Globalizing Air Pollution

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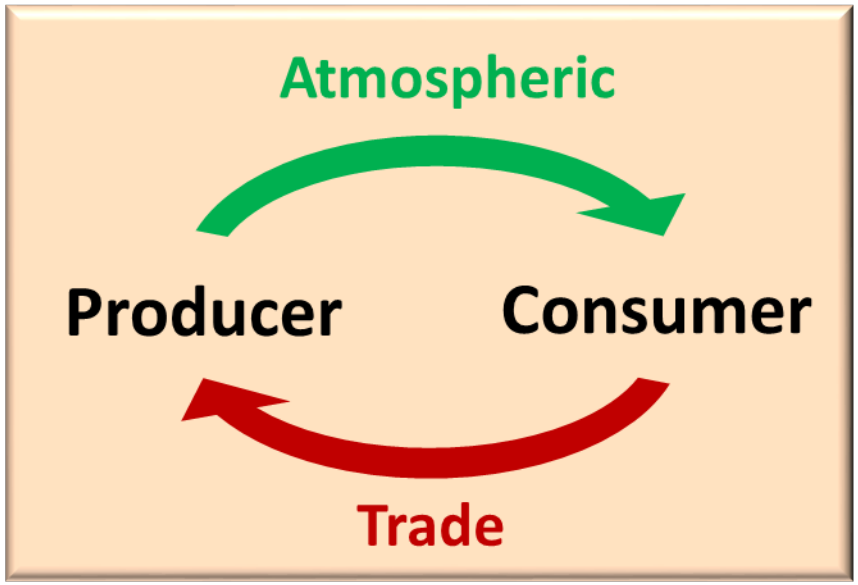
- **Europe:** D. Guan, Z. Liu …
- **Funding:** NSFC 41175127, 41422502, etc.

Globalizing Air Pollution

Advanced Satellite

High-Res Modeling



Pollution

Climate

Ecosystem

Regional

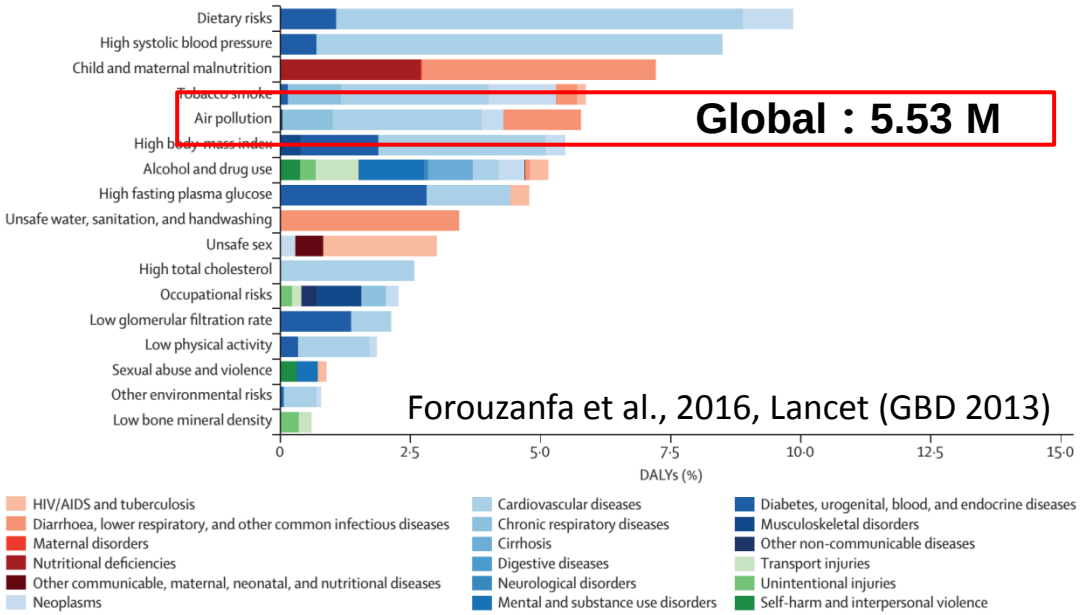
Historical

Future

Integrated Trade-Emission-Pollution Modeling

Haze Approaching !

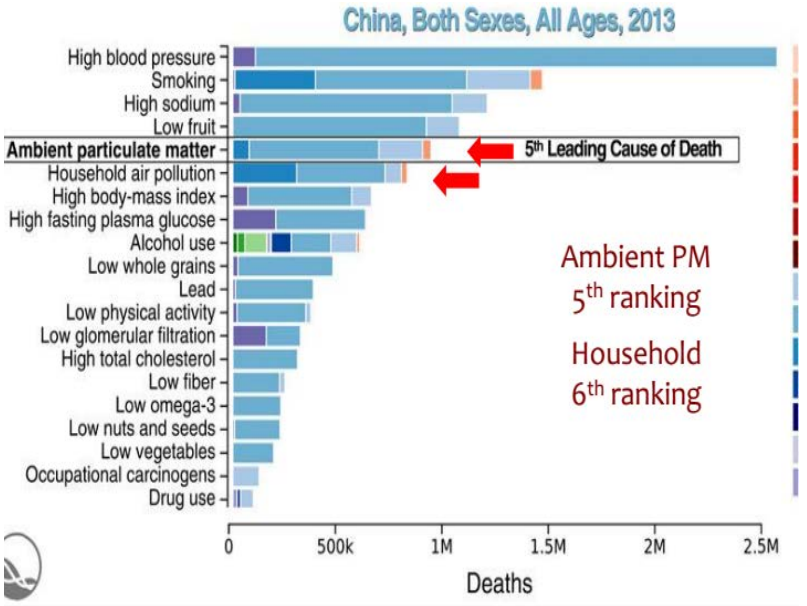
Air Pollution: Health Impacts



	1990 deaths (in thousands)	2013 deaths (in thousands)
Air pollution	**4808 (4459 to 5157)**	**5527 (5109 to 5944)**
Ambient particulate matter pollution	2238 (2154 to 2317)	2926 (2777 to 3066)
Household air pollution from solid fuels	2857 (2482 to 3216)	2893 (2463 to 3303)
Ambient ozone pollution	133 (105 to 162)	217 (161 to 272)

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

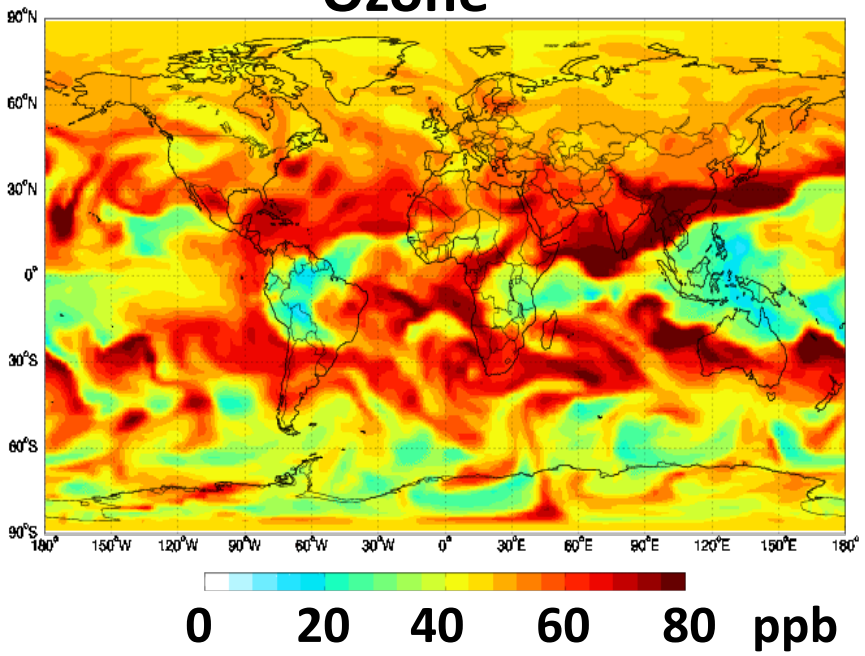
China Contributes 1/3 of Global PM-related Premature Deaths



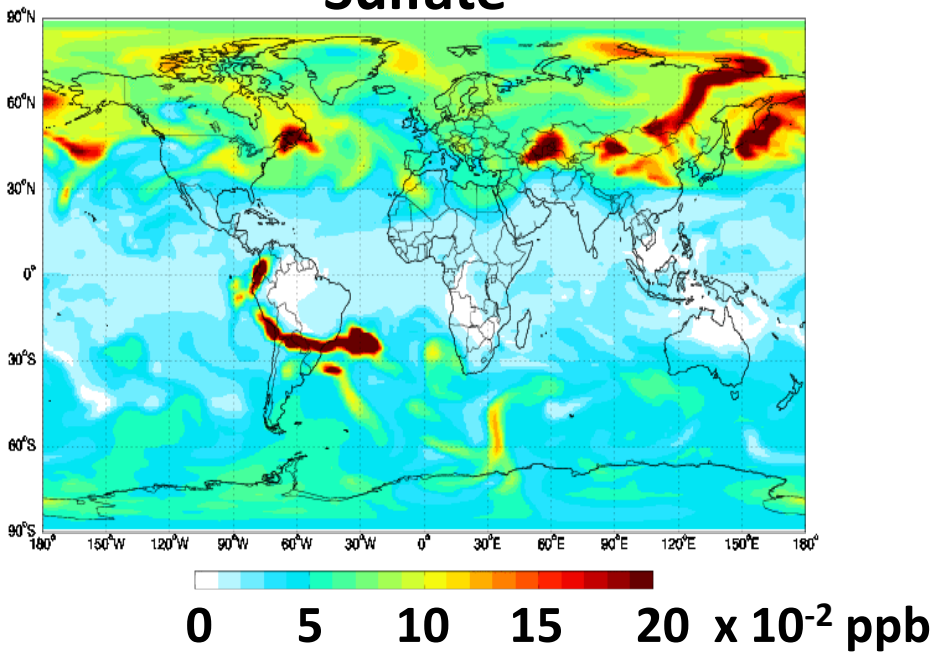
Atmospheric Transport

Mid-tropospheric Pollution in Jan 2009

Ozone



Sulfate



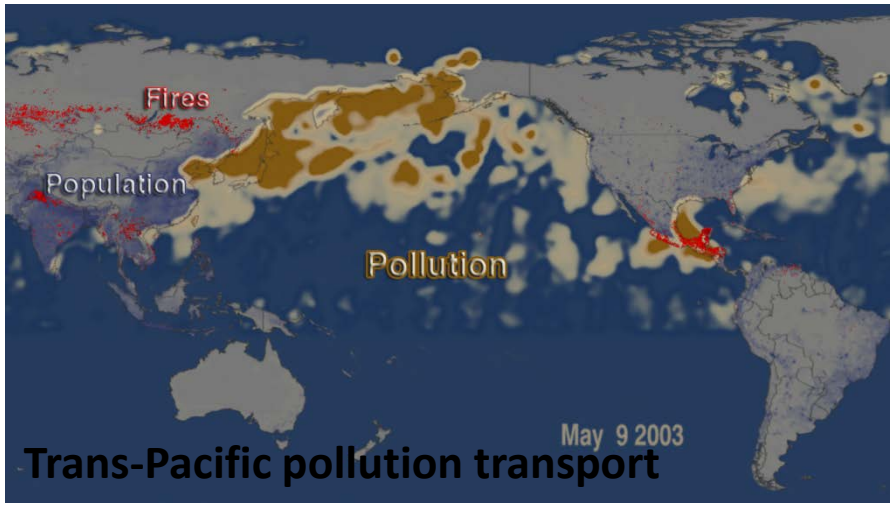
- **Atmospheric pollution transport is obvious**
- **The extent of transport depends on emissions, chemistry, etc.**

Yan et al., 2014 ACP; 2016 ACP

Atmospheric Transport: News Coverage

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

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



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

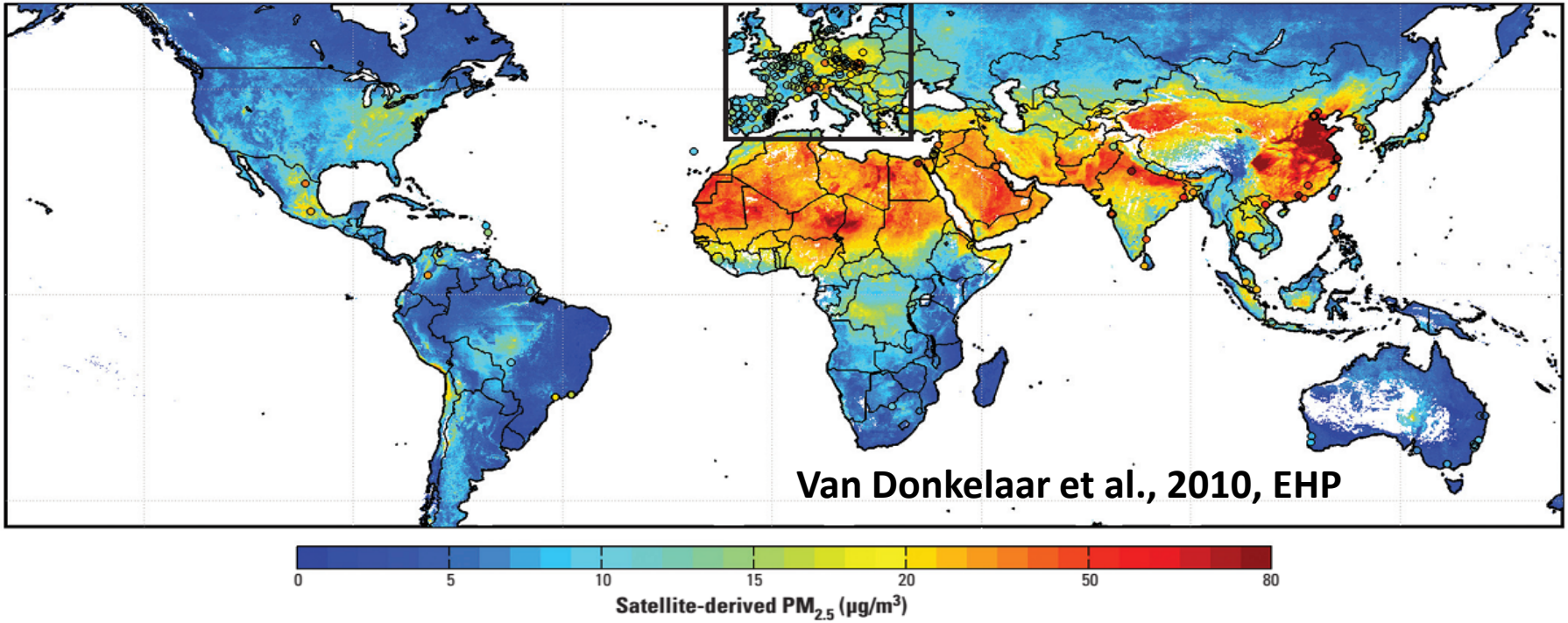
China: A Key Player

G8+ Country	GDP 2013 10^9 USD	Export 2013 10^9 USD	$PM_{2.5}$ Emis 2010 Tg	NOx Emis 2010 Tg	SO_2 Emis 2010 Tg	Population 2015 Million
China	9181 (2)	2210 (1)	11.8 (1) 4.4	27.1 (1) 1.1	27.6 (1) 1.6	1405 (1) 1.5
US	16768	1579	1.6	13.1	9.9	328
France	2519	568	0.22	1.0	0.25	67
UK	2385	477	0.06	1.1	0.43	65
Russia	1805	527	0.30	3.5	4.5	146
Japan	4870	715	0.05	1.3	0.41	127
Germany	3353	1453	0.09	1.2	0.48	80
Italy	1934	518	0.12	0.77	0.15	61
Canada	1731	458	0.23	1.9	1.6	36

Source: United Nations; HTAP v2

China Has World's Most Severe PM Pollution

Surface $PM_{2.5}$ concentration derived from satellite



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

v.s.

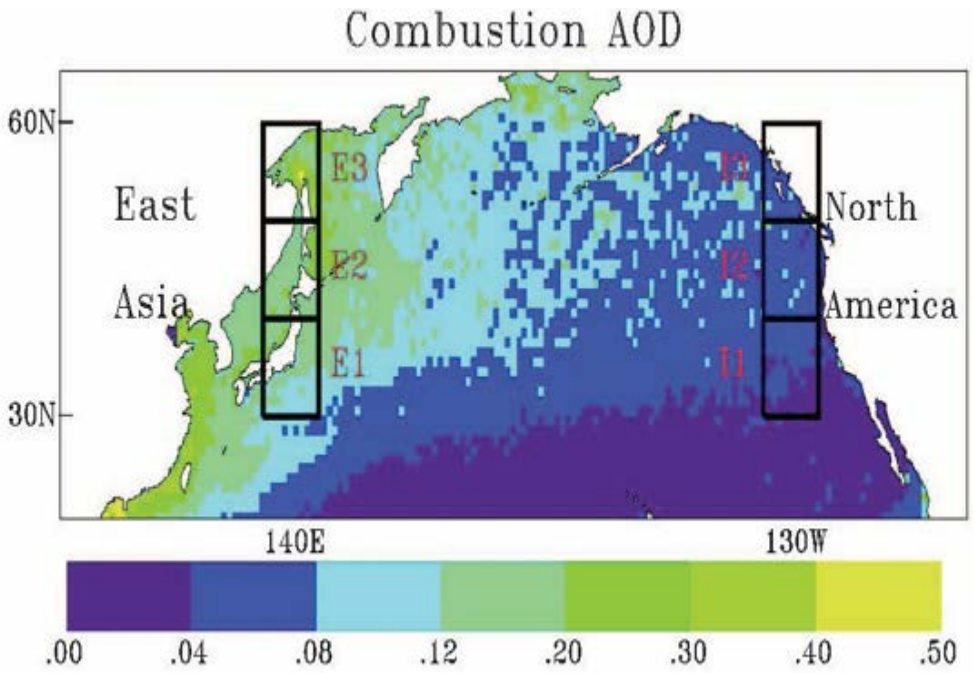
Beijing in 2013:
90 µg/m³

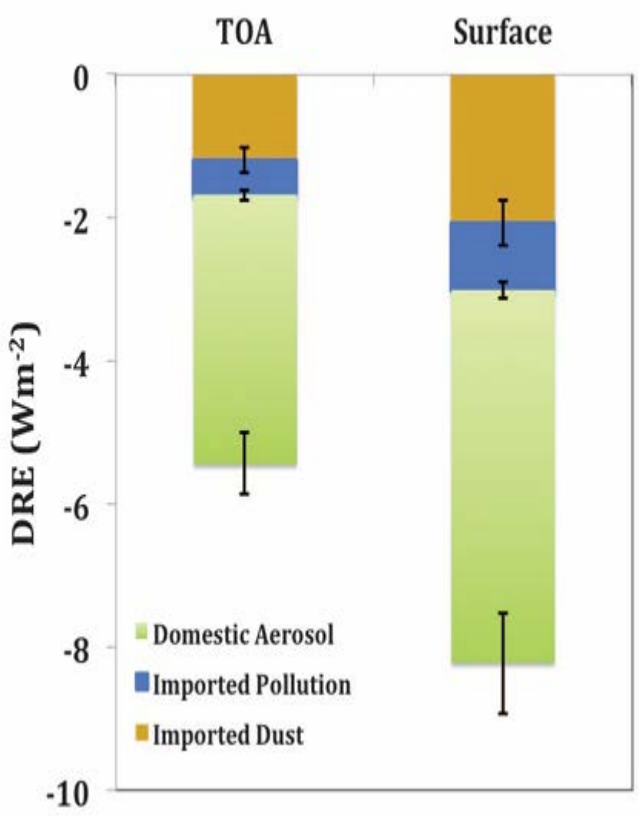
v.s. **WHO Guideline: 10 µg/m³, WHO IT1: 35 µg/m³**

Asian PM Transport Affects North America

Yu et al., 2012, Science

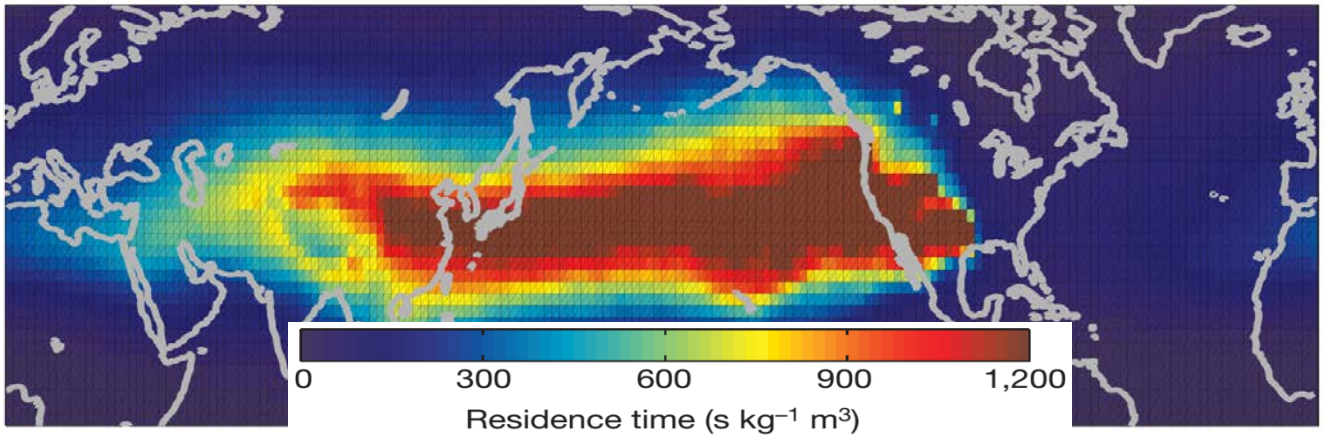
- **East Asian PM pollution contributes 6% of N.A. DRE**

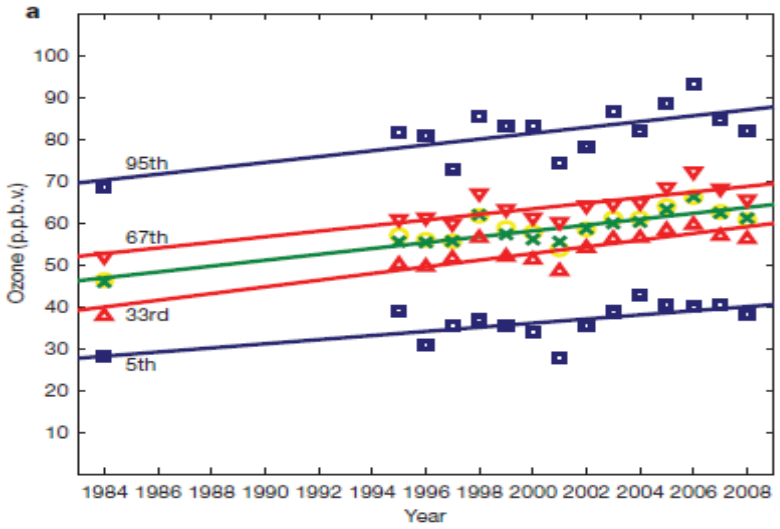




Atmospheric O_3 Transport from China to U.S.

Cooper et al., 2010, Nature

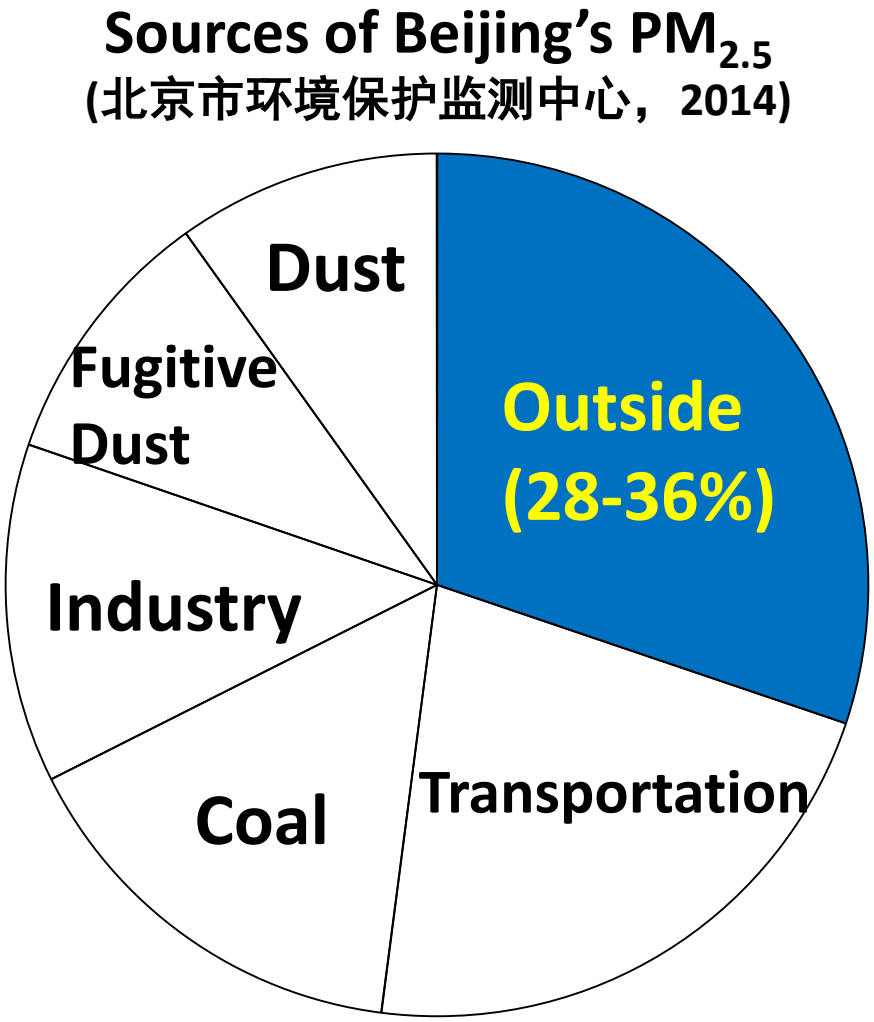




Percentile	1995–2008 increase (p.p.b.v. yr^{-1})	*P*
95th	0.56 ± 0.71	0.11
67th	0.62 ± 0.39	0.00
50th	0.63 ± 0.34	0.00
33rd	0.64 ± 0.35	0.00
5th	0.48 ± 0.53	0.07

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

Atmospheric $PM_{2.5}$ Transport Affects Beijing

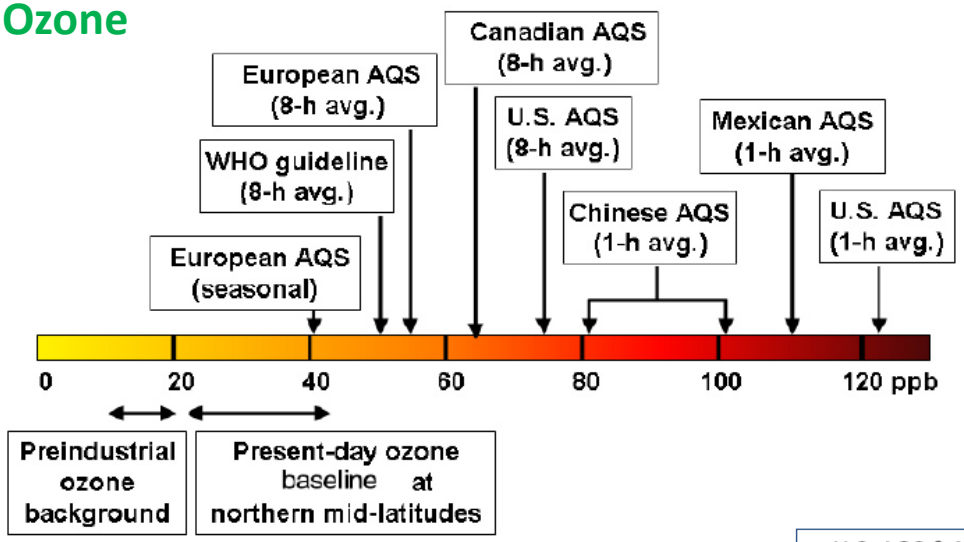


Key Questions on Globalizing Air Pollution

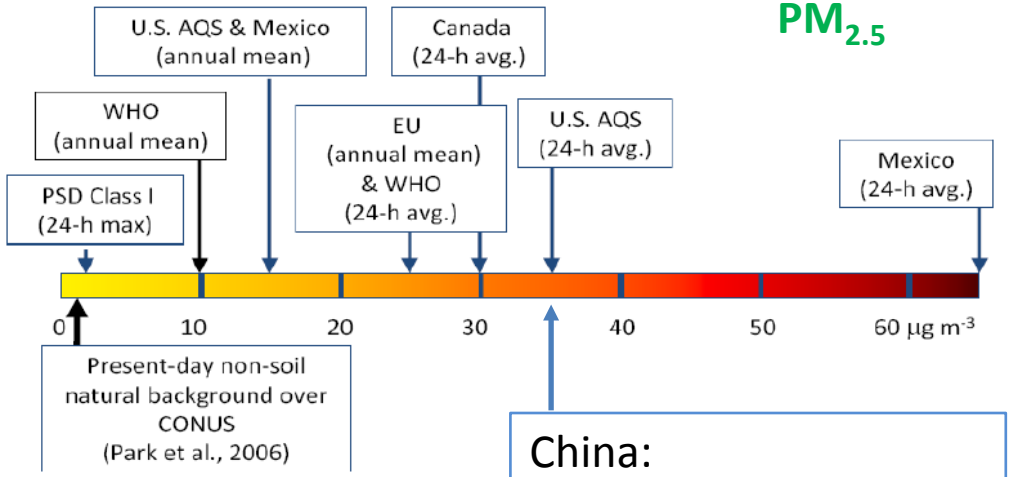
- **Severity and trends of China's air pollution**
  - **Satellite and Ground-based Measurements**
- **Mechanism of pollution and transport**
  - **High-resolution chemical transport model**
- **Socioeconomic drivers of air pollution**
  - **Role of production, consumption and trade**
  - **Globalizing air pollution via trade & transport**

Ambient Air Quality Standard

Ozone



$PM_{2.5}$

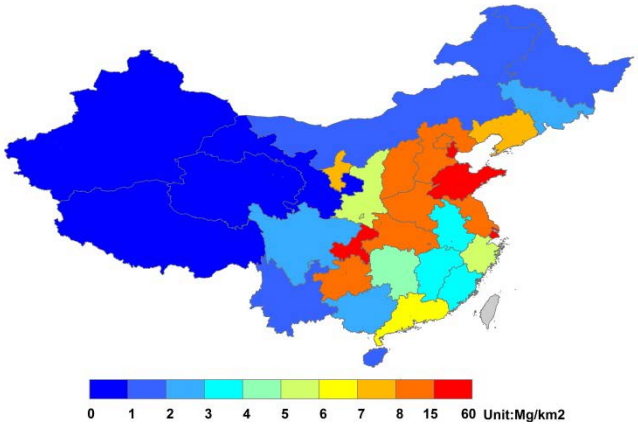


China:
75 μg m^{-3} for 24-h avg.
35 μg m^{-3} for 1-yr avg.

