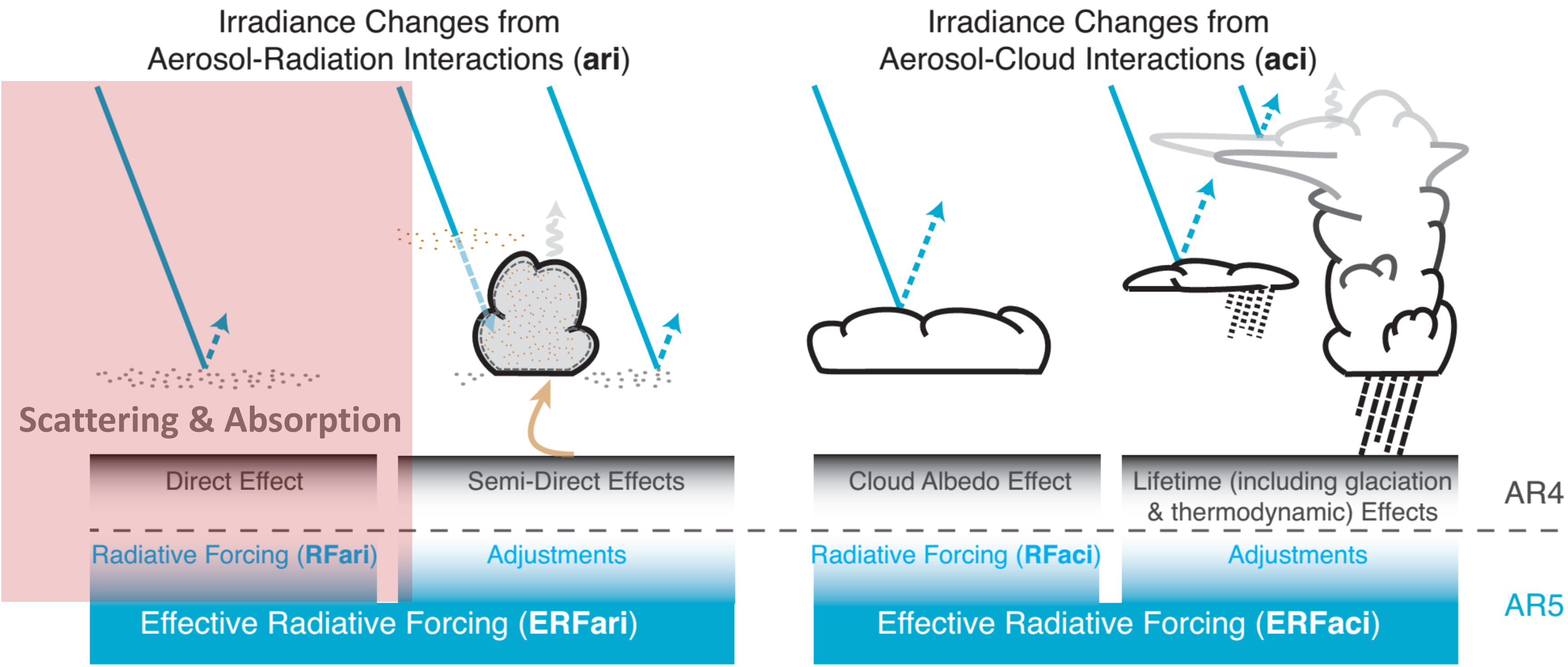
Lin et al., 2016, Nature Geoscience

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



Lin et al., under review

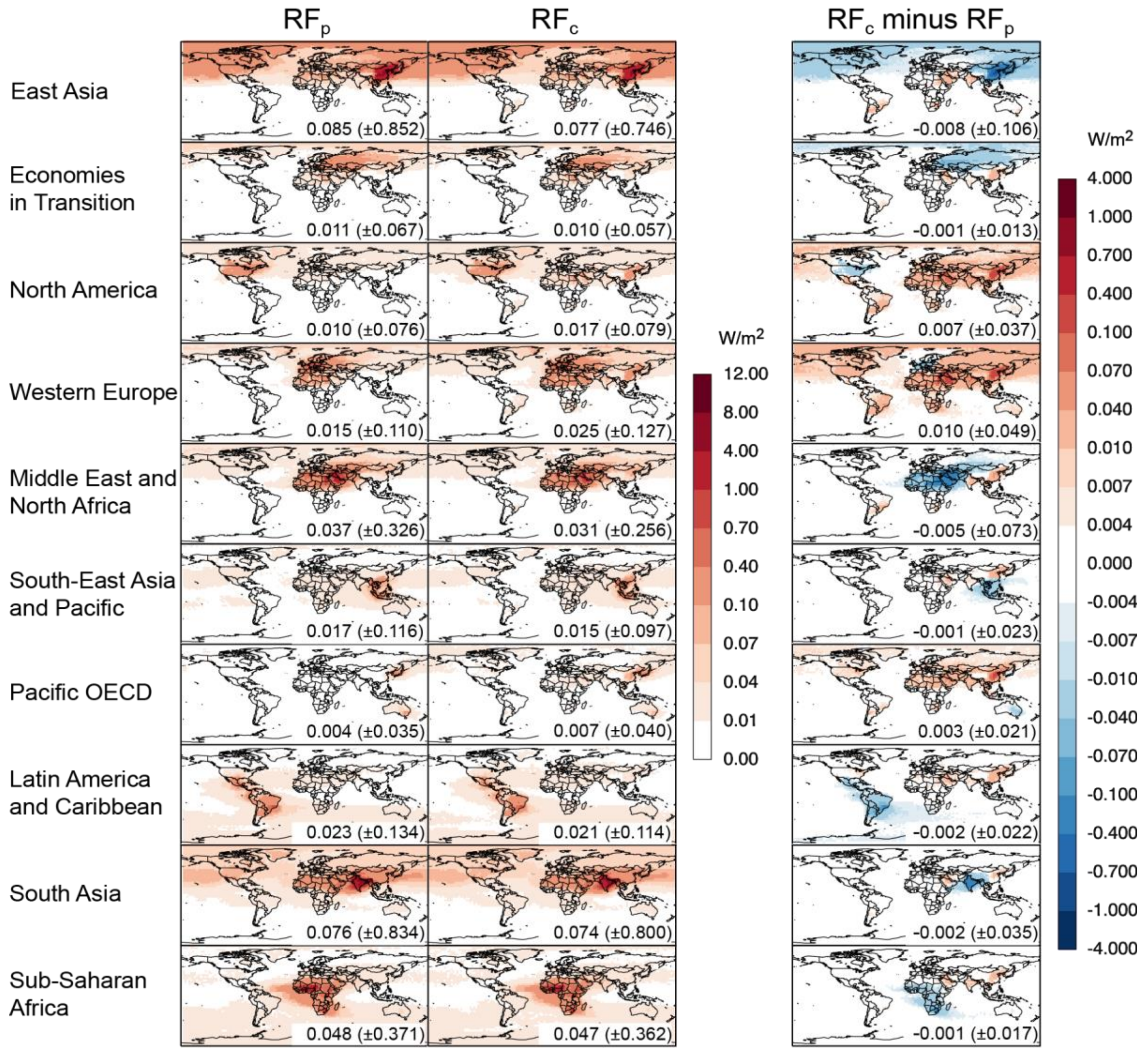
Radiative Forcing of Aerosols



IPCC, 2013

Trade Transfers Radiative Forcing: Rich → Poorer Regions

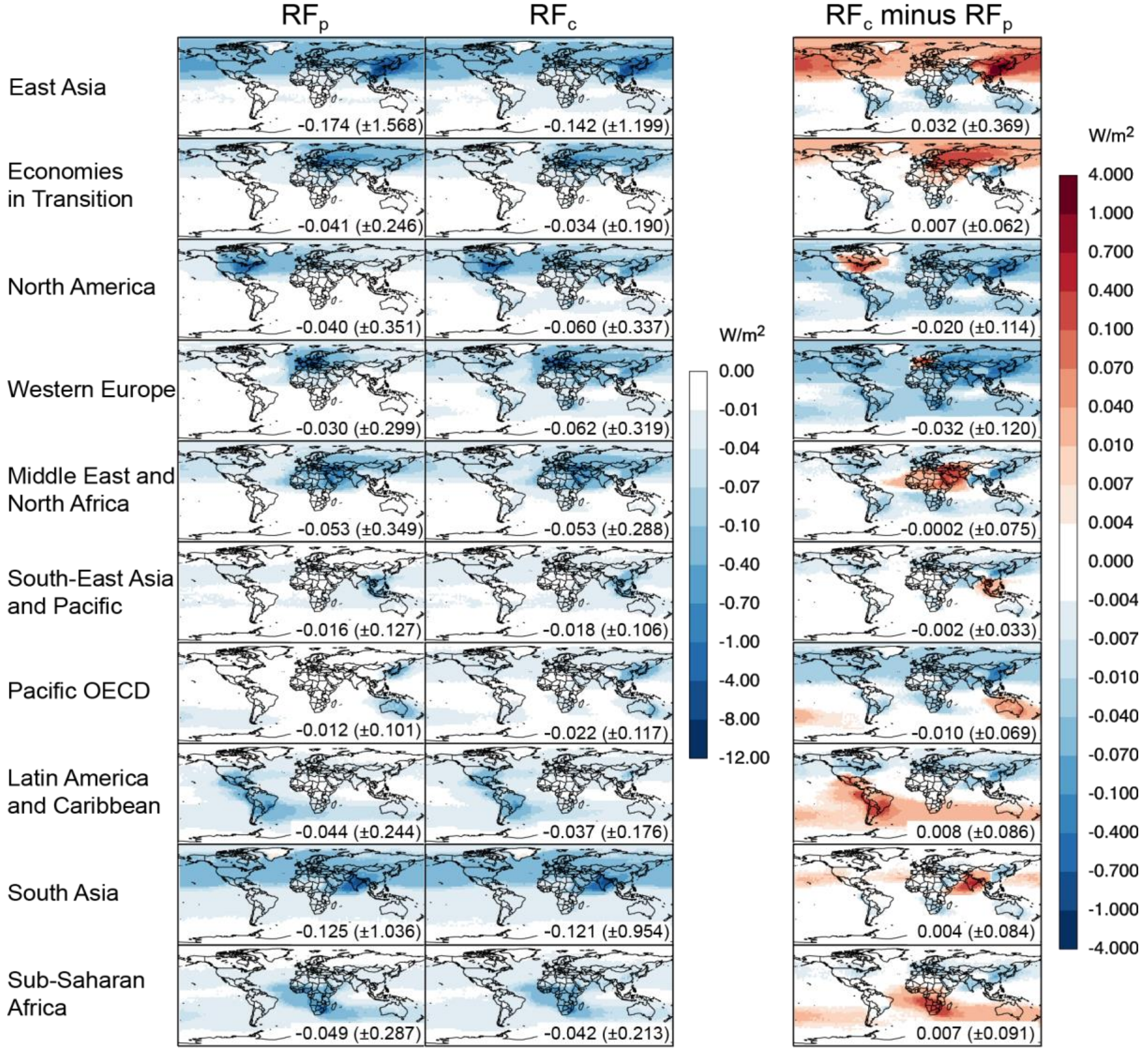
TOA direct radiative forcing of BC in 2007



Lin et al., 2016, Nature Geoscience

Trade Transfers Radiative Forcing: Rich → Poorer Regions

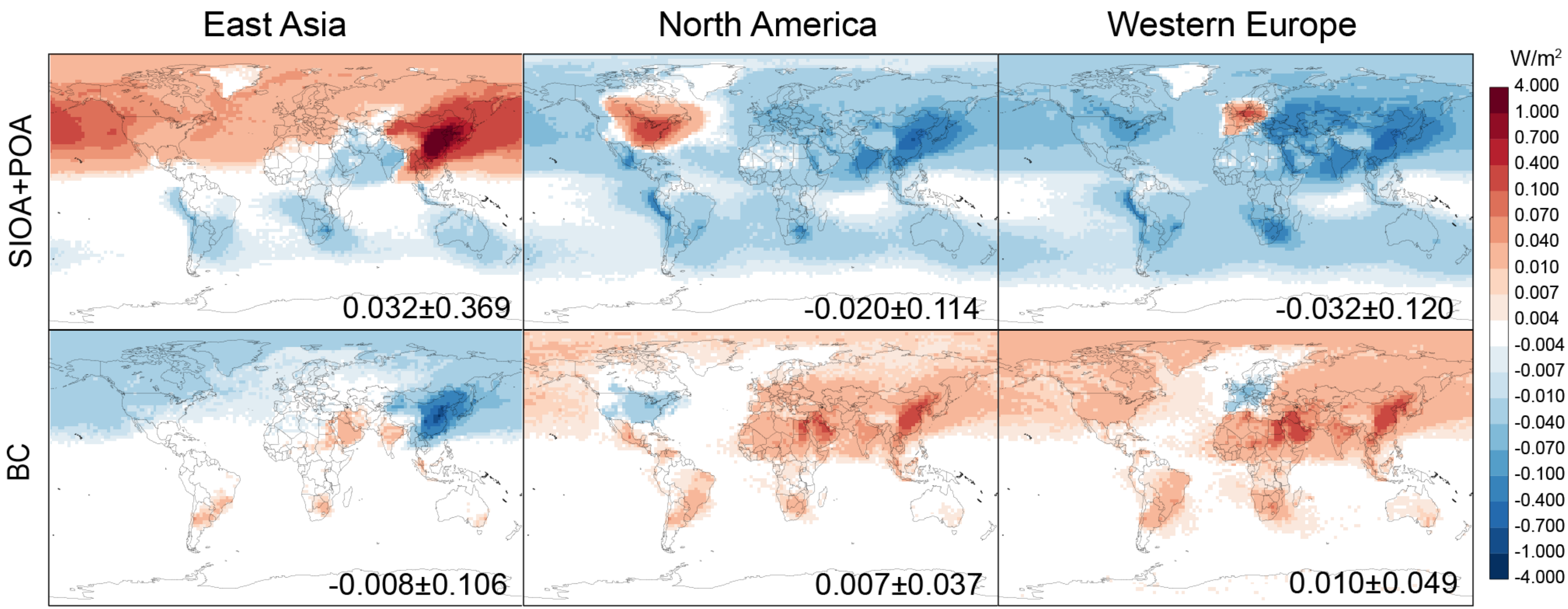
TOA direct RF of scattering aerosols (SO_4+NO_3+NH_4+POA) in 2007



Lin et al., 2016, Nature Geoscience

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

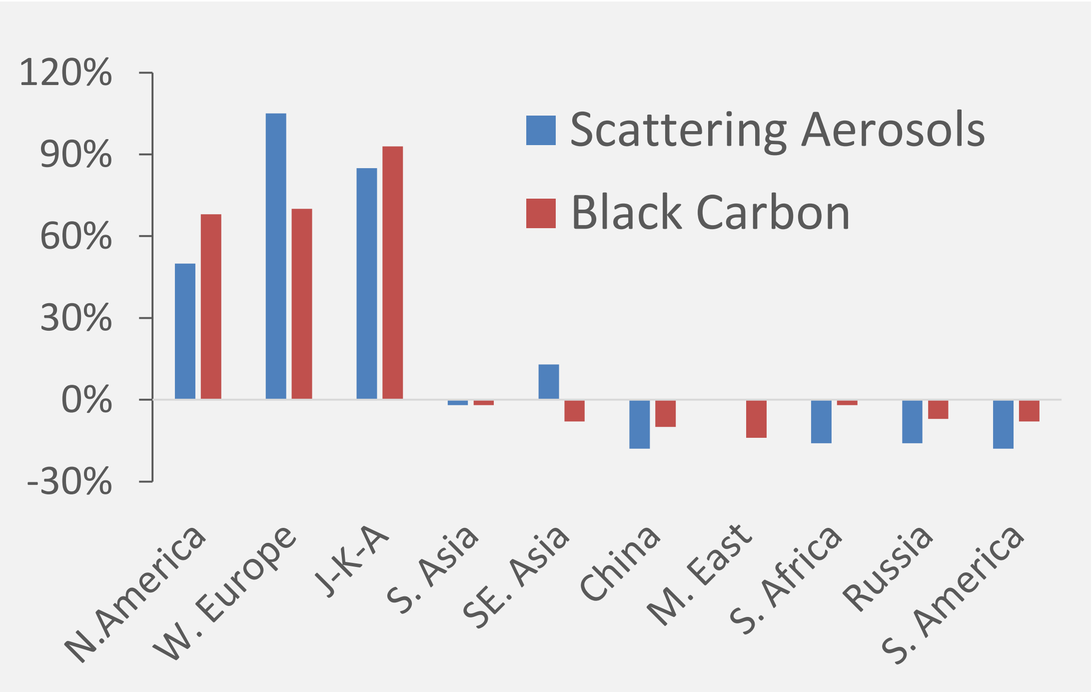
Consumption-based minus production-based TOA direct RF in 2007



