Chapter 2

Sources, Sinks and Global Cycling of Air Pollutants

北京大學
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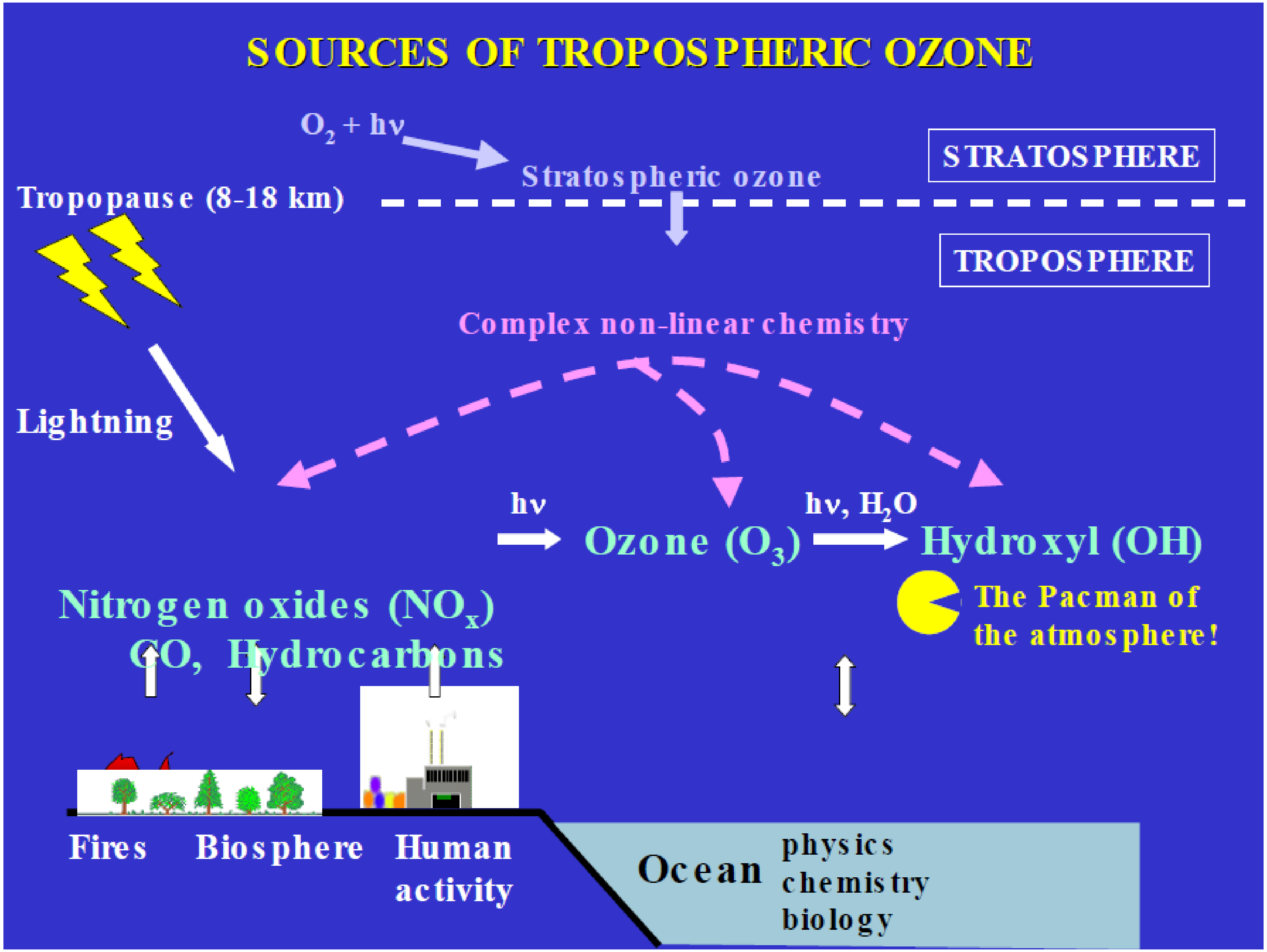
Quiz

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

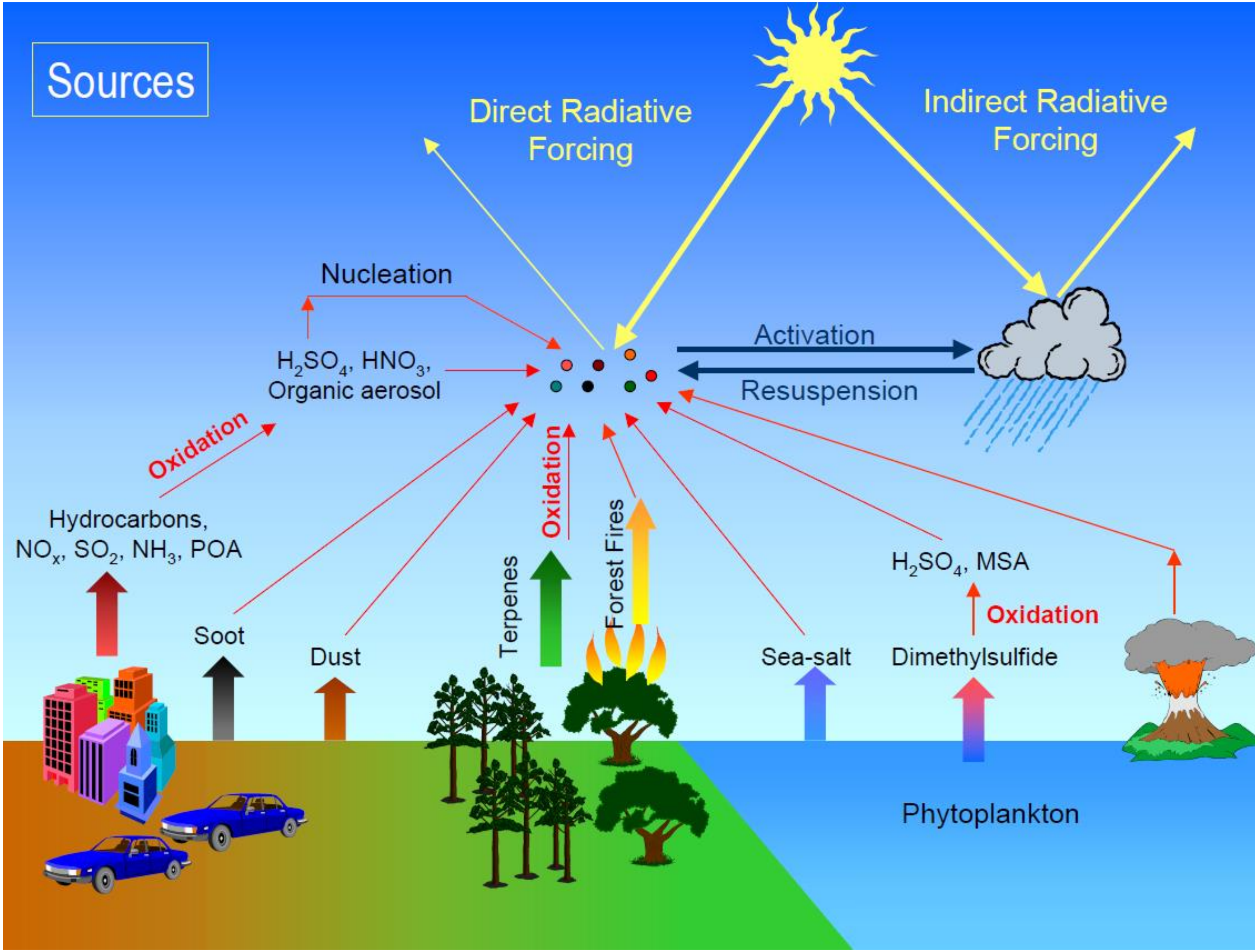
Key Chemical Species in the Troposphere

- **Main pollutants:** O_3, PM, CO, NO_2, SO_2, NMVOC...
- **Oxygen family:** $O_x = O_3 + O$ (+ NO_2)
- **Nitrogen family:** $NO_x = NO + NO_2$
- **Nitrogen family:** $NO_y = NO_x + NO_z = NO_x + NO_3 + 2N_2O_5 +$ $HONO + HNO_3 +$ PANs + ...
- **Ammonia species:** $NH_x = NH_3 + NH_4$
- **Carbon species:** CO, CH_4, NMVOC
- **Sulfur species:** SO_2, SO_4, SO_3, ...
- **Radicals:** $HO_x = OH + HO_2$; RO, RO_2, NO_3, Halogen
- **GHGs:** H_2O, CO_2, O_3, CH_4, N_2O, CFCs, HCFCs, HFCs, SF_6
- **PM species:** SO_4+NO_3+NH_4,, POA+SOA, BC, sea salts, dusts