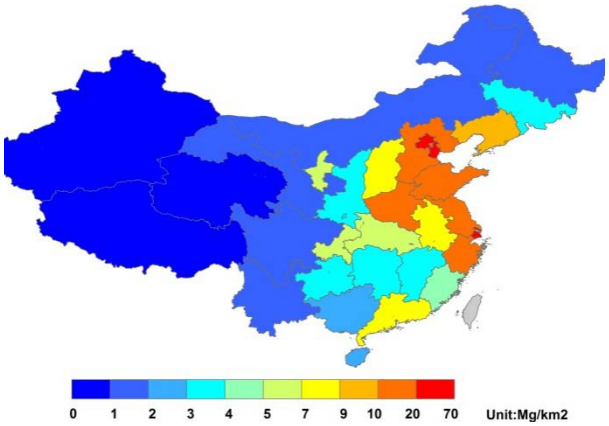
HTAP, 2010

Anthropogenic Emissions in China

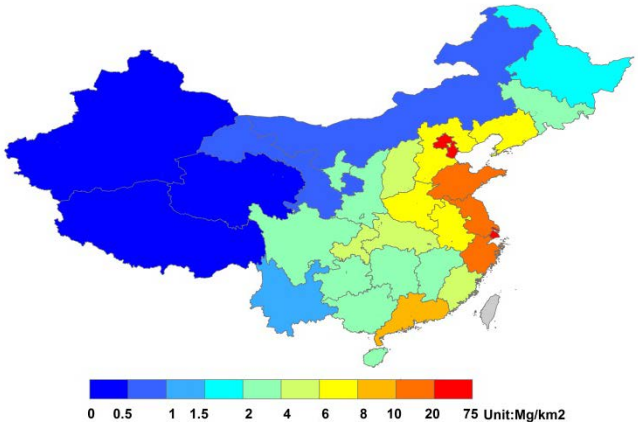
SO_2



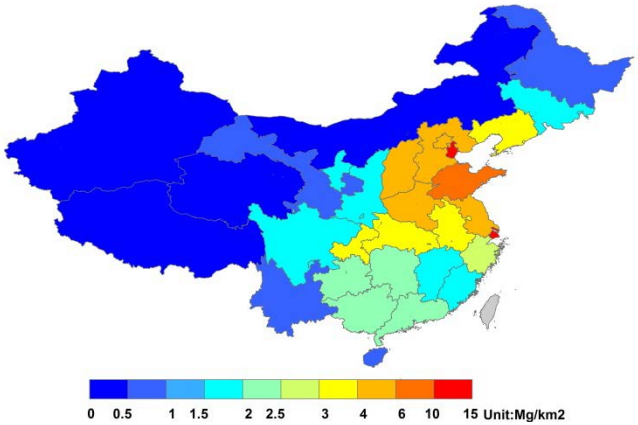
NO_x



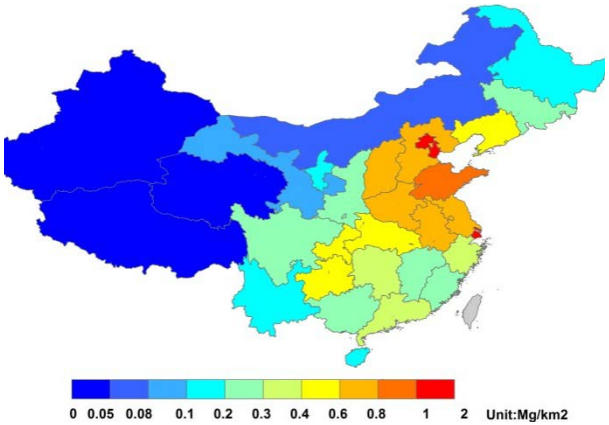
VOC



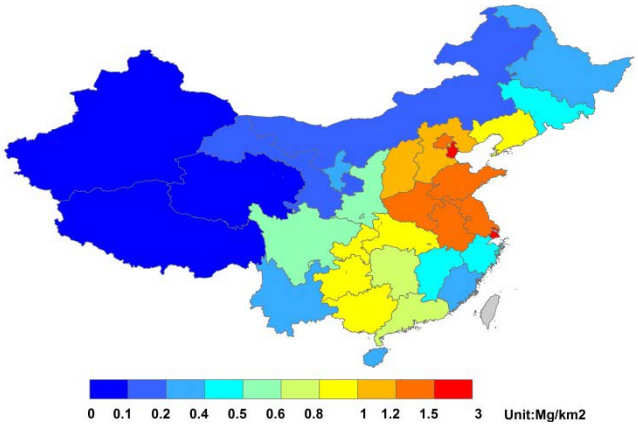
$PM_{2.5}$



BC

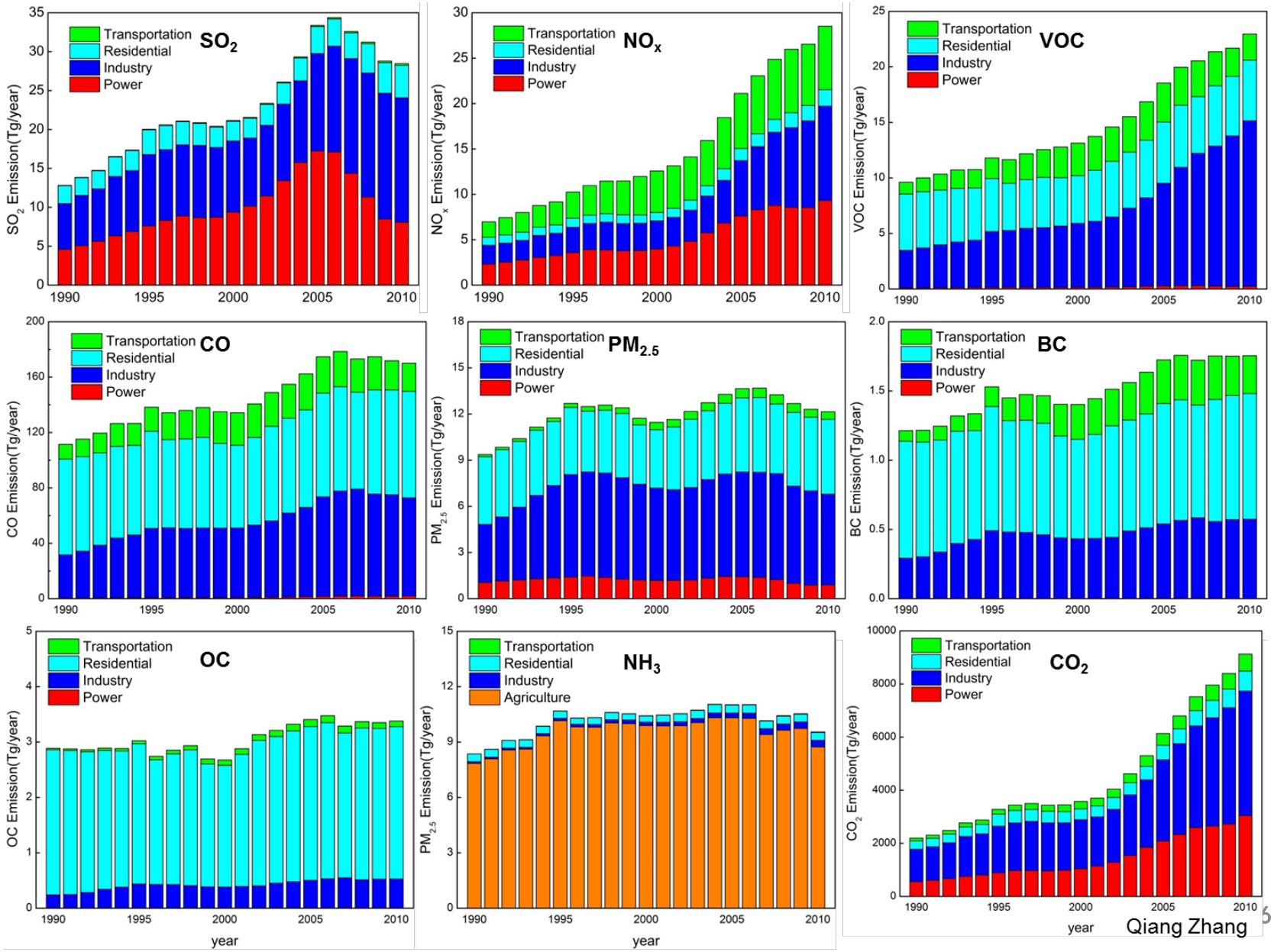


OC

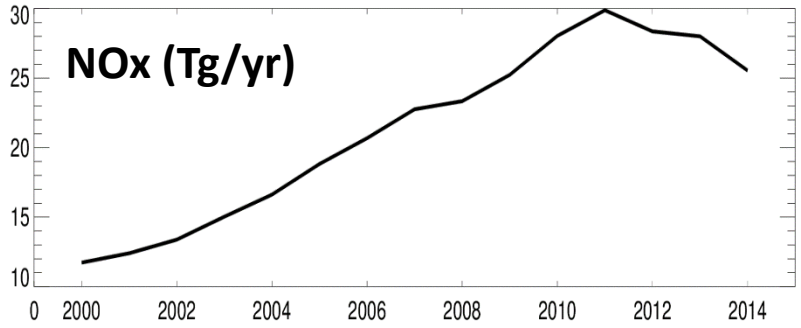


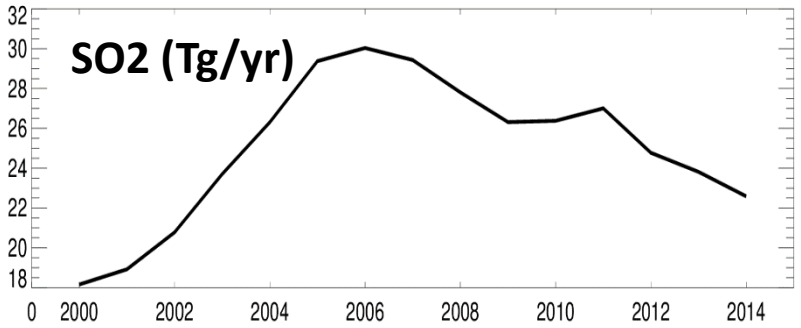
贺克斌，2014

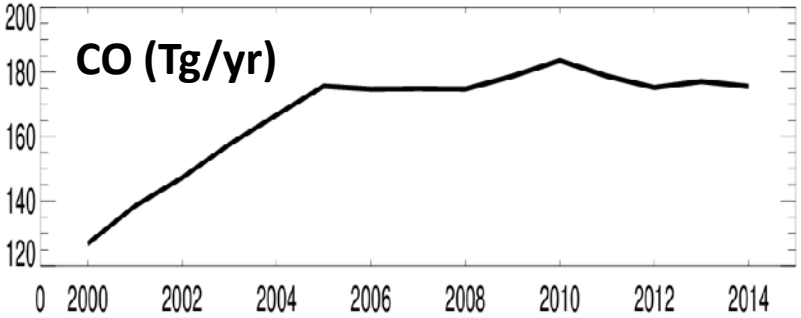
Anthropogenic Emissions in China: 1990-2010

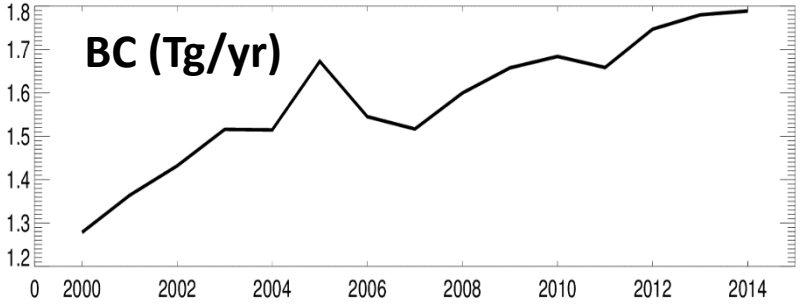


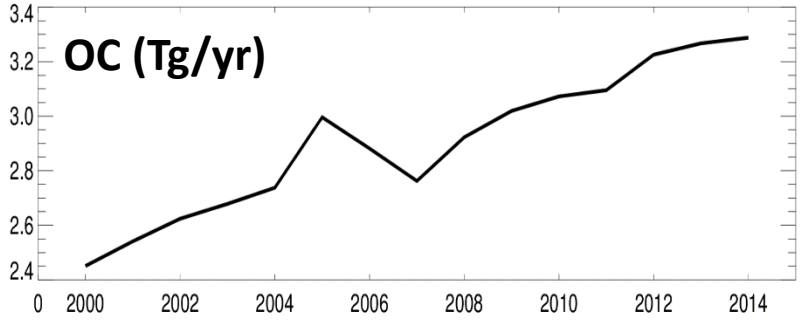
Anthropogenic Emissions in China: 2000-2014







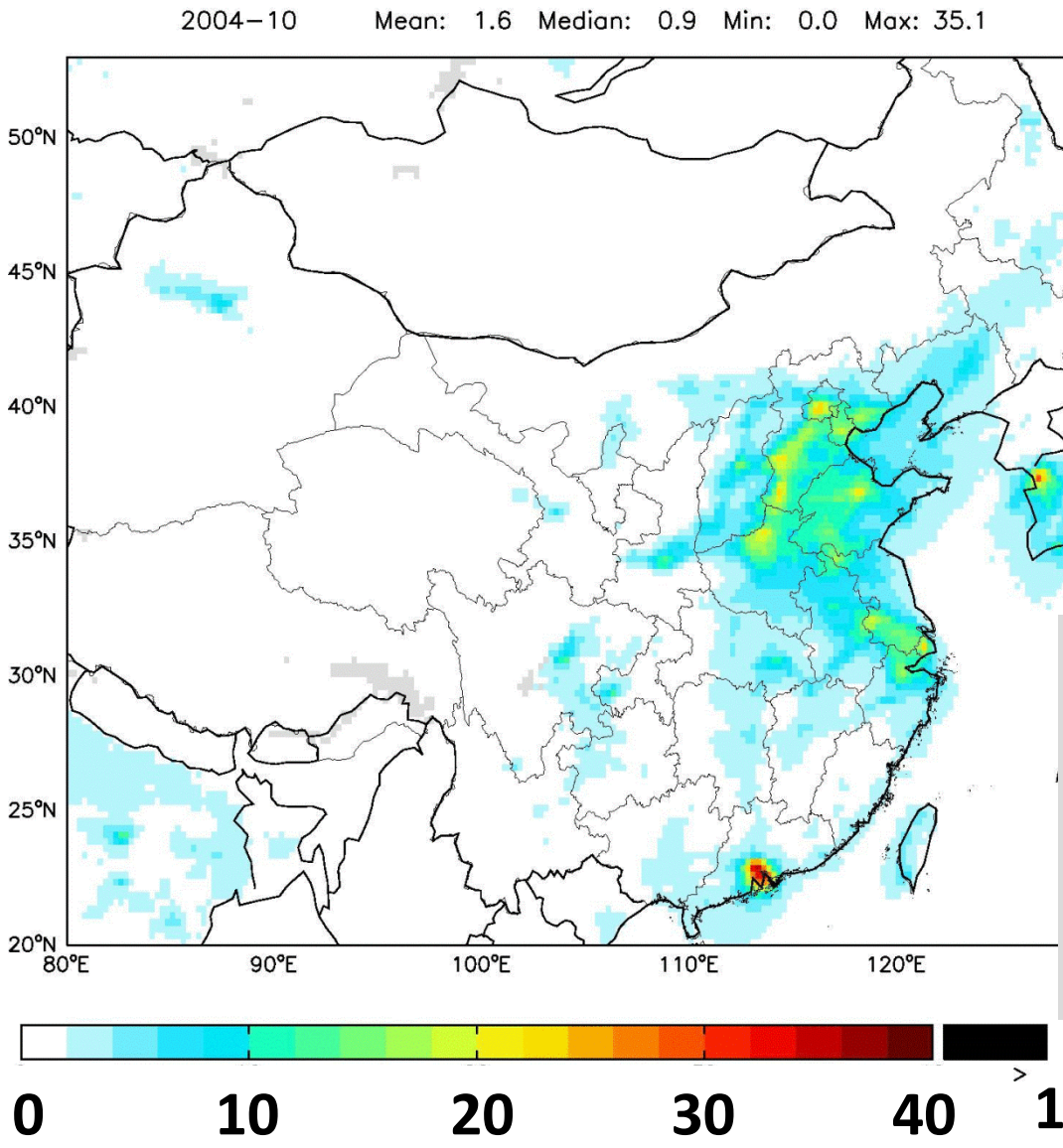




Source: Yu Zhao

POMINO – Peking University OMI NO_2 Product

www.phy.pku.edu.cn/~acm/ acmProduct.html#POMINO

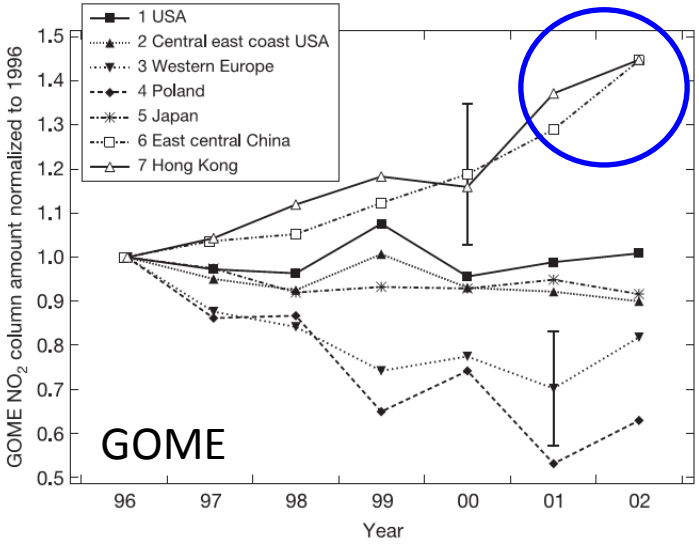


What's new:

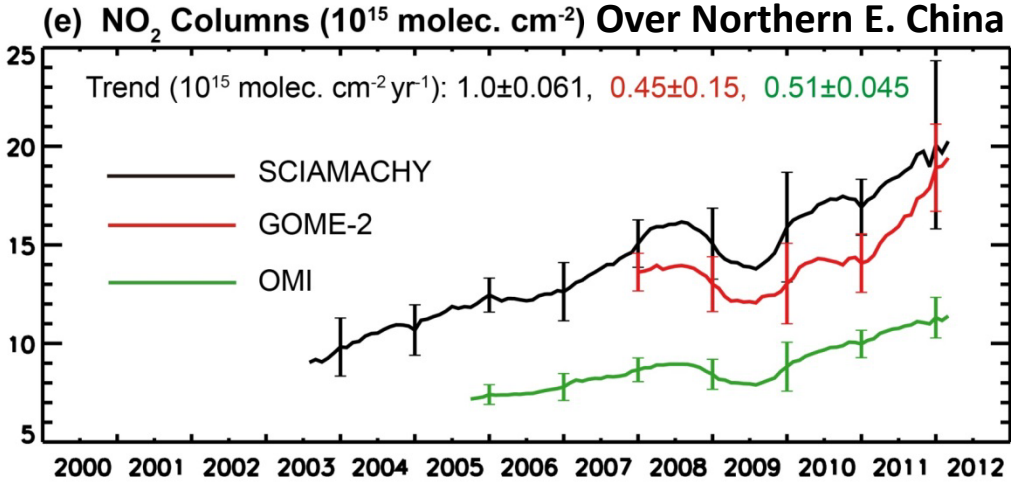
- Explicit aerosols
- Anisotropic Rs
- Coherent clouds
- High-res NO_2 prof.
- Pixel-specific RTM

Satellite: Worsening NOx Pollution over China

Richter et al., Nature, 2005



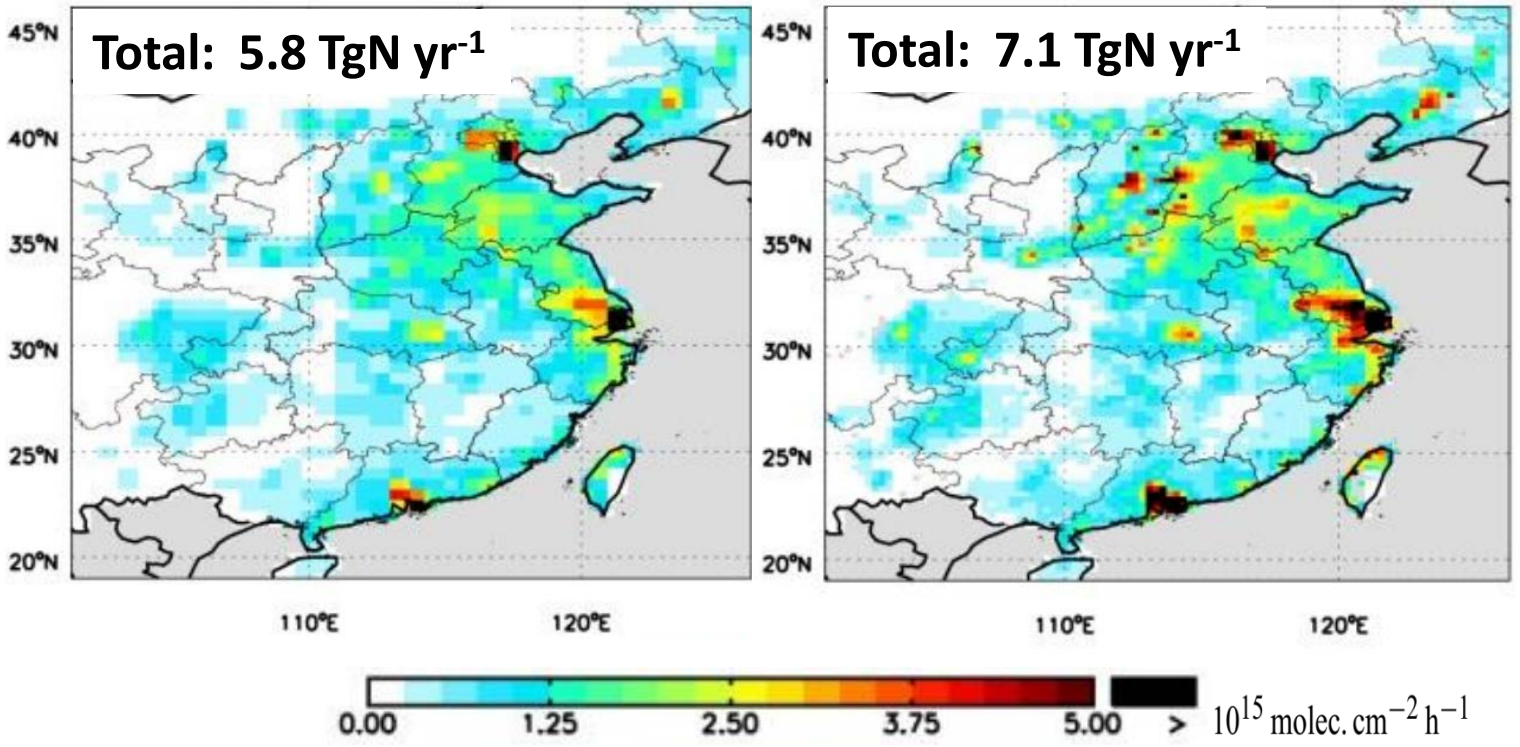
Lin et al., 2011; 2013



High-res Emission Inversion Reveals Urban Biases

High-resolution (25km) emission inversion for China

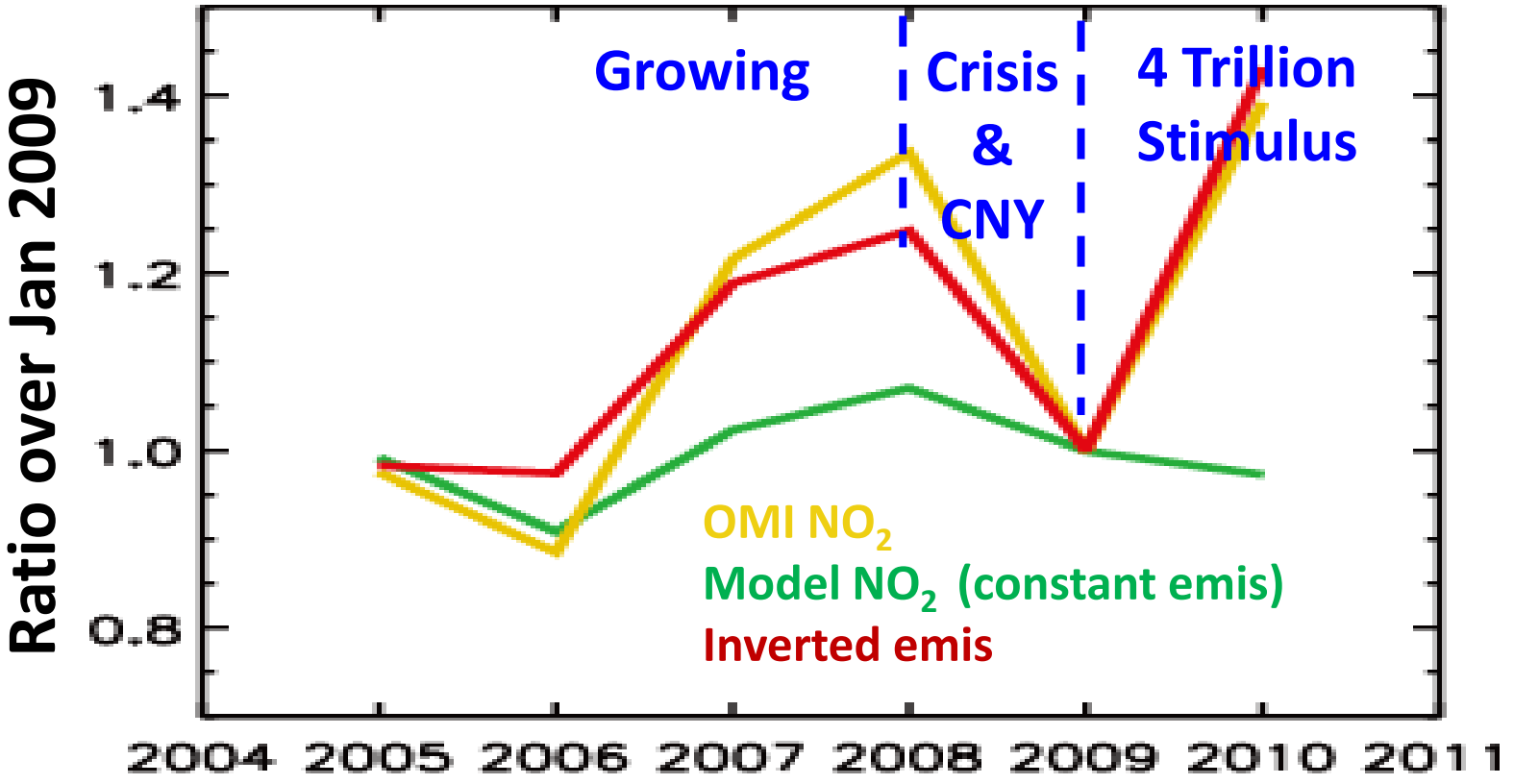
INTEX-B inventory | **OMI-based retrieval**