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

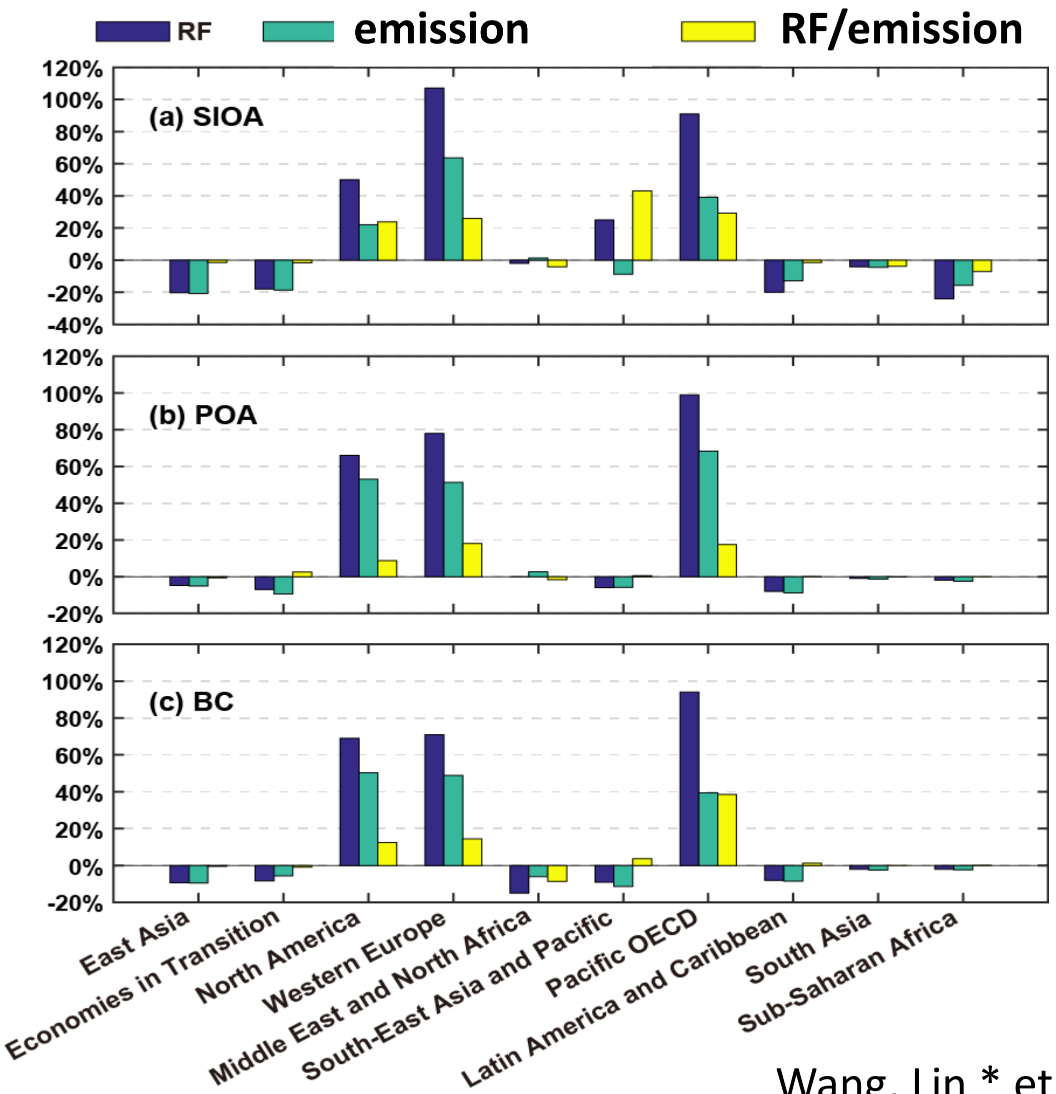


Method:
Emission inventory +
GTAP MRIO table +
GEOSChem + RRTMG

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

Lin et al., 2016, Nature Geoscience

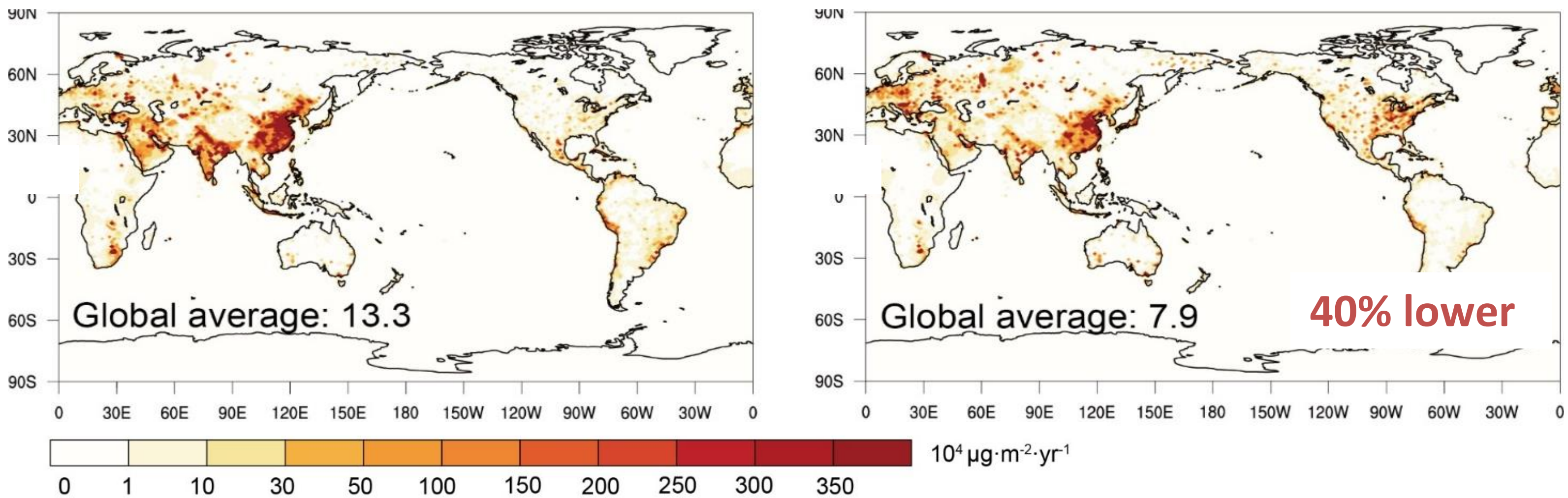
Drivers of Difference Between Consumption- and Production-based Aerosol Radiative Forcing



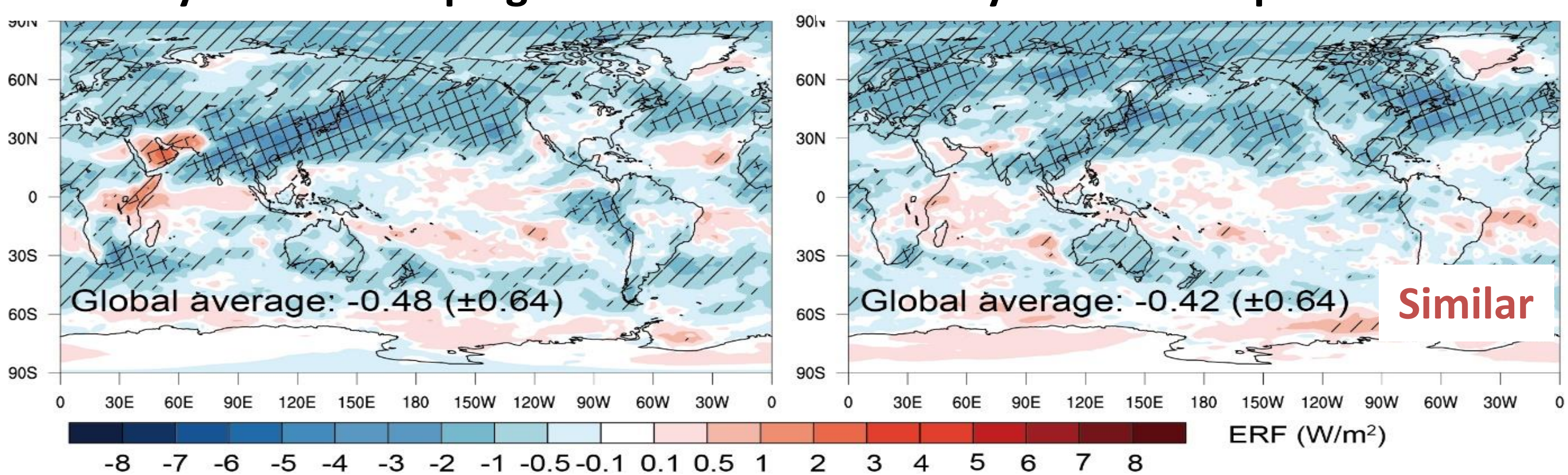
Wang, Lin * et al., 2019

Effective Radiative Forcing (= ERF_{ari} + ERF_{aci}) of Ec

Ec of developing countries | **Ec of developed countries**

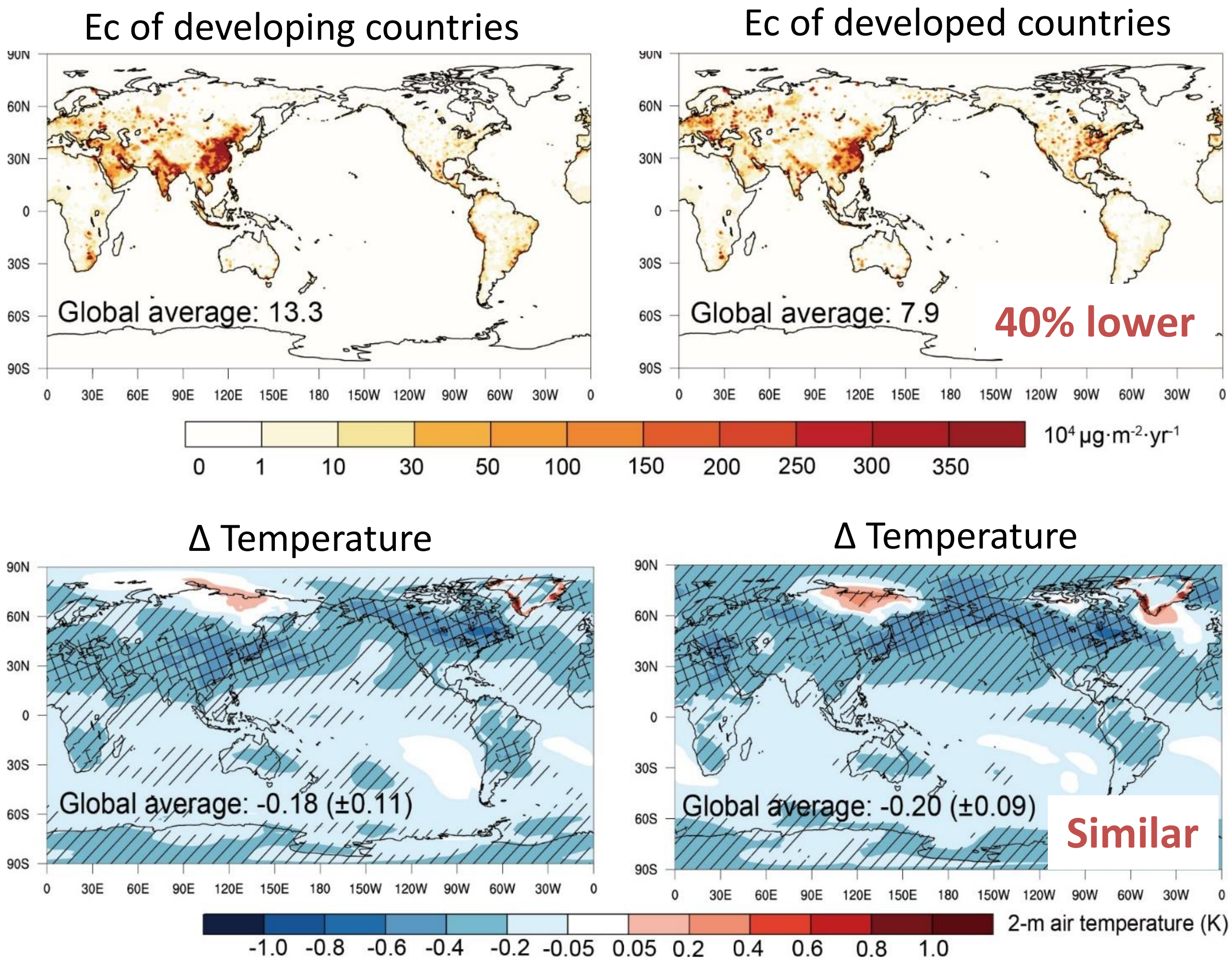


ERF by Ec of developing countries | **ERF by Ec of developed countries**



Lin et al., Nature Geoscience, 2022

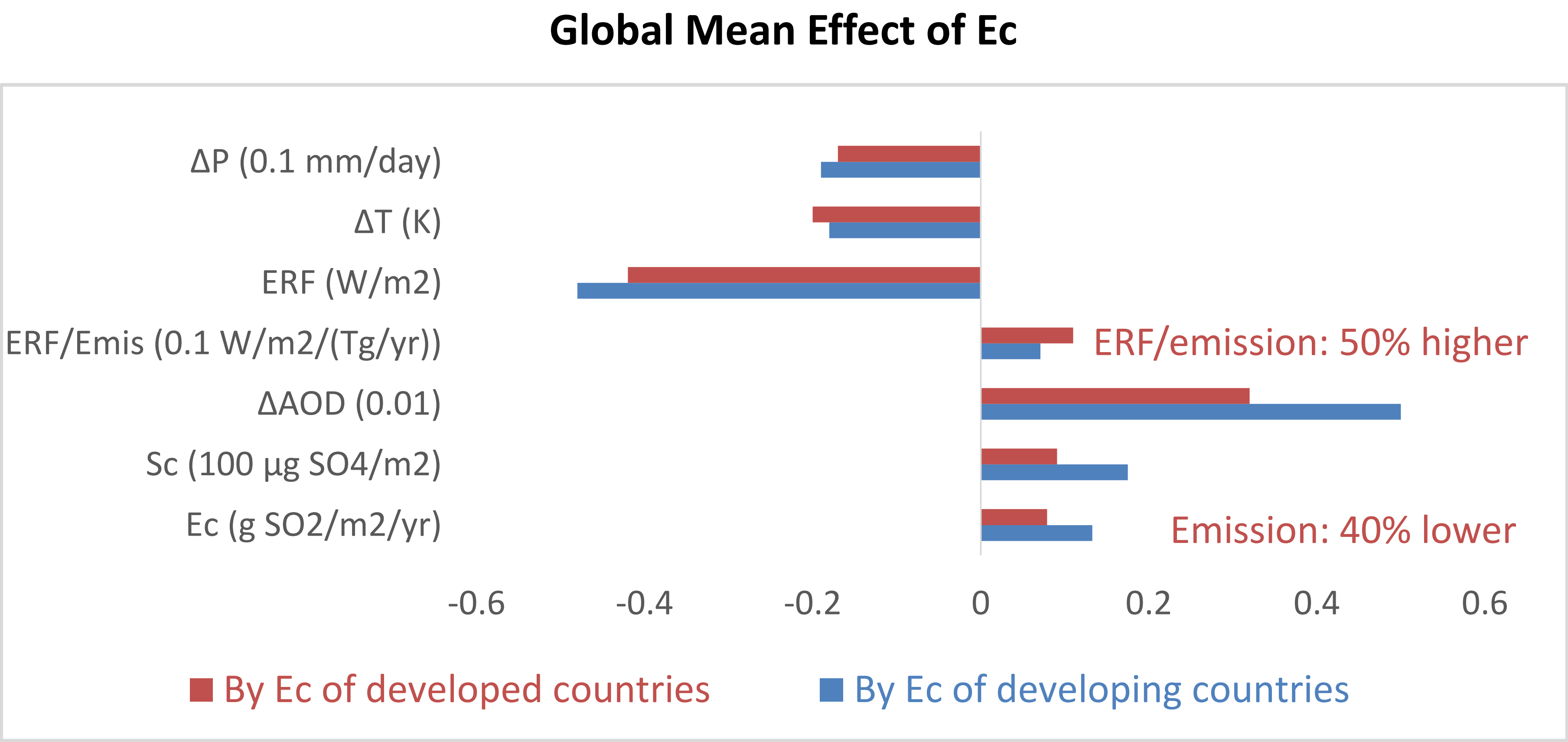
Sulfur Emissions from Consumption of Developing and Developing Countries Produce Comparable Climate Impacts