Sources of Tropospheric Ozone

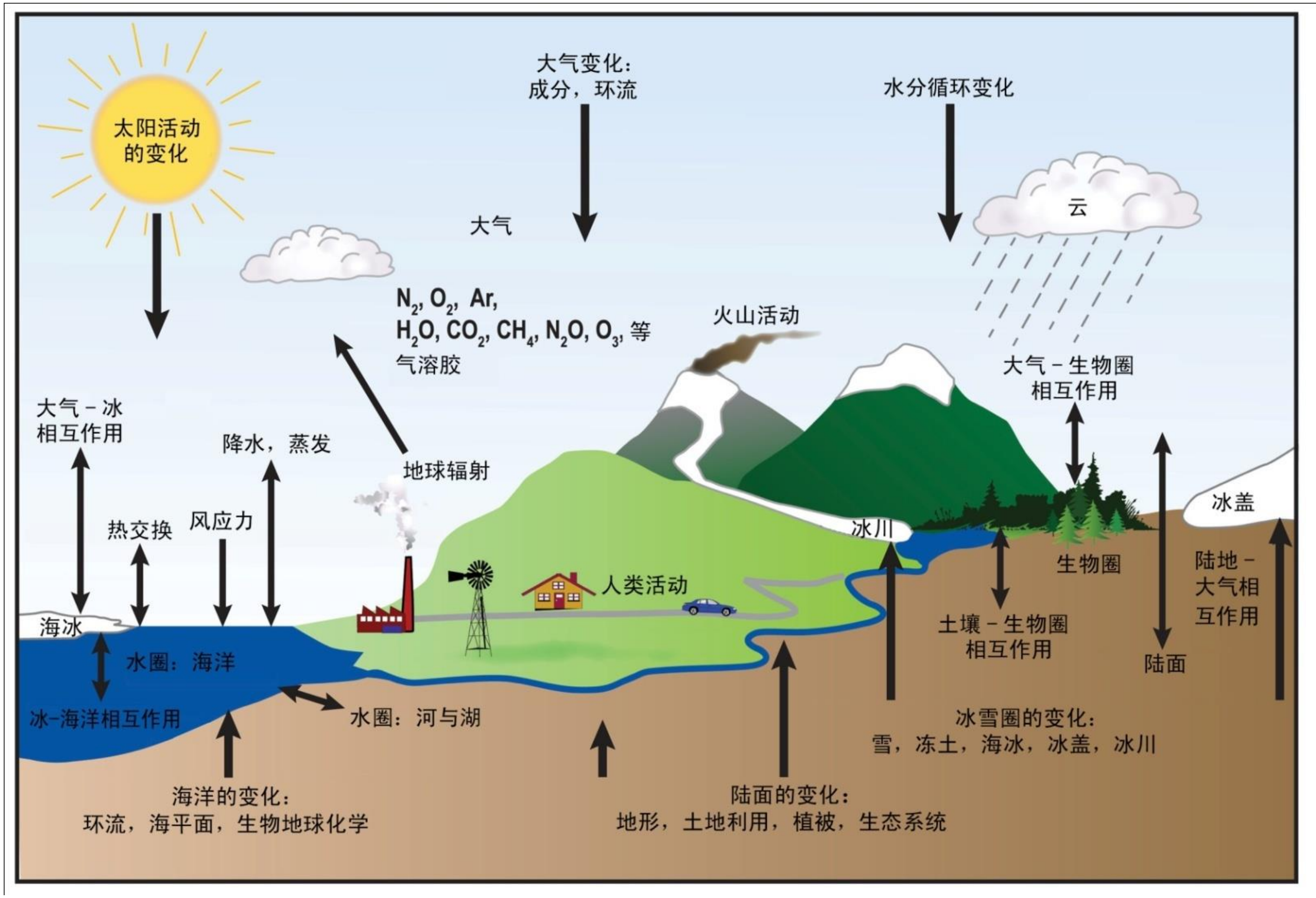


Sources of PM



地球系统中的气候和生地化循环

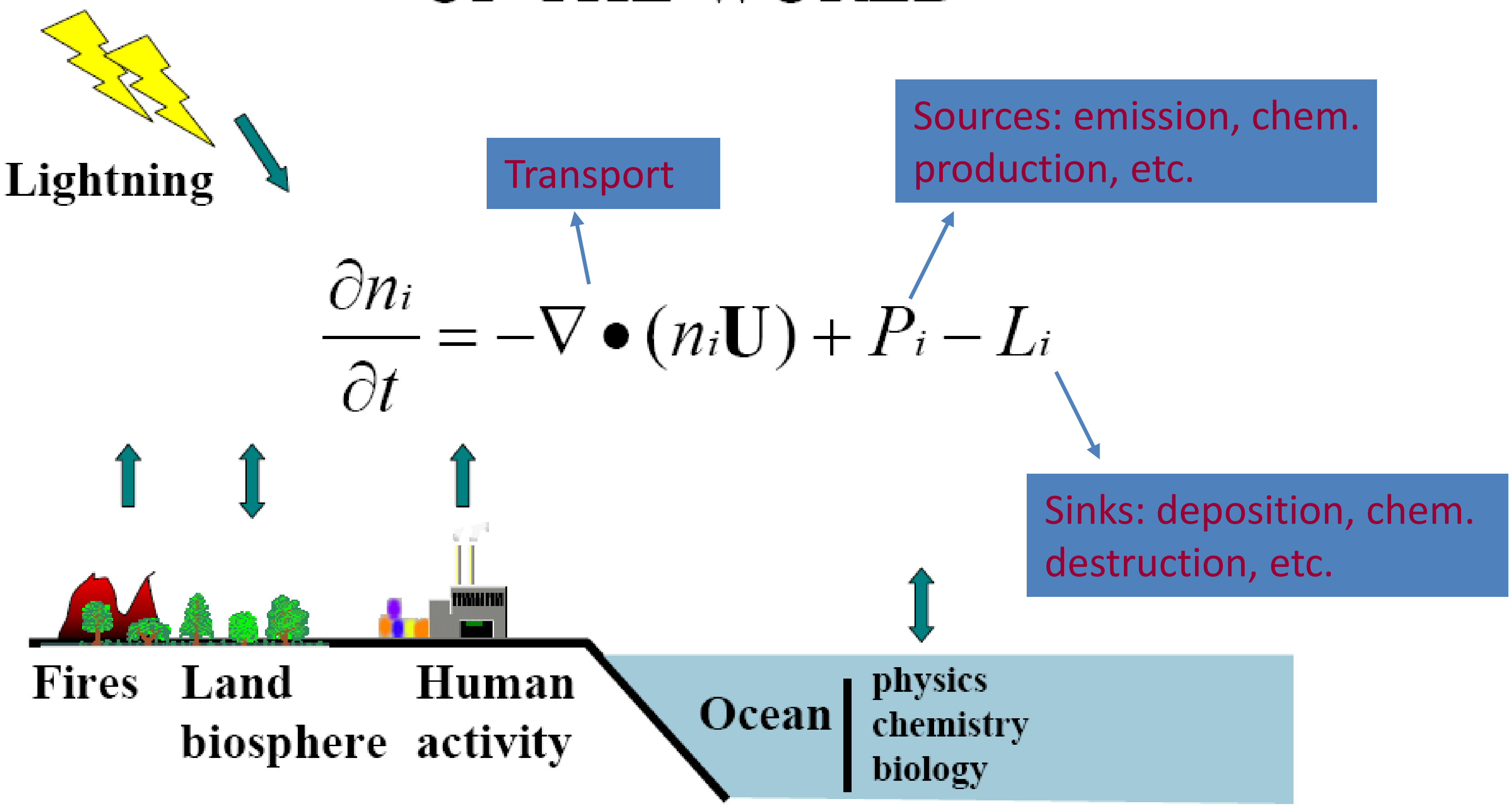
- ➢碳循环
- ➢氮循环
- ➢硫循环



IPCC, 2013

Budget of Air Pollutants

AN ATMOSPHERIC CHEMIST'S VIEW OF THE WORLD

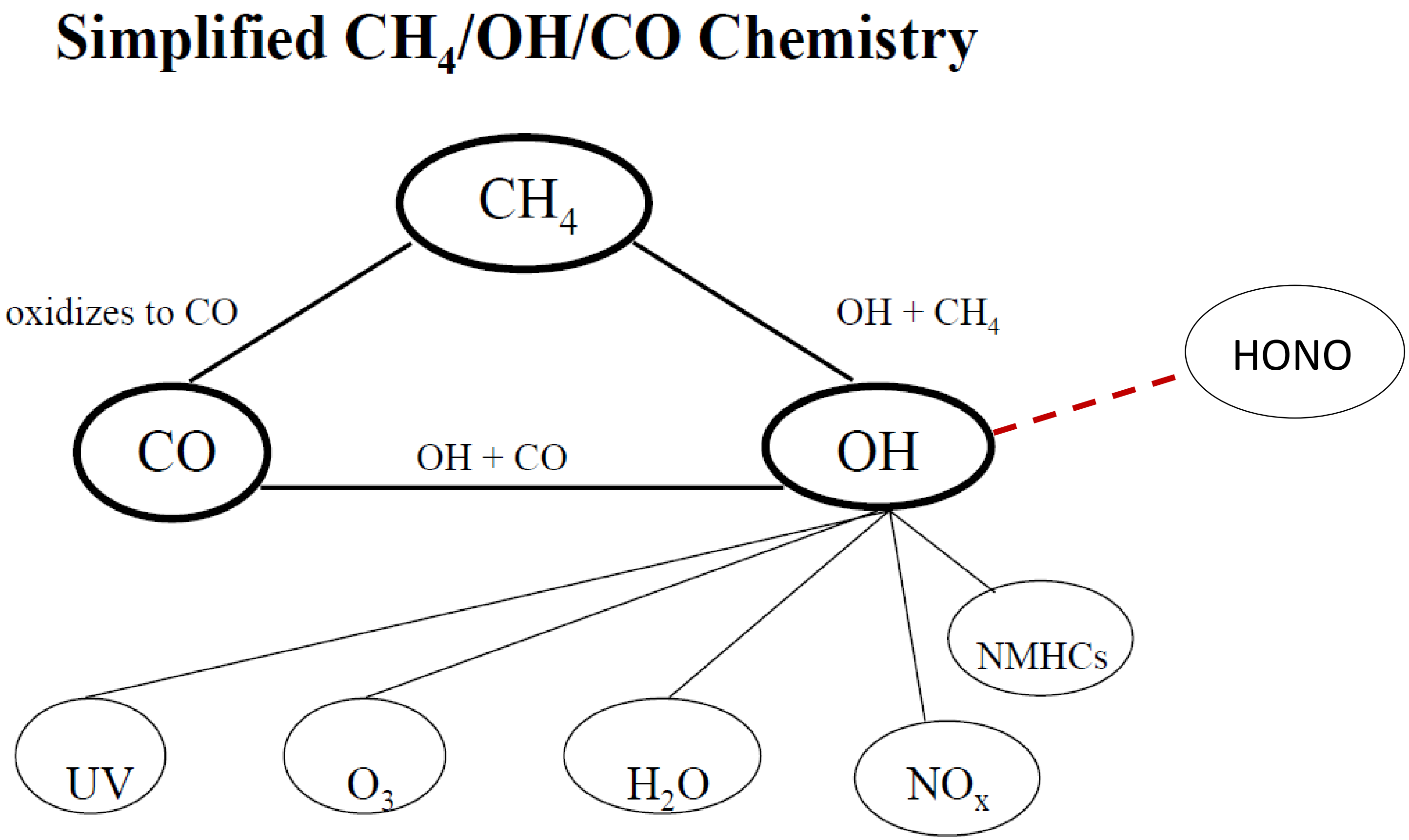


Modified from Don Wuebbles' Lecture

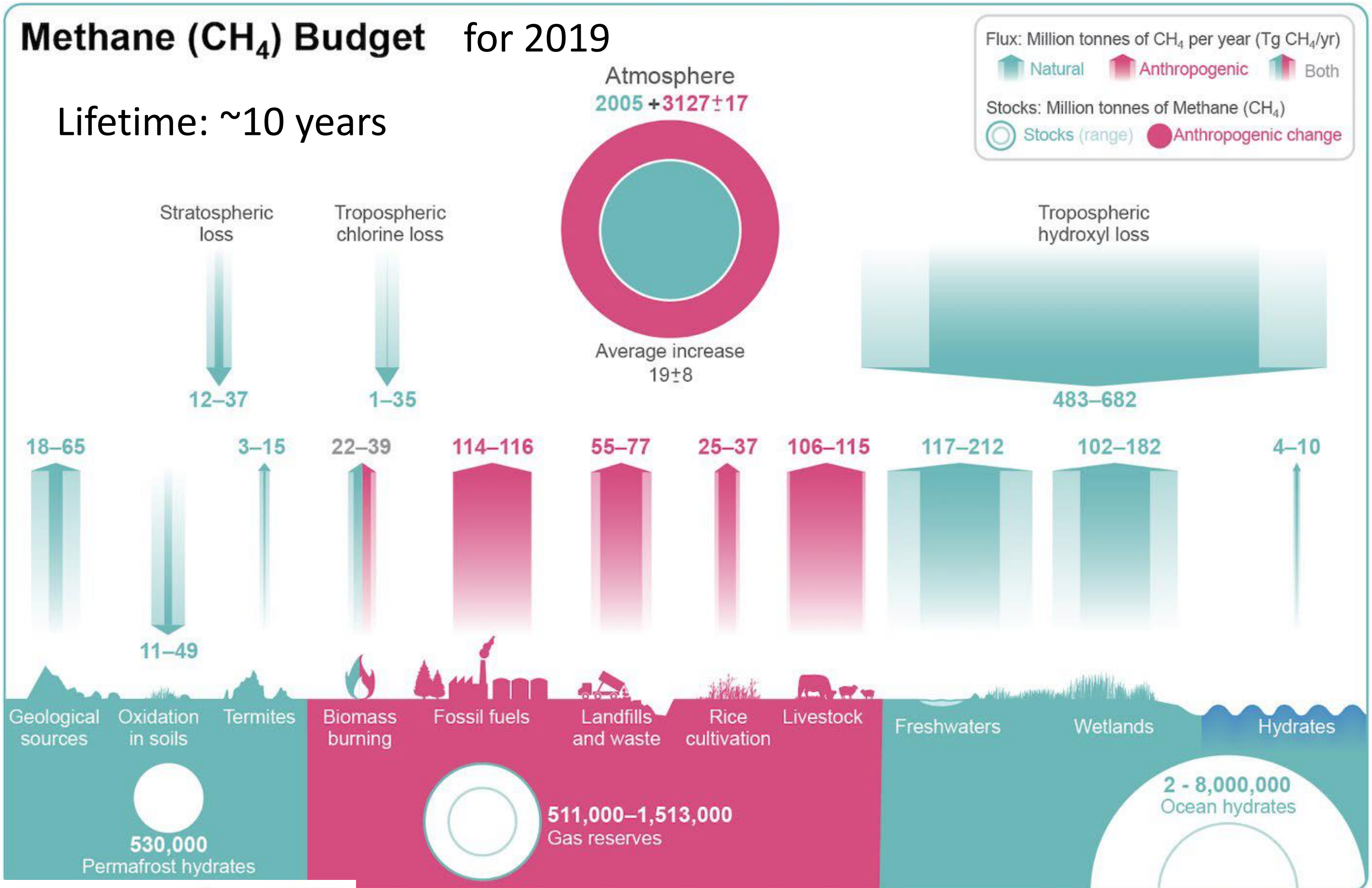
Characteristics of Emissions of Various Trace Species

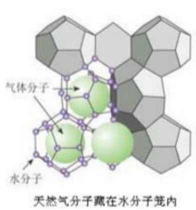
Species	From Combustion?	Source in comb.	Leakage from fuel	Microbial
CH_4	Incomplete combustion	Fuel	Abundant	Abundant
CO, BC, POC	Incomplete combustion	Fuel	Little to None	Little to none
NMVOC	Incomplete combustion	Fuel	Abundant	Abundant
NOx (mostly as NO)	High-temp. combustion	Fuel + air	None	Significant