Lin, 2012 ACP

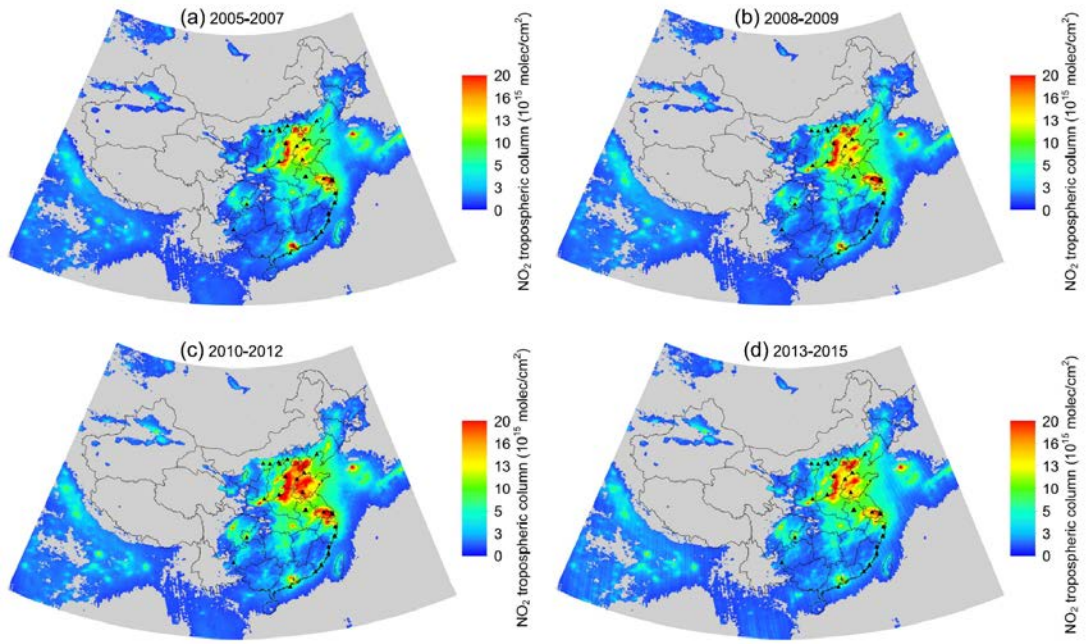
Economy-driven Emission Trends

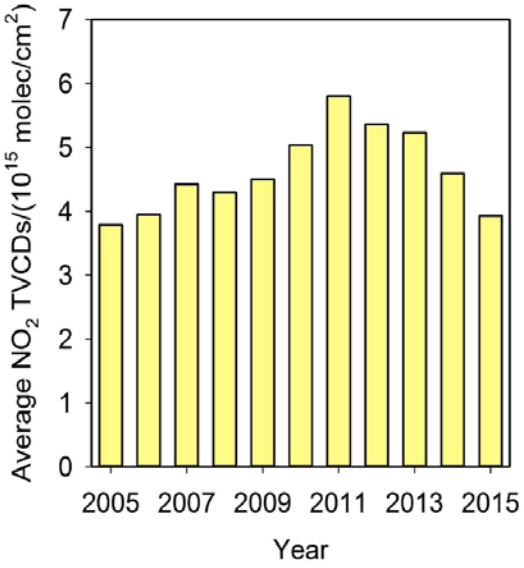
E. China NOx Emissions in January: 2005–2010

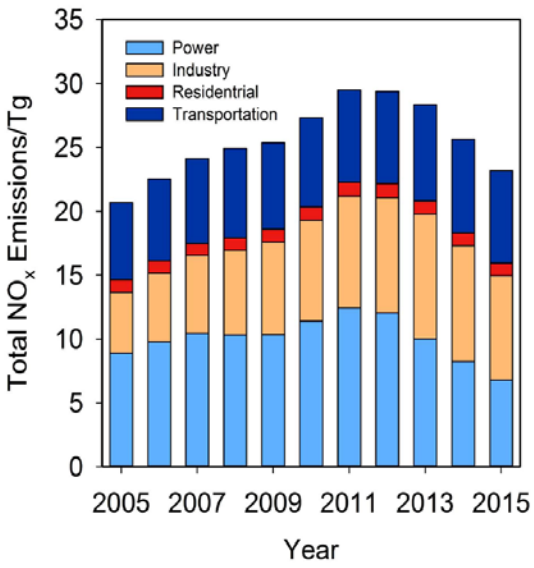


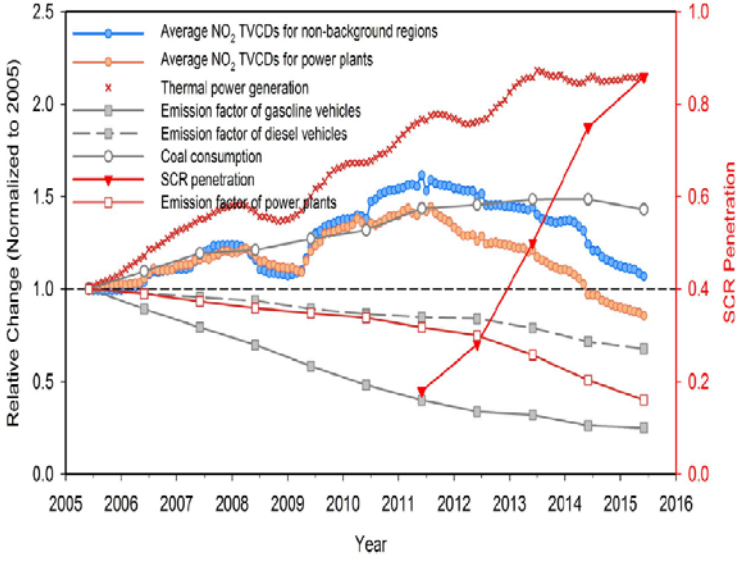
Lin and McElroy, 2011 ACP

Recent Reductions in NO_2 VCD over China







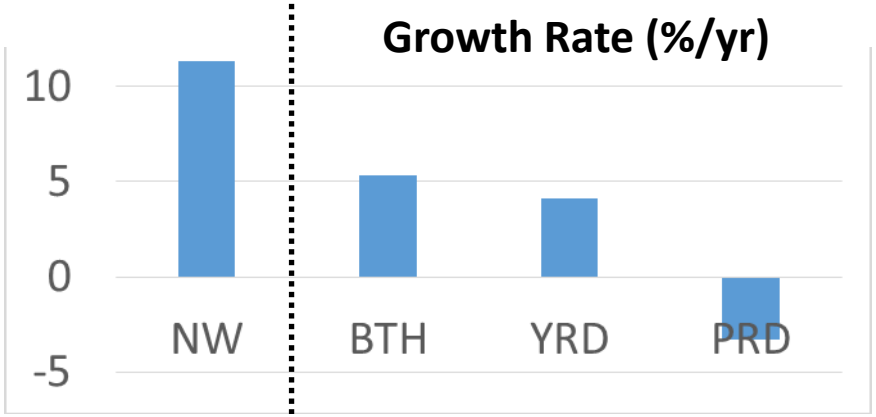


Liu et al., 2016, ERL

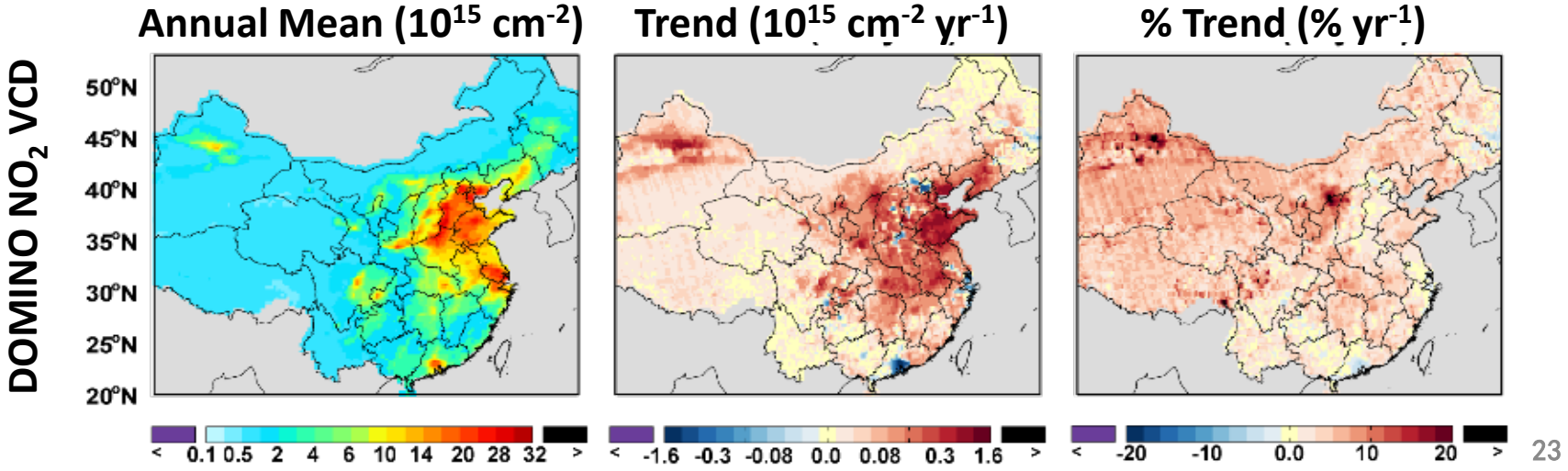
Increases of NO_2 VCD: West versus East China

OMI NO_2 Trends over 2005 – 2013

Cui et al., 2016, ACP

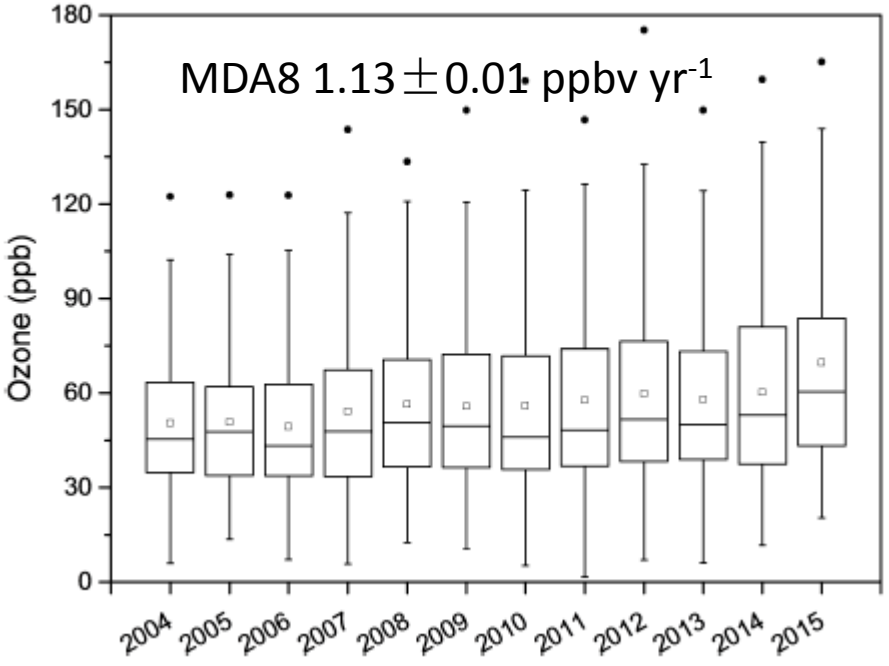


Yan et al., 2017

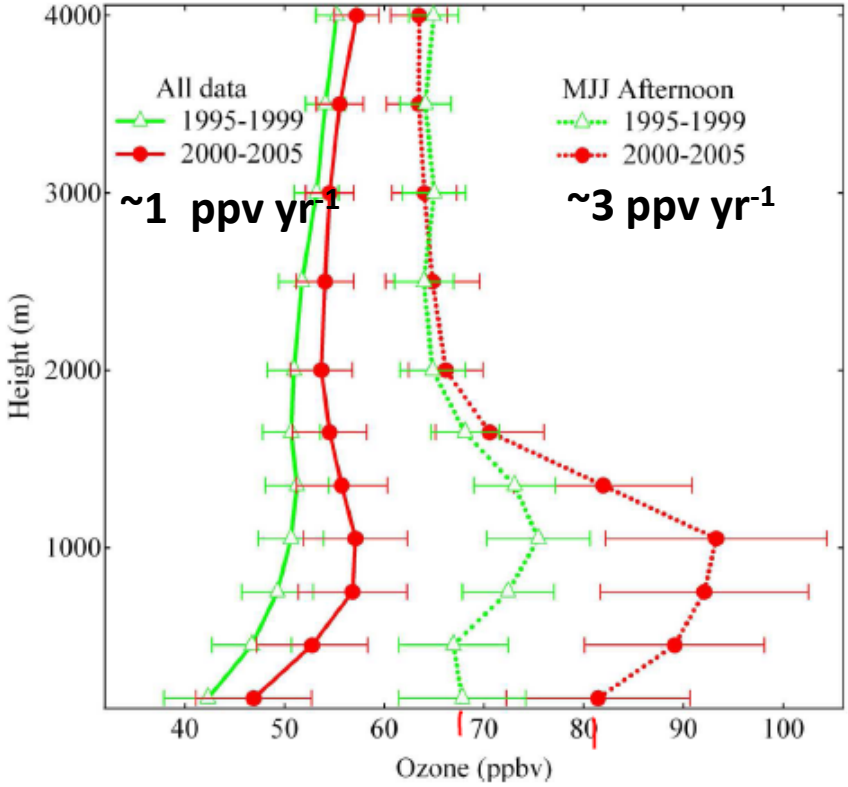


Growing O_3 Pollution over Beijing

Shangdianzi, regional background



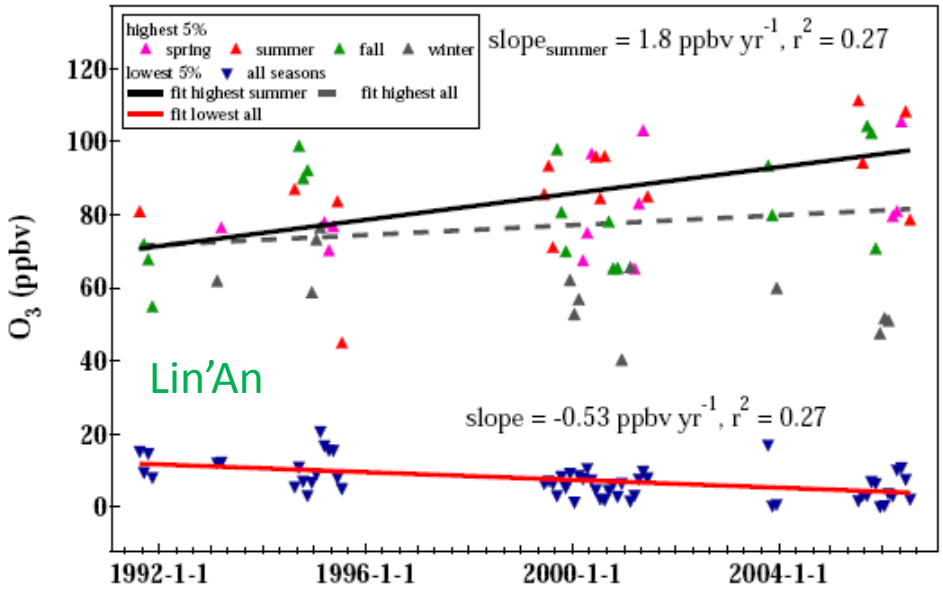
Beijing airport, MOZAIC



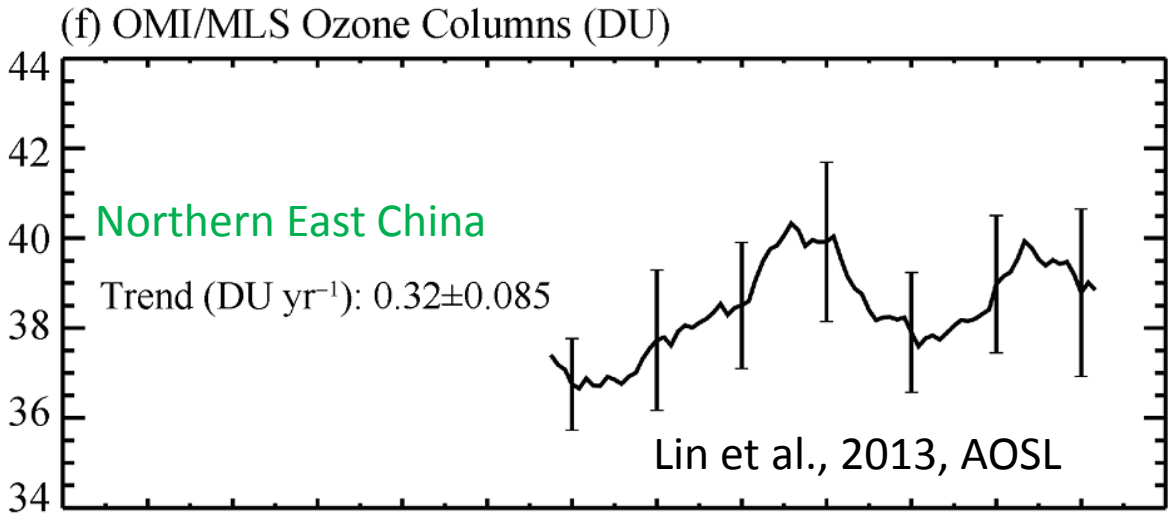
Emission changes in VOCs dominated

Ma et al., 2016; Ding et al., 2008, ACP

Regional O_3 Concentrations are Increasing



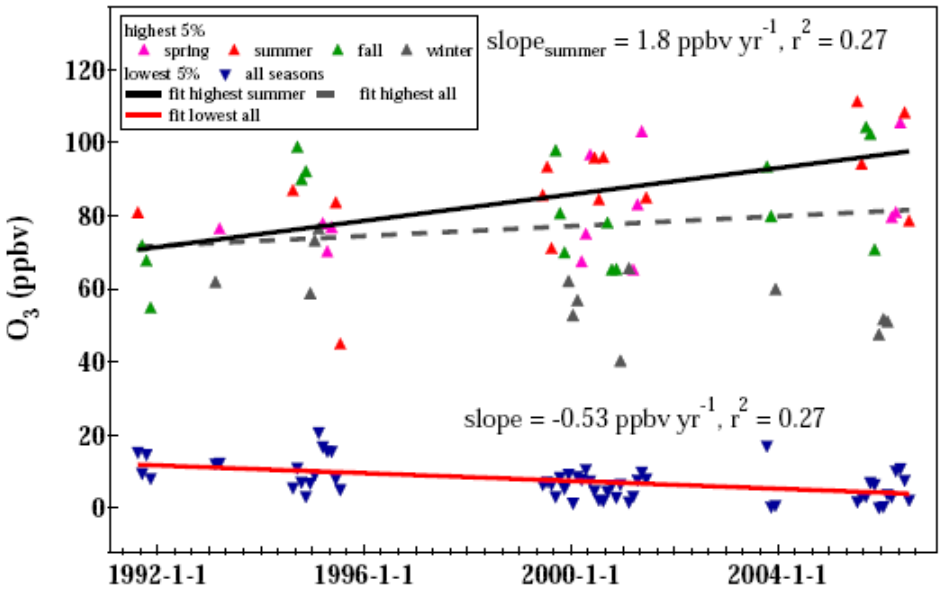
Xu et al., 2008, ACP



Lin et al., 2013, AOSL

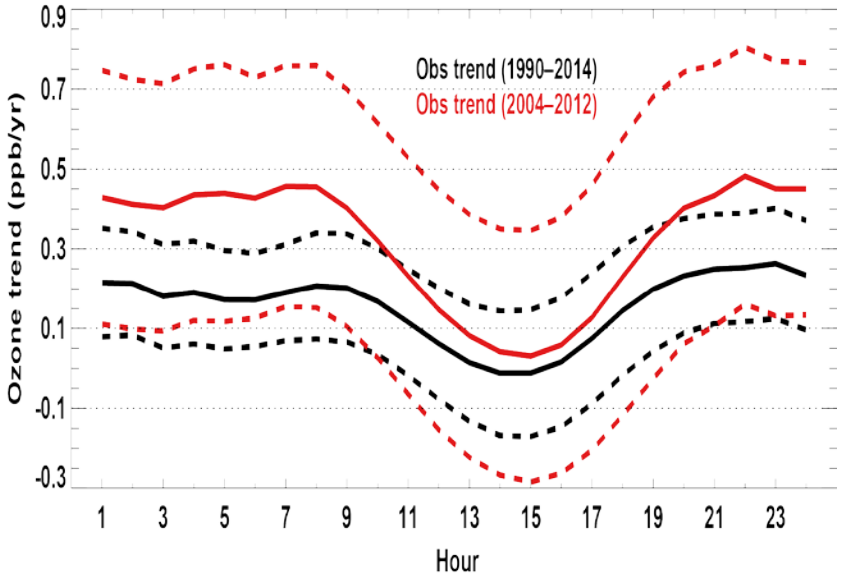
China versus USA in Recent O_3 Trends

Lin'An in the Yangtze River Delta

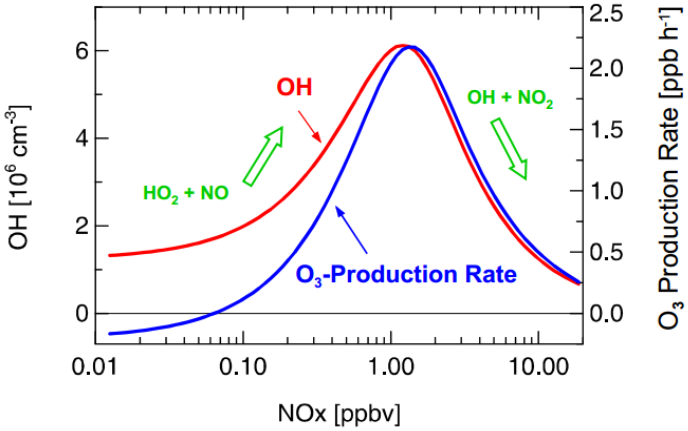


Xu et al., 2008, ACP

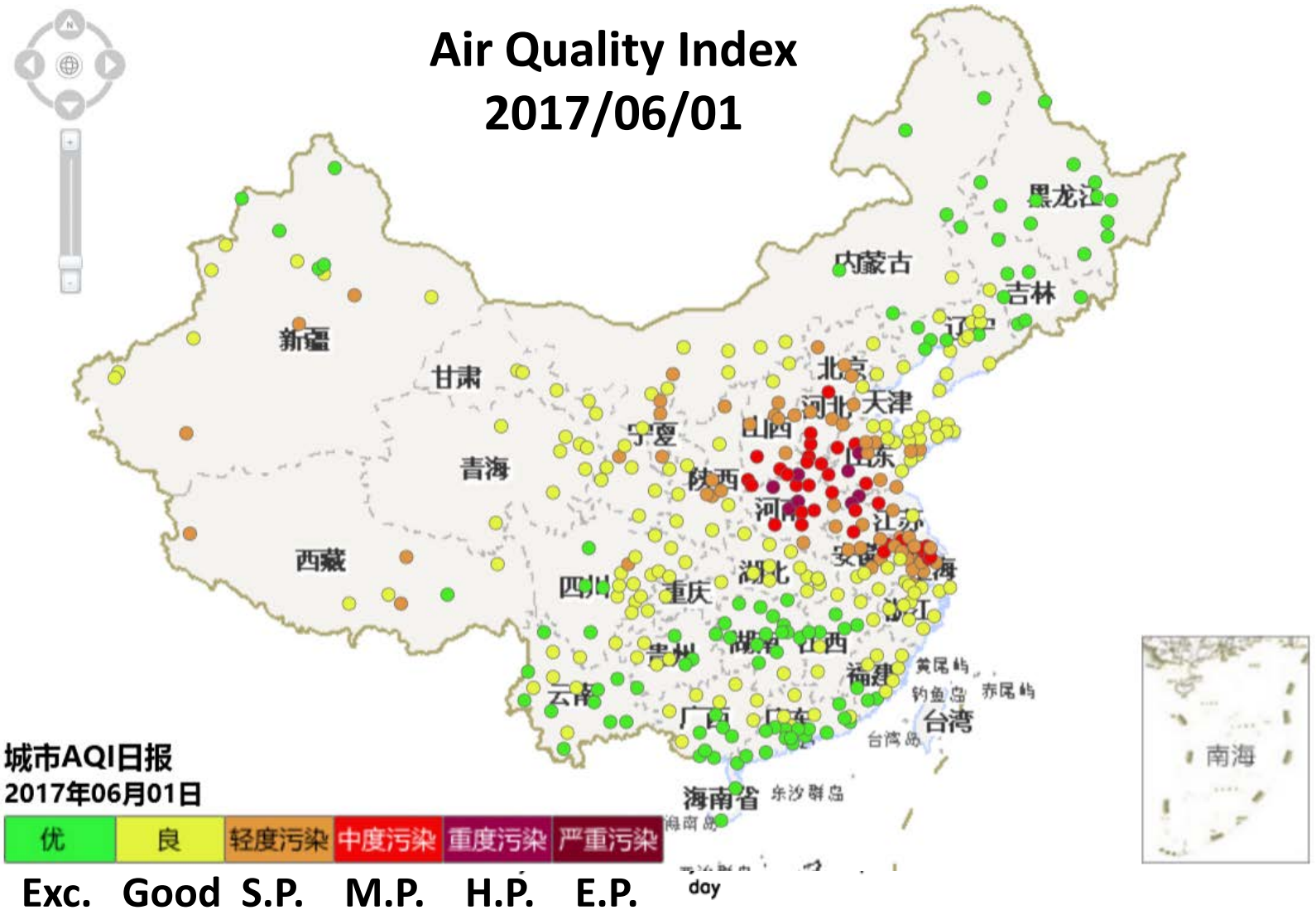
USA average (1000 sites)