Method:
Emissions
+ GTAP
+ CESM2

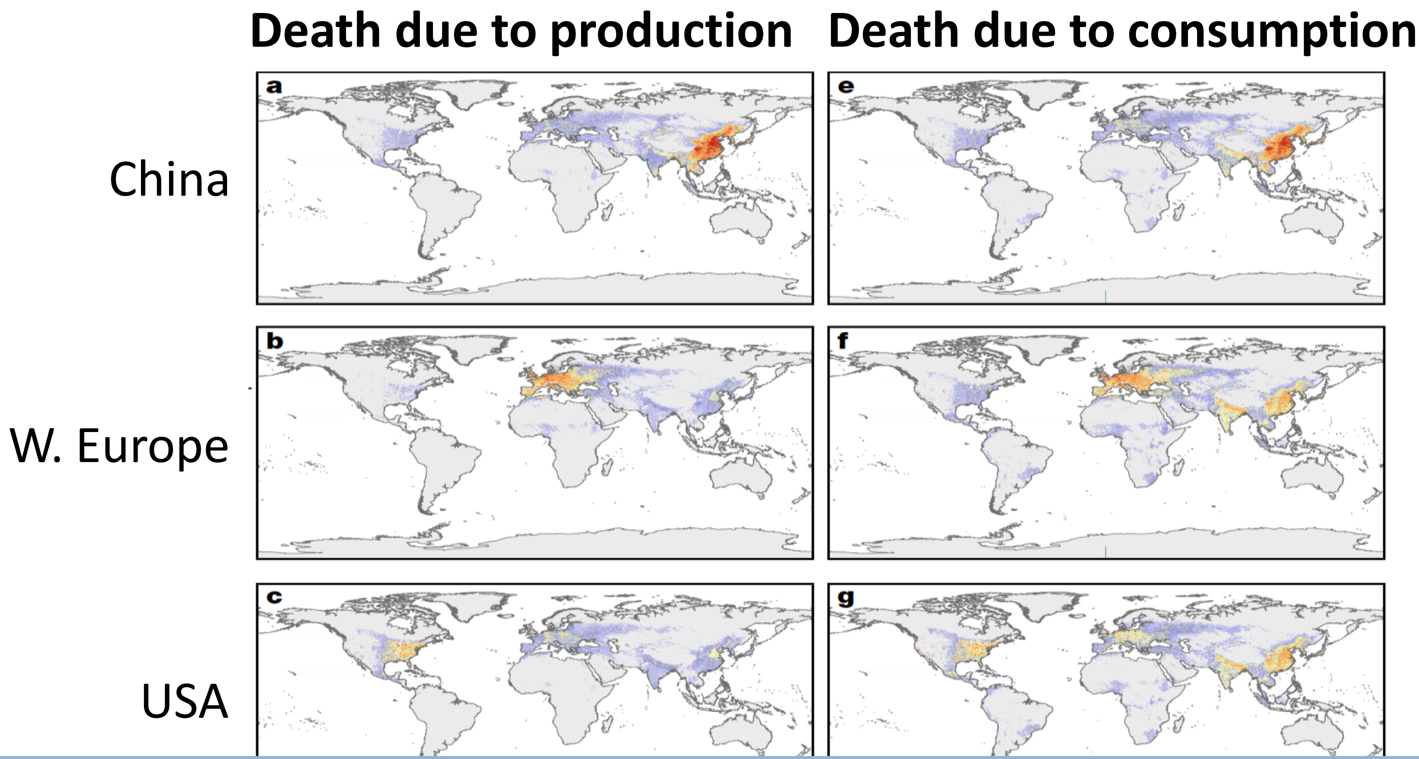
Lin et al., Nature Geoscience, 2022

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



Lin et al., Nature Geoscience, 2022

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



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

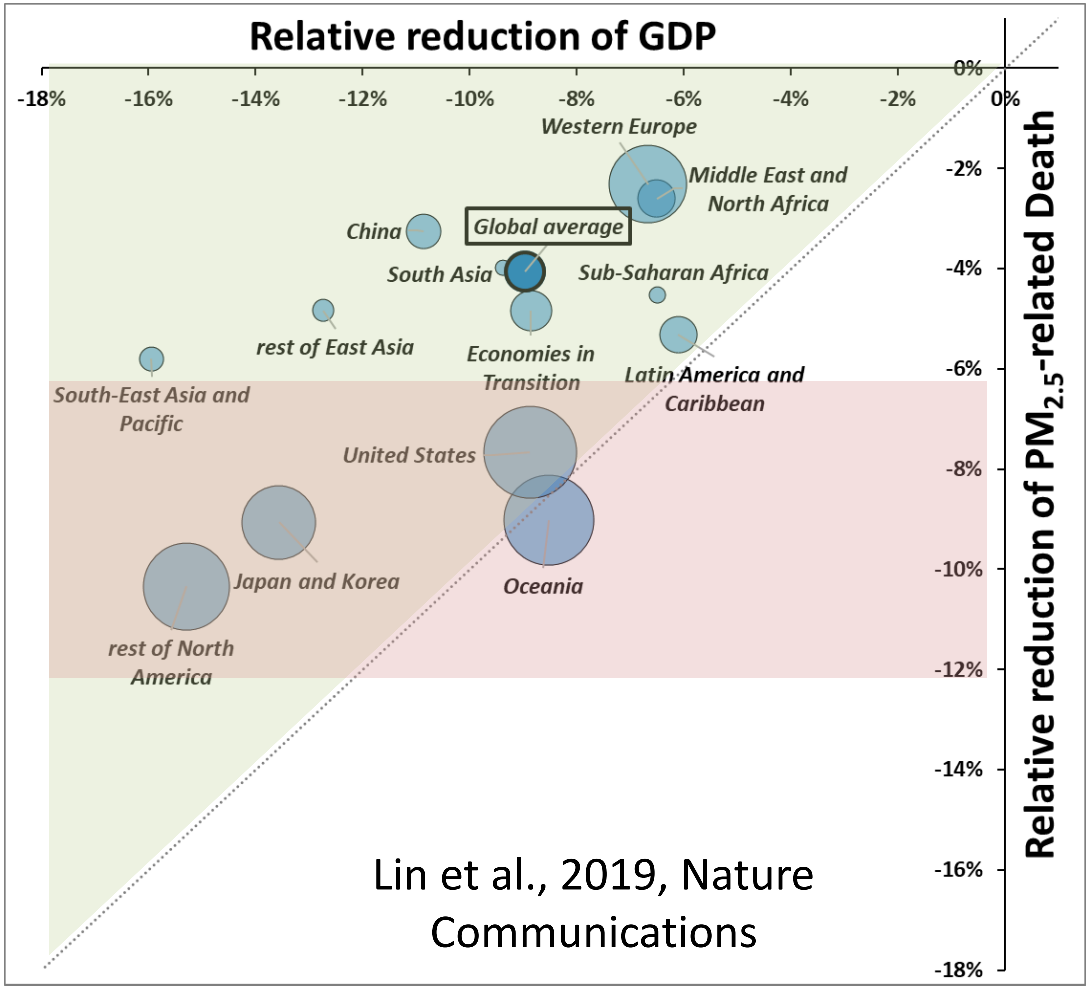
- **410,000 (12%) is due to atmospheric transboundary transport**
- **760,000 (22%) is due to consumption in a different region (trade + atmos)**

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

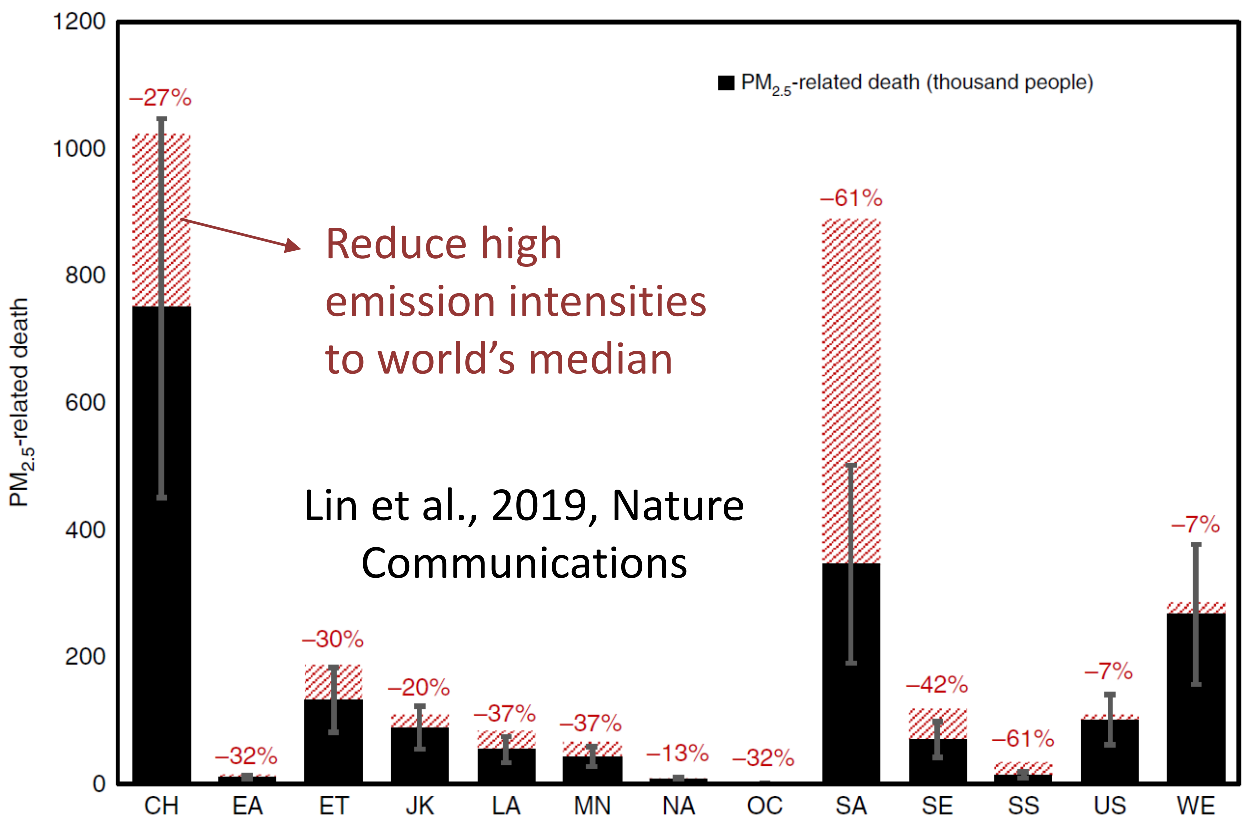
Distinctive Changes in Economy & $PM_{2.5}$ Mortality from *Free Trade* to *Current tariff plus an additional 25% tariff*



- 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**

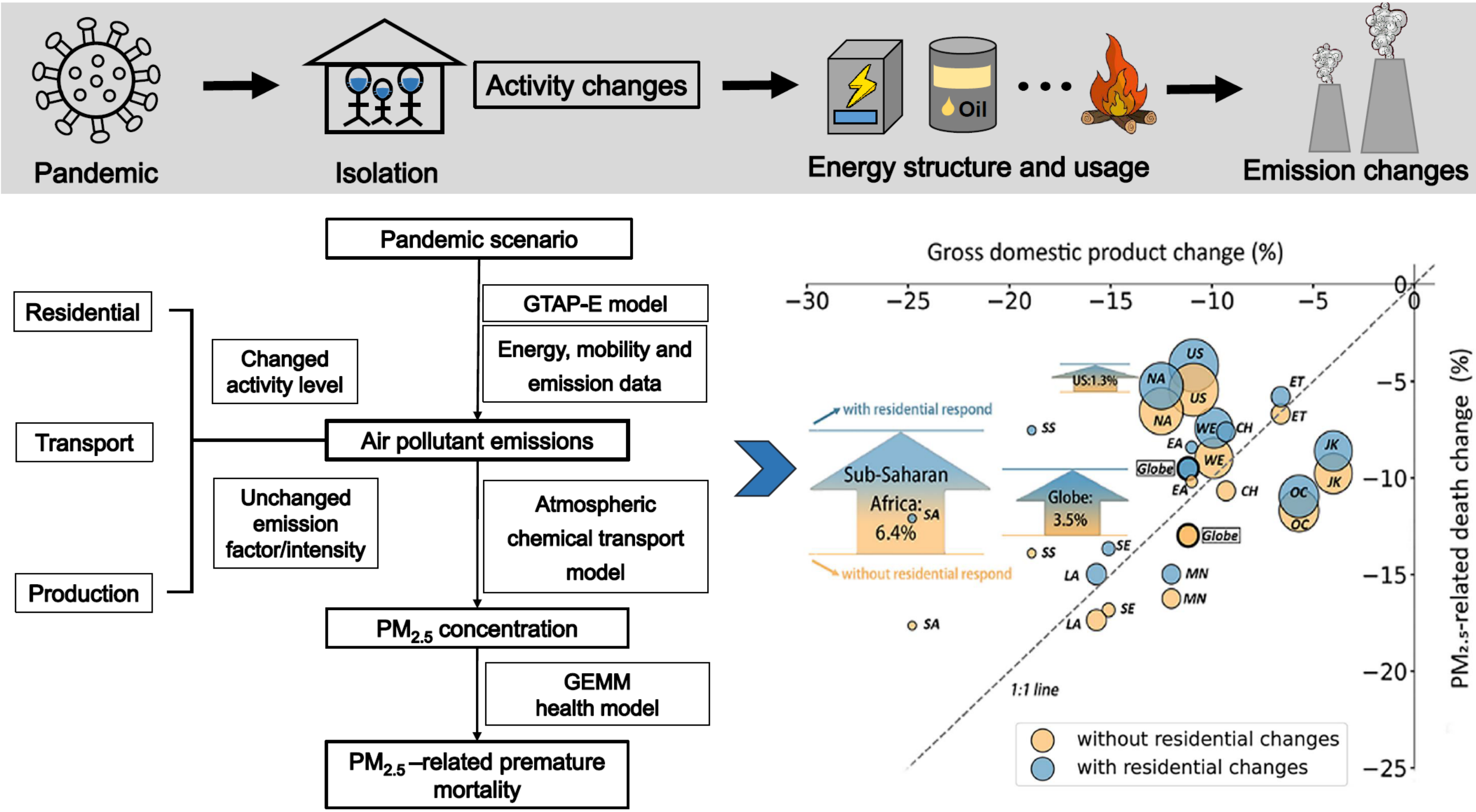
Method: Emissions + GTAP CGE + GEOS-Chem + Satellite + GEMM