NH_3	Little ?	Fuel + additive	None	Mostly
SO_2	Mostly	Fuel	None	Little

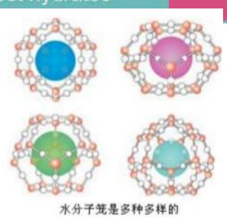
Roles of CH_4 and CO in Atmospheric Chemistry



Global Methane Cycle







IPCC, 2021

可燃冰：CH4水合物

CH_4 Emissions from Oil, Gas and Coaling Mining

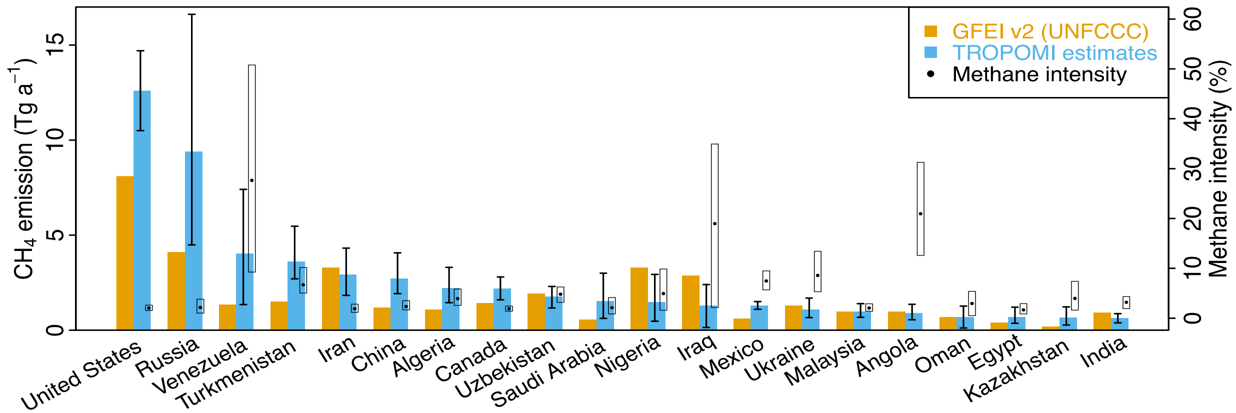
Method: Satellite XCH4 data + Bayesian inversion

Prior information | Obs information

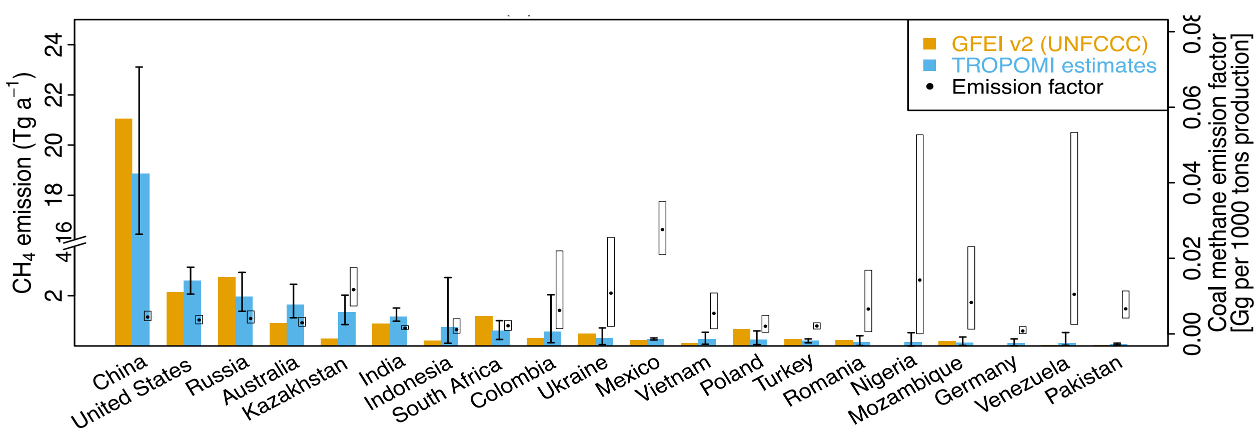
$$J(\boldsymbol{x}) = (\boldsymbol{x}-\boldsymbol{x}_A)^T \mathbf{S}_A^{-1} (\boldsymbol{x}-\boldsymbol{x}_A) + \gamma (\boldsymbol{y}-\mathbf{K}\boldsymbol{x})^T \mathbf{S}_O^{-1} (\boldsymbol{y}-\mathbf{K}\boldsymbol{x})$$

- US and Russia under reported their emissions by 30-50%
- The natural gas leakage rate is >20% in 8 countries including Venezuela and Iraq