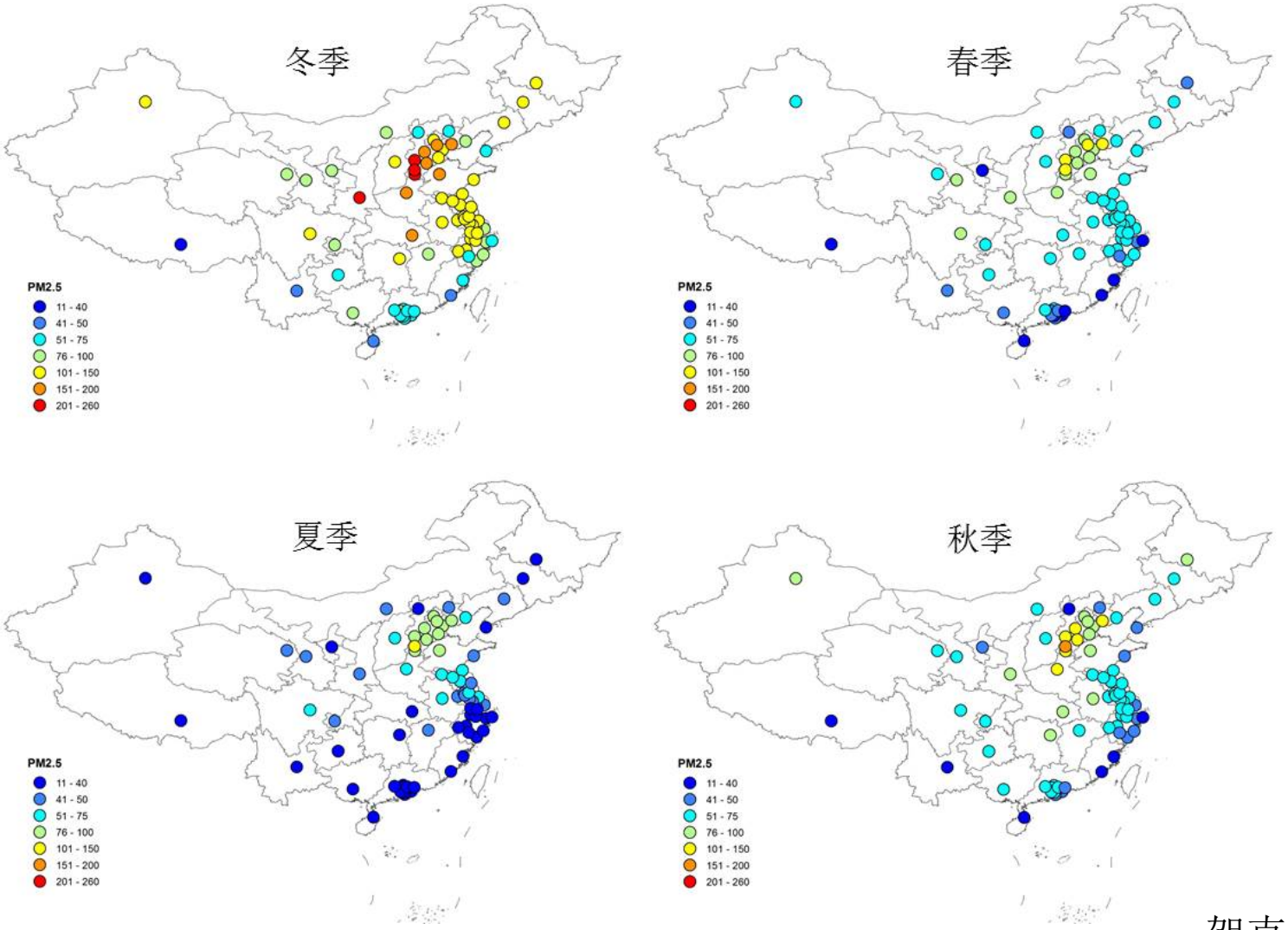
Yan et al., 2017, submitted



China Is Facing Increasingly Severe Ozone Pollution



Seasonal Variation of $PM_{2.5}$ in China



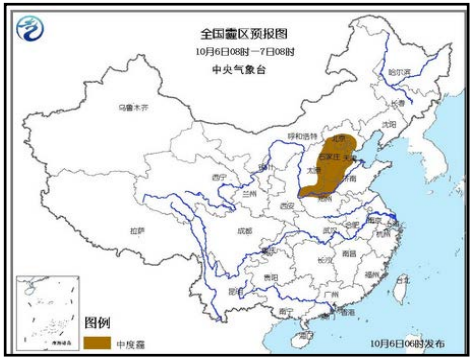
贺克斌，2014

Severe Haze in 2013

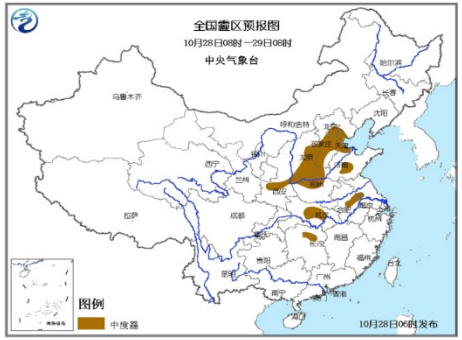
Jan 14-15, 2013

Jan 29, 2013

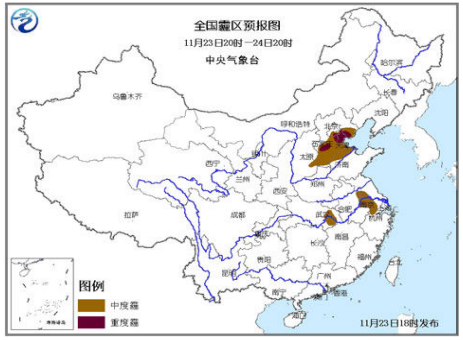
Feb 24-25, 2013



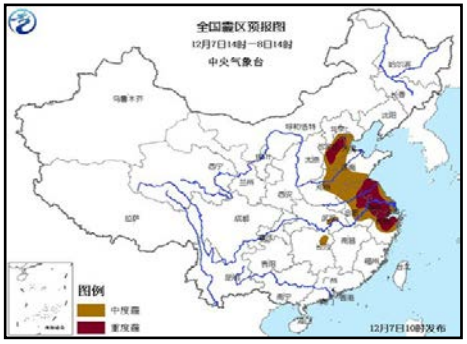
Oct 06-07, 2013



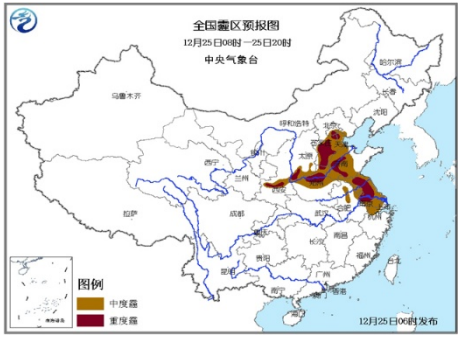
Oct 28-29, 2013



Nov 23-24, 2013



Dec 07-08, 2013

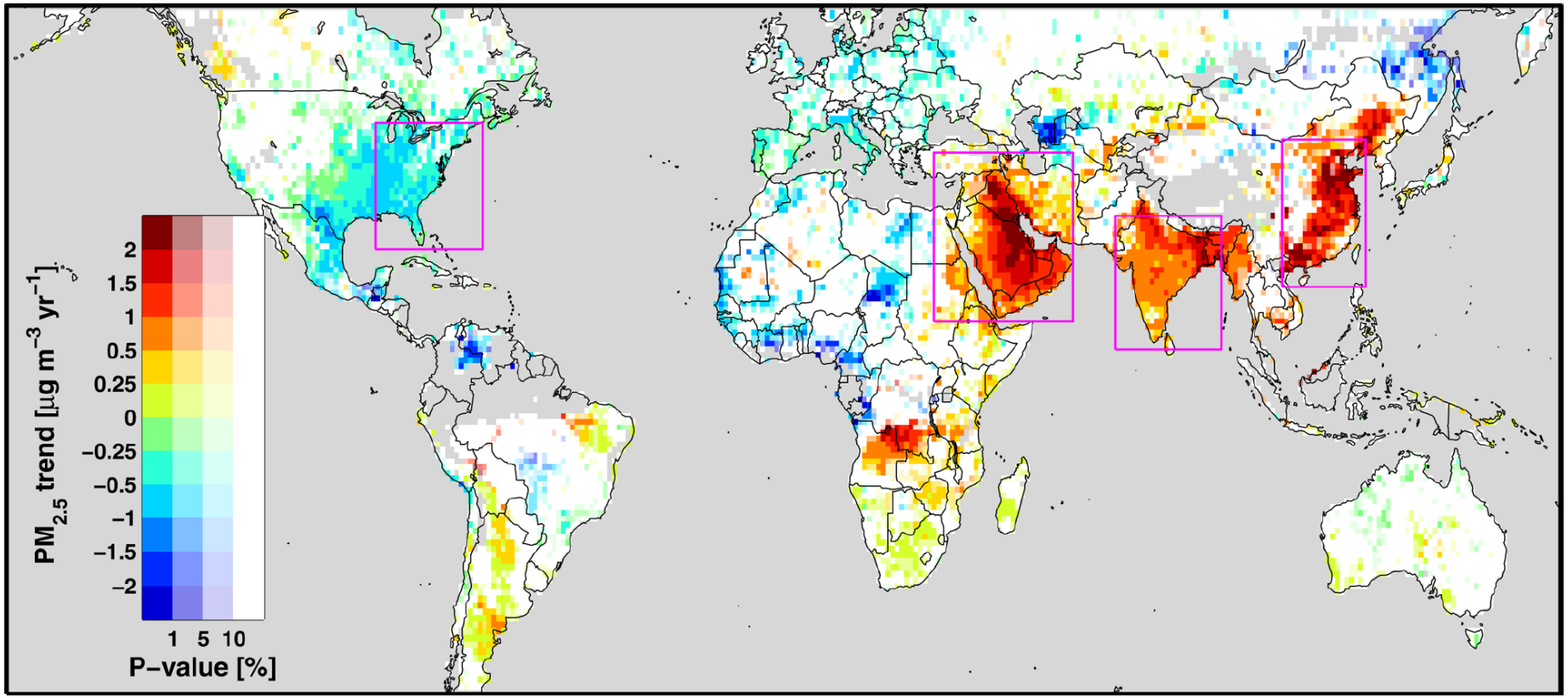


Dec 25, 2013

贺克斌，2014

Varying Growth of PM Inferred from Satellite Obs

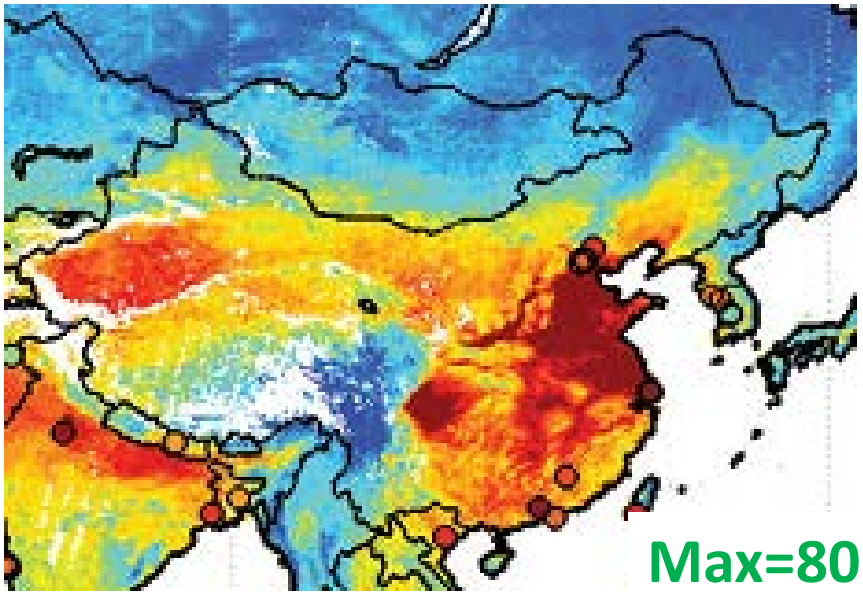
Global $PM_{2.5}$ Growth Rate Over 1998-2012 inferred from MISR-SeaWiFS



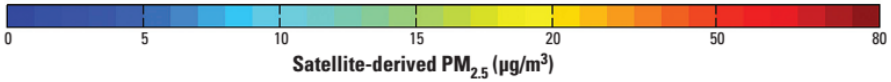
Boys et al., 2014, EST

Worsening Chinese PM Pollution ?

2000–2006; old study



Max=80

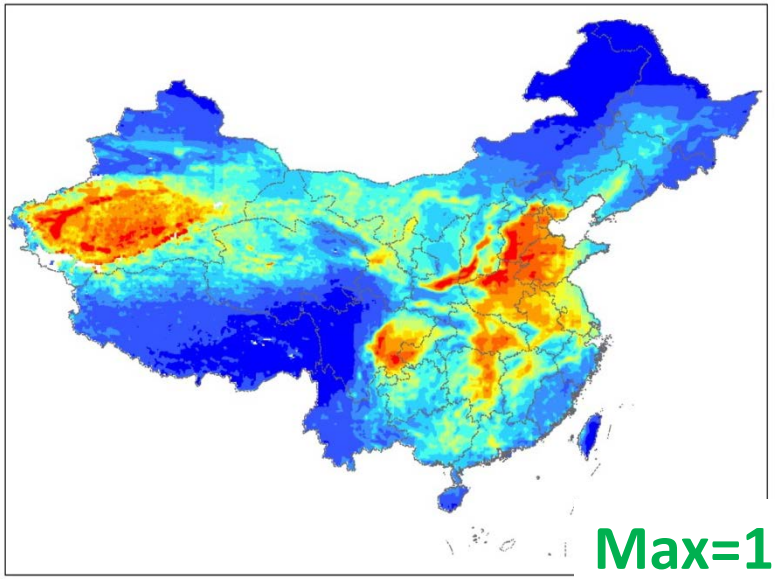


23 Million

>100 µg/m³

Van Donkelaar et al., 2010 EHP

2006–2012; updated study



Max=150

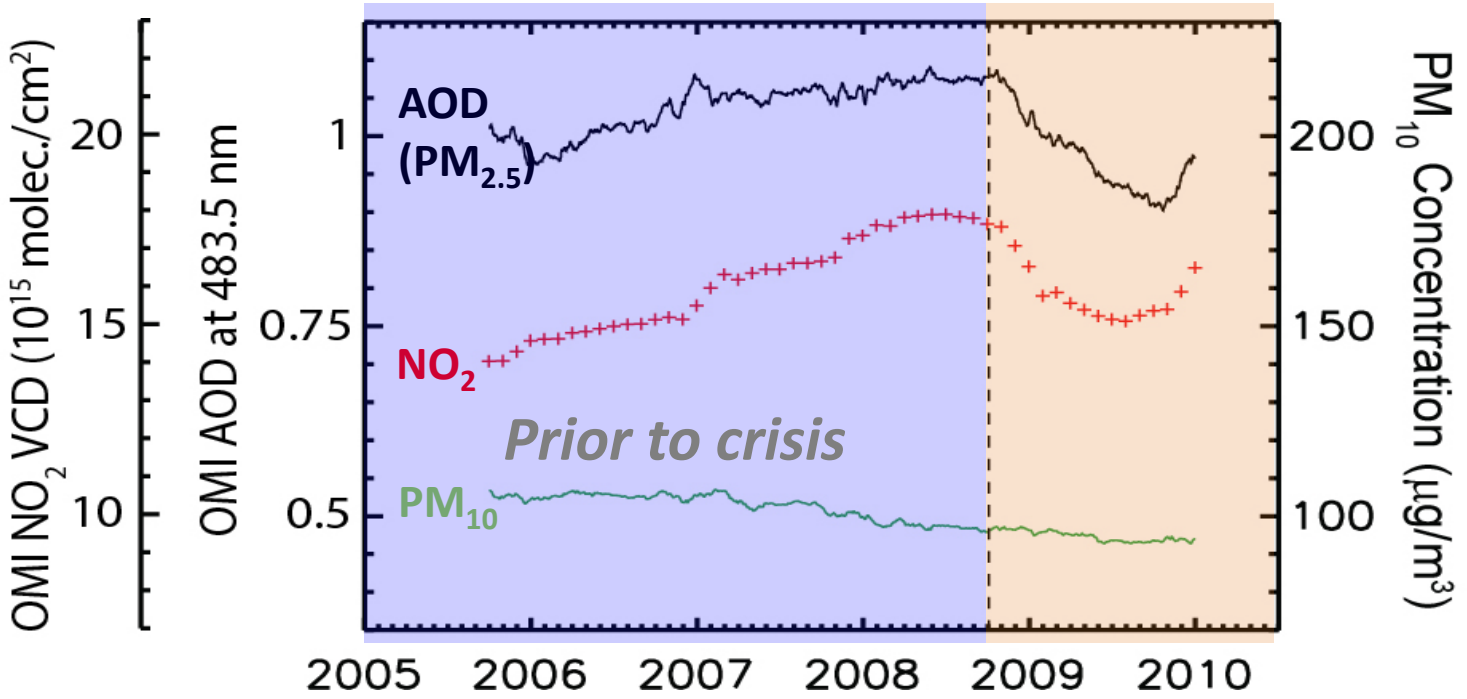
320 Million

>100 µg/m³

Geng et al., 2015 RSE

China's Increasing NOx Drives $PM_{2.5}$ Growth

E. China NOx and PM over 2005–2010

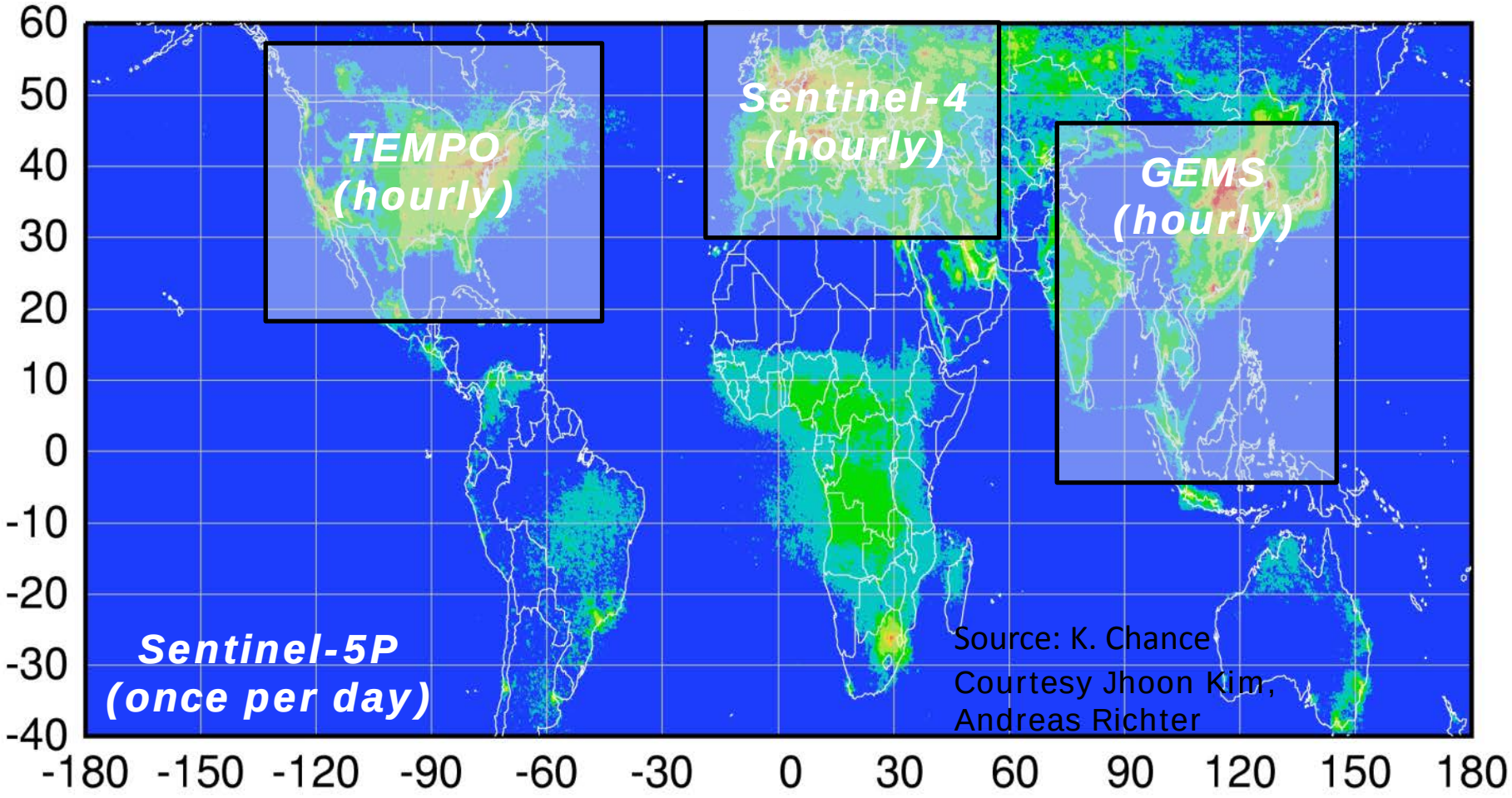


(Natural factors ruled out) we find that *before crisis*:

- **$PM_{2.5}$ grew due to increasing NOx, etc.**
- **PM_{10} declined due to controls on primary PM**

Lin et al., 2010 EST

Future-Generation Satellite Measurements: High-Resolution Geostationary and Polar Orbiting



Key Questions on Globalizing Air Pollution

- Severity and trends of China's air pollution
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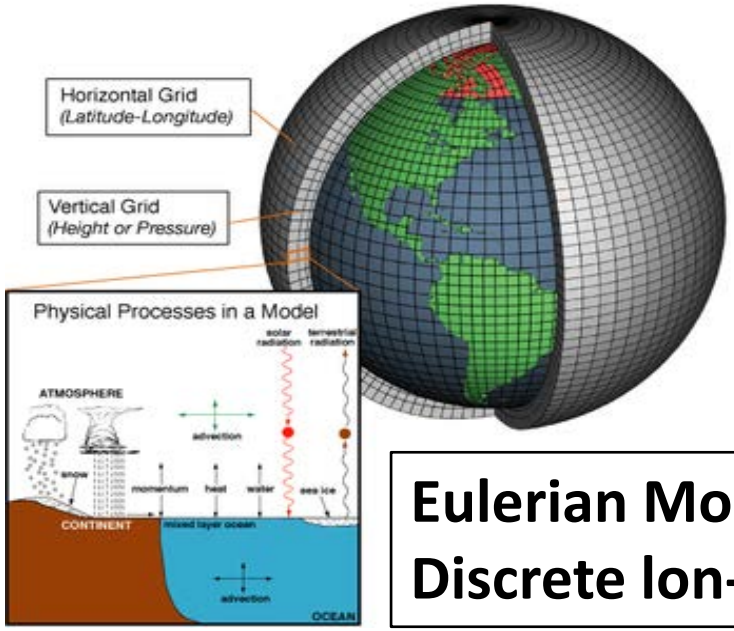
Atmospheric Chemical Transport Modeling

Emis **Dep** **Transport & Mixing** **Chemistry**

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

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**

Limited by Resolution
Models Often Misrepresent Small-scale Processes

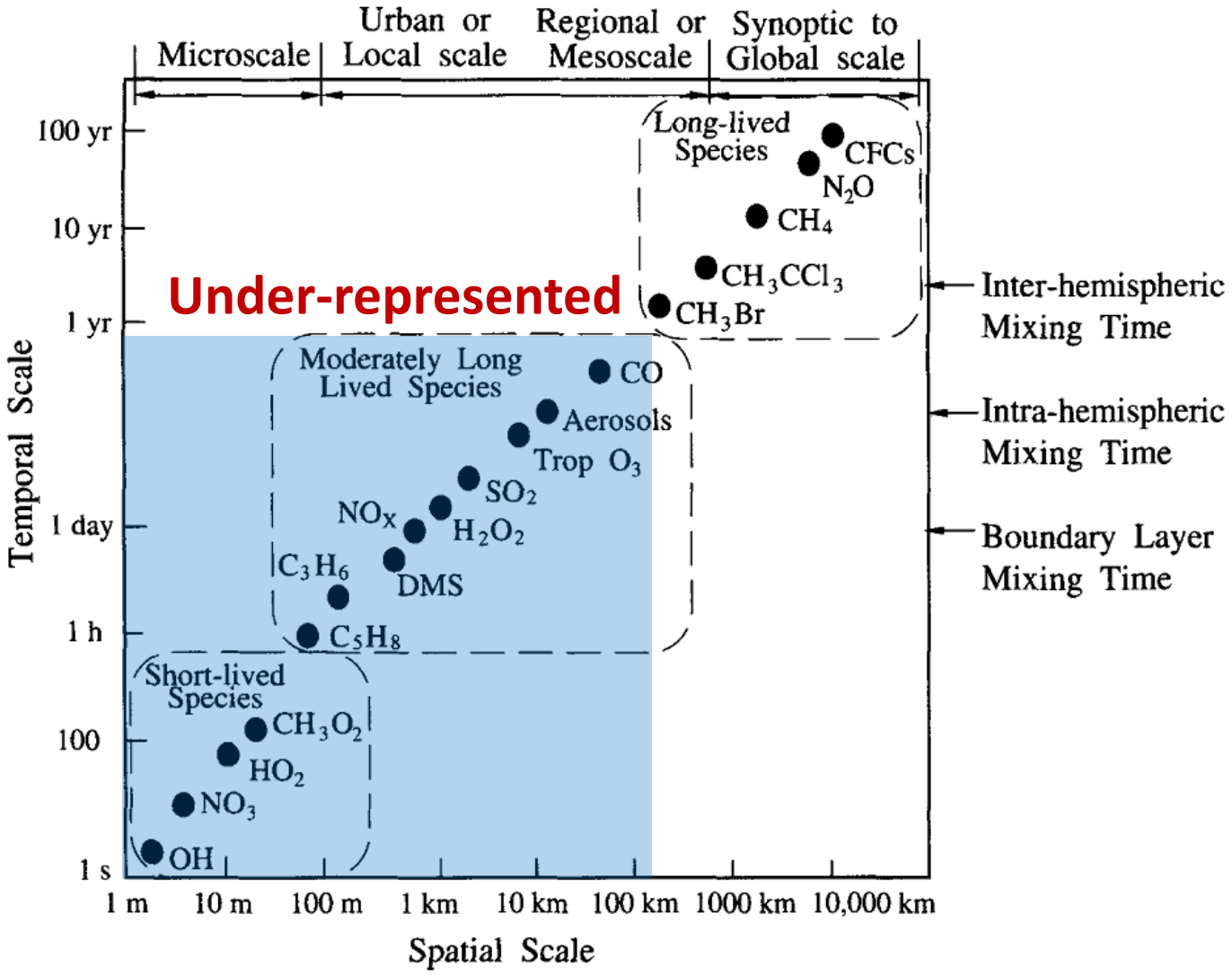
- **Un-even terrain**
- **Small-scale meteorology**
- **Variability in land use, vegetation, etc.**
- **Small-scale horizontal & vertical transport**
- **Small-scale variability in chemistry & emissions**

model **reality**

$$\overline{A}\cdot\overline{B}-\overline{A\cdot B}=-\overline{A'\cdot B'}=-r_{AB}\cdot\sigma_A\cdot\sigma_B$$