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



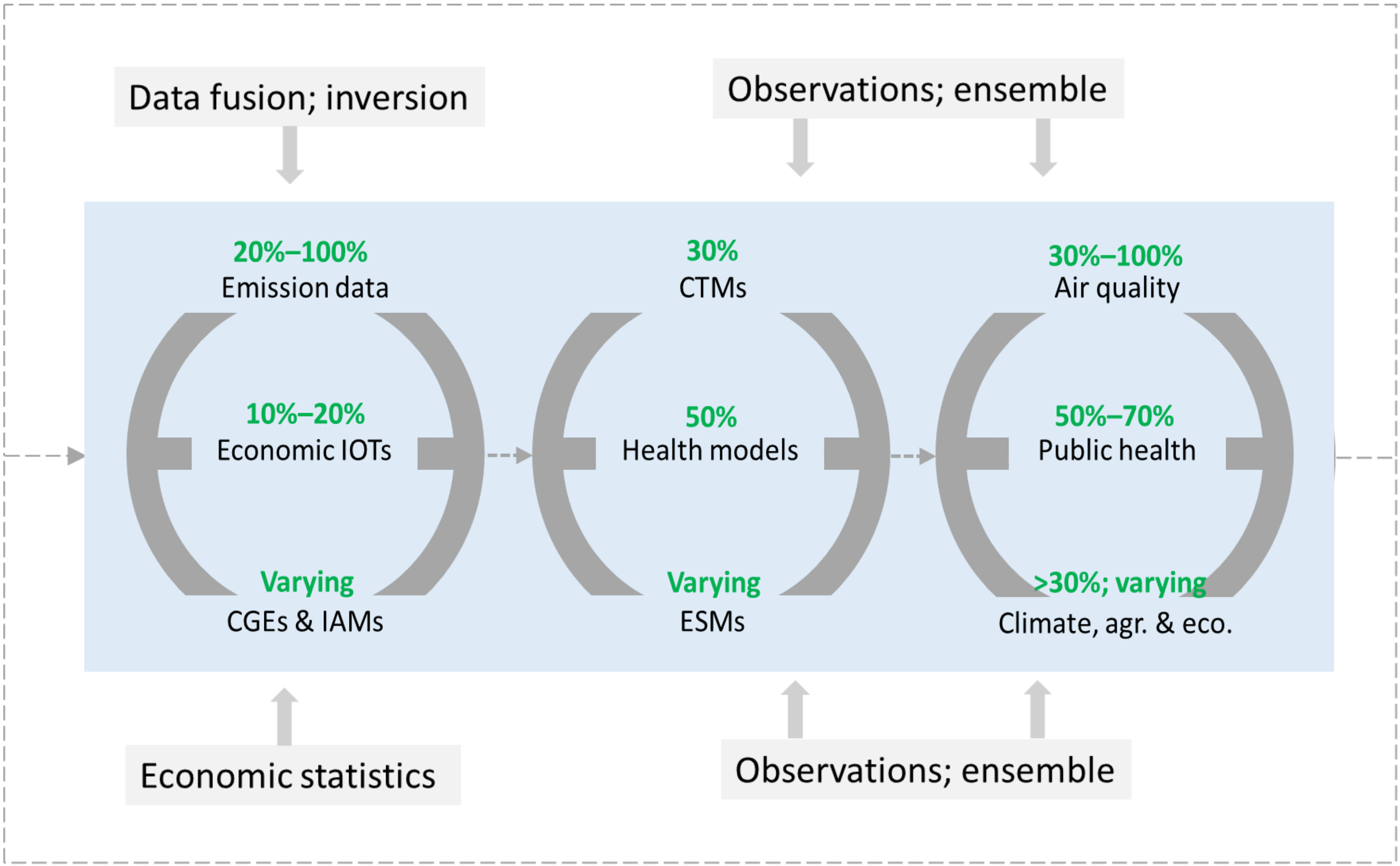
Method: Emissions + GTAP CGE + GEOS-Chem + Satellite + GEMM

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



Li et al., SOTEN, 2023

Uncertainties in GAP Studies

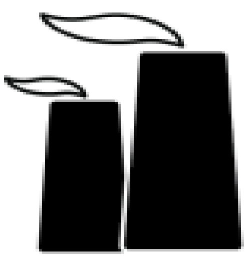


Lin et al., under review

From Production to Consumption Perspective

Trade

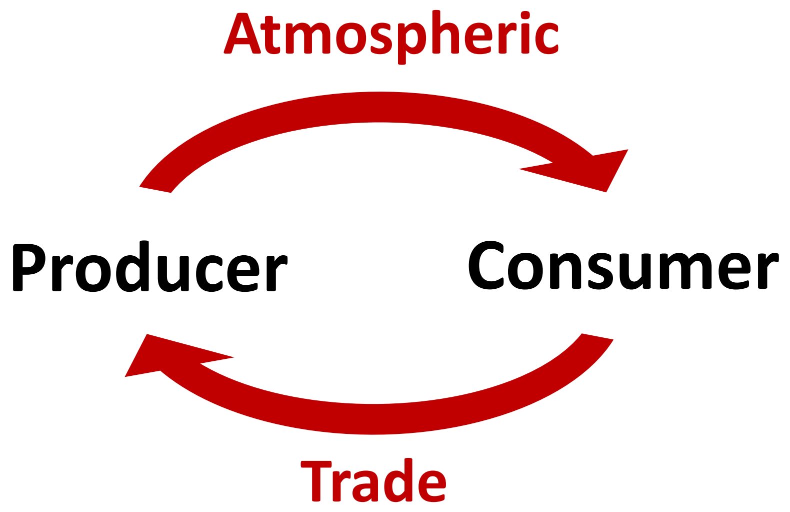
Production → Impacts ← Consumption



- 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

- Could trade-associated redistribution of emissions and impacts occur for greenhouse gases? Any differences from transboundary air pollution?
- Any synergy and/or trade-off between transboundary greenhouse gases and air pollution, including impacts and mitigation?
- How can climate change respond and feedback to the transboundary pollution via synergy of trade and transport?
- Roles of industries, sectors and individual consumers in pollution and mitigation
- Challenges in calculating and verifying production-based and consumption-based pollution. What are the uncertainties due to integration of theory, method and data from multiple disciplines? How can satellite remote sensing improve quantification of trade-related pollution?
- How can AI help assess the transboundary pollution, their impacts and associated uncertainties? Will AI-based Monte Carlo simulations play a role?
- Prospects and challenges of inter-regional (or global) agreement to mitigate transboundary pollution. How can China play a role?
- Should consumption-based pollution accounting be part of environmental policymaking?

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

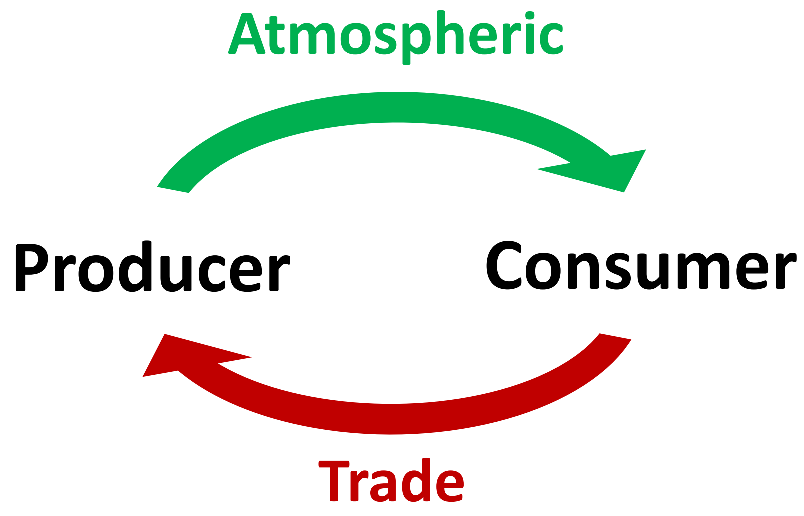
↓

Global Change

Consumption & trade re-locates pollution

from consumers to producers

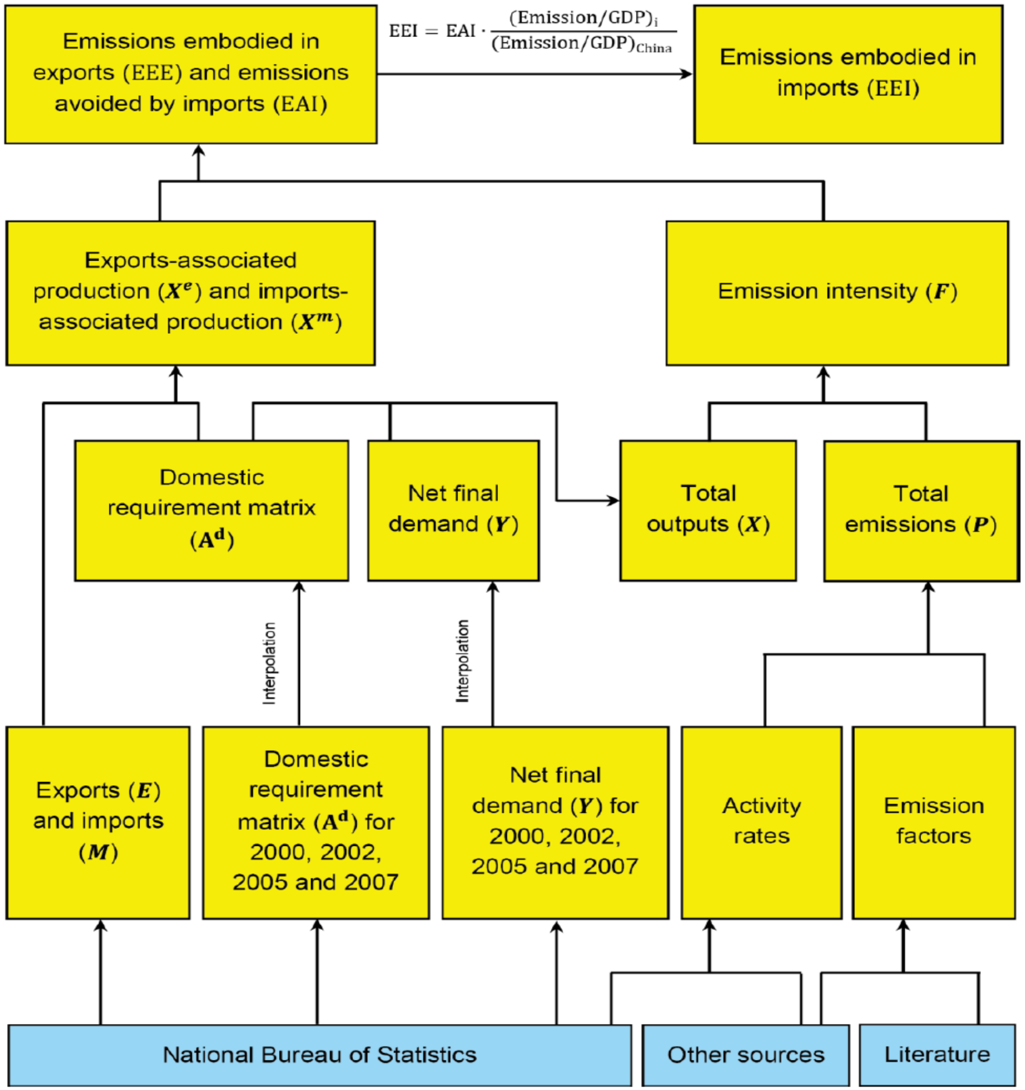
Globalizing Air Pollution



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

Lin et al., 2014, PNAS

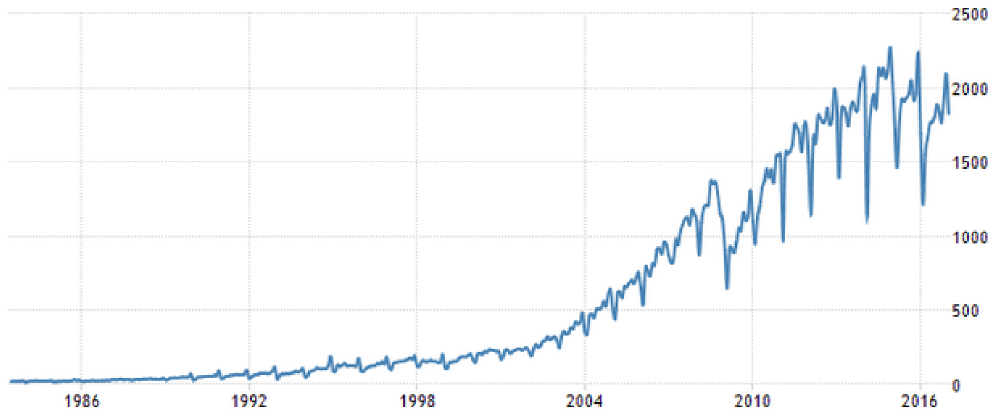
Calculating Emissions Embodied in Bilateral Trade of China Based on Bilateral Trade



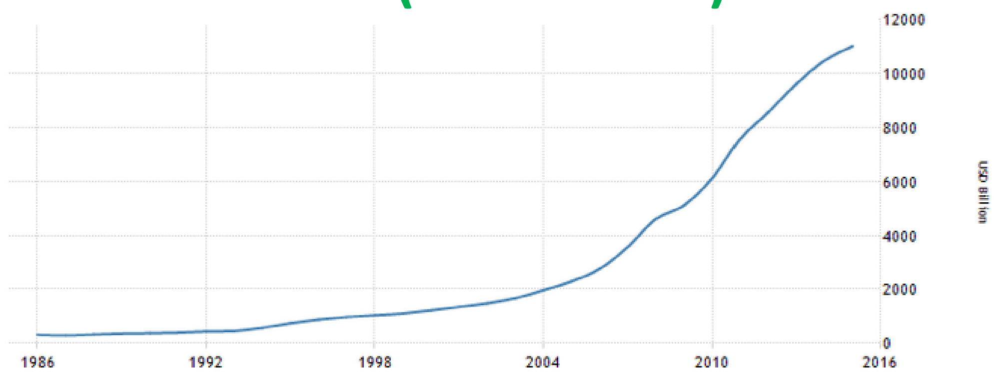
Lin et al., 2014, PNAS

Export and Total GDP of China

Export volume (Billion USD)



Total GDP (Billion USD)