Oil & gas mining



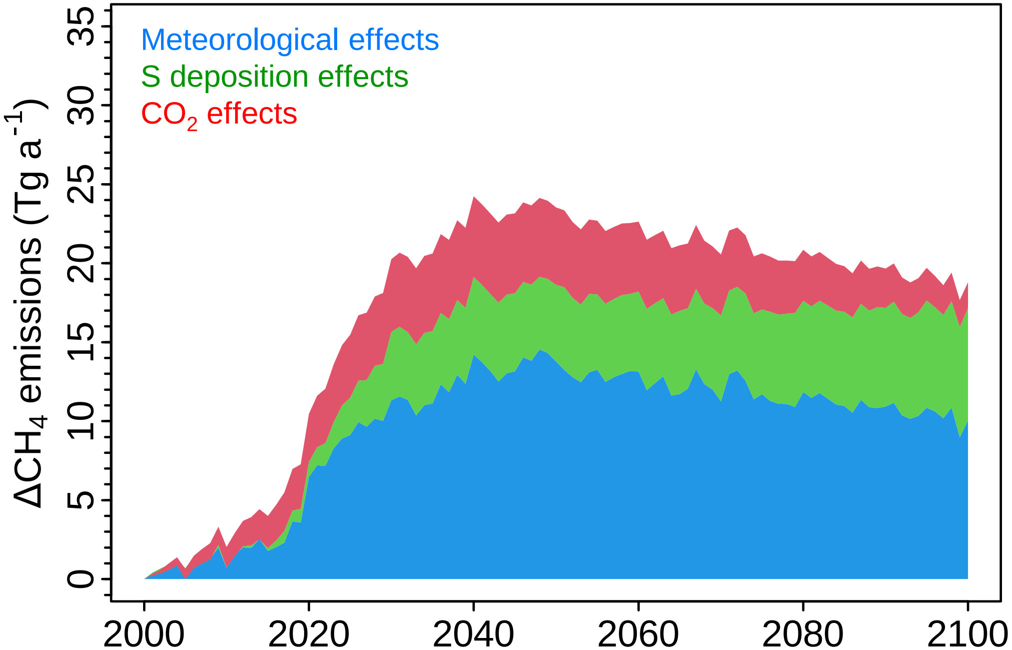
Coal mining



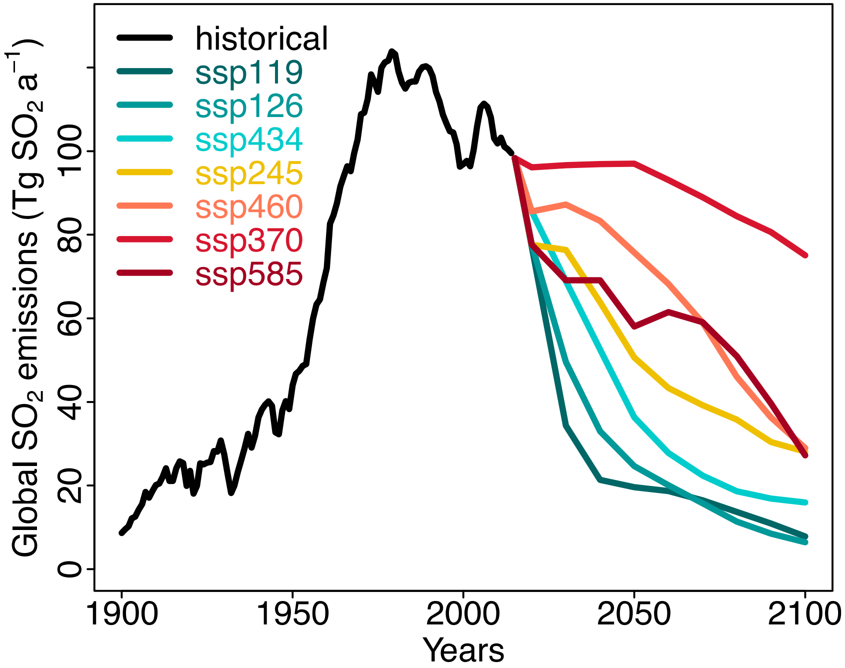
Shen et al., Nature Communications, 2023

Changes in CH_4 Emissions from Wetland: Shaped by Meteorology, CO2 and Sulfur Deposition

Natural wetland emissions
following the 1.5°C climate mitigation pathway

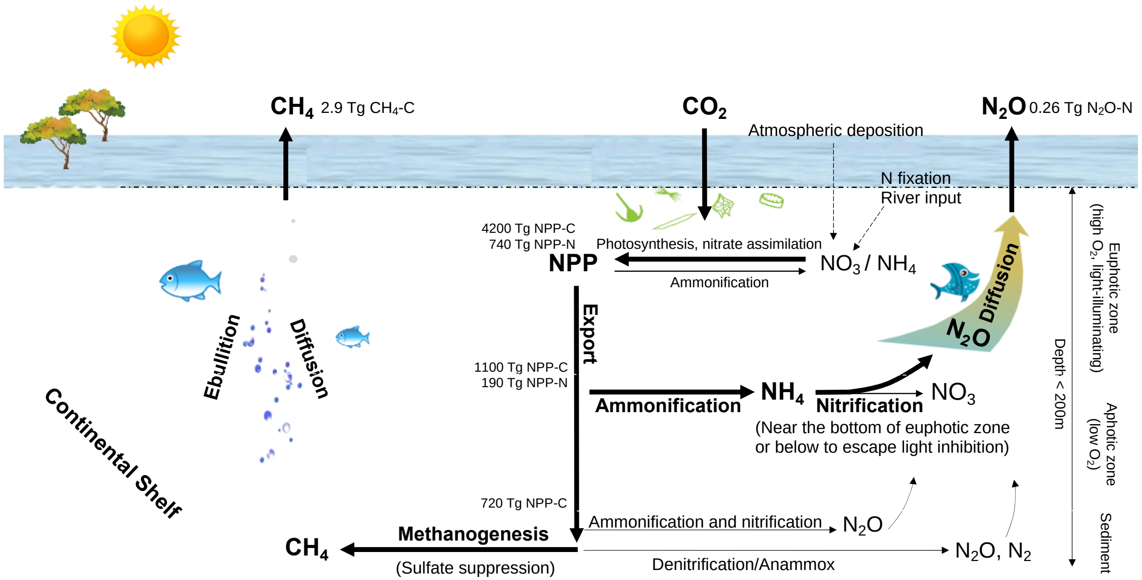


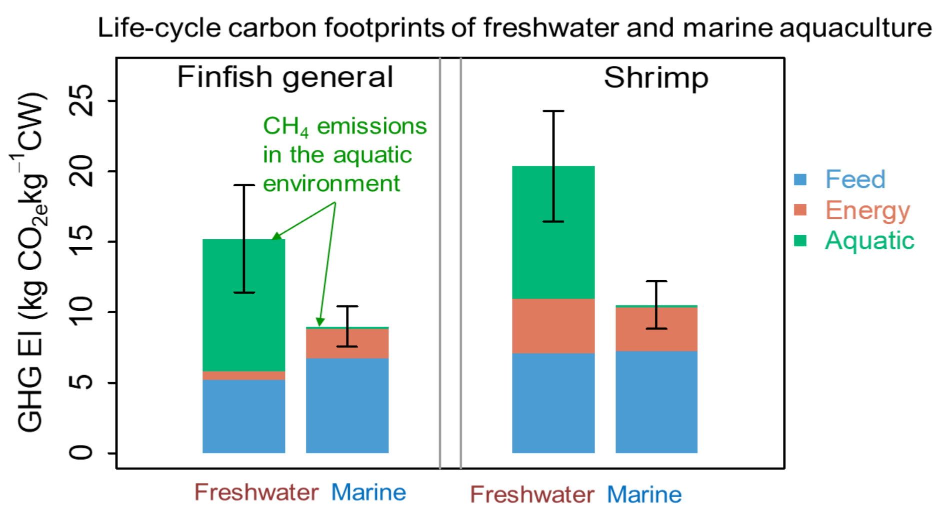
Global anthropogenic SO_2 emissions
from 1900-2100



Shen et al., Science Advances, 2024

CH_4 Emissions from Aquaculture



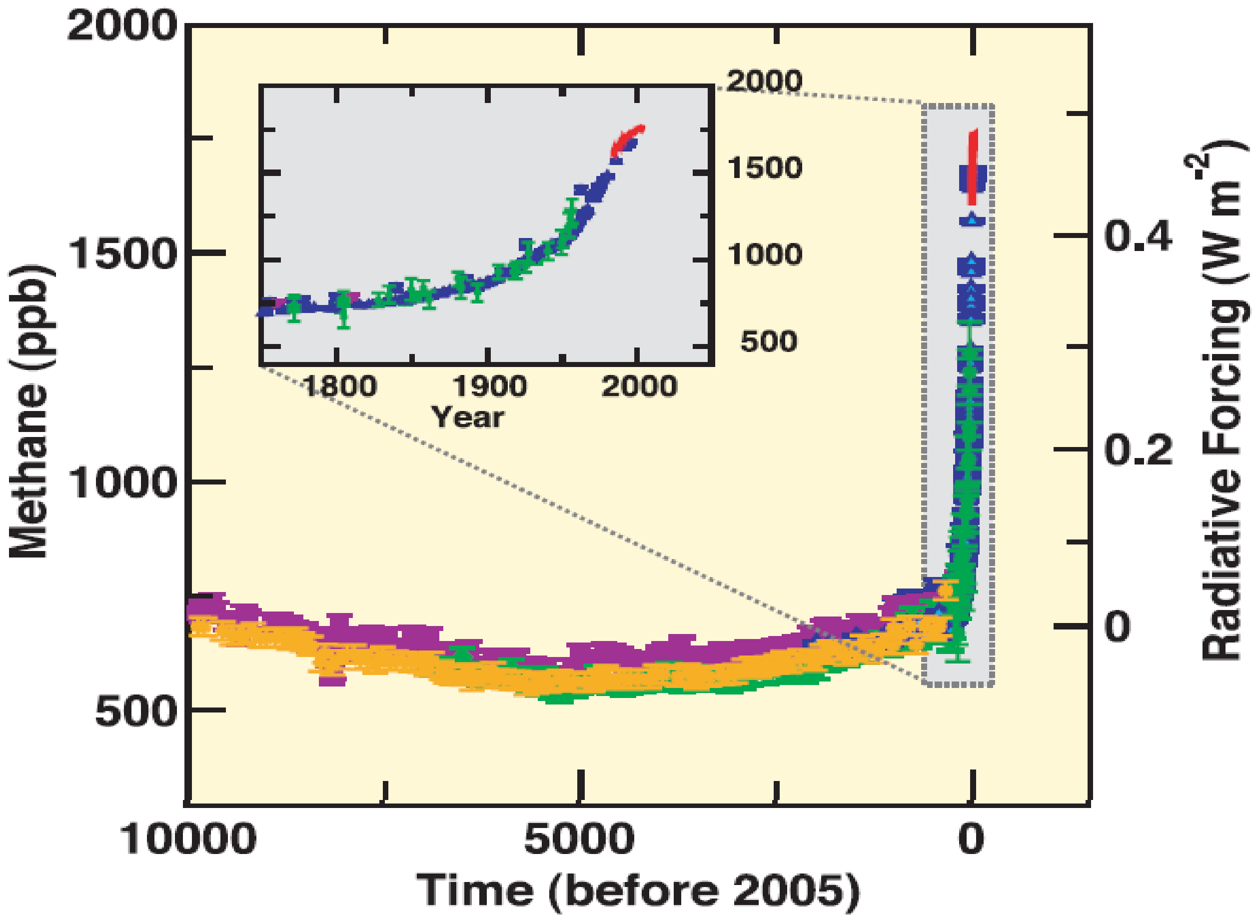


Shen et al., Nature Food, 2024

- The carbon footprint of marine aquaculture is 40% lower than that of freshwater aquaculture.