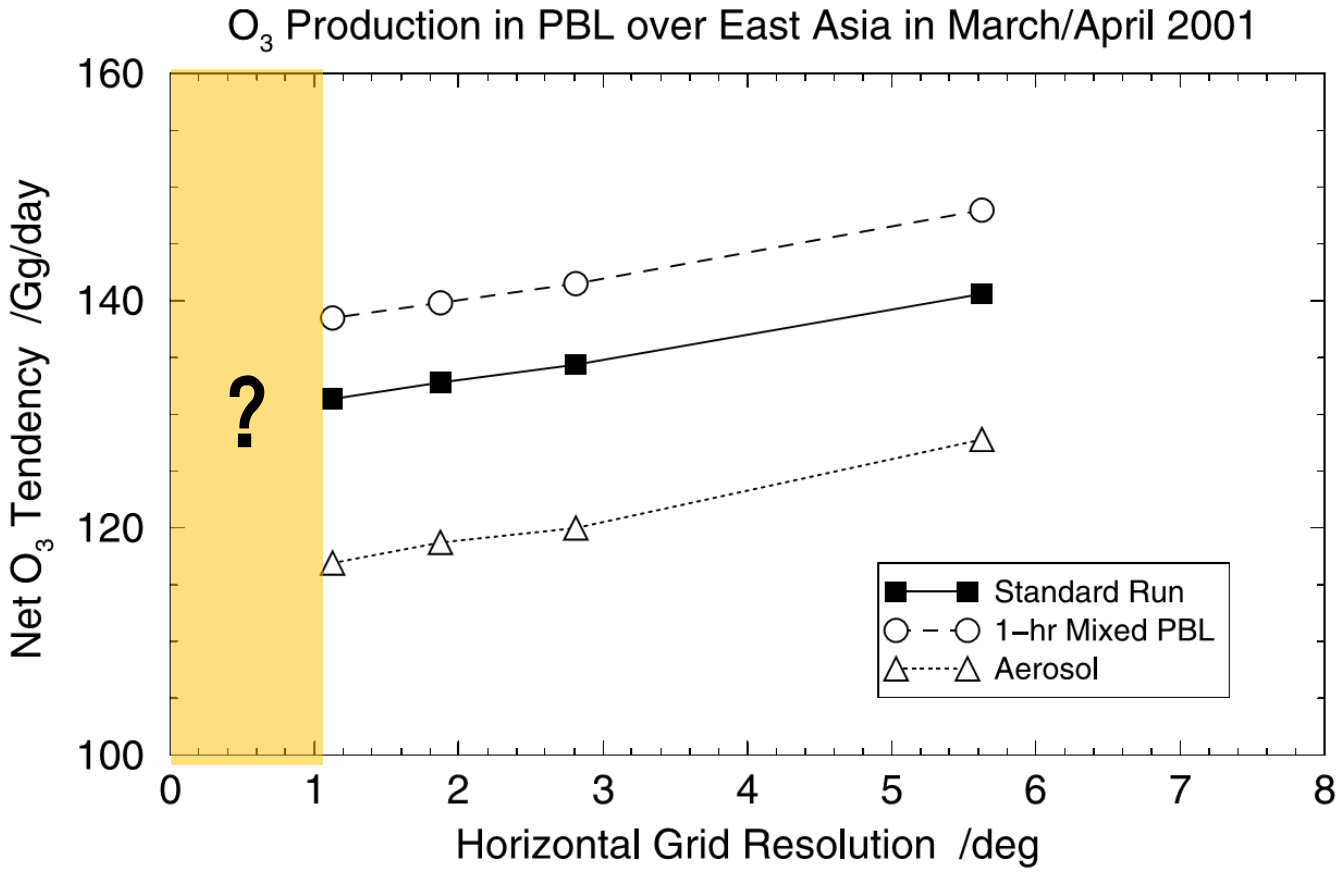
- $r_{AB} < 0$: Model has an **overestimation**
- $r_{AB} > 0$: Model has an **underestimation**

Coarse Models Under-represent Small Scales



Seinfeld and Pandis, 2006

Resolution-dependent Net Ozone Production



Wild an Prather, 2006

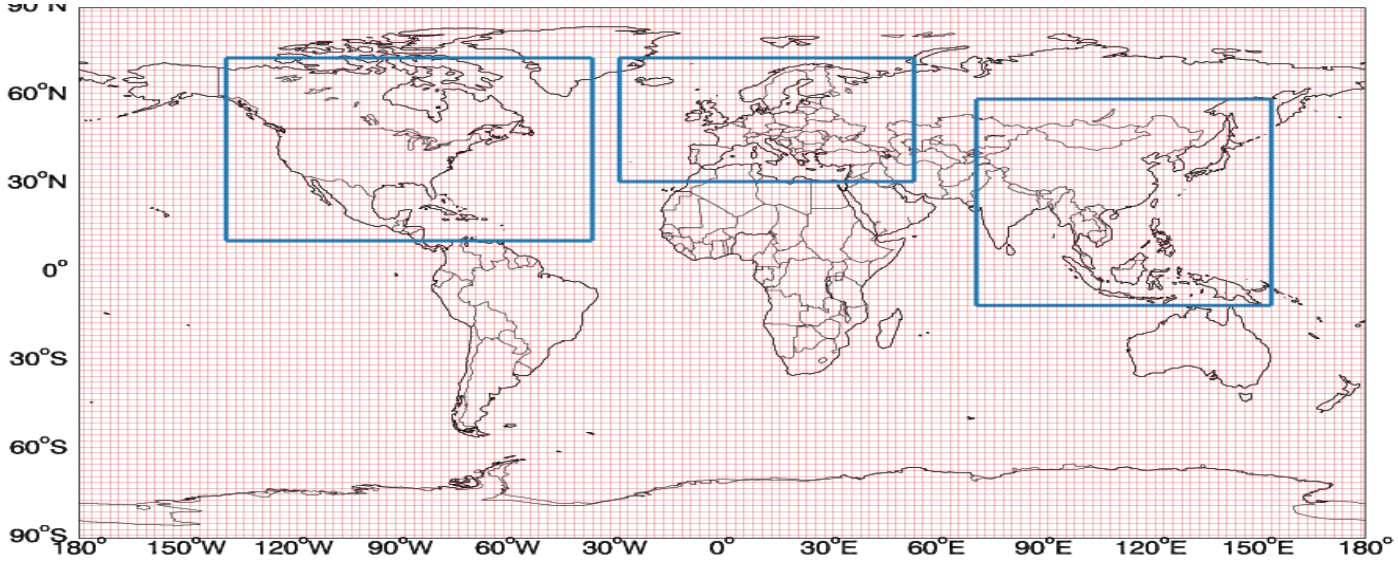
Global versus Regional Models

Global Models

- Covers the globe
  - Good for global studies
  - No LBCs are necessary
- Low-resolution (≥ 100 km)
  - No small-scale processes
- Example: GEOS-Chem, AM3

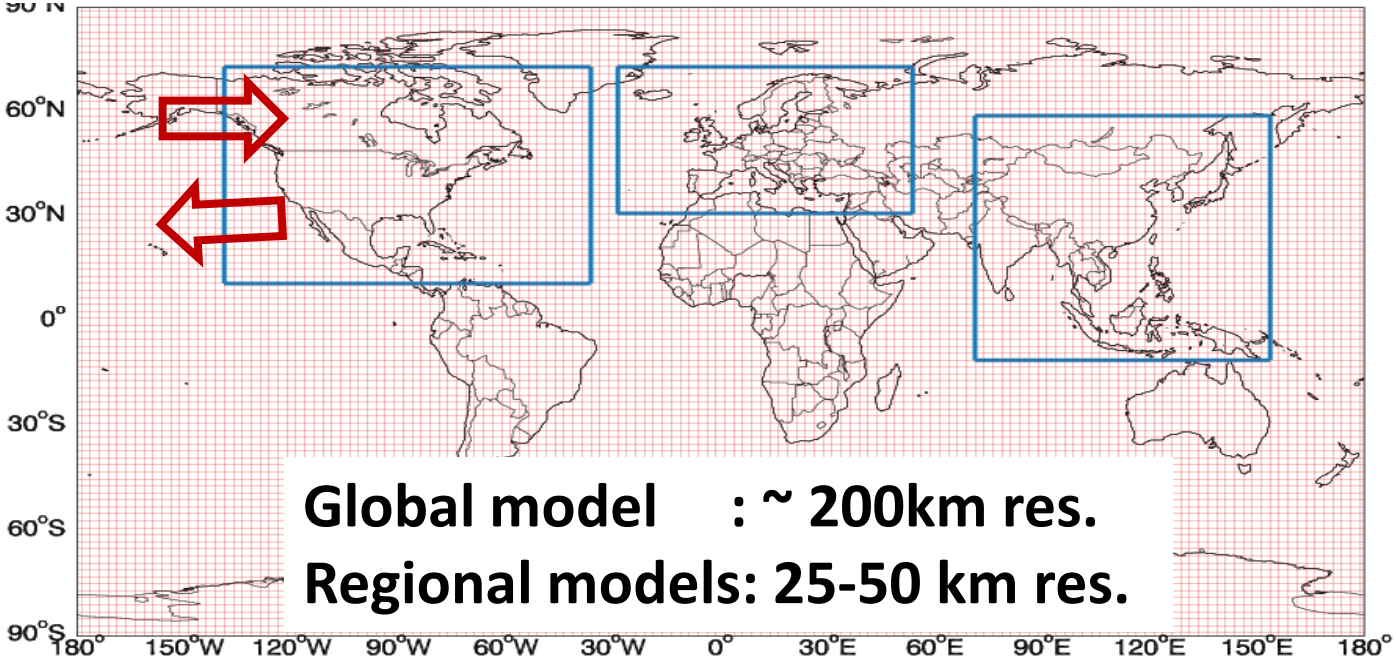
Regional Models

- Covers a region
  - Need LBCs from global models via 1-way nesting
- High-resolution (~ 10 km)
  - Resolve small-scale processes
- Example: CMAQ, WRF-Chem



Global-multi-regional Two-way Coupled Modeling
Based on GEOS-Chem

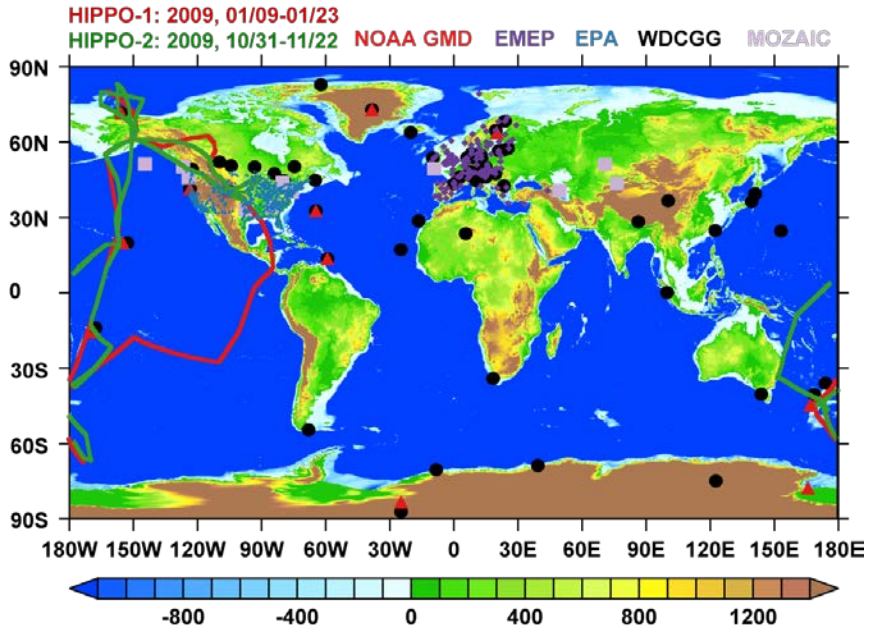
- High-res regional nested simulations 'correct' global model
- Global and multiple regional models interact simultaneously
- High computation efficiency and low model complexity



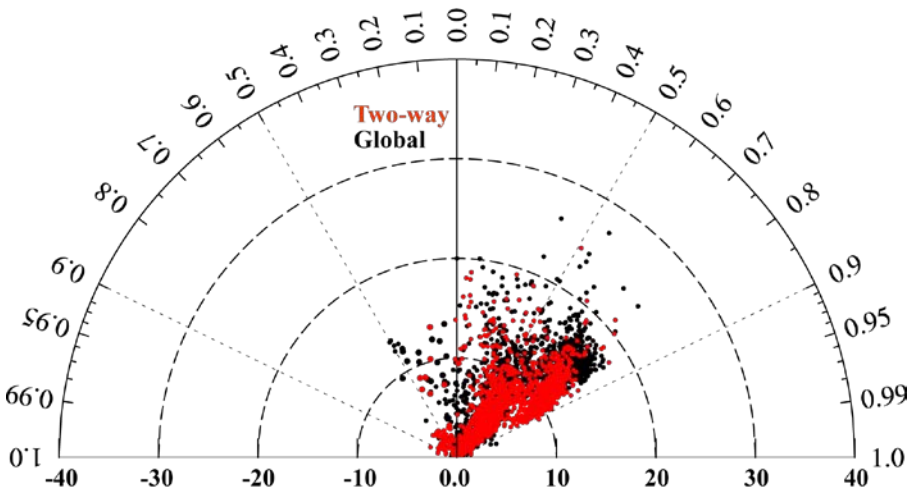
Yan Y.-Y. et al., 2014, ACP

2-way Model Better Simulates Surface O_3

# of ground sites = 1420



Correlation



Bias

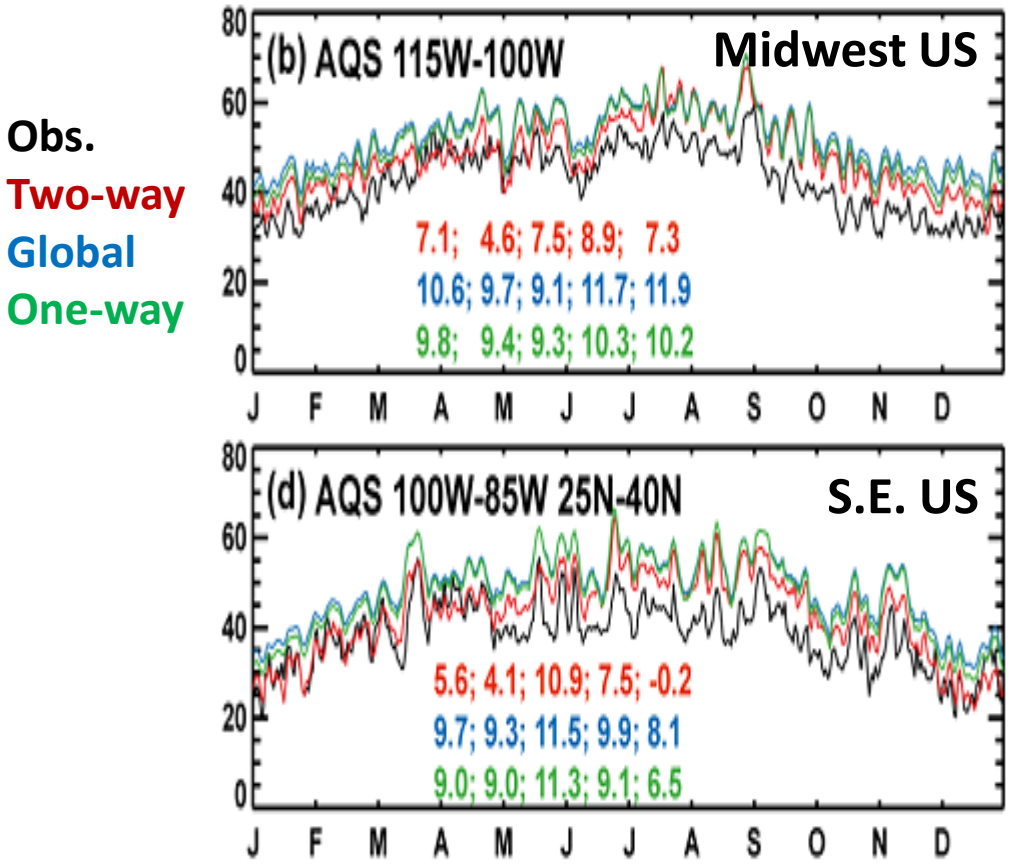
- **Mean R increases from 0.51 to 0.65**
- **Mean bias decreases by 4.8 ppb**

Yan Y.-Y. et al., 2016 ACP

2-way Model Better Simulates Surface O_3

Comparisons with AQS and EMEP observations:

- **Improvement is most significant in cold season**
- **Improvement from global to 2-way is 2-8 times that from global to 1-way**

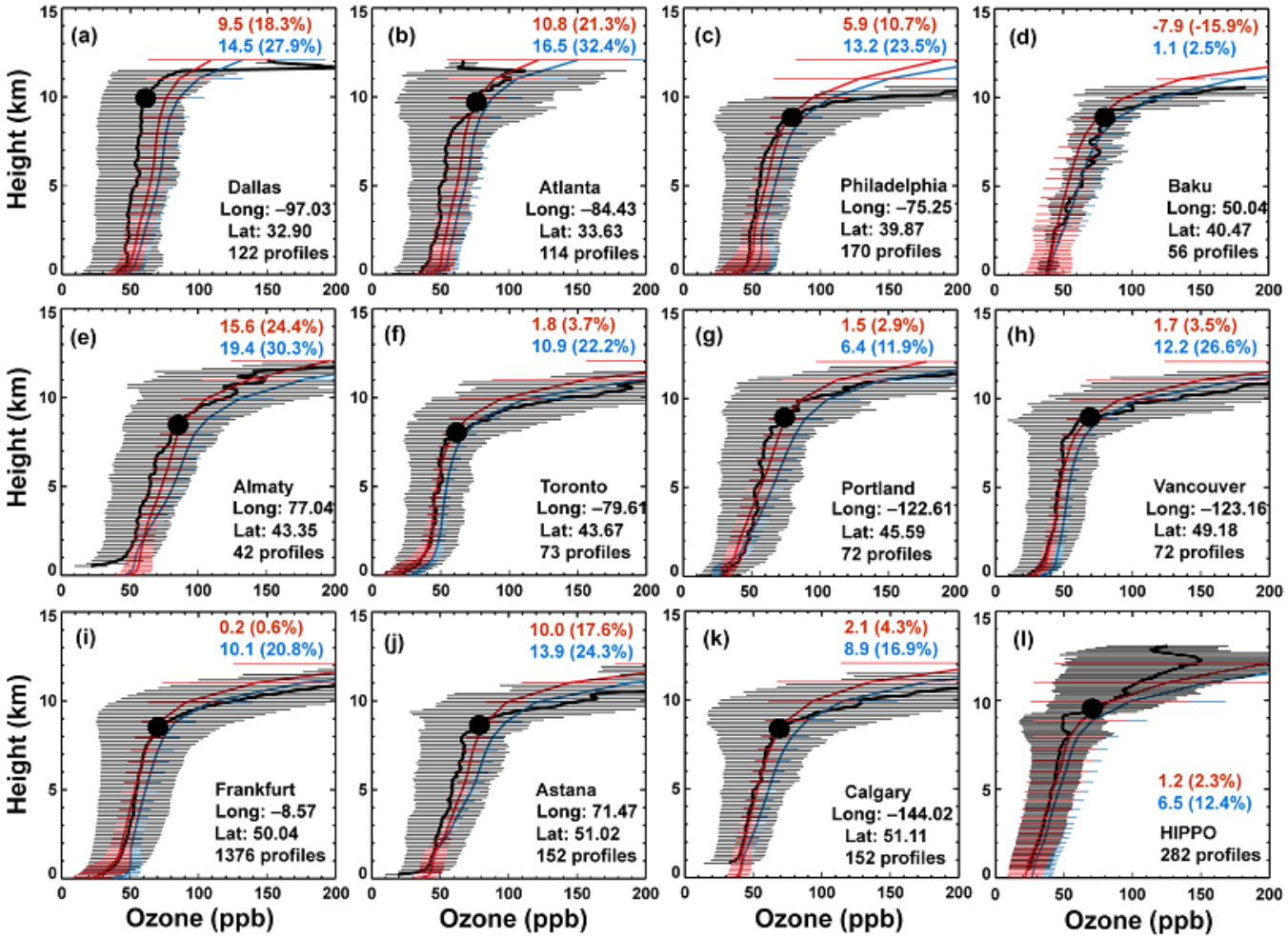


Yan Y.-Y. et al., ACP, 2014, 2016

2-way Model Better Simulates O_3 Profiles

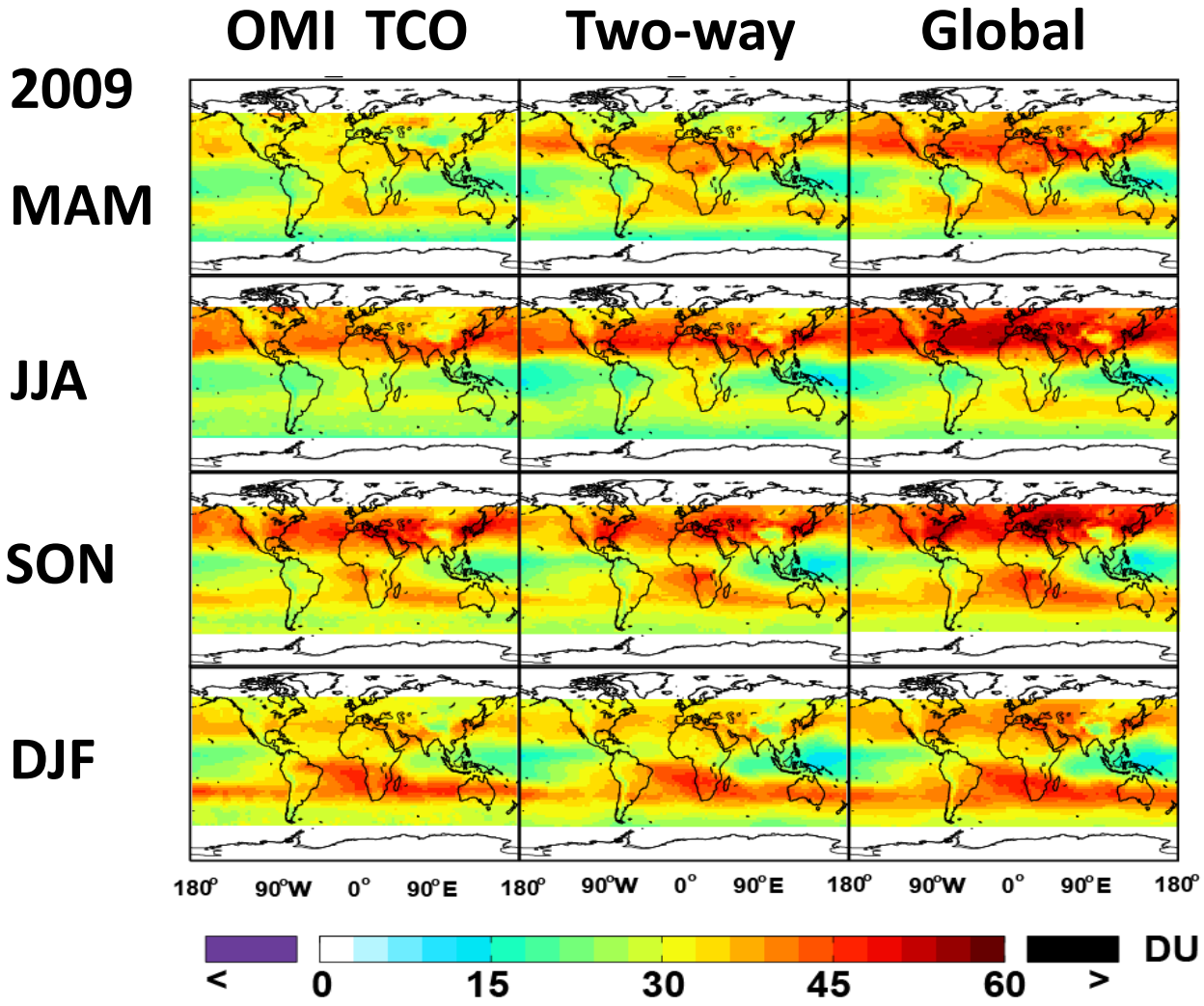
Obs
Two-way
Global

Comparisons with MOZIAC and HIPPO profiles



Yan Y.-Y. et al., ACP, 2014, 2016

2-way Model Better Simulates Tropospheric O_3



Yan Y.-Y. et al., 2016 ACP

2-way Coupling Improves Tropospheric Simulation

	Global Model	Two-way Model	'Observation'
OH (10^5 cm^{-3})	11.8	11.2 (– 5% *)	10.4 – 10.9
MCF lifetime (yr)	5.58	5.87 (+ 5.2%)	6.0 – 6.3
CH_4 lifetime (yr)	9.63	10.12 (+ 5.1%)	10.2 – 11.2
O_3 (DU)	34.5	31.5 (– 8.7%)	31.1 ± 3 (OMI/MLS)
O_3 (Tg)	384	348 (– 9.5% #)	
NOx (TgN)	0.169	0.176 (+ 4.1%)	
CO (Tg)	359	398 (+ 10.8% &)	
NMVOC (TgC)	10.1	10.2	

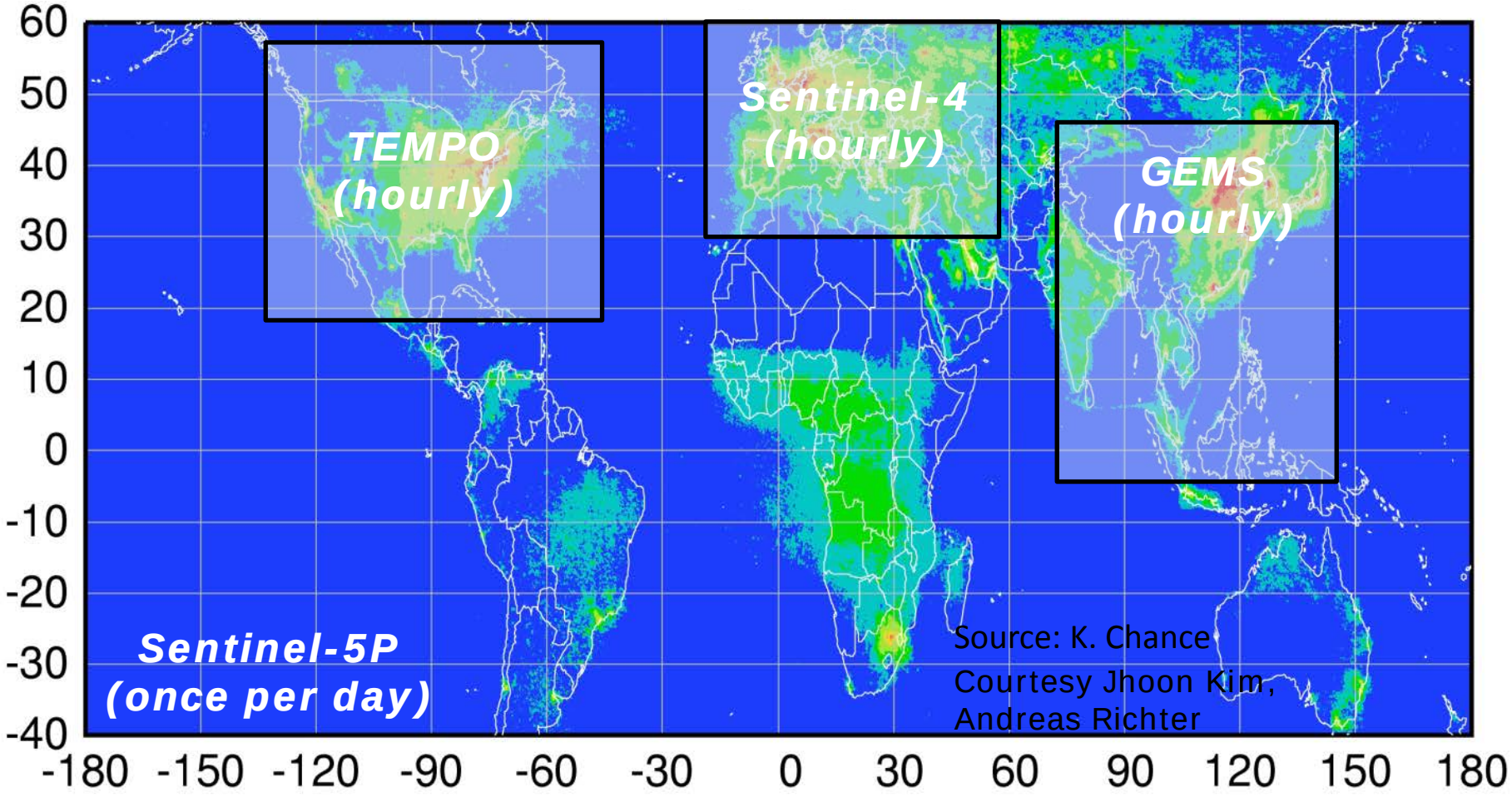
* Greater than its interannual variability (2.3%)