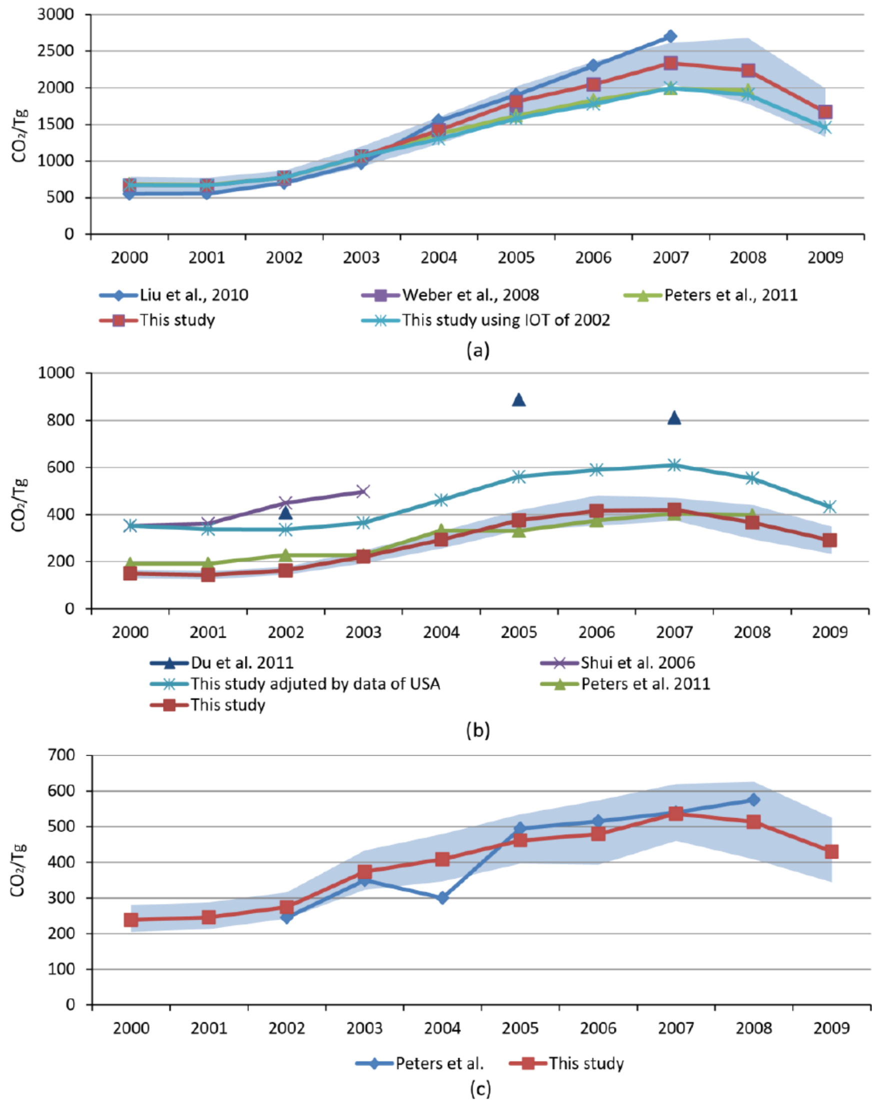
Source: Xujia Jiang

China's Export- and Import-related CO_2 Emissions

Export

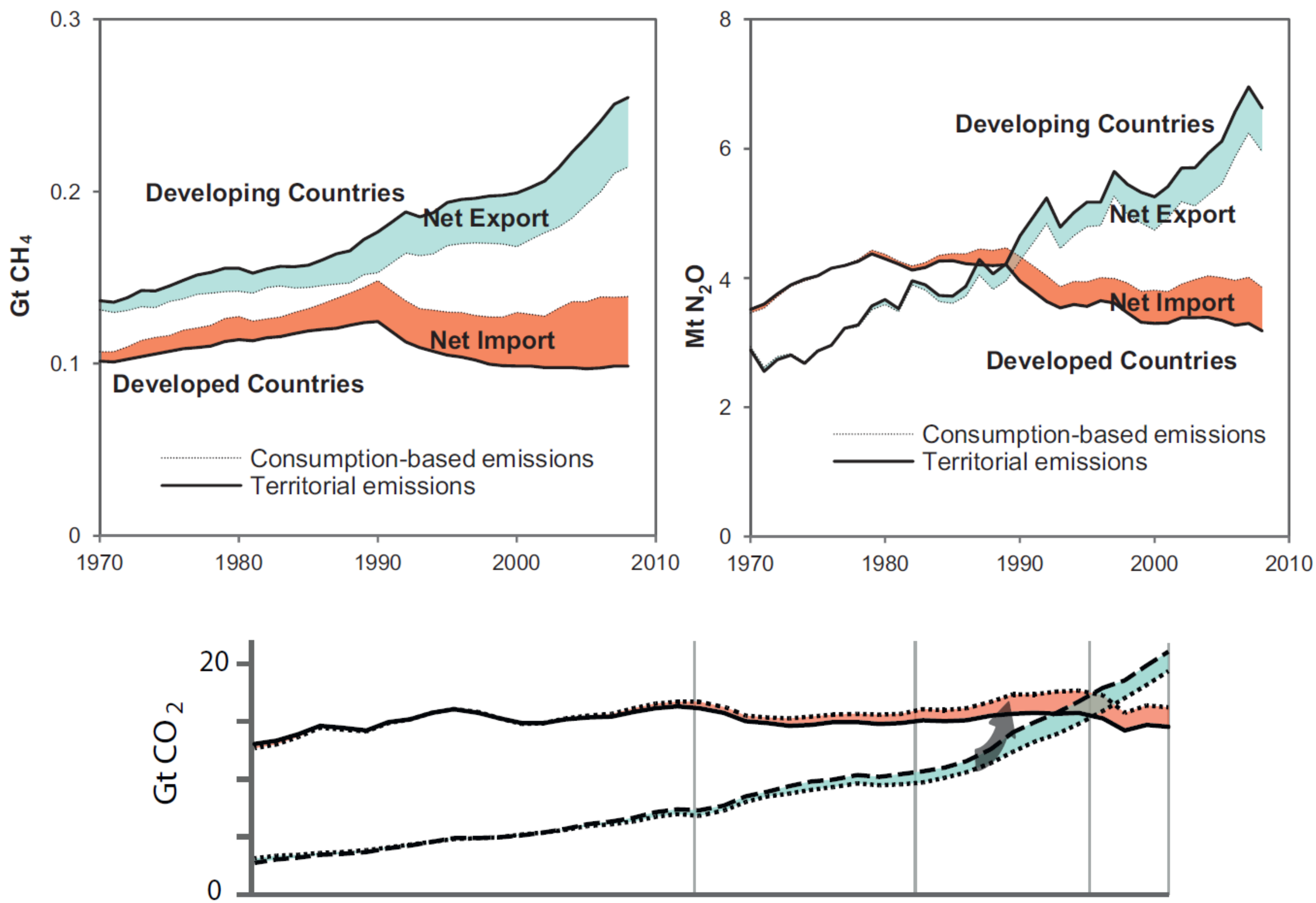
Import

Net Export



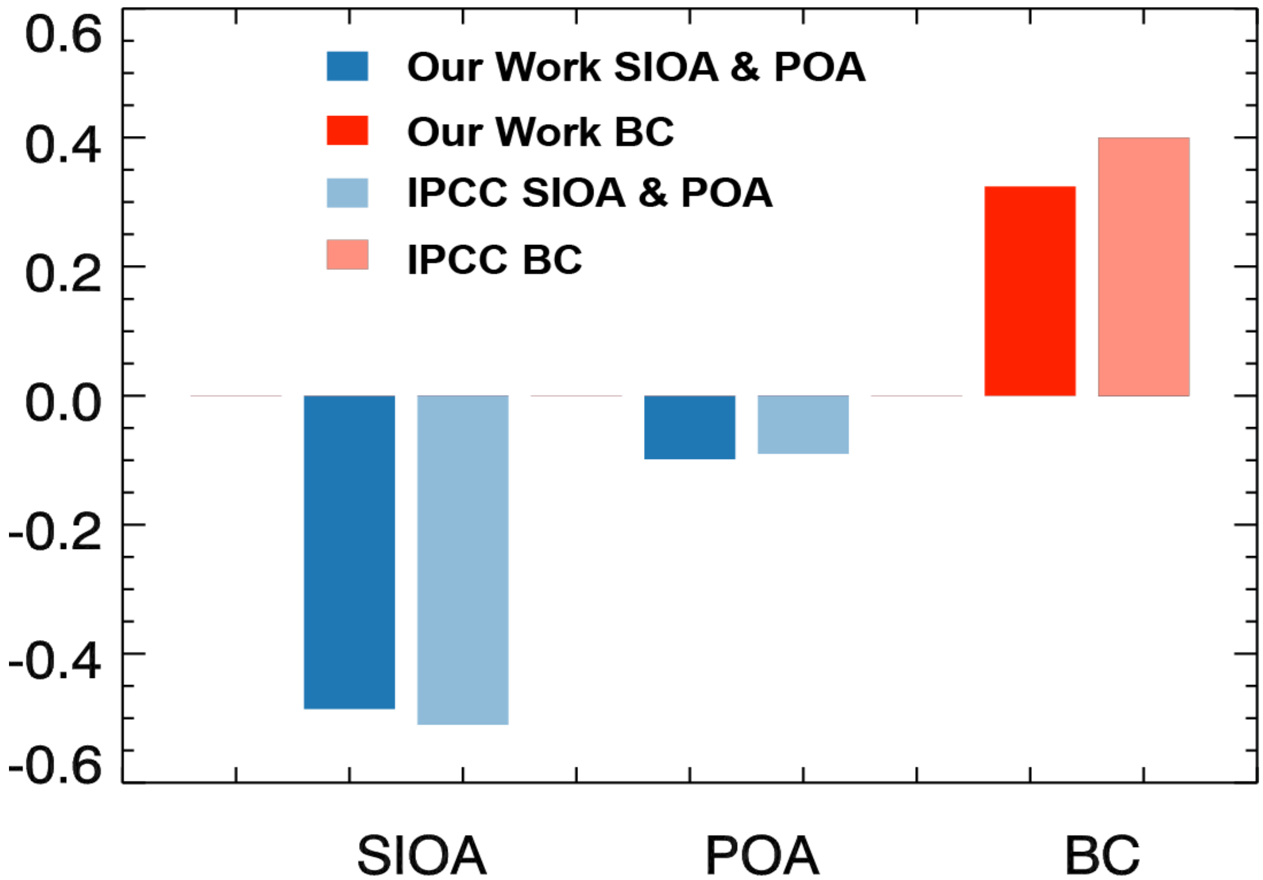
Lin et al., 2014, PNAS

Consumption and Trade Drives Emission Redistribution



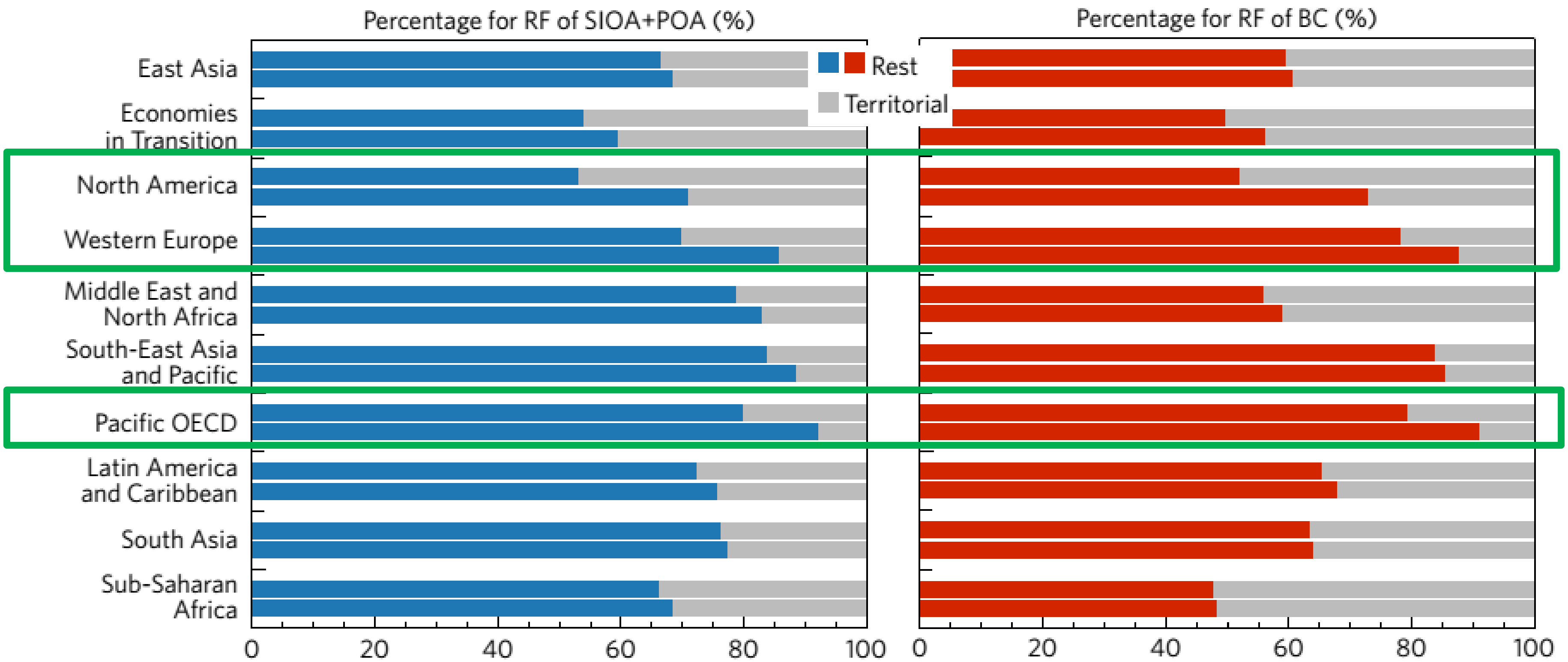
Kanemoto et al., 2014, GEC

TOA Direct RF of SIOA, POA, and BC



Lin et al., 2016, Nature Geoscience

Trade Transfers RF from Rich to Poorer Regions

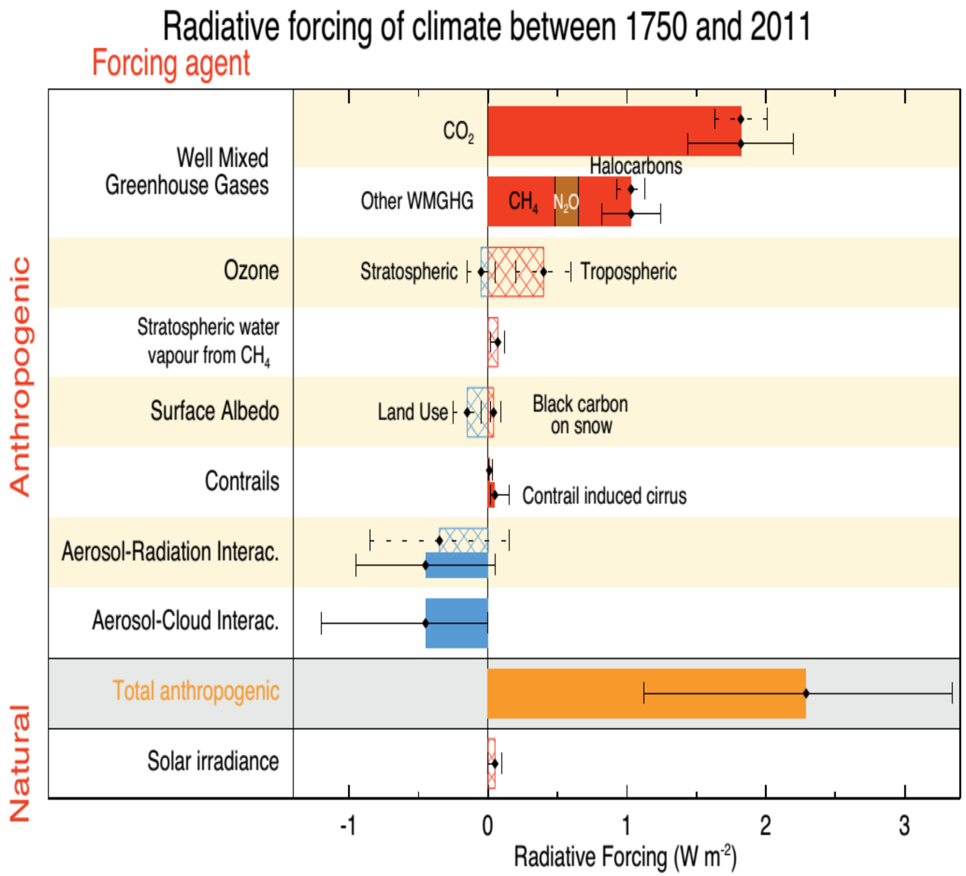


- Stronger *cumulated RF* outside than within the source region
- Terrestrial share is much reduced from RF_p to RF_c