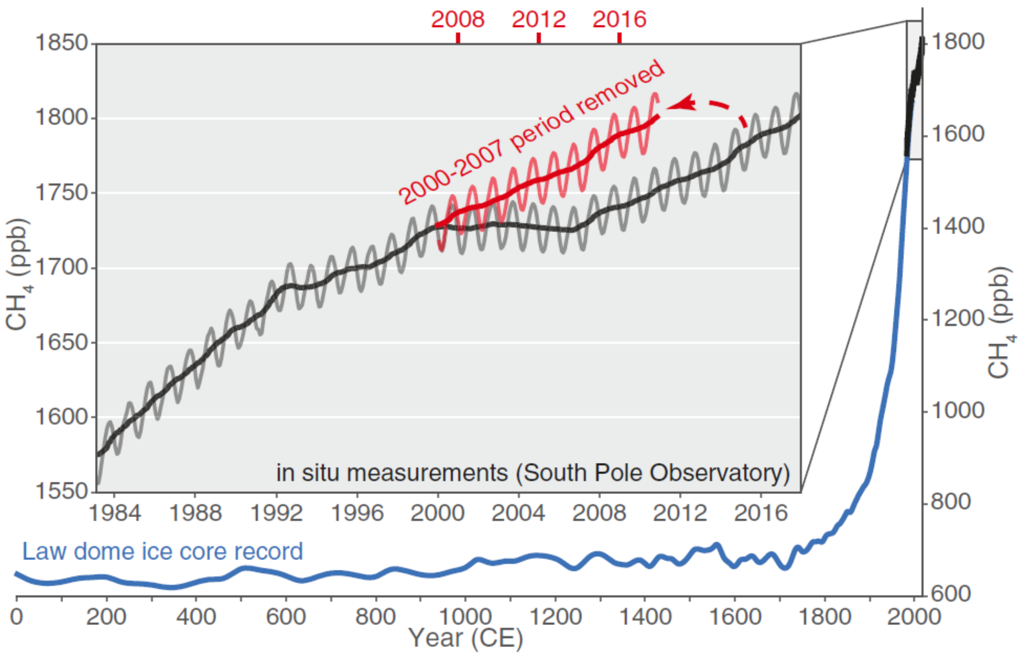
Rapid Growth of CH_4 in the Industrial Era

Ice core & modern data

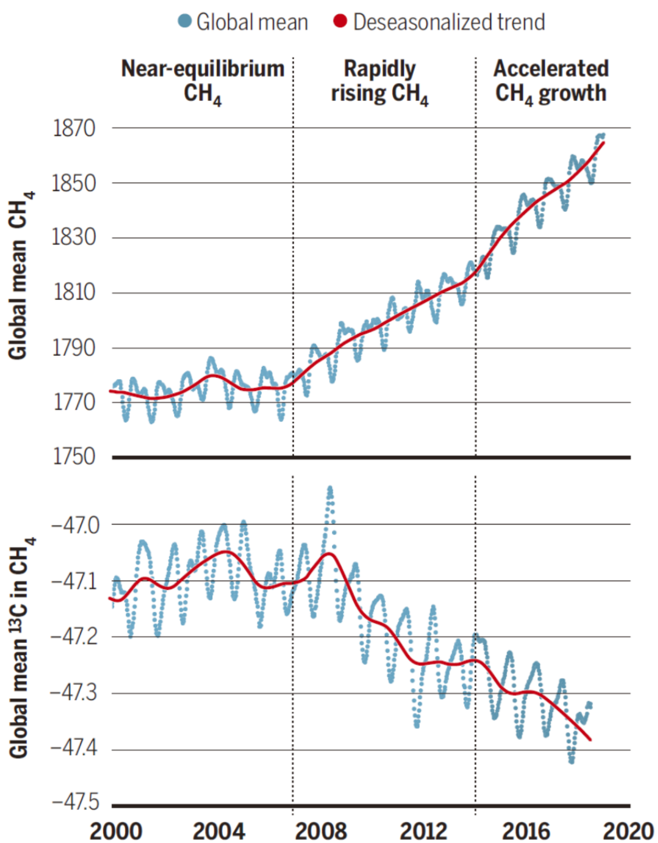


IPCC, 2007

Global CH_4 Growth

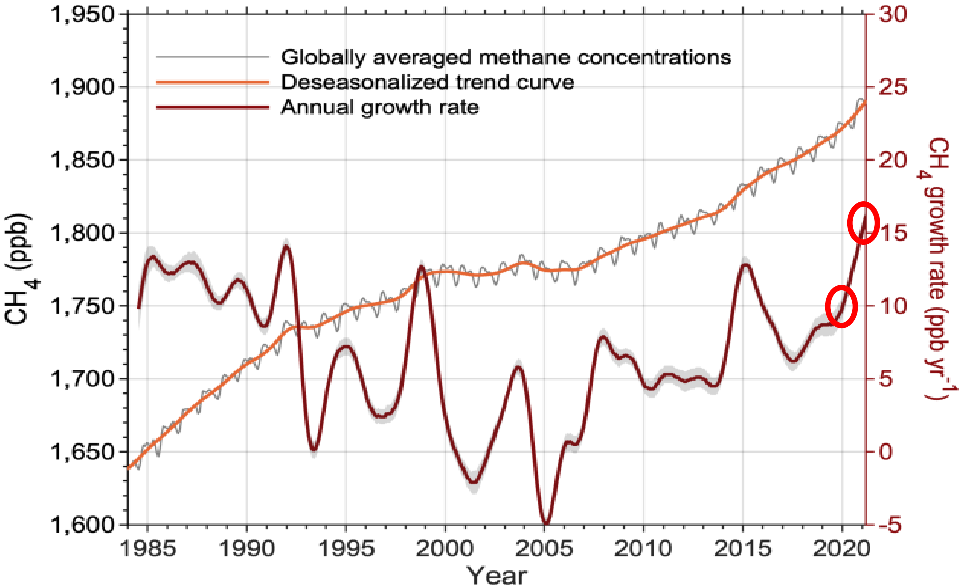


Turner et al., 2019, PNAS

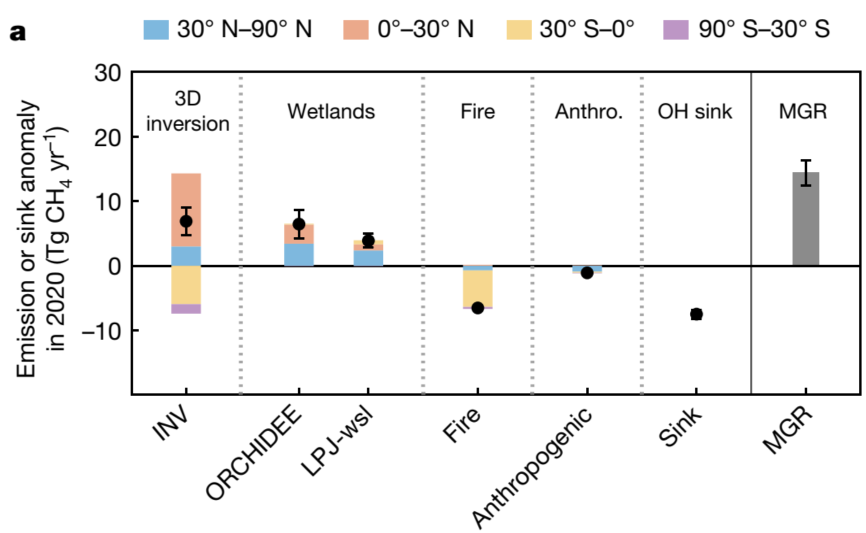


Fletcher et al., 2019, Science

Enhanced Growth of CH_4 Associated with COVID



Peng et al., Nature, 2022

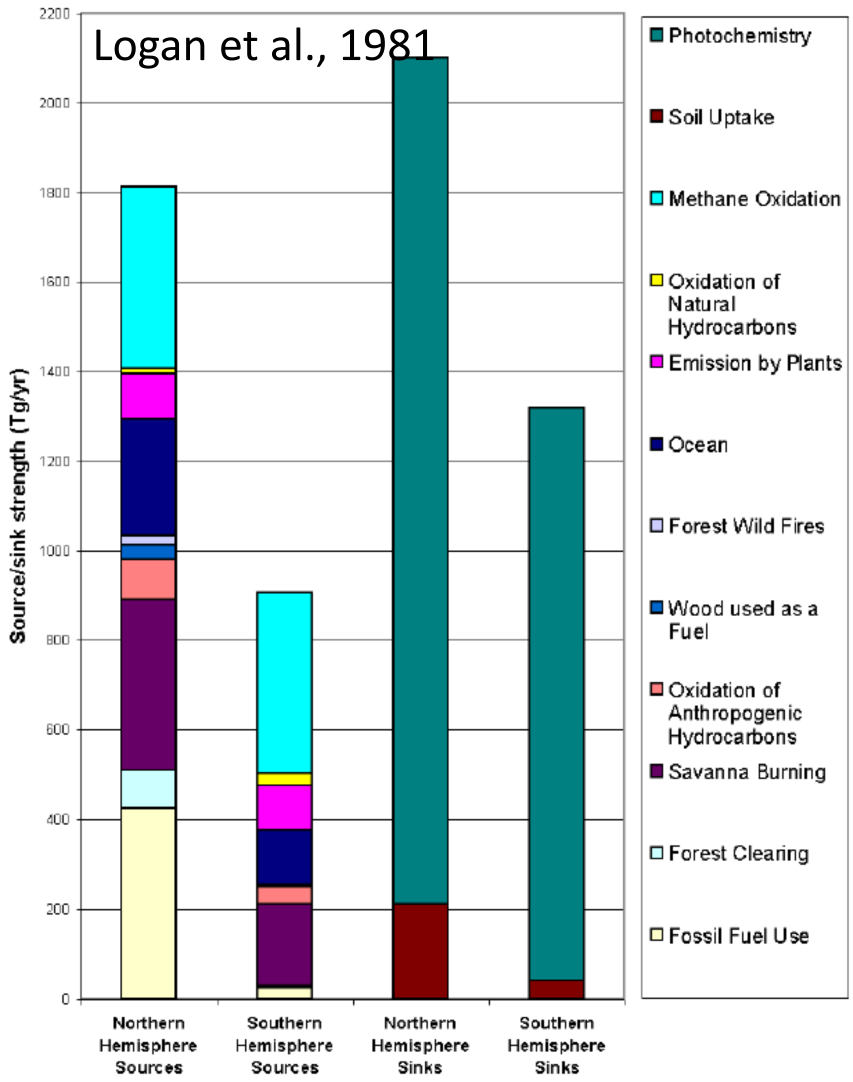


Growth rate:

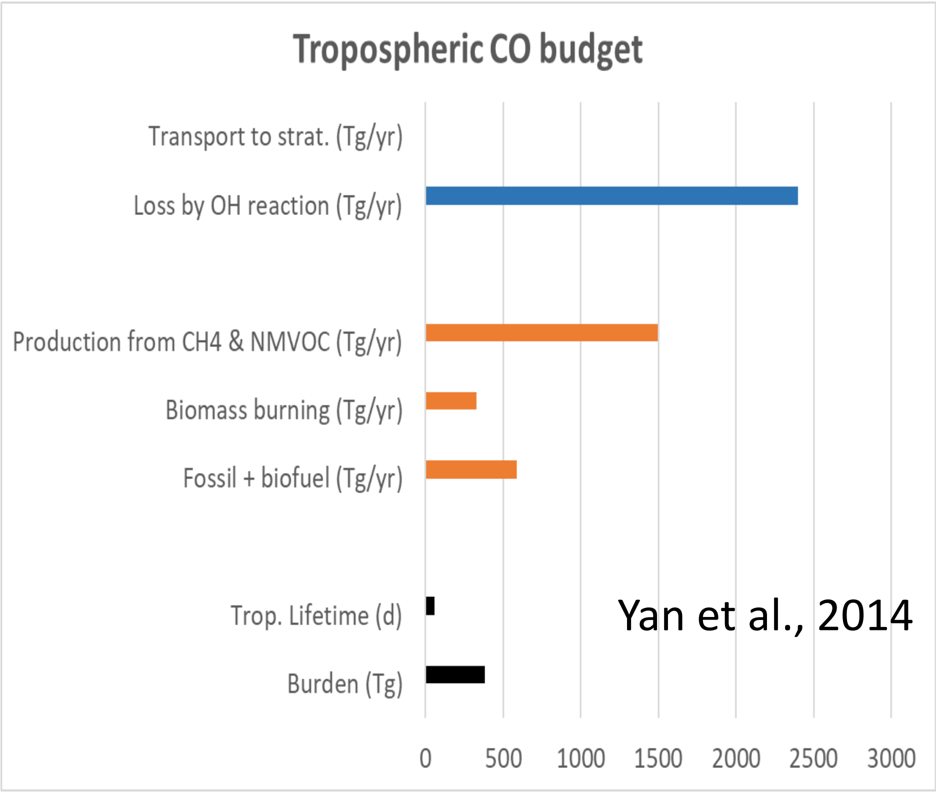
2020.1.1-2019.1.1: 9.9±0.6 ppb yr^{-1}

2021.1.1-2020.1.1: 15.1±0.4 ppb yr^{-1}

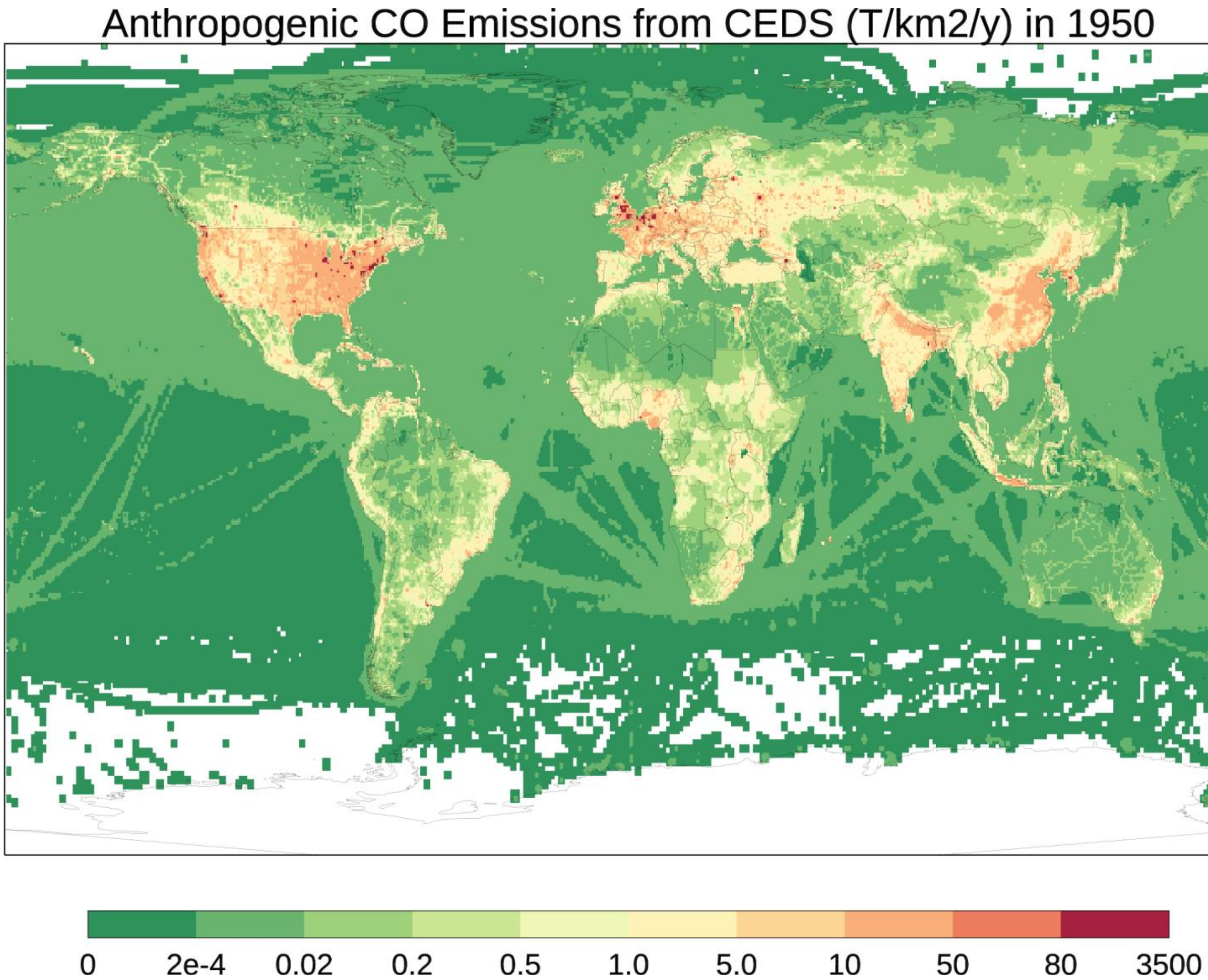
Global Budget of CO



CO sources and sinks in 2009

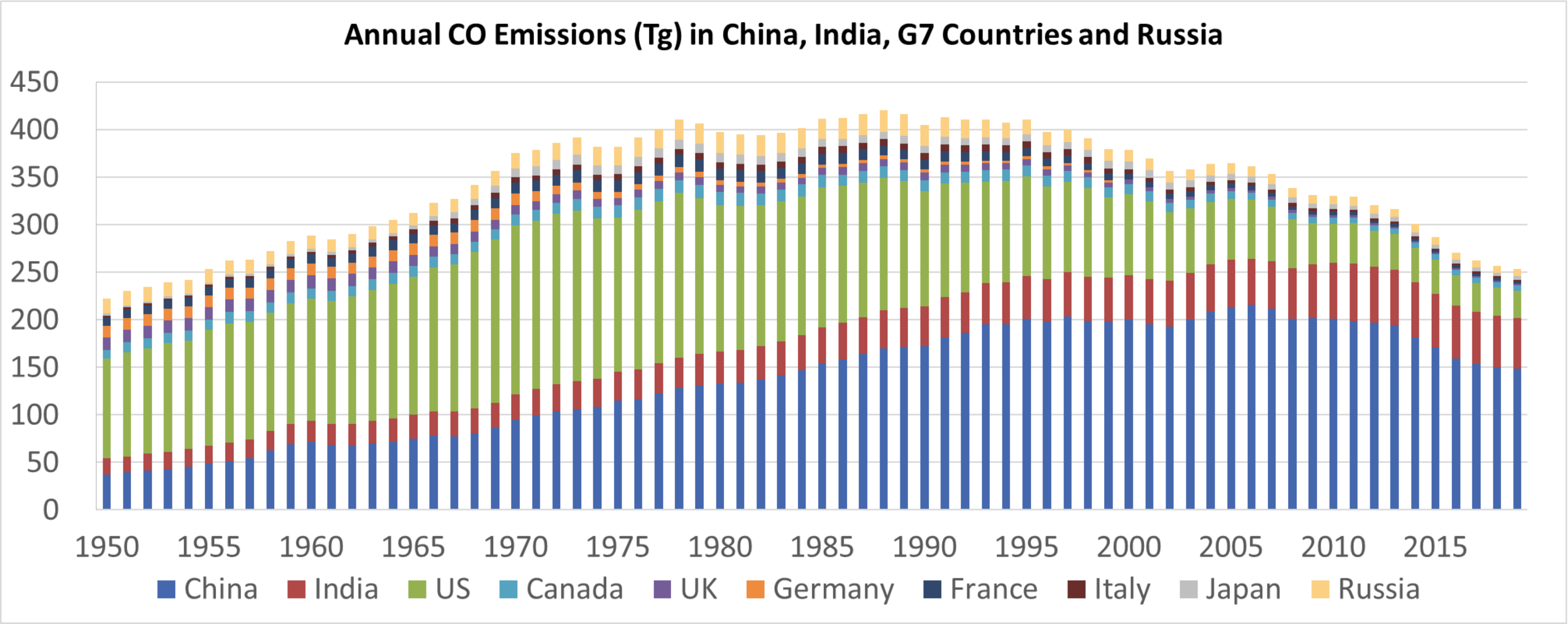


Anthropogenic Emissions of CO: 1950-2014



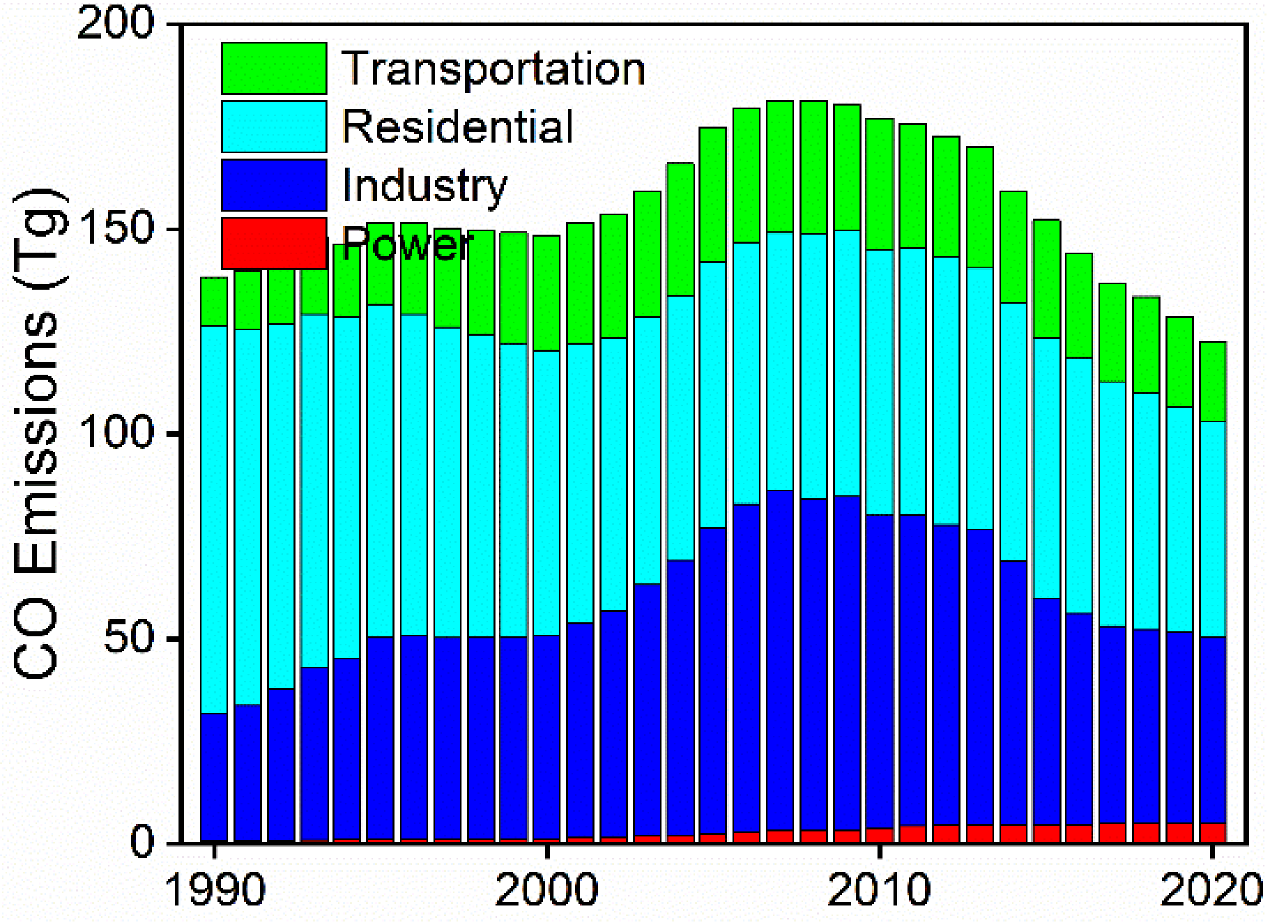