Greater than the change from 2000 to 2100 under RCP6.0

& Equivalent to a 25% increase in global CO emissions

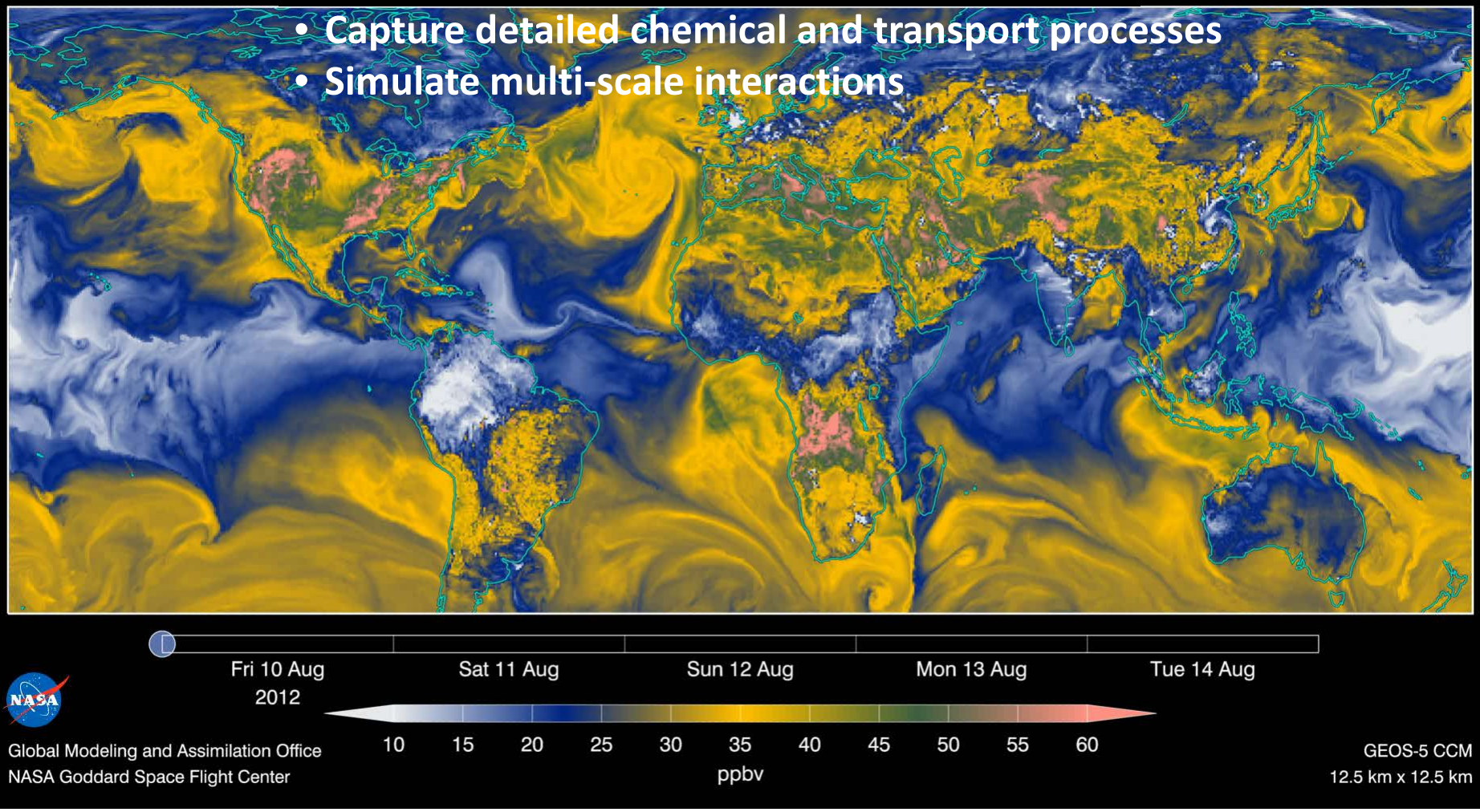
Yan Y.-Y. et al., ACP, 2014, 2016

Integrating Two-Way Coupled Modeling with Future-Generation Satellite Measurements



High-resolution Modeling of Pollution Transport & Chemistry

Surface ozone simulation at 12.5 km x 12.5 km



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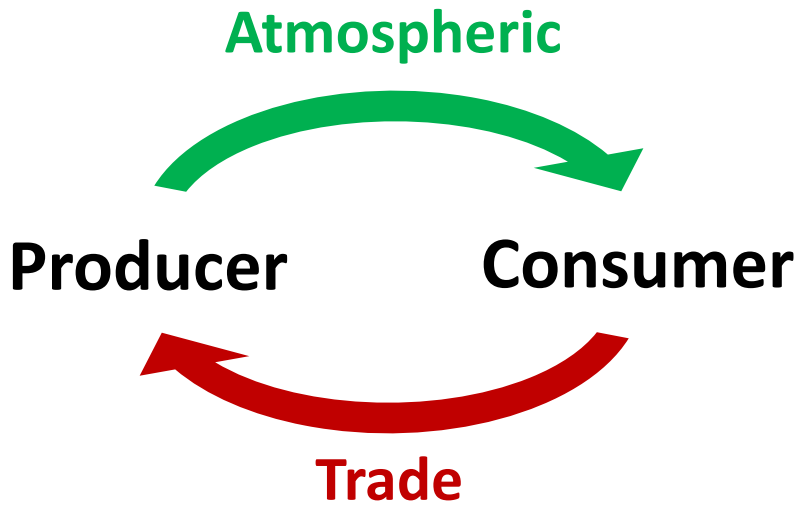
Globalizing Air Pollution

Pollution

Climate

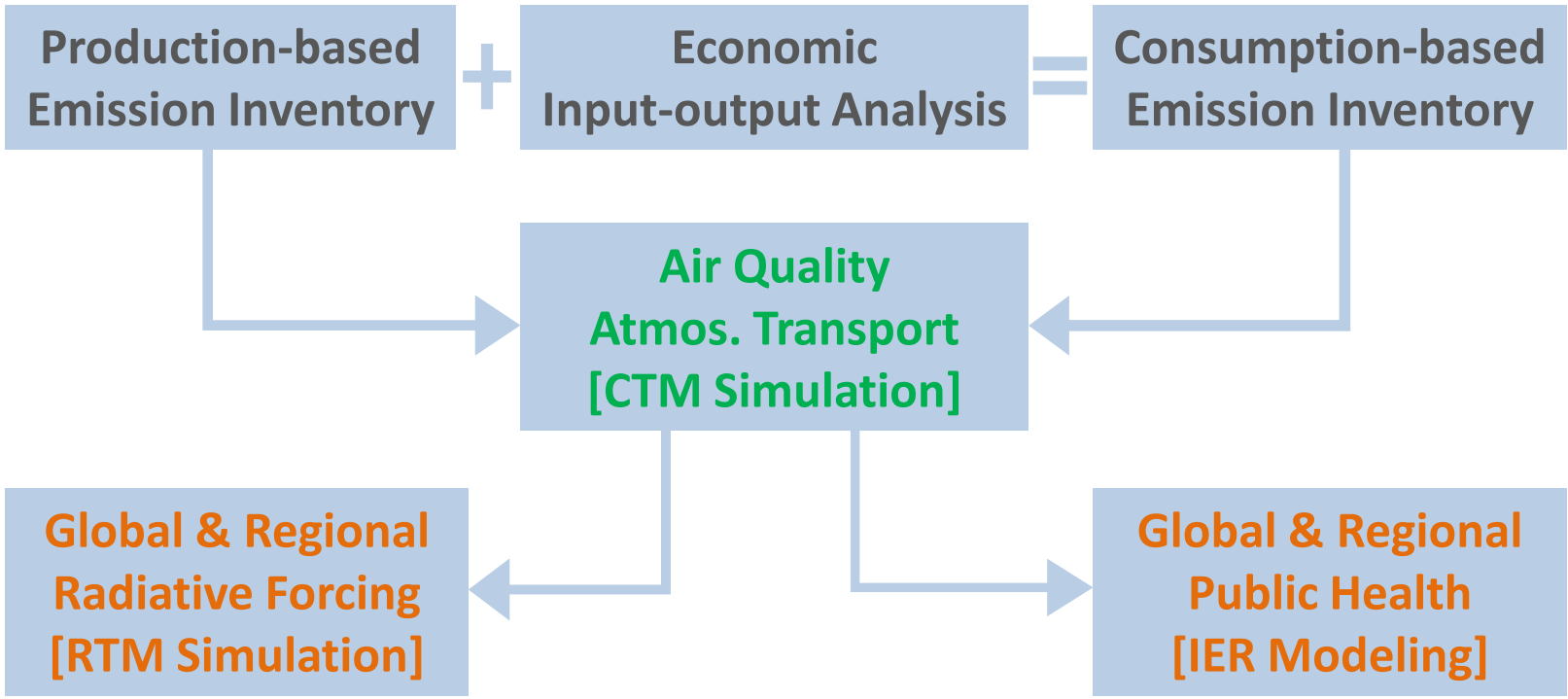
Ecosystem



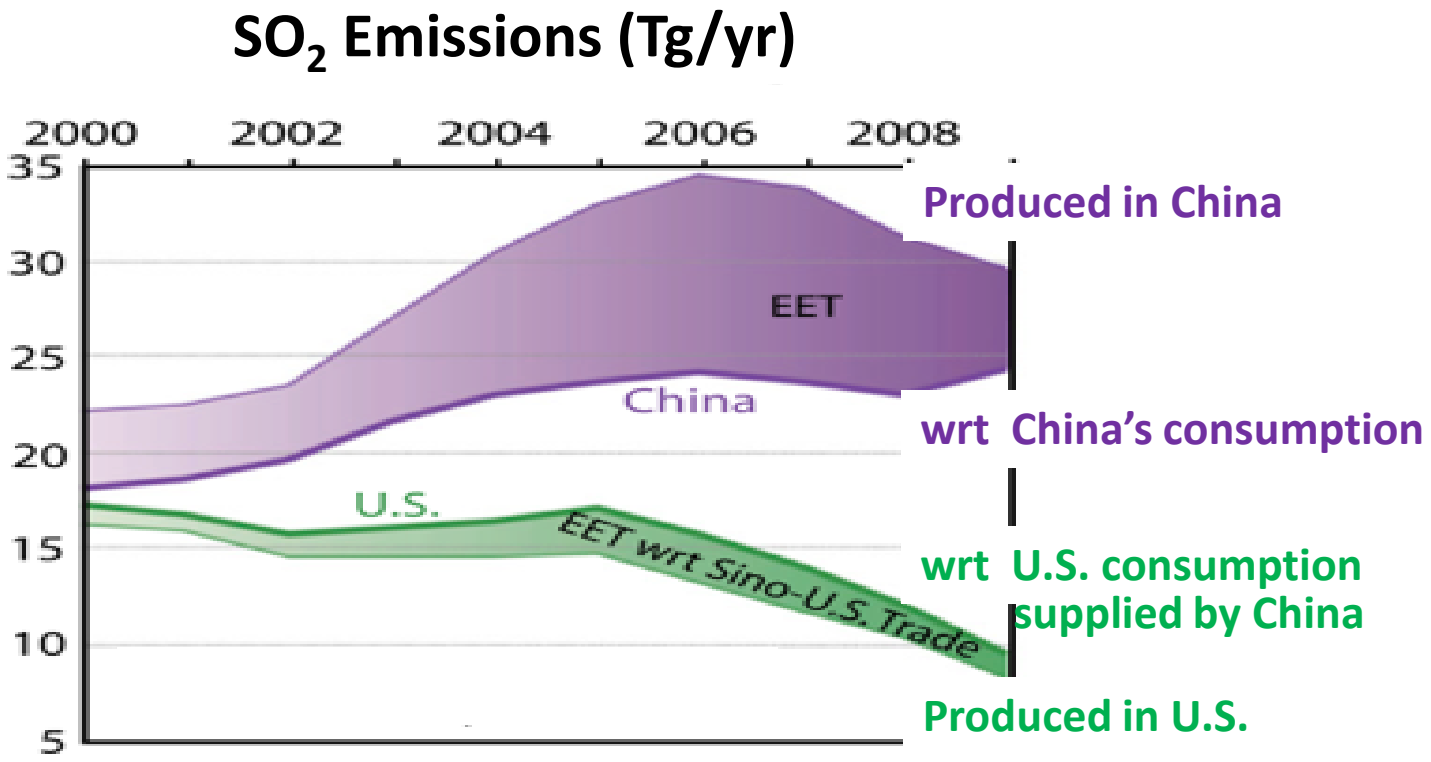
- Atmosphere: Move pollution from producer to consumer
- Trade : Move Pollution from consumer to producer

Lin et al., 2014, PNAS

An Interdisciplinary Approach to Calculating Globalizing Air Pollution



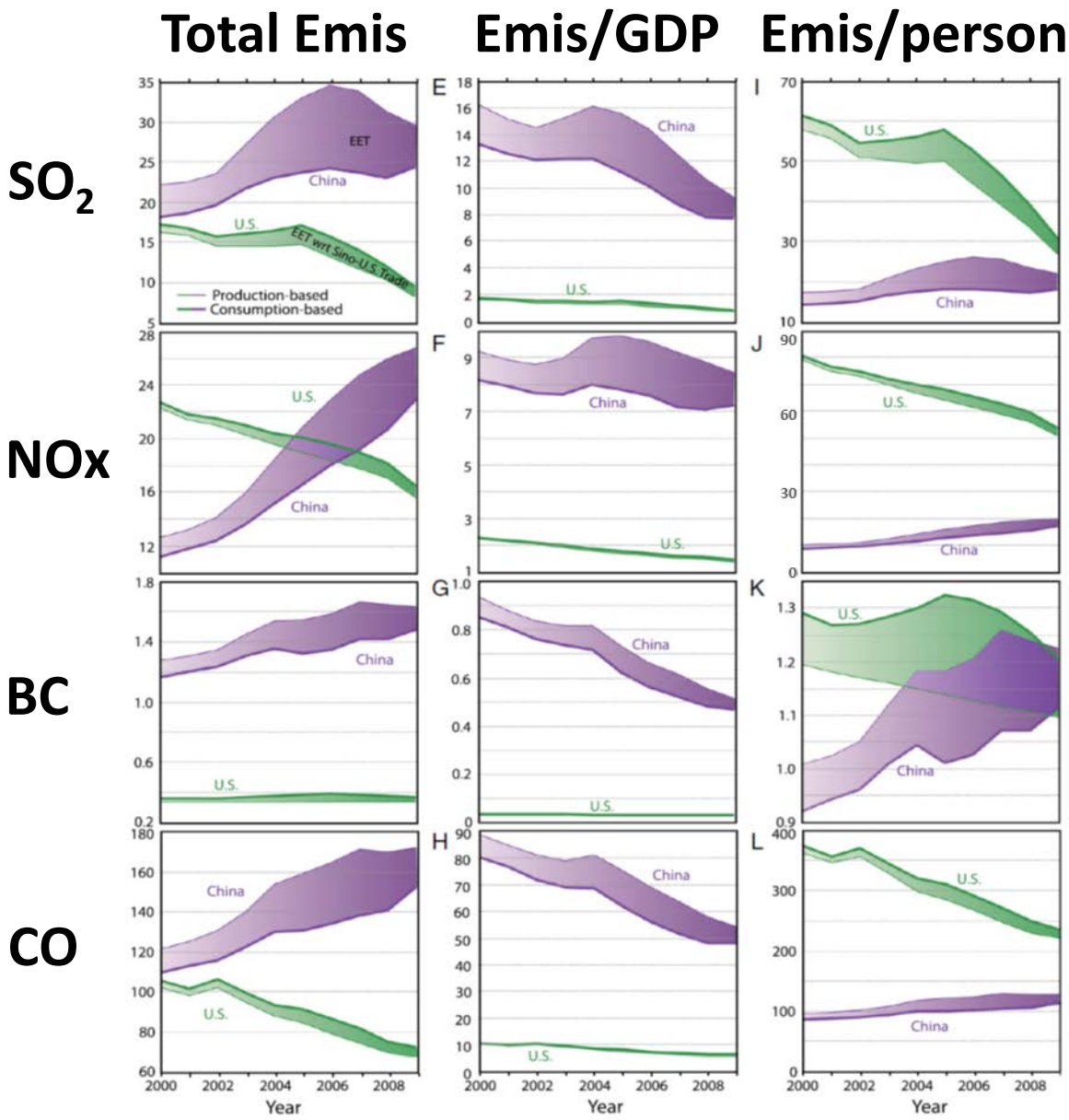
Trade Redefines Chinese and U.S. Emissions



- 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/per**
- **Net emis due to exports**

Lin et al., 2014, PNAS

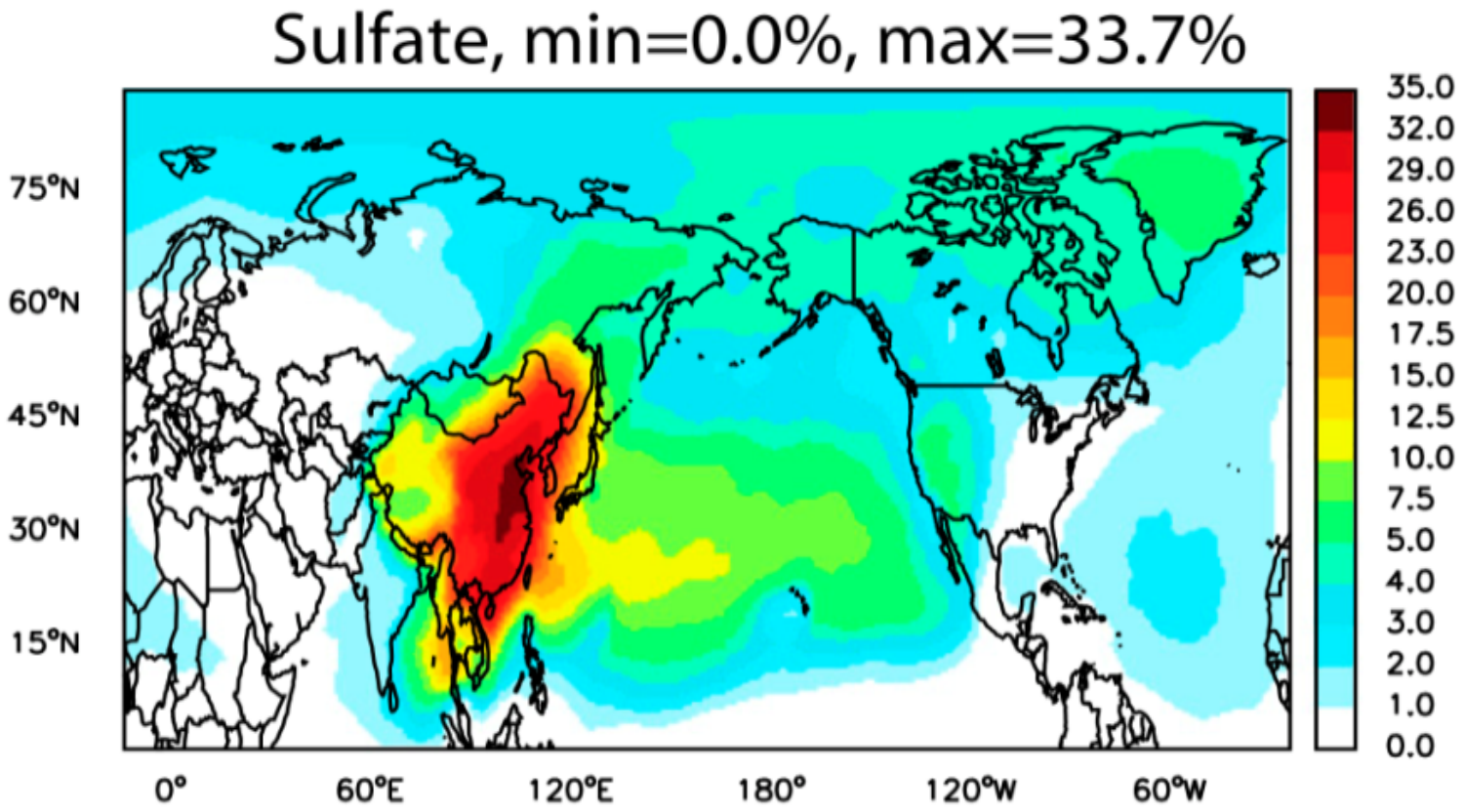
China's High Emissions Embedded in Export

- Higher export than import volumes
- More emission-intensive products for export
- Higher emission intensity overall:
  - 5-33 times that of U.S.; 3-5 times world mean
  - Manufacture-driven economy
  - Coal-dominated energy sources
  - Relatively low emission control levels

Lin et al., 2014, PNAS

Goods Export Contributes ~ 30% of China's Sulfate

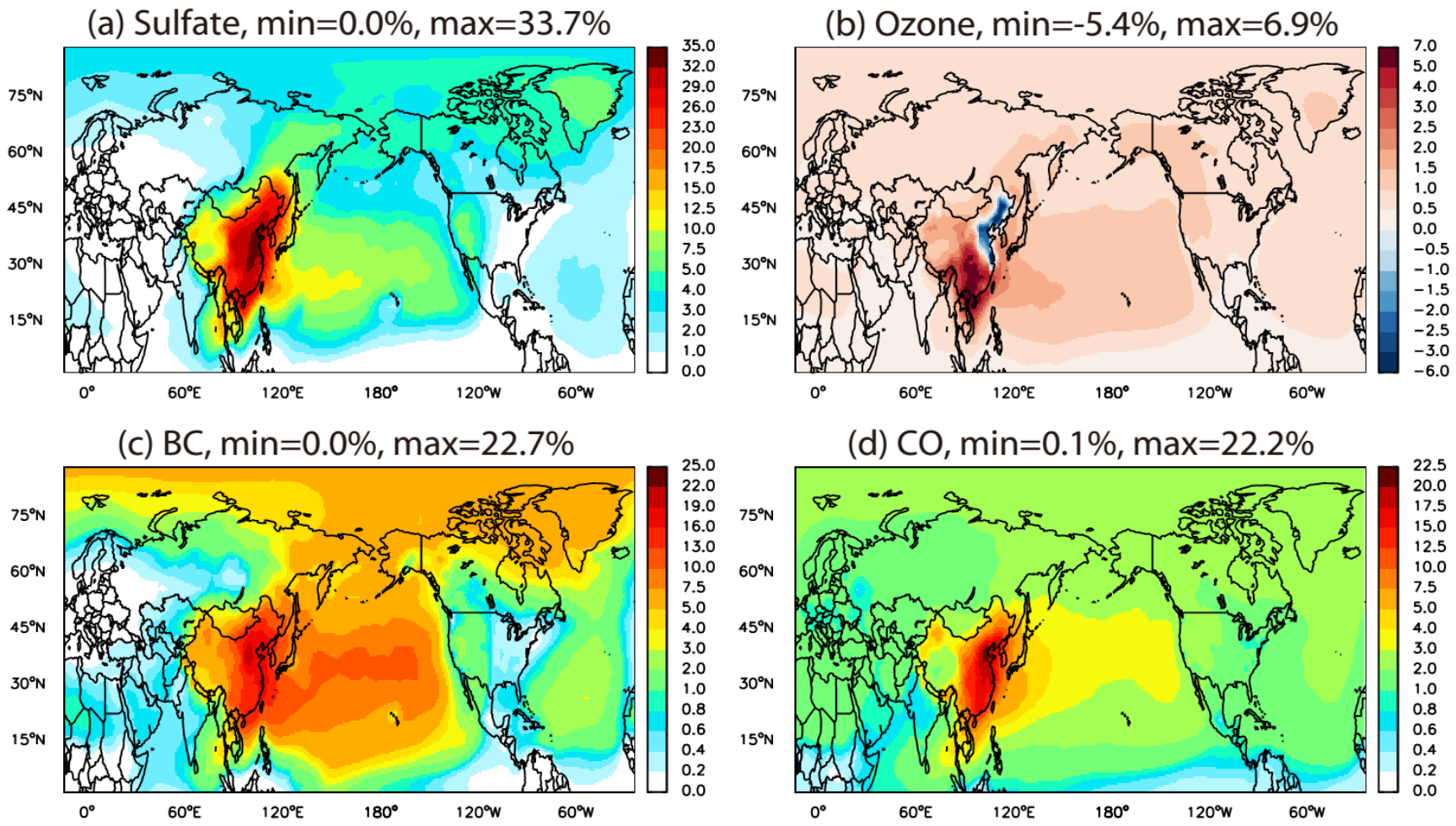
% contribution of China's export-related pollution to total pollution anywhere in the world



Lin et al., 2014, PNAS

Export of Goods Contributes to China's Pollution

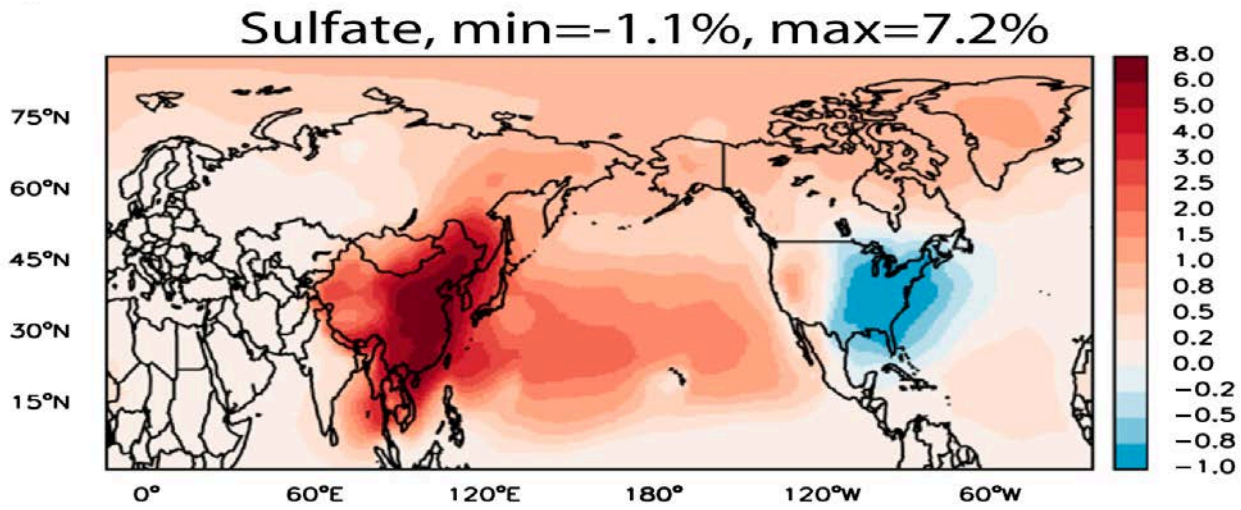
% contribution of China's export-related pollution to total pollution anywhere in the world



Lin et al., 2014, PNAS

USA Consumption And China's Sulfate Pollution

% change in sulfate



USA imports goods from China versus self-production:

(accounting for differences in emission intensity)