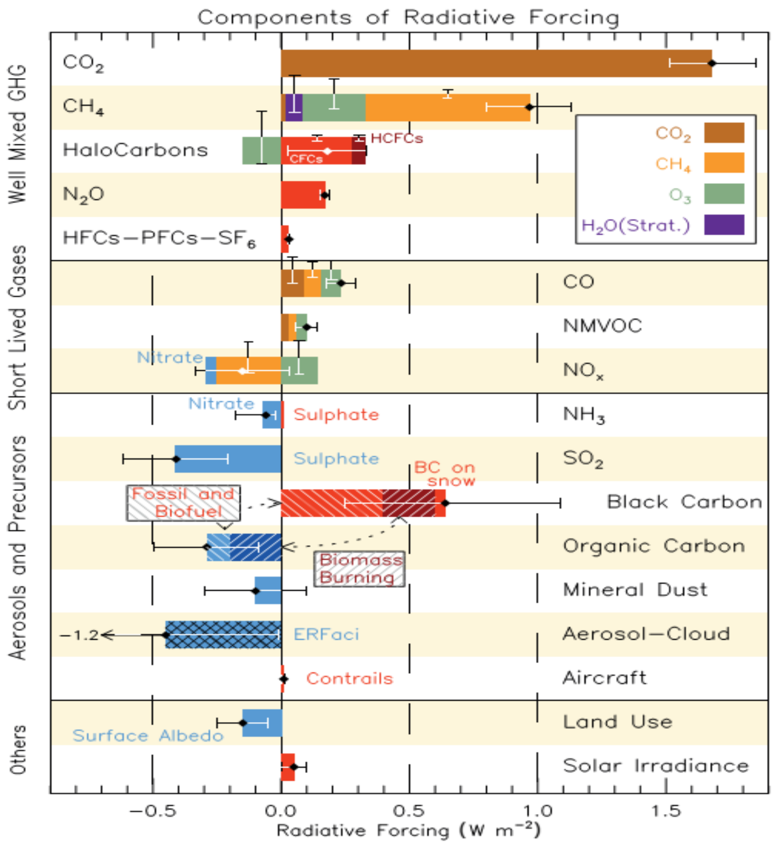
Lin et al., 2016, Nature Geoscience

Air Pollutants Exert Strong Radiative Forcing

Based on concentration change



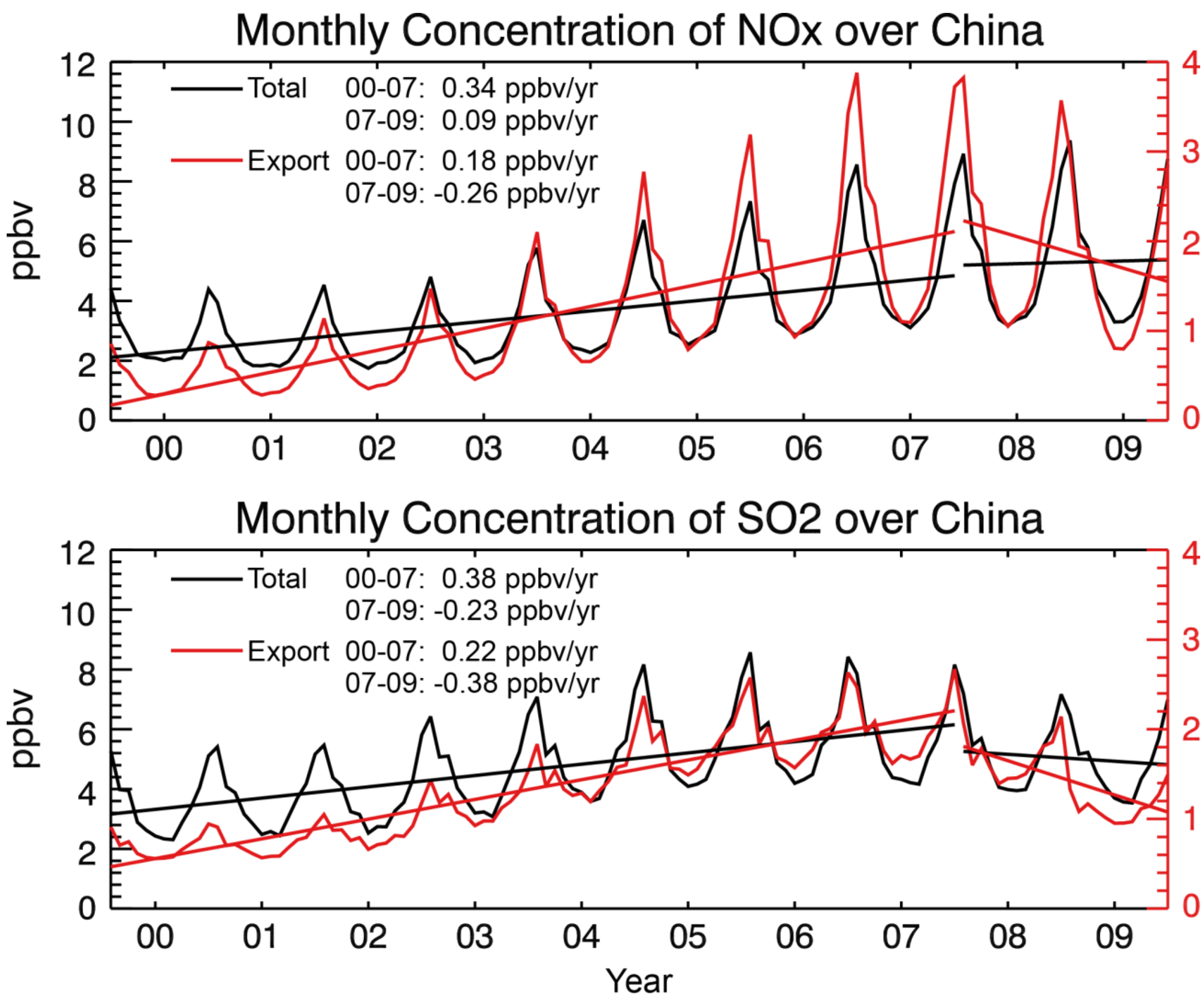
Based on emission change



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

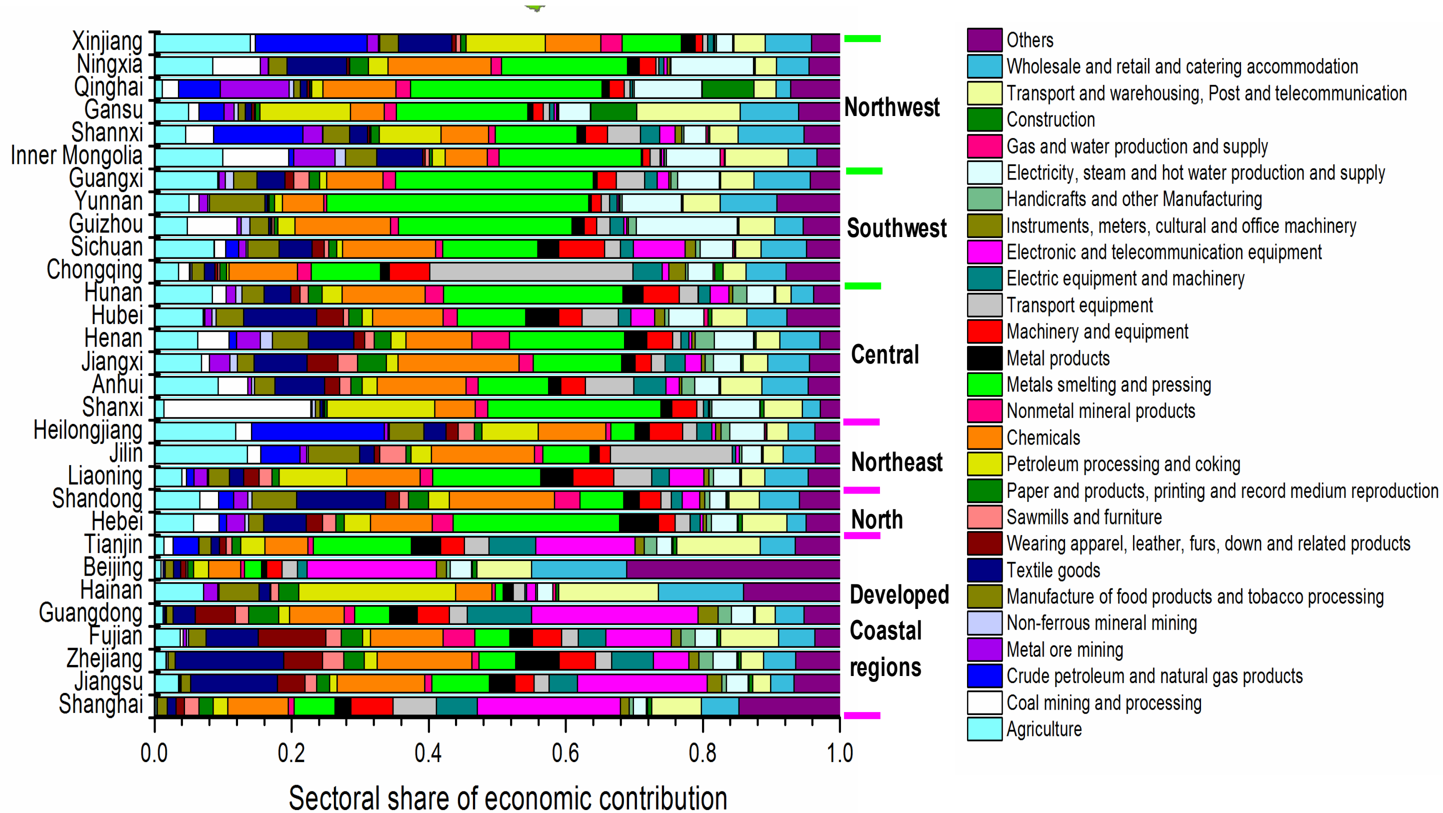
IPCC, 2013

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

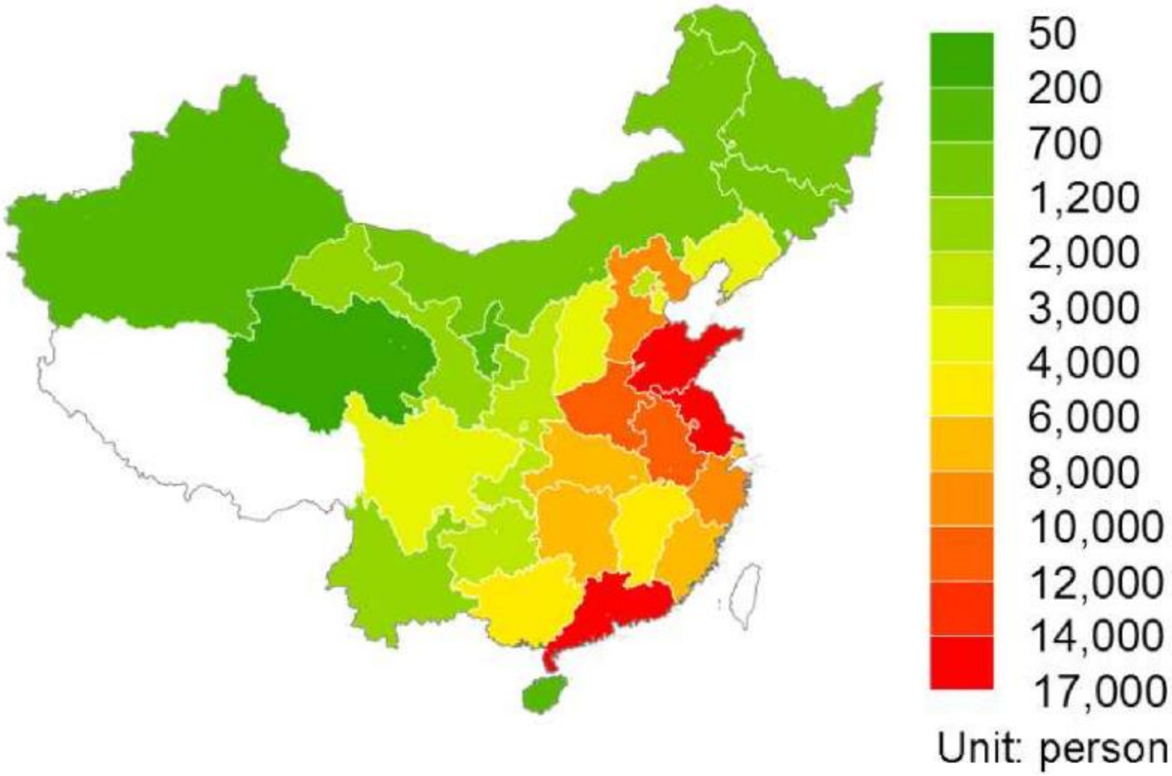
EX-related sectors in coastal provinces

- Electronics and other downstream (final) products

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

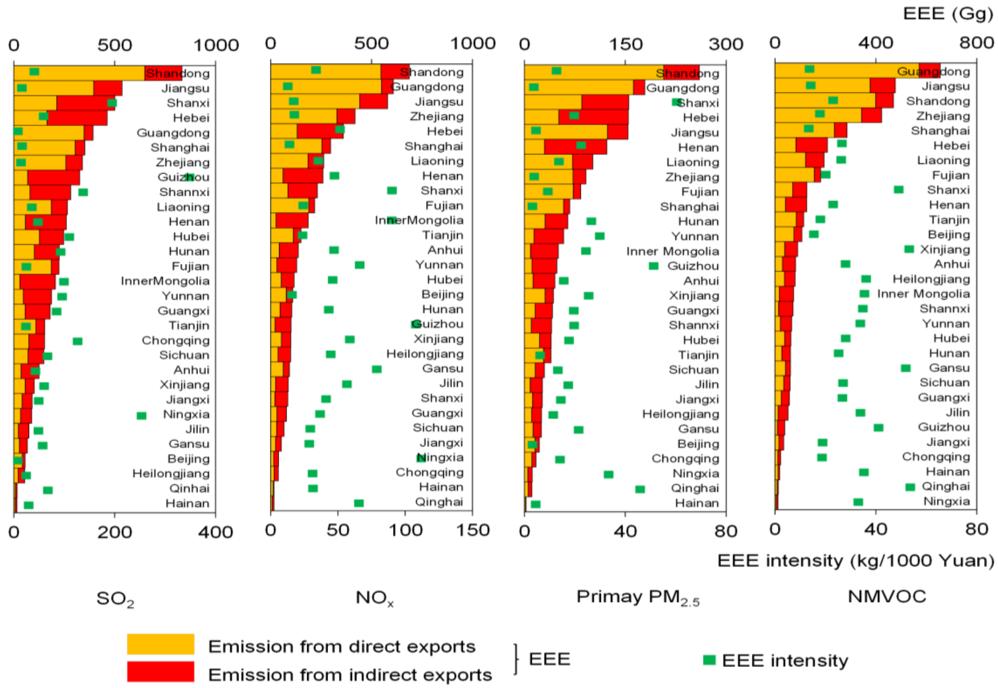
China's Inter-provincial Trade for Export Causes A Large Quantity of Deaths