CEDS inventory

Anthropogenic Emissions of CO: 1950-2019



CEDS v2 inventory

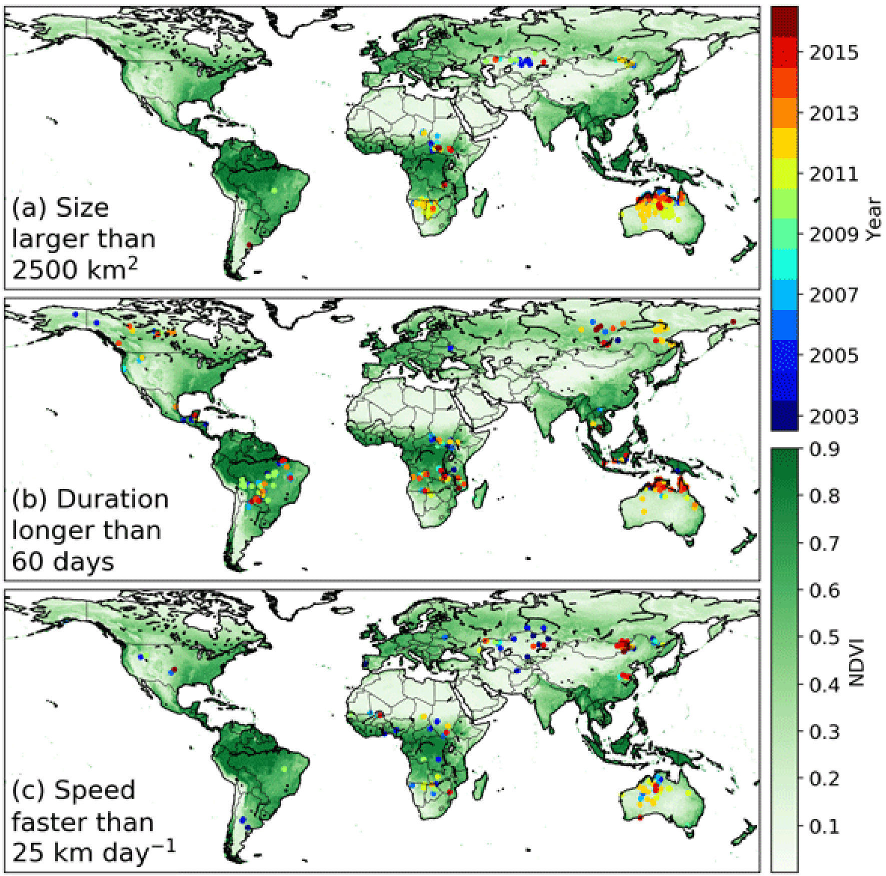
Anthro. Emission Trends of CO in China: 1990-2020



Source: MEIC data from Bo Zheng

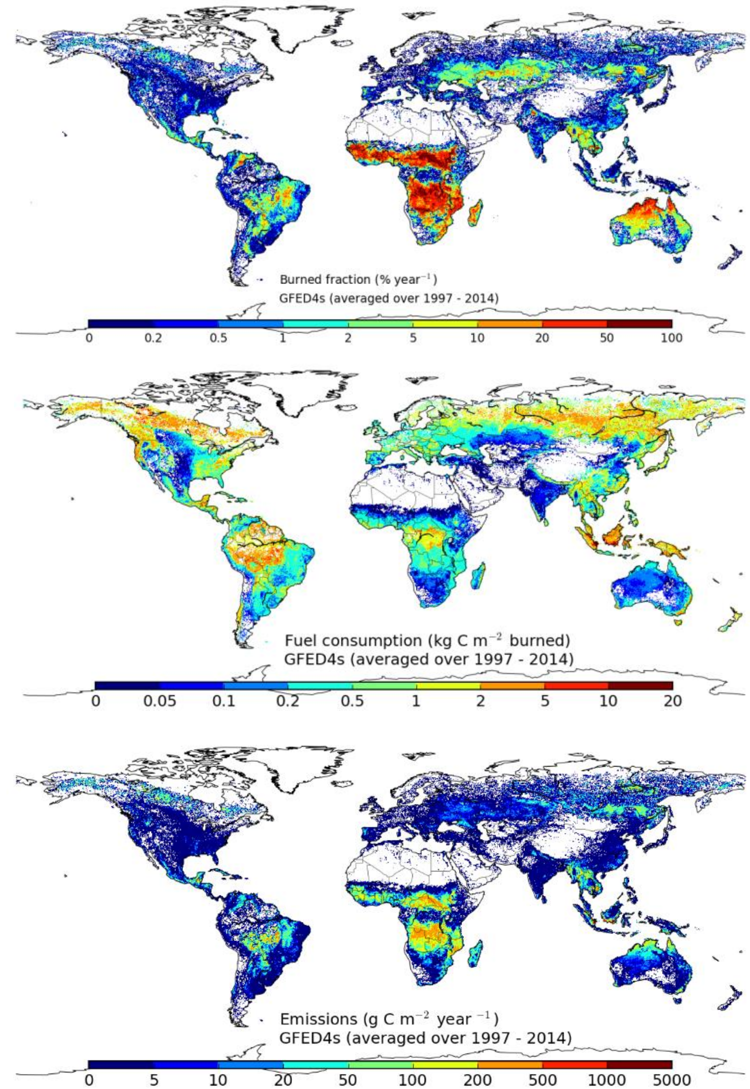
Biomass Burning Emissions of Carbon

Global fire atlas (2003-2016)