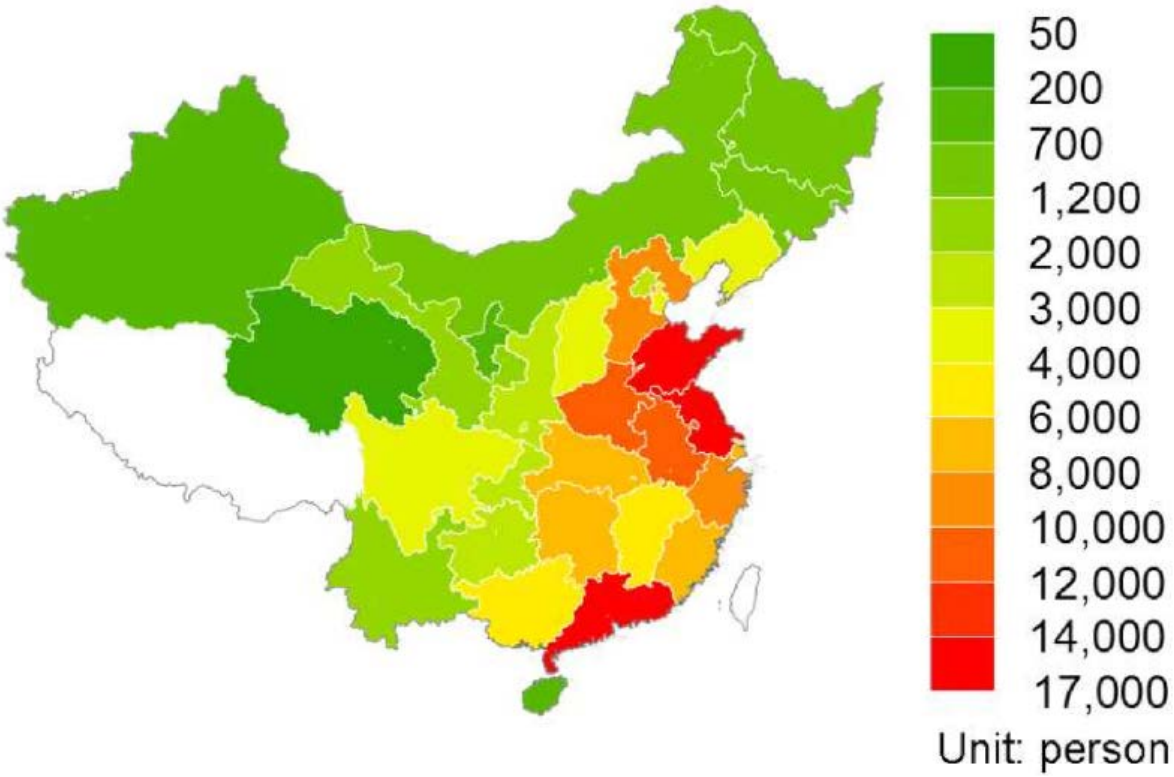
- **Increase China's sulfate PM**
- **Decrease USA's sulfate PM overall, GOOD for USA**

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

Lin et al., 2014, PNAS

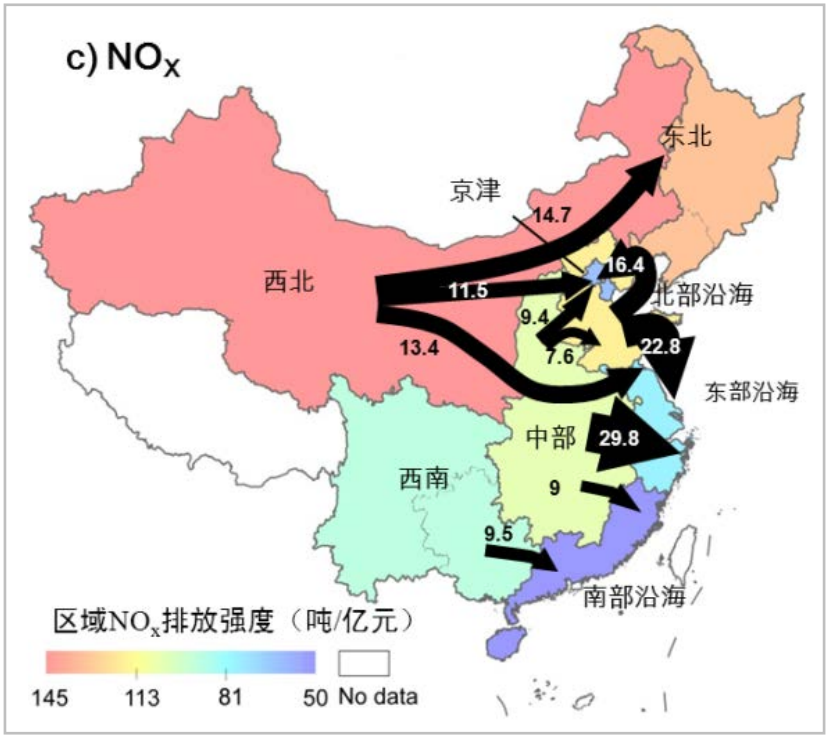
China's Export Causes A Large Quantity of Deaths

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

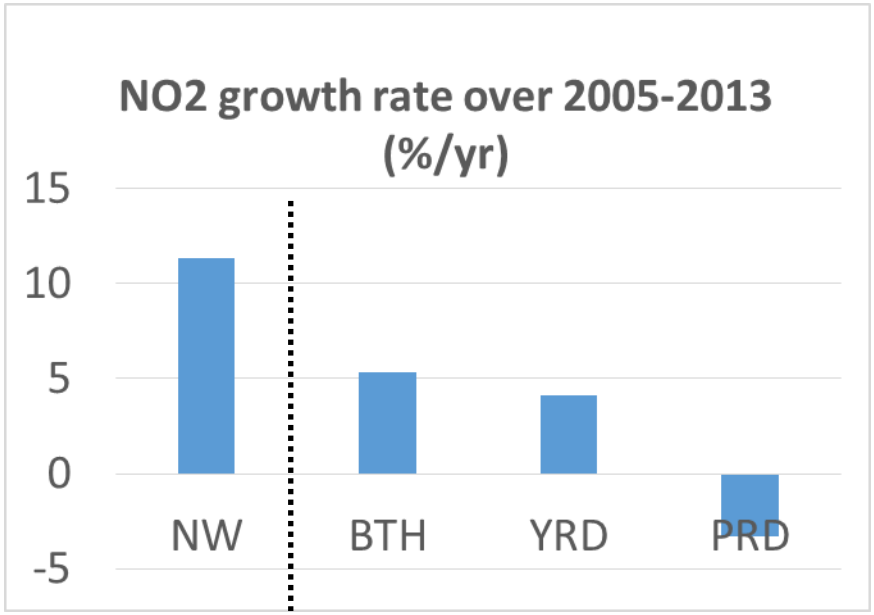


Jiang et al., EST, 2015

China's Inter-regional Pollution Transport Via Trade



Zhao et al., ACP, 2015



Cui et al., ACP, 2016

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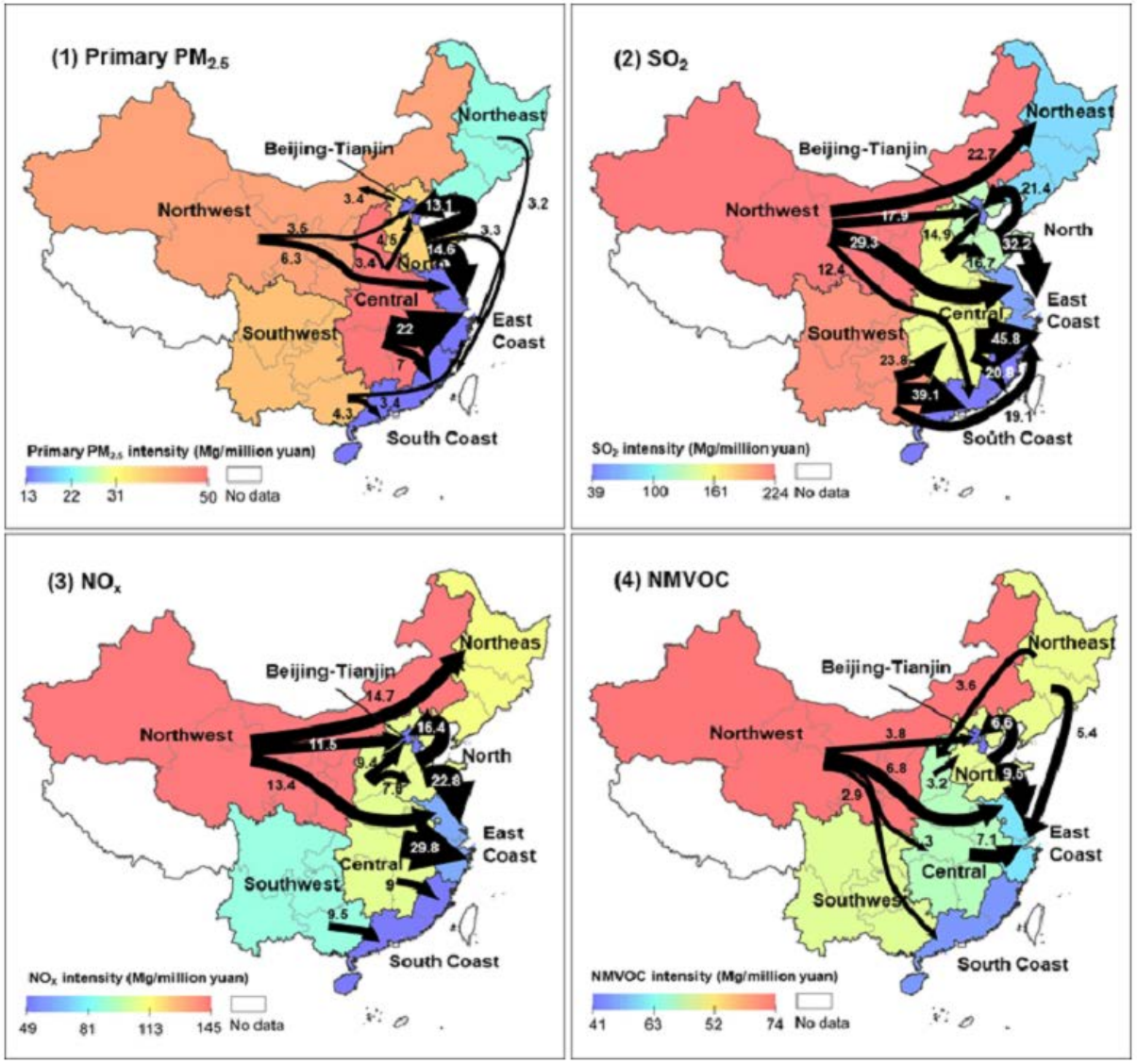
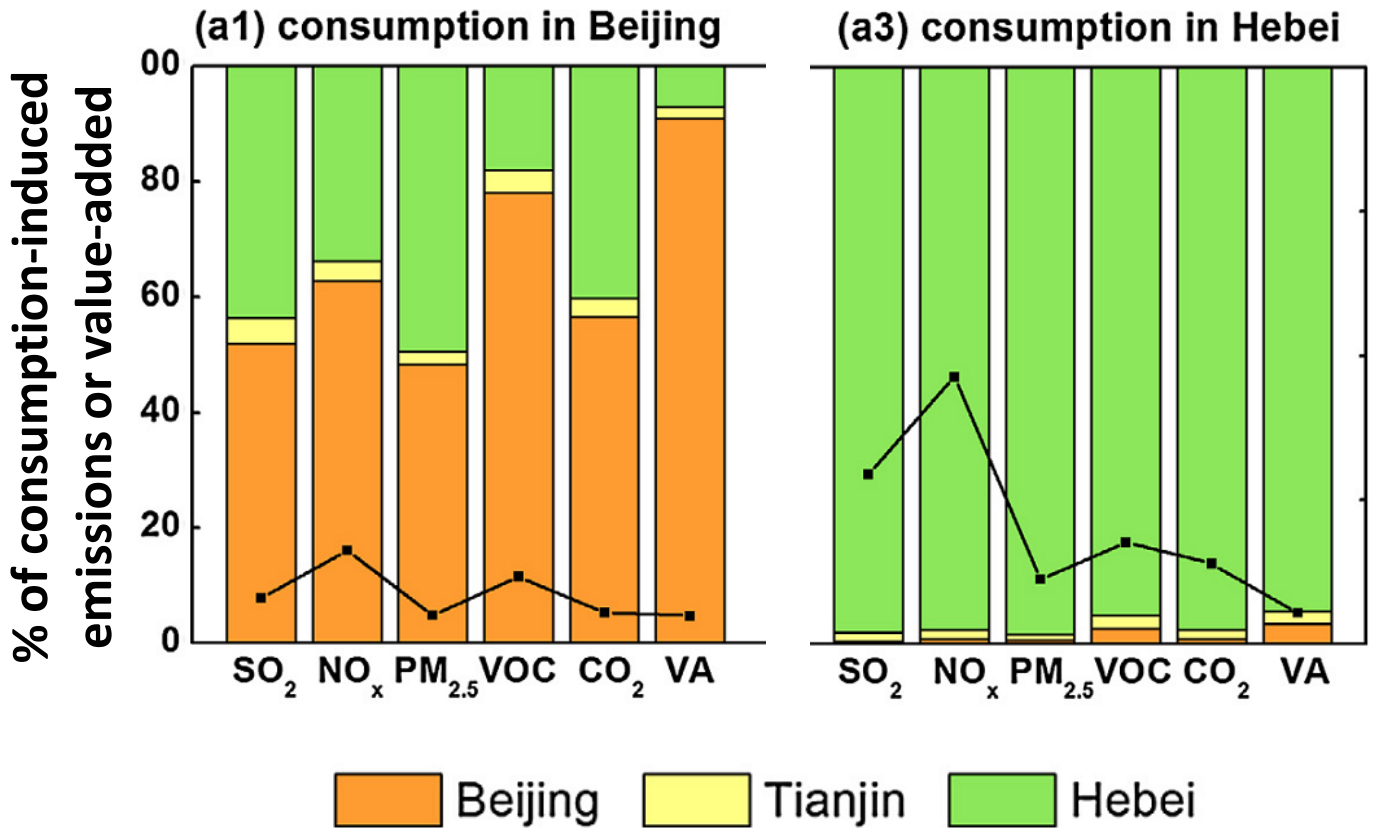


Zhao et al., ACP, 2015

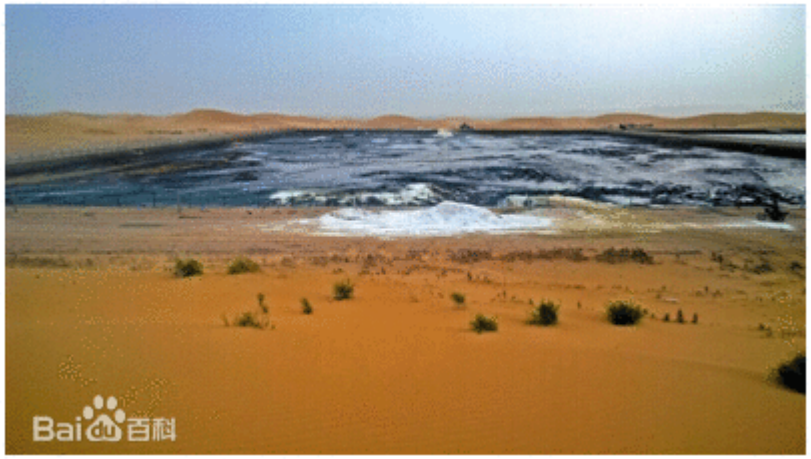
Pollution Transfer Due to Trade: Beijing → Hebei



Zhao et al., Applied Energy, 2016

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

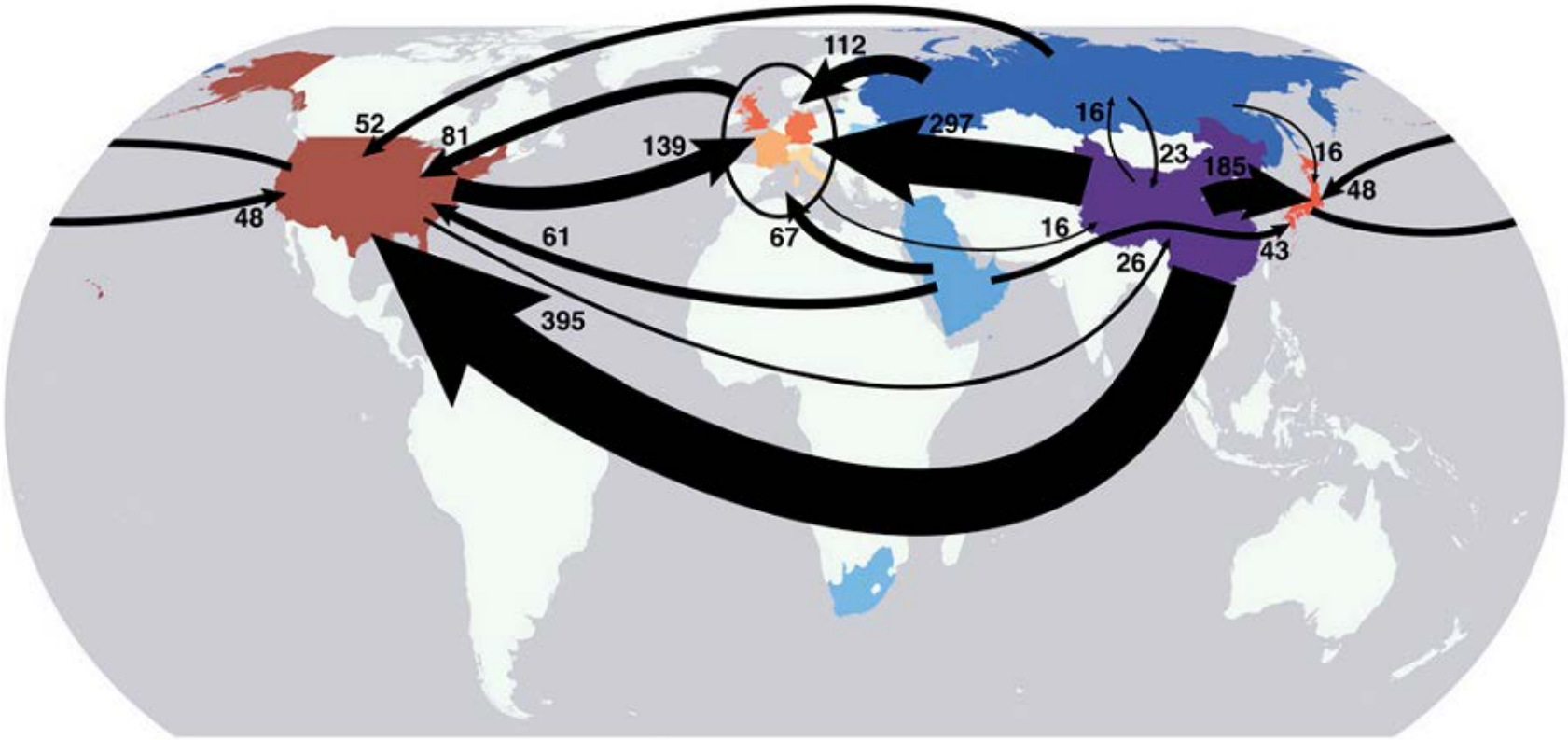
Pollution in Tenggeli Desert (2014/08/31)



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

Global Trade Leads to Complex Emission Transfer

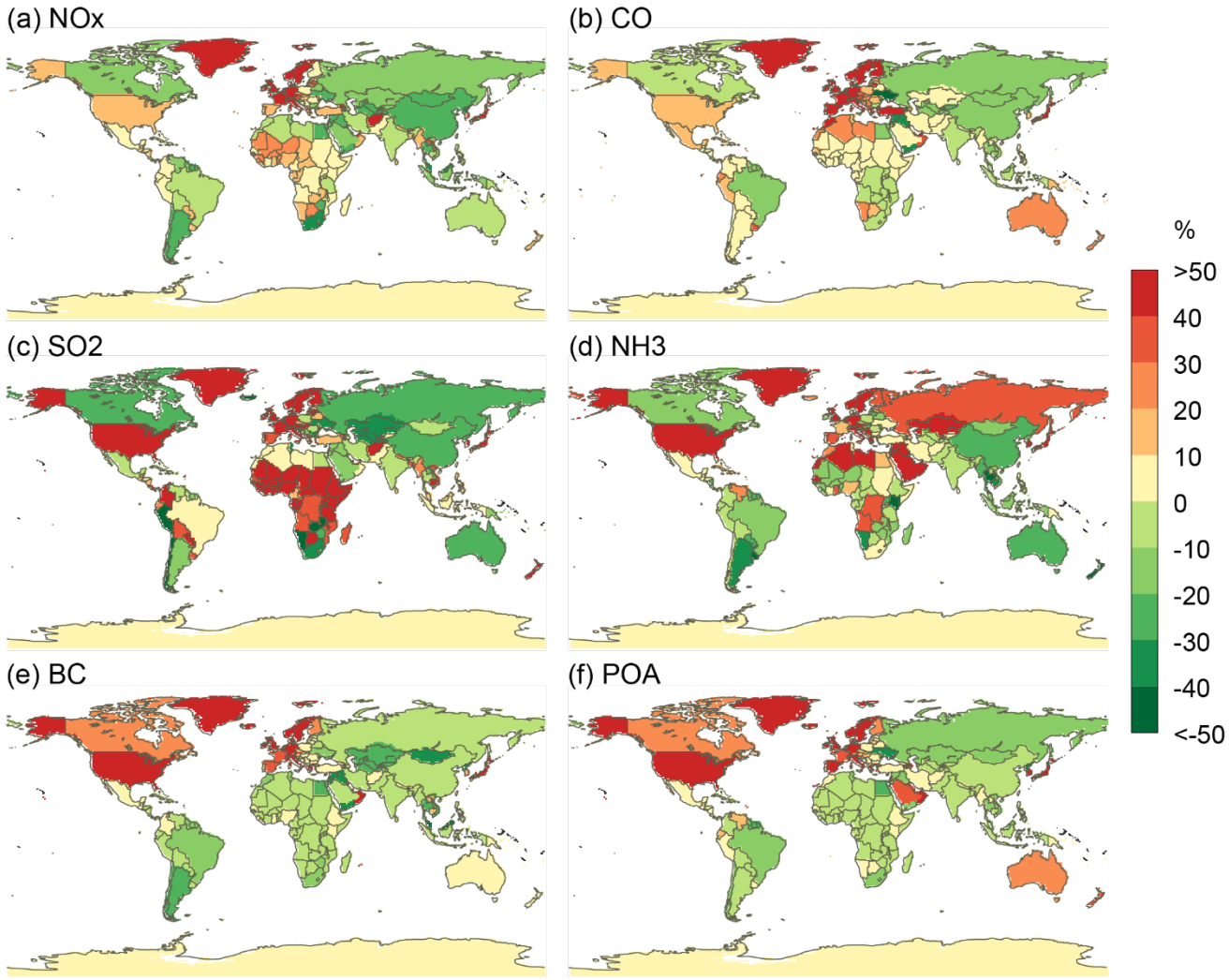
CO_2 emission transfer via trade



Davis and Caldaria, 2010, PNAS

Trade Transfers Emissions from Rich to Poorer Regions

Consumption-based minus Production-based Emissions in 2007



Lin et al., 2016, Nature Geoscience

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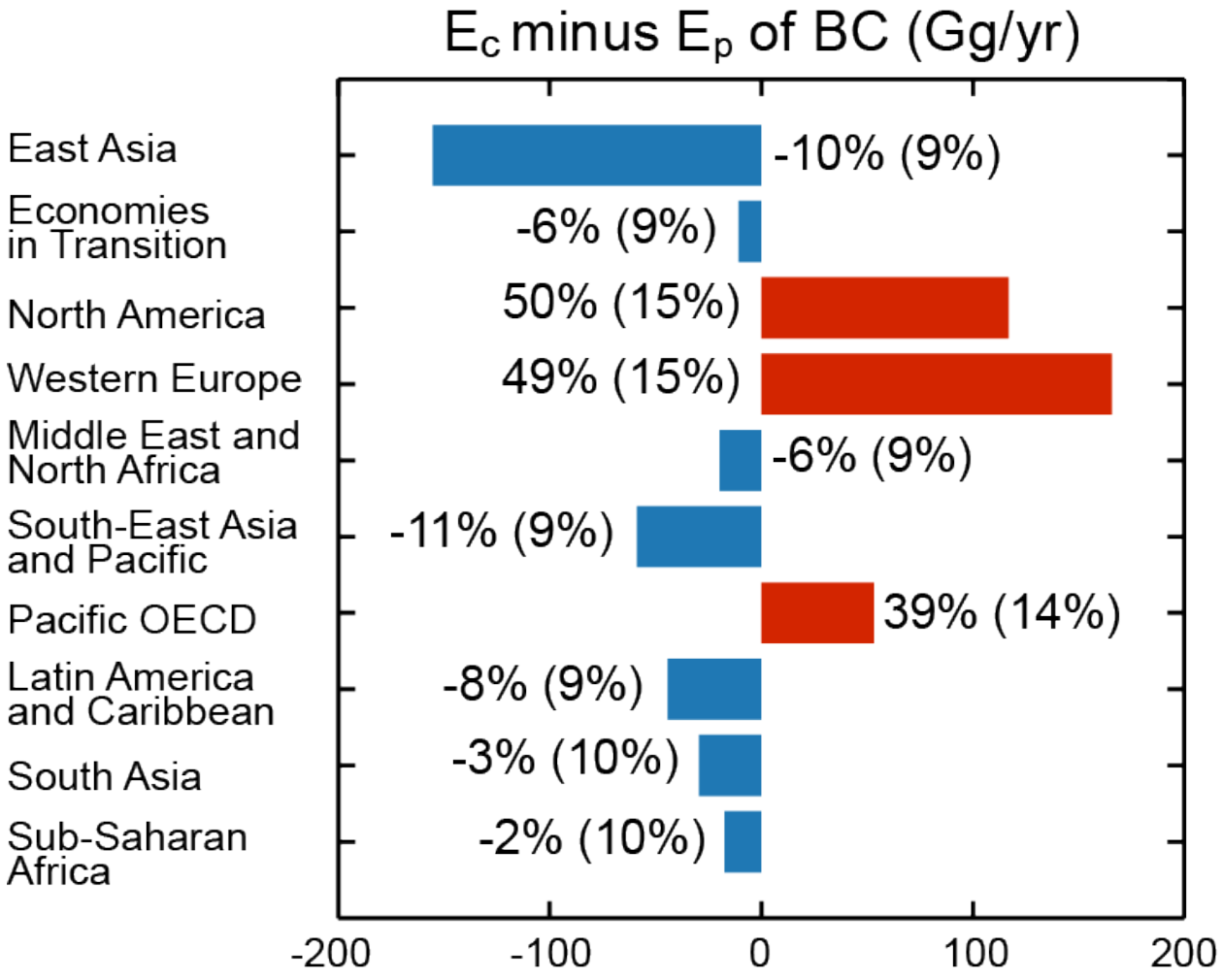