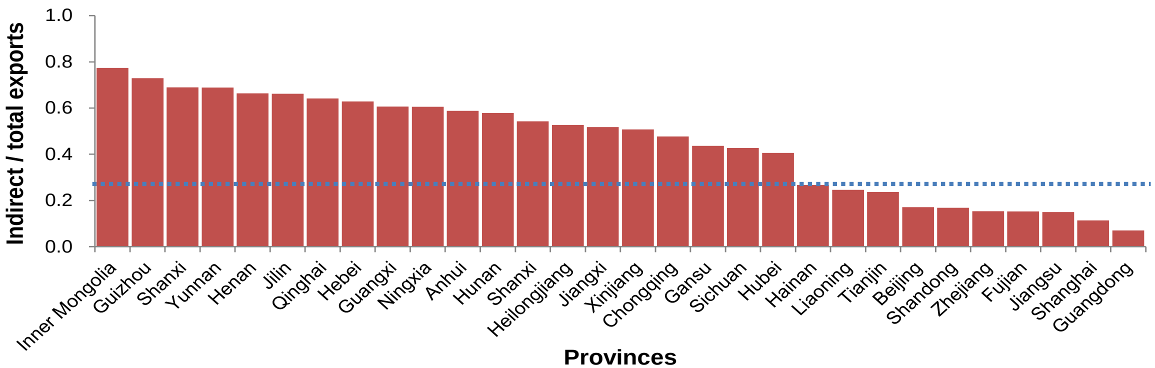
China's export-related death toll in 2007 = 157,000, larger than all deaths in the US and the UK from ambient PM and O_3



Jiang et al., EST, 2015

Inter-Provincial Disparity in Export-related Emissions

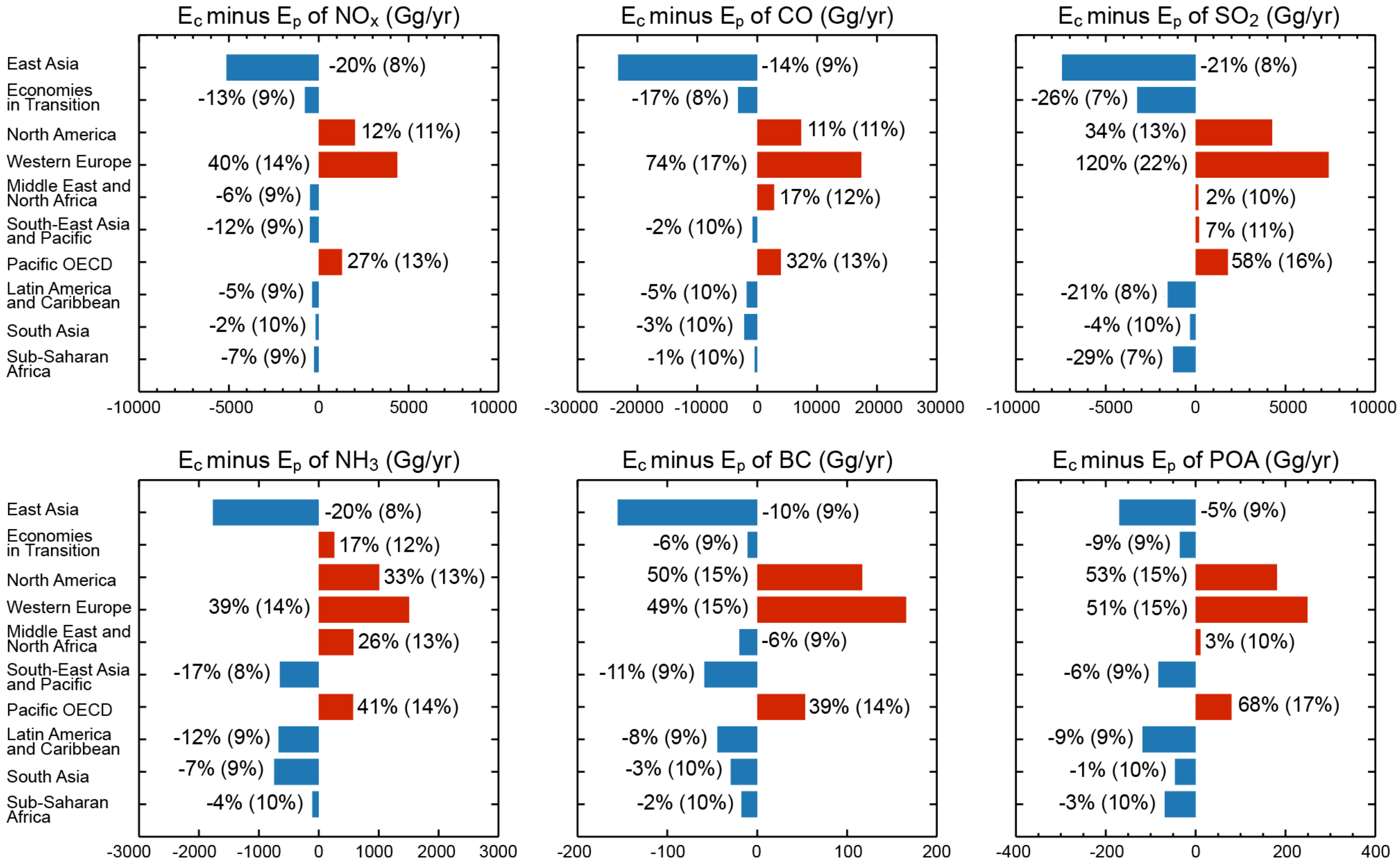




Zhao et al., 2015, ACP; Jiang et al., EST, 2015

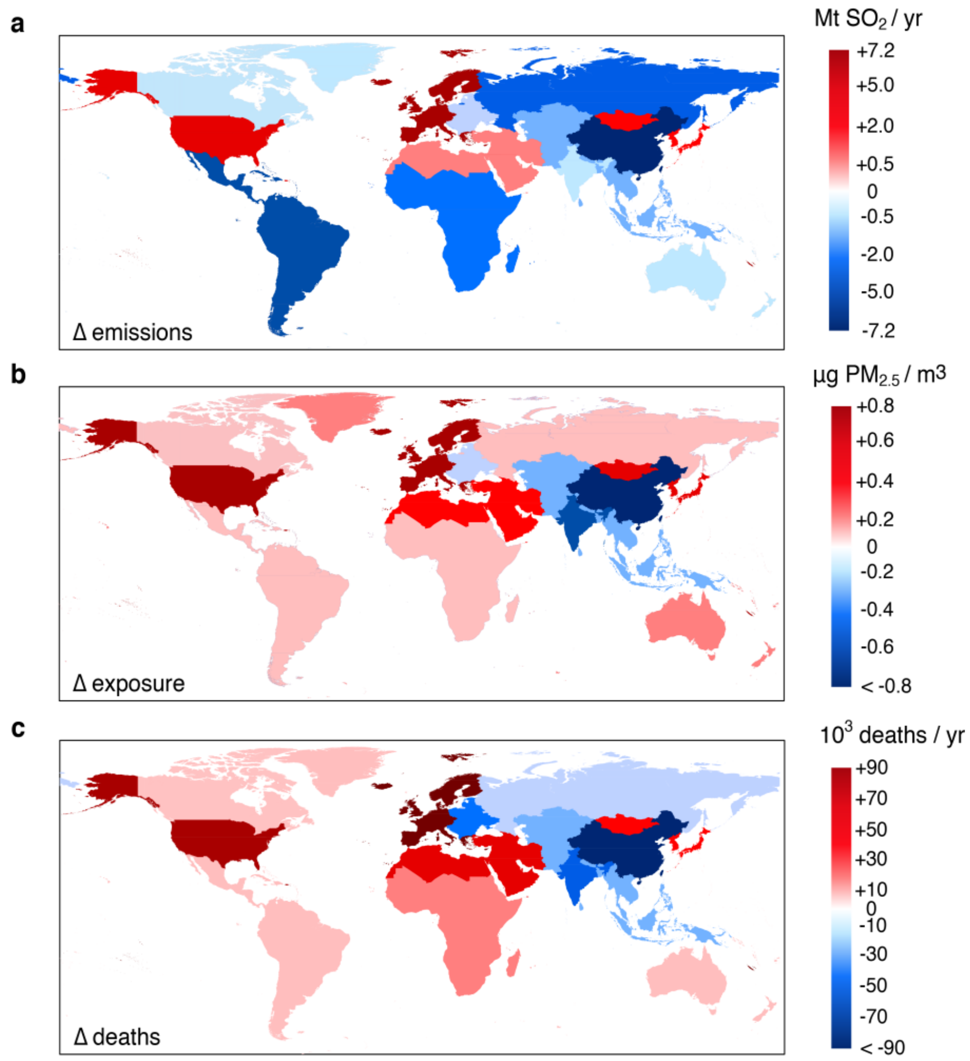
Trade Transfers Emissions from Rich to Poorer Regions

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

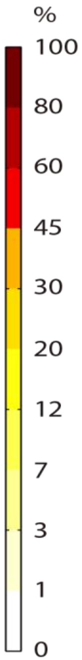
- A region's RF is largely due to emissions in other regions
- A region's RF_c is much more spreaded spatially than RF_p

Percentage RF_p of SIOA+POA

Source Region \ Recption Region	East Asia	Economies in Transition	North America	Western Europe	Middle East and North Africa	South-East Asia and Pacific	Pacific OECD	Latin America and Caribbean	South Asia	Sub-Saharan Africa	Rest of World	
	-73	-51	-39	-15	-20	-7	-6	-16	-34	-28	-294	
East Asia	79.9%	22.6%	24.3%	9.1%	5.7%	40.3%	29.0%	4.4%	2.2%	2.3%	28.9%	-174
Economies in Transition	3.3%	36.7%	3.6%	11.1%	8.7%	0.4%	1.6%	0.3%	1.5%	2.9%	4.5%	-41
North America	0.6%	3.4%	47.5%	4.6%	2.0%	0.1%	0.5%	2.5%	0.3%	0.5%	5.8%	-40
Western Europe	0.6%	10.7%	1.2%	59.3%	7.2%	0.1%	0.5%	0.2%	0.2%	2.6%	4.3%	-30
Middle East and North Africa	2.9%	13.8%	3.5%	5.3%	56.5%	1.1%	1.5%	1.0%	6.7%	20.4%	7.6%	-53
South-East Asia and Pacific	1.1%	0.5%	0.9%	0.5%	0.9%	36.7%	3.3%	1.6%	0.6%	1.3%	3.7%	-16
Pacific OECD	0.3%	0.3%	0.3%	0.1%	0.0%	0.4%	37.8%	0.4%	0.0%	0.1%	3.0%	-12
Latin America and Caribbean	0.4%	0.8%	3.8%	1.0%	1.4%	0.5%	6.3%	77.5%	0.4%	2.4%	9.6%	-44
South Asia	10.4%	10.4%	14.1%	8.3%	14.0%	19.2%	7.8%	7.0%	87.2%	8.7%	22.9%	-125
Sub-Saharan Africa	0.5%	0.7%	0.9%	0.7%	3.5%	1.3%	11.7%	5.0%	0.9%	58.9%	9.7%	-49

Percentage RF_c of SIOA+POA

Source Region \ Recption Region	East Asia	Economies in Transition	North America	Western Europe	Middle East and North Africa	South-East Asia and Pacific	Pacific OECD	Latin America and Caribbean	South Asia	Sub-Saharan Africa	Rest of World	
	-72	-51	-40	-16	-20	-7	-6	-16	-35	-28	-300	
East Asia	62.2%	18.7%	19.6%	7.7%	5.9%	31.9%	25.5%	5.9%	2.7%	3.9%	23.5%	-142
Economies in Transition	3.4%	26.8%	3.1%	9.9%	7.1%	1.0%	2.2%	1.2%	1.3%	2.7%	4.0%	-34
North America	5.9%	6.7%	43.5%	6.7%	4.8%	5.0%	6.1%	9.9%	2.5%	3.8%	9.6%	-60
Western Europe	6.2%	17.3%	5.7%	56.2%	13.2%	5.4%	7.7%	7.6%	3.6%	9.4%	9.7%	-62
Middle East and North Africa	3.9%	13.6%	4.3%	6.0%	45.7%	2.6%	4.1%	2.9%	6.8%	17.1%	7.8%	-53
South-East Asia and Pacific	1.9%	1.1%	1.4%	0.9%	1.3%	29.1%	4.9%	2.1%	1.0%	1.8%	3.9%	-18
Pacific OECD	3.8%	2.4%	2.7%	1.5%	2.0%	3.5%	26.0%	2.3%	1.0%	2.2%	4.3%	-22
Latin America and Caribbean	1.2%	1.6%	4.7%	1.7%	1.9%	1.2%	5.0%	56.0%	0.7%	2.4%	7.4%	-37
South Asia	10.4%	10.6%	13.6%	8.1%	14.3%	18.4%	9.4%	7.3%	79.0%	9.4%	21.8%	-121
Sub-Saharan Africa	1.0%	1.2%	1.2%	1.1%	3.9%	1.8%	9.1%	4.8%	1.4%	47.2%	7.9%	-42