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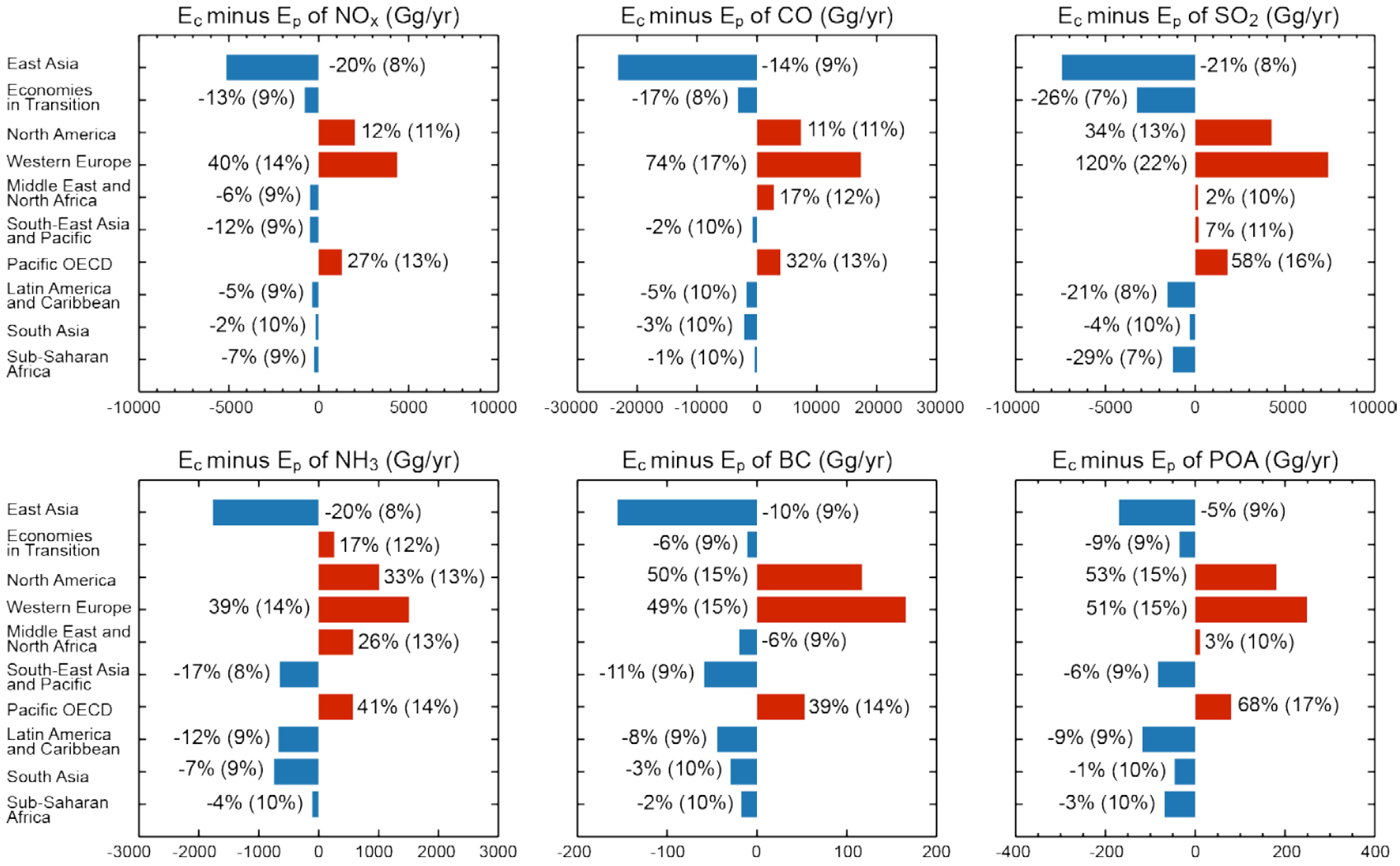
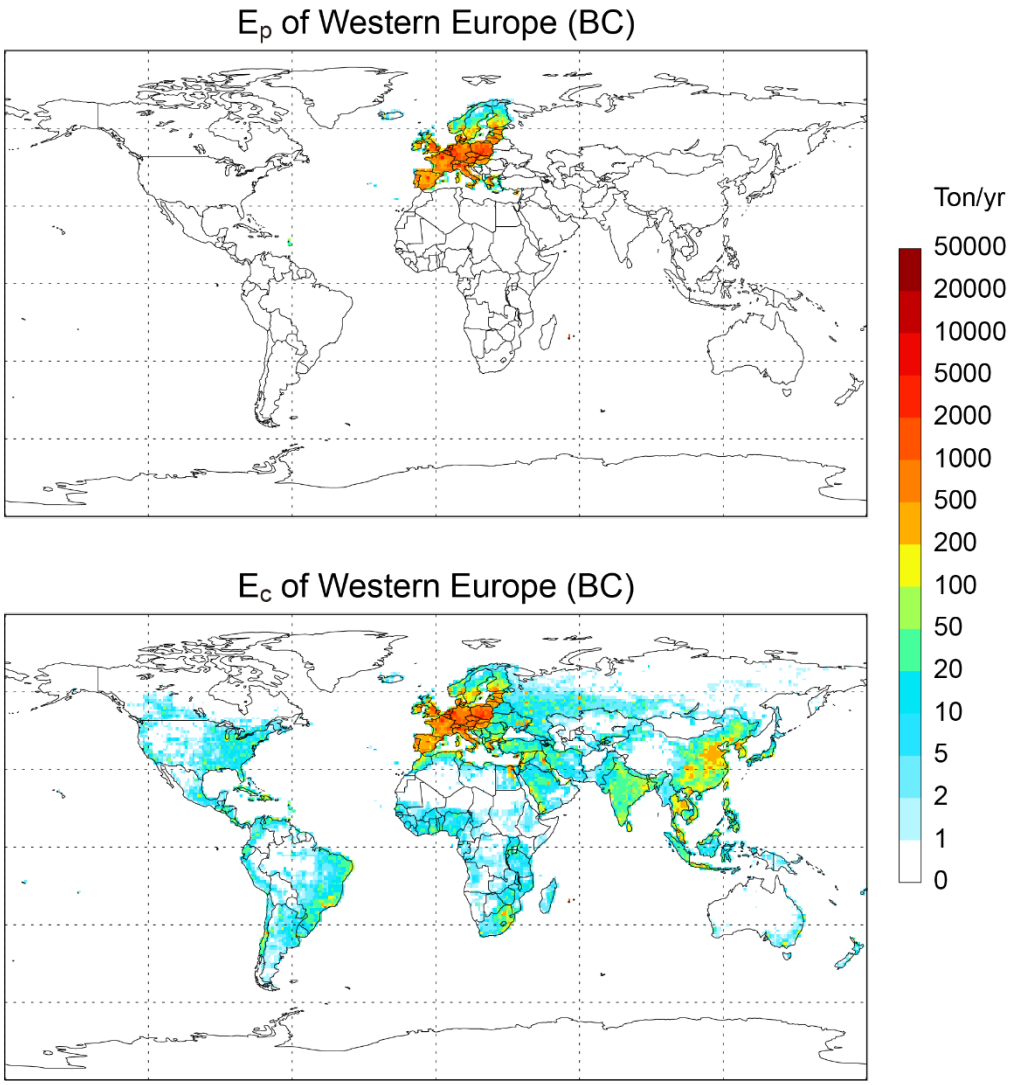


Lin et al., 2016, Nature Geoscience

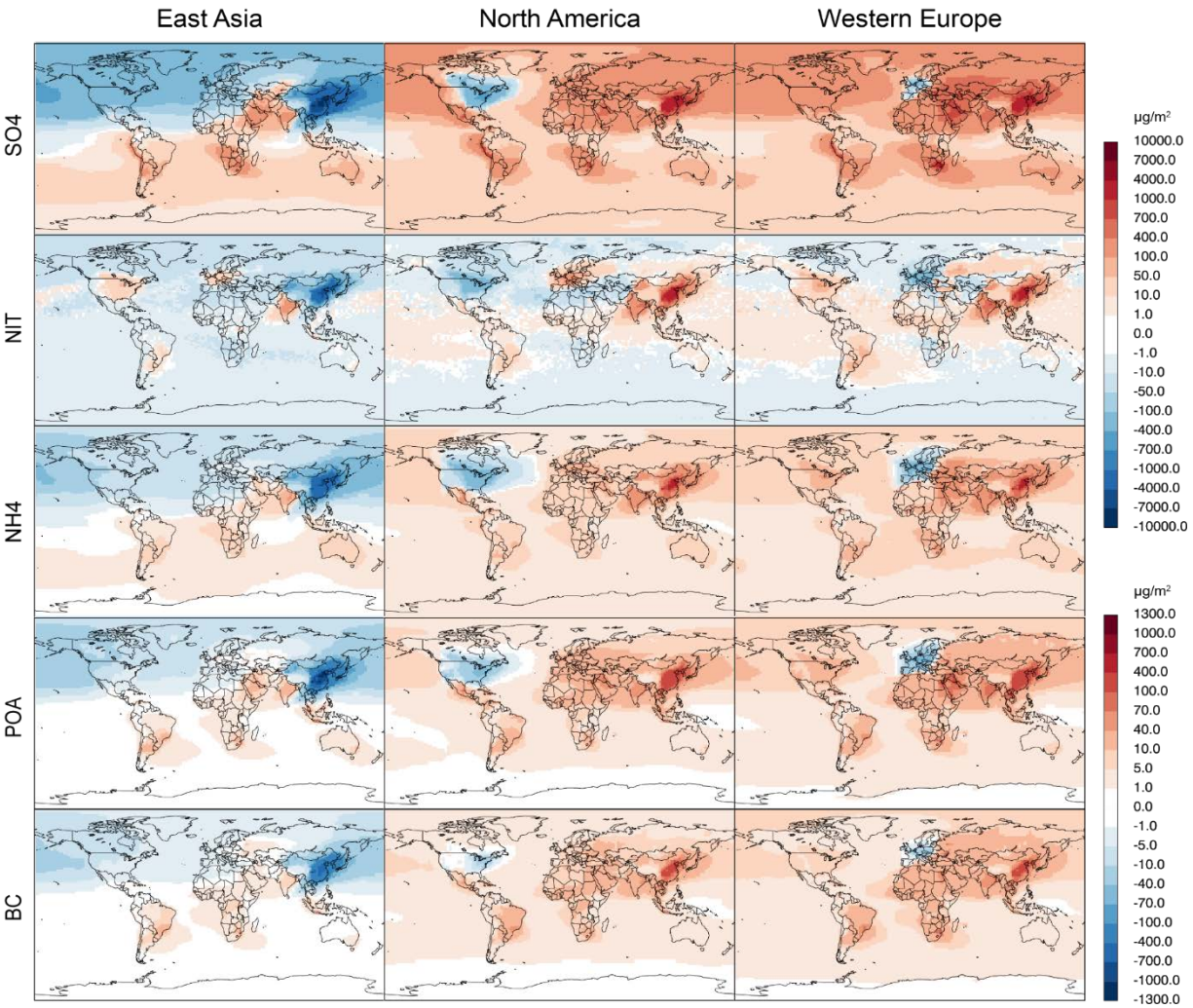
Trade Redistributes Emissions



Lin et al., 2016, Nature Geoscience

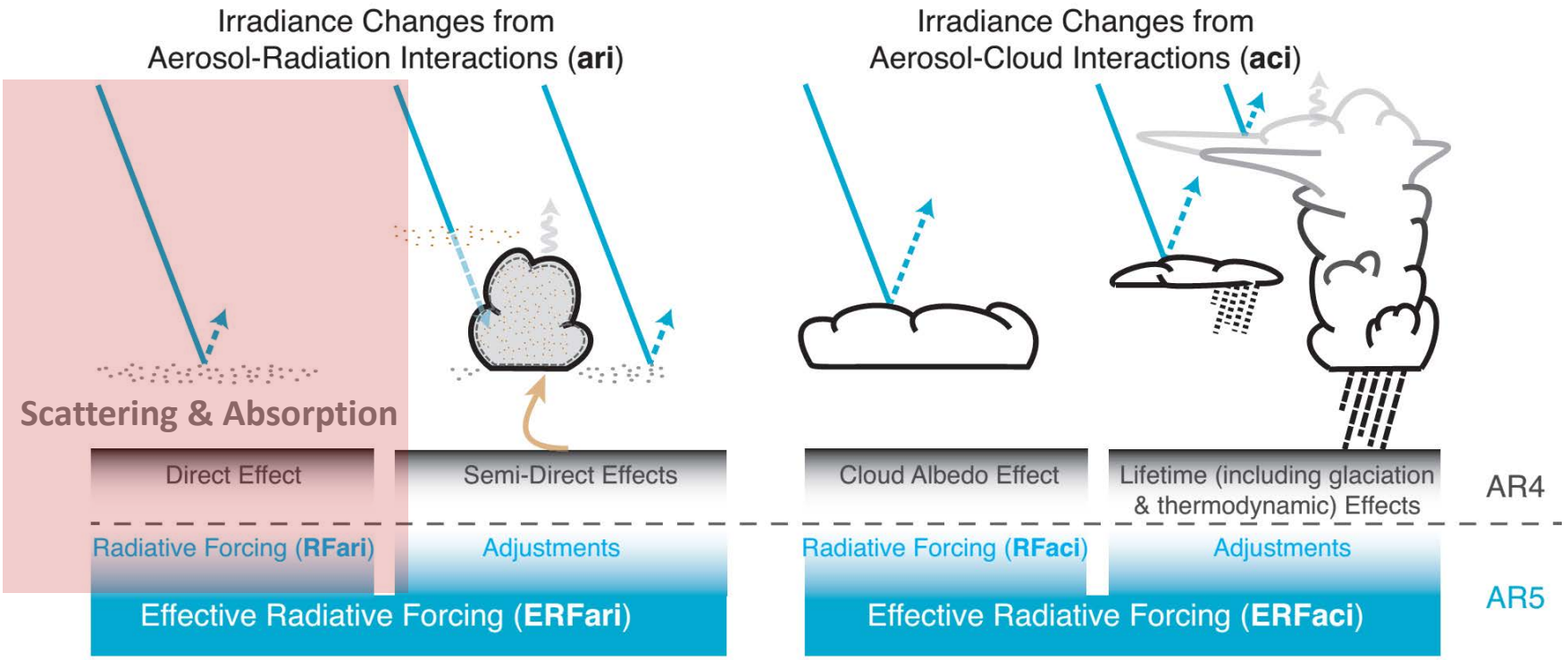
Trade Transfers Pollution from Rich to Poorer Regions

Consumption-based minus production-based PM in 2007



Lin et al., 2016, Nature Geoscience

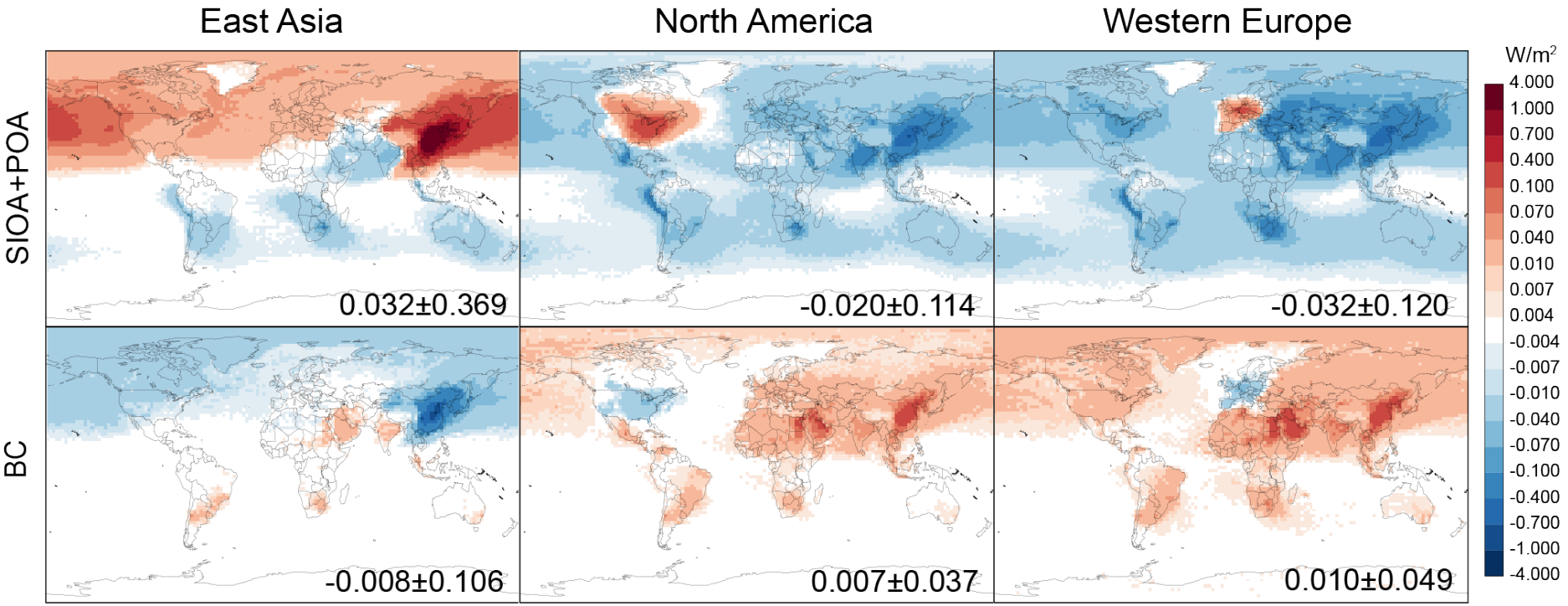
Radiative Forcing of Aerosols



IPCC, 2013

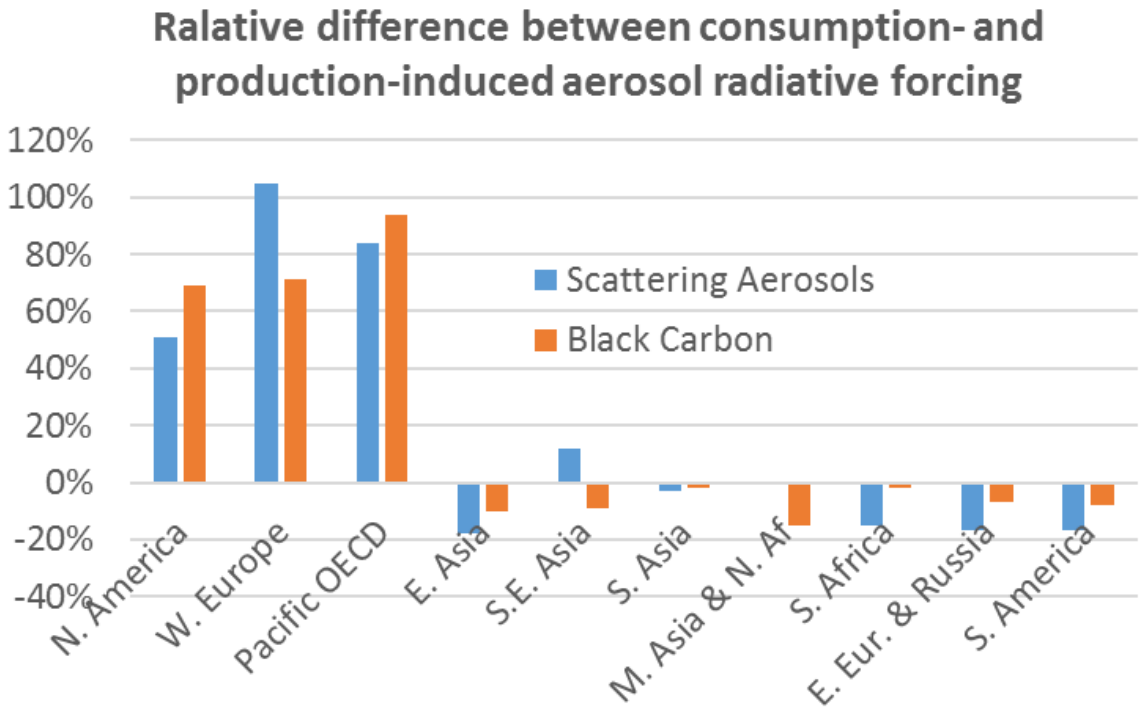
Trade Transfers RF from Rich to Poorer Regions

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



Lin et al., 2016, Nature Geoscience

Trade Transfers RF from Rich to Poorer Regions

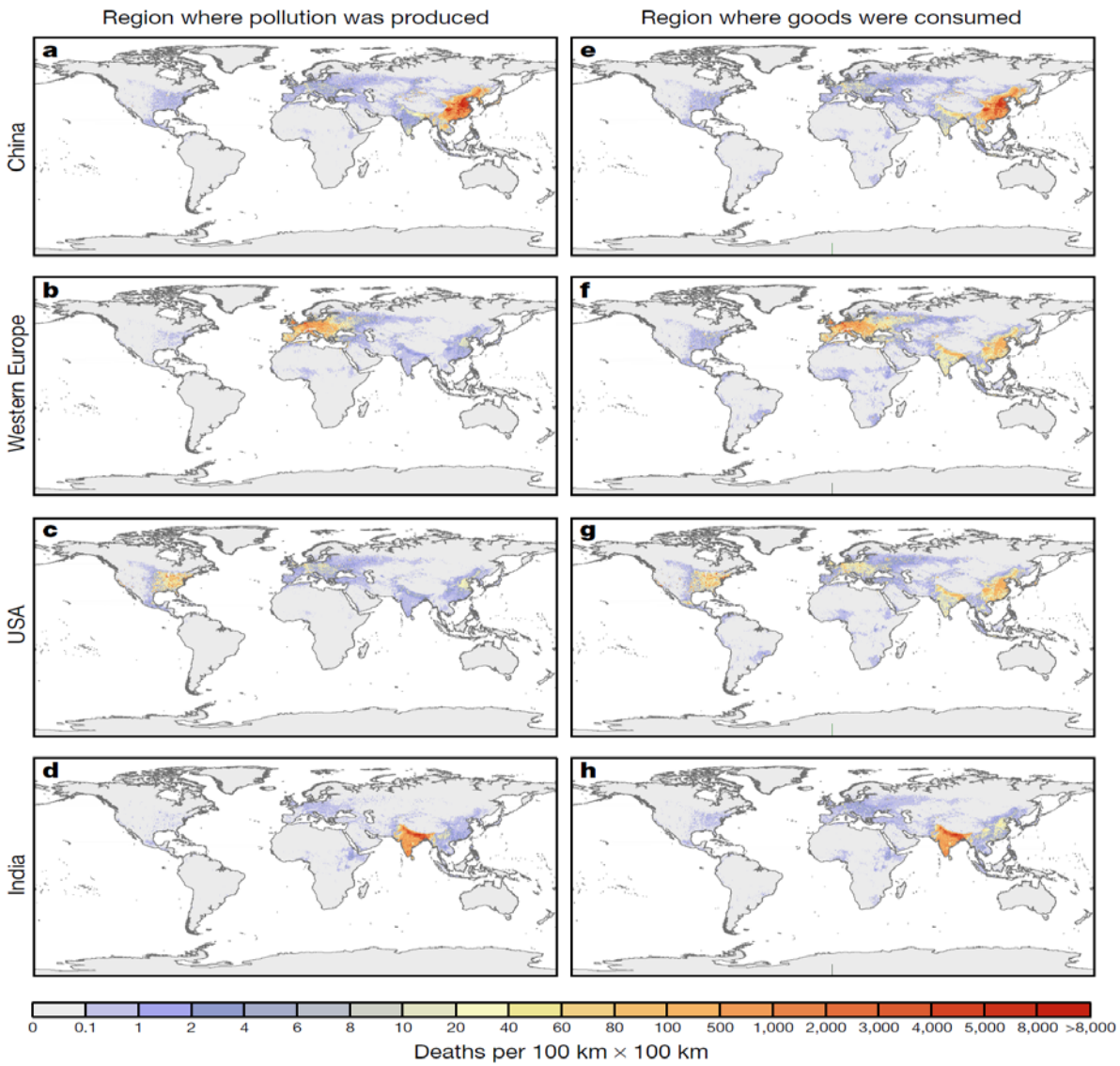


- Developed regions: RF_c is higher than RF_p by 50–100%
- Developing regions: RF_c is smaller than RF_p

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

Lin et al., 2016, Nature Geoscience

Transport and Trade are Related to Large Deaths

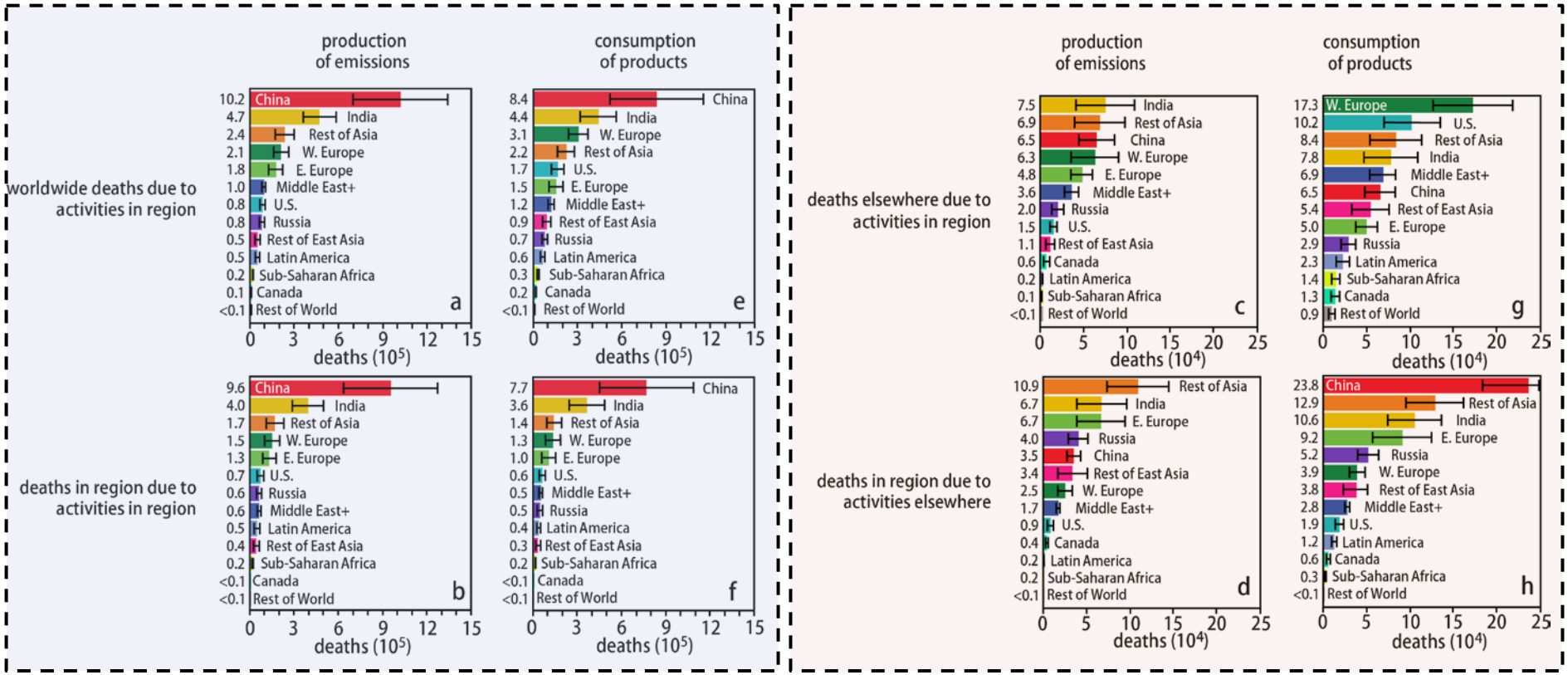


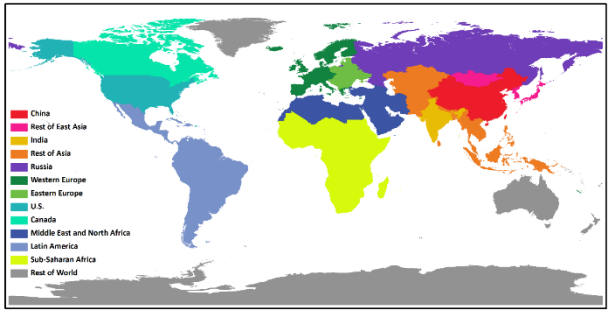
Zhang et al., 2017, Nature

Transport and Trade are Related to Large Deaths

Local as "source" & "receptor"

Local as "source" vs "receptor"





Zhang et al., 2017, Nature

From Production to Consumption Perspective

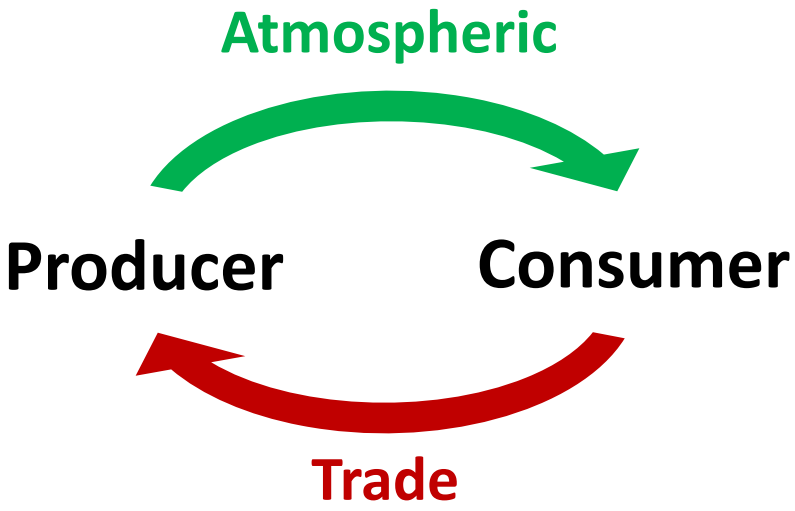
Trade

Production → Impacts ← Consumption

- Air Quality
- Climate
- Agriculture
- Ecosystems
- Sustainability

Summary: Globalizing Air Pollution

We hire postdocs



In recognition of dual routes of pollution transport :

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

References: www.phy.pku.edu.cn/~acm/acmPublication.html