Lin et al., 2016, Nature Geoscience

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

Percentage RF_p of BC

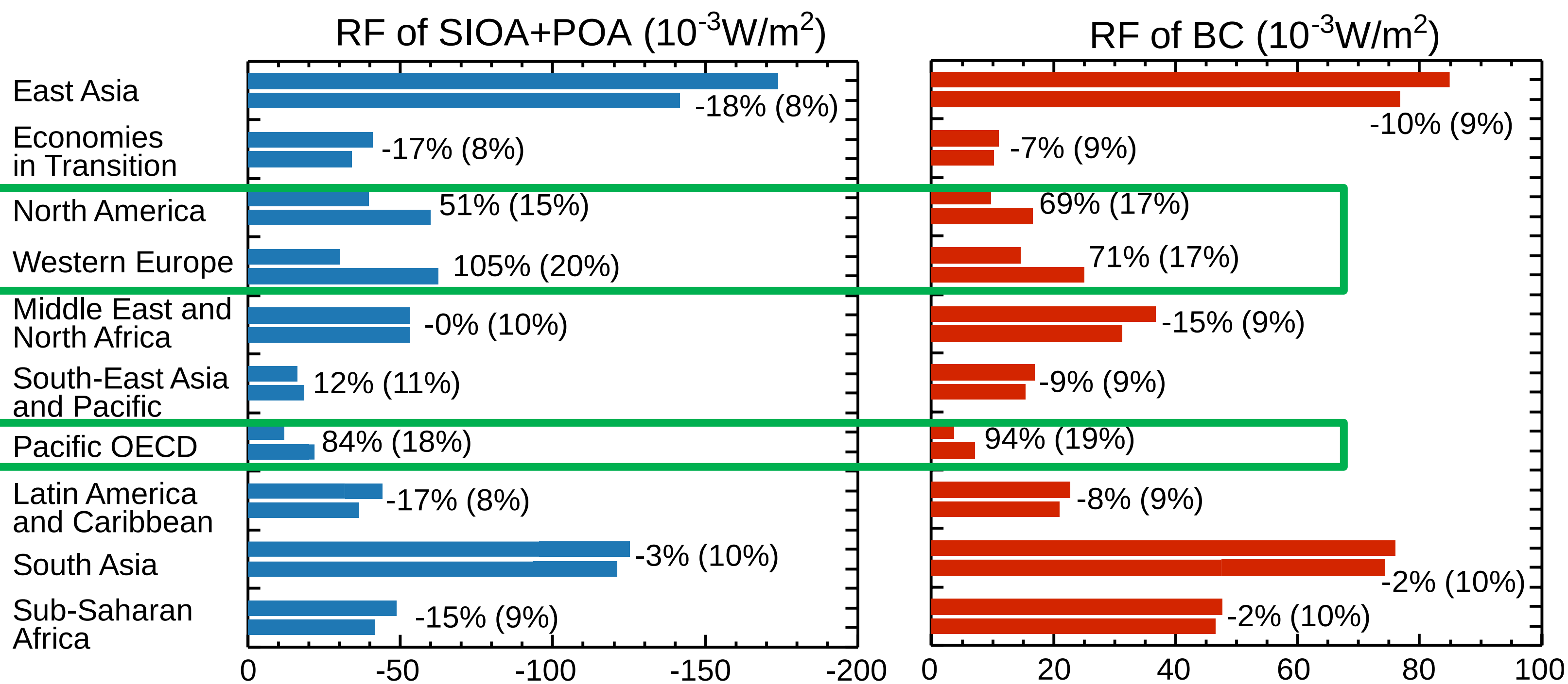
Source Region \ Recption Region	East Asia	Economies in Transition	North America	Western Europe	Middle East and North Africa	South-East Asia and Pacific	Pacific OECD	Latin America and Caribbean	South Asia	Sub-Saharan Africa	Rest of World	
	44	24	15	5	31	6	3	10	31	39	117	
East Asia	78.4%	28.1%	33.3%	11.5%	5.8%	27.6%	27.3%	3.7%	1.8%	2.3%	27.5%	85
Economies in Transition	1.4%	23.2%	2.5%	6.1%	3.5%	0.1%	0.6%	0.1%	0.5%	1.1%	2.2%	11
North America	**0.4%**	2.7%	30.5%	3.3%	1.3%	0.0%	0.3%	1.4%	0.1%	0.4%	2.9%	10
Western Europe	**0.7%**	13.0%	2.3%	59.9%	8.2%	0.0%	0.5%	0.1%	0.2%	3.1%	3.3%	15
Middle East and North Africa	2.7%	15.8%	4.9%	6.3%	52.7%	0.5%	1.7%	0.7%	3.8%	15.8%	6.0%	37
South-East Asia and Pacific	2.0%	1.5%	2.6%	1.3%	1.8%	48.7%	11.4%	3.3%	1.0%	2.0%	8.7%	17
Pacific OECD	**0.4%**	0.8%	1.0%	0.3%	0.1%	0.2%	25.0%	0.2%	0.0%	0.0%	2.0%	4
Latin America and Caribbean	0.4%	1.3%	4.4%	1.4%	1.6%	0.4%	8.1%	76.8%	0.3%	1.8%	10.3%	23
South Asia	12.6%	11.3%	16.3%	8.2%	15.8%	21.0%	8.8%	6.2%	90.9%	8.8%	22.8%	76
Sub-Saharan Africa	0.9%	2.2%	2.2%	1.8%	9.2%	1.4%	16.4%	7.4%	1.4%	64.6%	14.4%	48

Percentage RF_c of BC

Source Region \ Recption Region	East Asia	Economies in Transition	North America	Western Europe	Middle East and North Africa	South-East Asia and Pacific	Pacific OECD	Latin America and Caribbean	South Asia	Sub-Saharan Africa	Rest of World	
	43	24	15	5	31	6	3	10	31	39	117	
East Asia	69.4%	25.7%	30.0%	10.6%	6.1%	25.6%	25.4%	4.7%	1.9%	2.7%	24.9%	77
Economies in Transition	1.6%	18.8%	2.4%	6.0%	3.6%	0.5%	1.0%	0.8%	0.5%	1.3%	2.2%	10
North America	**3.2%**	5.0%	28.9%	5.1%	4.6%	3.1%	3.2%	4.8%	1.2%	2.1%	5.0%	17
Western Europe	**3.7%**	17.0%	5.5%	57.2%	13.6%	3.9%	4.4%	4.3%	1.8%	6.1%	6.4%	25
Middle East and North Africa	3.0%	14.0%	4.8%	6.2%	41.3%	1.3%	2.4%	1.8%	3.6%	12.6%	5.5%	31
South-East Asia and Pacific	2.2%	1.7%	2.6%	1.5%	2.0%	40.1%	10.6%	3.2%	1.1%	1.9%	7.7%	15
Pacific OECD	**2.1%**	2.1%	2.4%	1.3%	1.7%	2.2%	21.1%	1.3%	0.4%	0.8%	2.9%	7
Latin America and Caribbean	0.9%	1.8%	5.0%	1.8%	2.1%	0.9%	7.3%	65.2%	0.5%	1.9%	9.3%	21
South Asia	12.7%	11.4%	16.0%	8.2%	15.7%	20.6%	9.2%	6.3%	87.4%	8.7%	22.2%	74
Sub-Saharan Africa	1.2%	2.5%	2.5%	2.1%	9.3%	1.9%	15.3%	7.6%	1.6%	62.0%	13.8%	47

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

a

Rows: Region where pollution was produced. Columns: Region where deaths occurred.

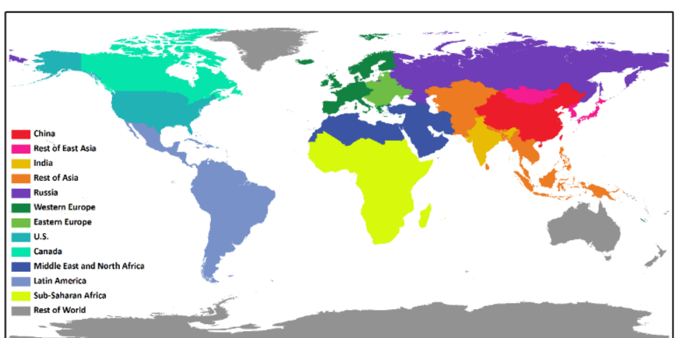
	China	Rest of East Asia	India	Rest of Asia	Russia	W. Europe	E. Europe	Middle East +	U.S.	Canada	Latin America	Sub-Saharan Africa	Rest of World	Total deaths
	994,133	76,231	463,391	276,260	101,444	173,692	196,412	76,875	77,760	8,119	50,218	20,229	721	
China	96.5	40.5	0.9	7.7	3.2	0.8	0.7	0.9	2.2	2.0	0.5	0.2	0.1	1,023,689
Rest of East Asia	1.0	55.5	0.0	0.1	0.2	0.1	0.1	0.1	0.2	0.2	0.0	0.0	0.0	53,224
India	0.2	0.1	85.5	26.3	0.1	0.1	0.1	0.3	0.1	0.1	0.1	1.2	0.0	471,484
Rest of Asia	0.9	0.6	11.6	60.5	4.3	0.1	0.3	1.4	0.2	0.3	0.1	0.4	0.1	236,467
Russia	0.5	1.4	0.0	0.6	60.2	0.7	4.8	1.9	0.3	0.6	0.0	0.0	0.0	80,949
W. Europe	0.2	0.4	0.0	0.1	6.5	85.4	24.1	8.3	0.2	0.4	0.0	0.4	0.0	211,639
E. Europe	0.1	0.4	0.1	0.3	20.7	9.8	66.1	8.3	0.2	0.3	0.0	0.4	0.0	177,205
Middle East +	0.3	0.6	1.7	4.0	3.9	1.4	2.6	77.7	0.4	0.5	0.1	4.7	0.0	95,433
U.S.	0.3	0.4	0.1	0.2	0.8	1.3	1.0	0.8	88.9	47.2	1.9	0.1	0.0	83,808
Canada	0.0	0.1	0.0	0.0	0.1	0.2	0.2	0.1	6.2	48.2	0.1	0.0	0.0	10,090
Latin America	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	1.0	0.1	96.6	0.1	0.9	50,627
Sub-Saharan Africa	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.3	92.5	1.4	19,899
Rest of World	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	97.5	971

Consumption Perspective

b

Rows: Region where goods were consumed. Columns: Region where deaths occurred.

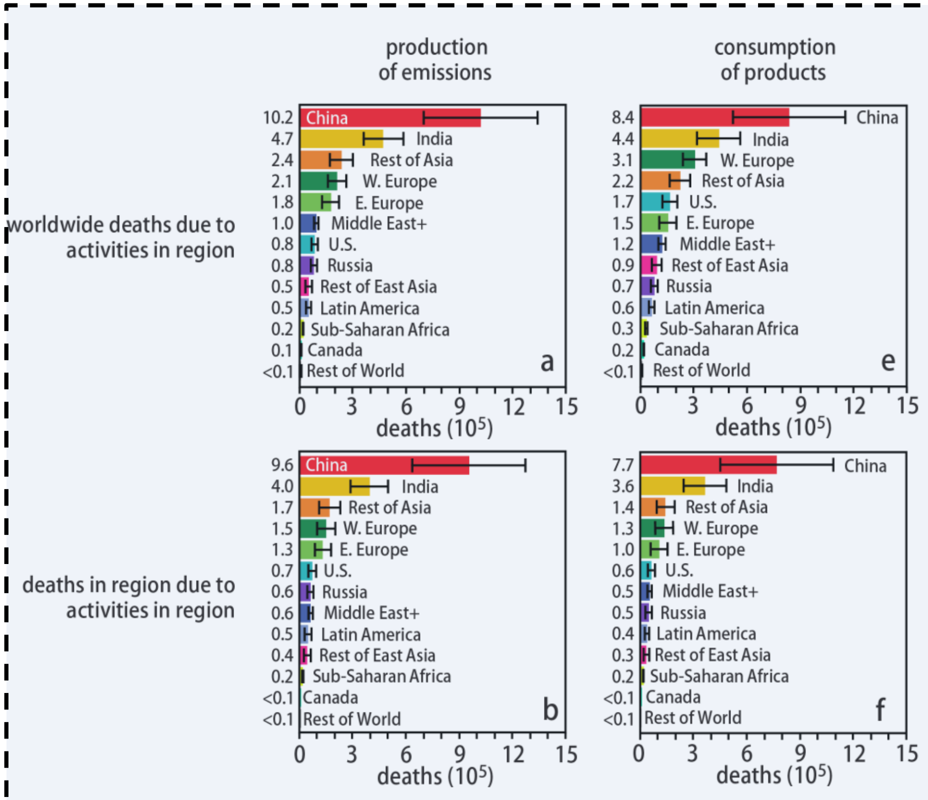
	China	Rest of East Asia	India	Rest of Asia	Russia	W. Europe	E. Europe	Middle East +	U.S.	Canada	Latin America	Sub-Saharan Africa	Rest of World	Total deaths
	1,007,500	72,309	470,481	268,728	97,378	171,586	194,074	77,037	81,202	7,790	48,560	19,870	730	
China	76.4	34.3	1.5	7.2	4.0	1.4	1.2	1.8	3.3	3.3	2.3	1.1	5.6	835,110
Rest of East Asia	3.9	47.4	0.6	1.4	1.5	0.9	0.7	1.2	2.4	2.7	1.3	0.8	6.0	88,657
India	0.6	0.5	77.4	25.1	0.5	0.4	0.4	1.1	0.4	0.6	0.5	1.5	2.6	441,900
Rest of Asia	2.1	1.8	10.7	51.9	4.2	0.8	1.0	1.9	1.0	1.4	0.7	0.8	3.6	223,108
Russia	1.0	1.6	0.2	0.8	46.3	1.3	5.3	2.3	0.4	0.6	0.4	0.2	0.4	74,006
W. Europe	5.4	4.9	3.0	3.9	14.4	77.0	29.7	14.9	4.1	5.4	5.5	3.7	6.0	304,940
E. Europe	0.7	0.8	0.3	0.7	17.7	9.3	52.8	7.0	0.5	0.6	0.4	0.5	0.4	152,349
Middle East +	1.8	1.8	2.9	4.5	6.8	3.0	4.6	63.9	1.8	2.1	1.4	4.1	2.7	118,053
U.S.	5.4	4.6	2.1	2.8	3.1	3.7	2.7	3.7	77.1	52.3	11.0	1.7	4.1	164,931
Canada	0.5	0.4	0.2	0.3	0.3	0.4	0.3	0.3	4.6	27.1	0.7	0.2	0.5	15,144
Latin America	1.1	1.0	0.4	0.5	0.8	0.9	0.7	0.8	3.7	2.9	74.9	0.5	1.4	58,913
Sub-Saharan Africa	0.6	0.5	0.6	0.6	0.4	0.6	0.4	0.7	0.4	0.5	0.7	84.8	1.4	30,752
Rest of World	0.5	0.5	0.2	0.4	0.2	0.3	0.2	0.2	0.3	0.3	0.2	0.1	65.2	9,382



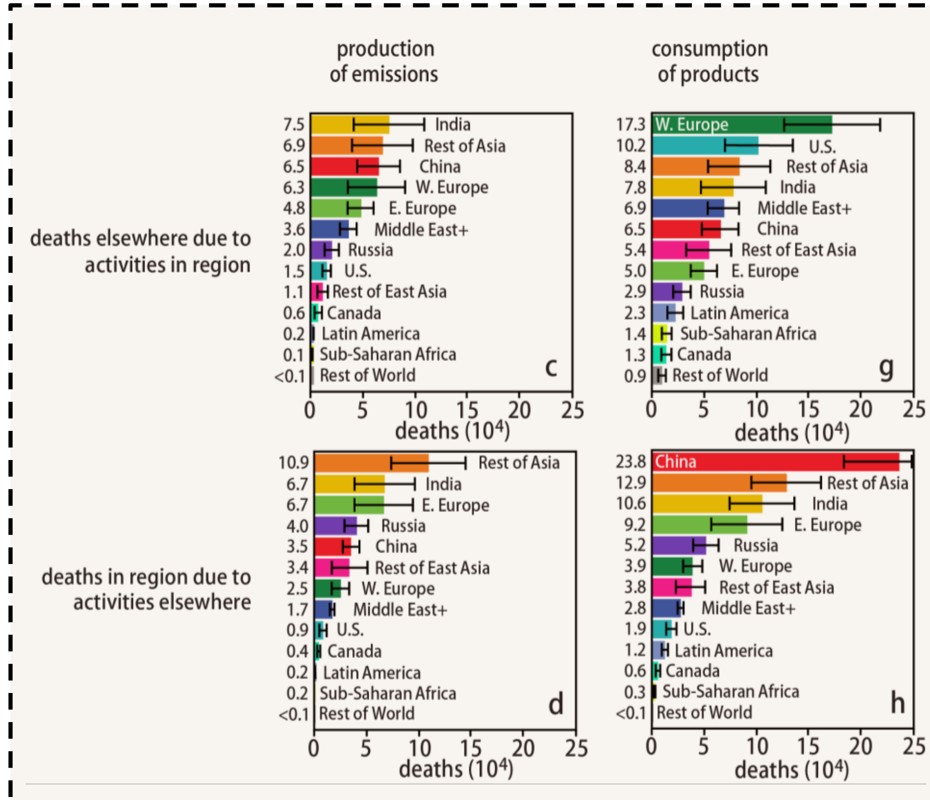
Zhang et al., 2017, Nature

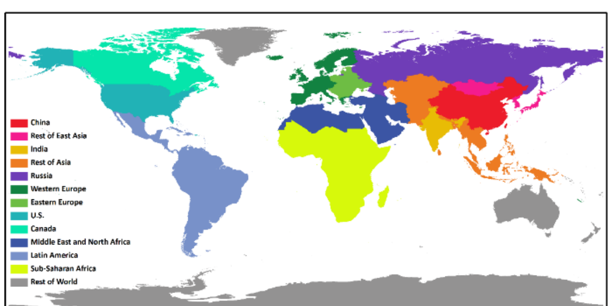
Transport and Trade are Related to Large Deaths

Local as “source”



Local as “receptor”





Zhang et al., 2017, Nature