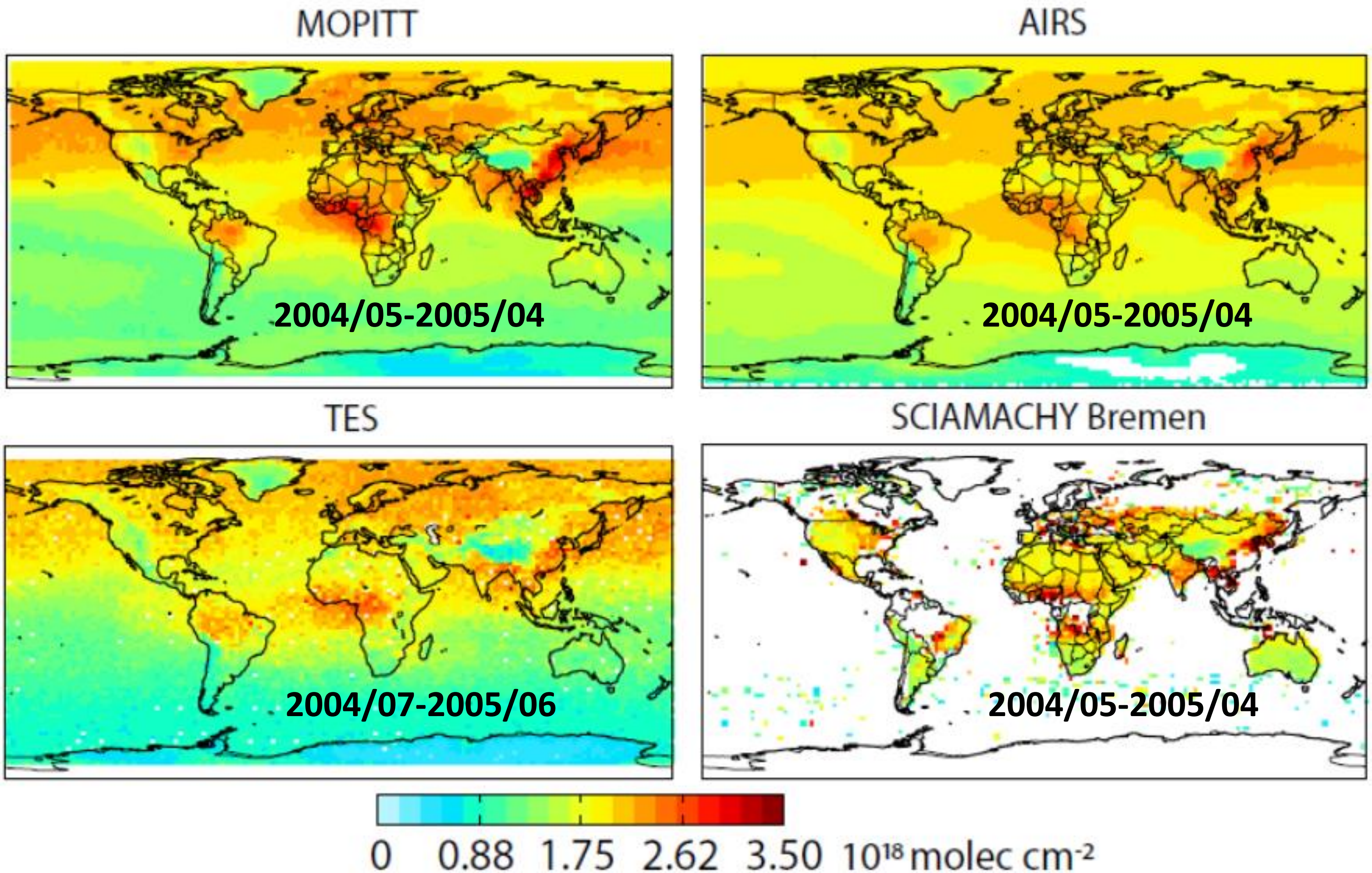


GFED4: http://www.globalfiredata.org

Global fire emissions (1997-2014)

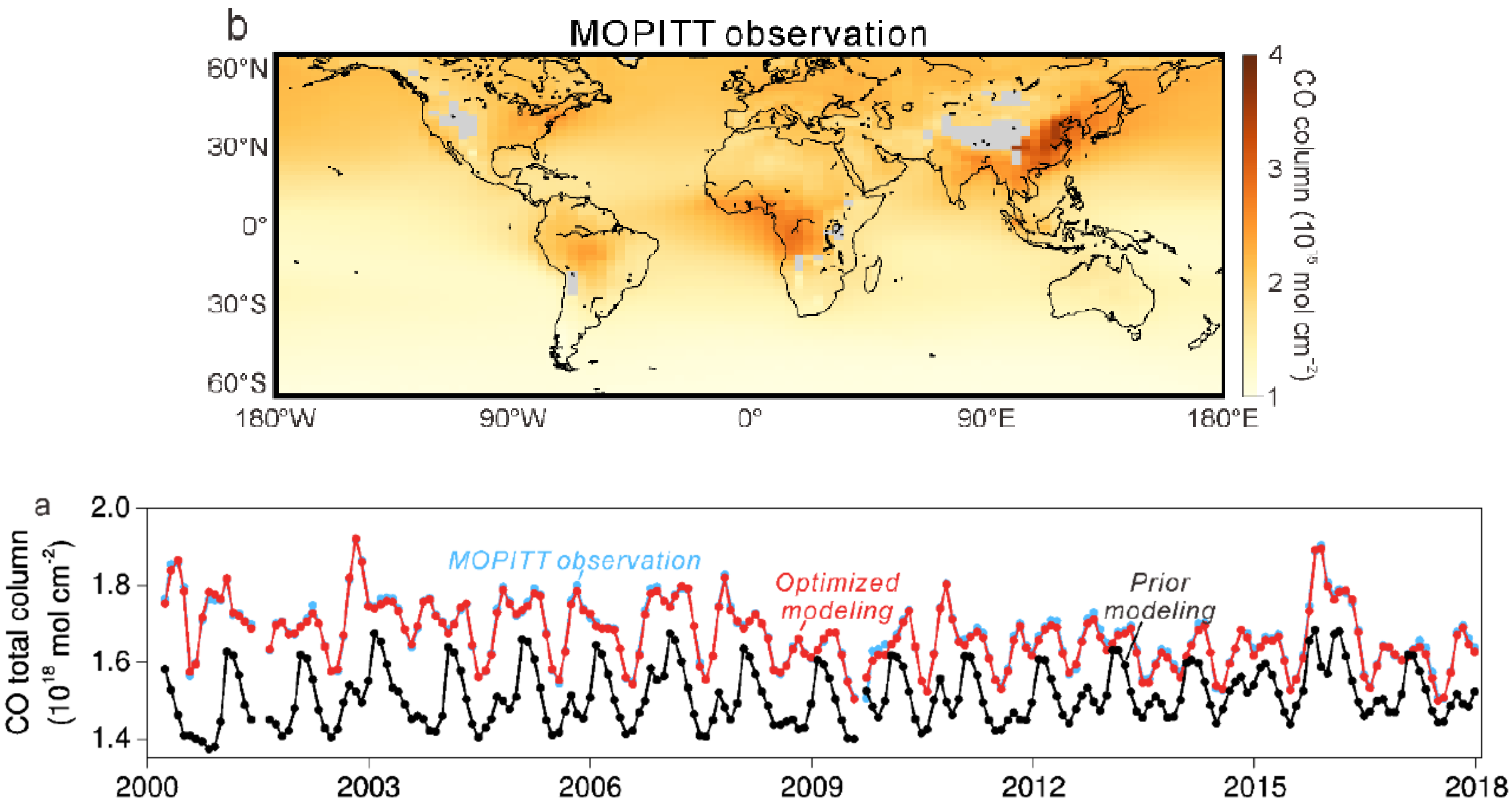


Satellite Measurements of CO



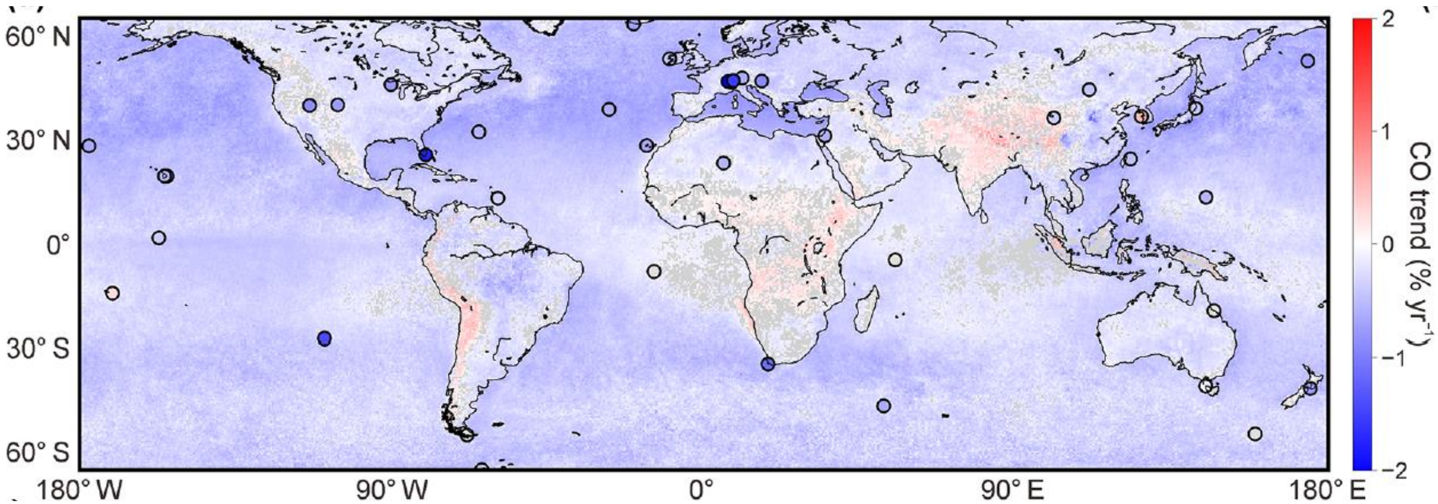
Kopacz et al., 2010, ACP

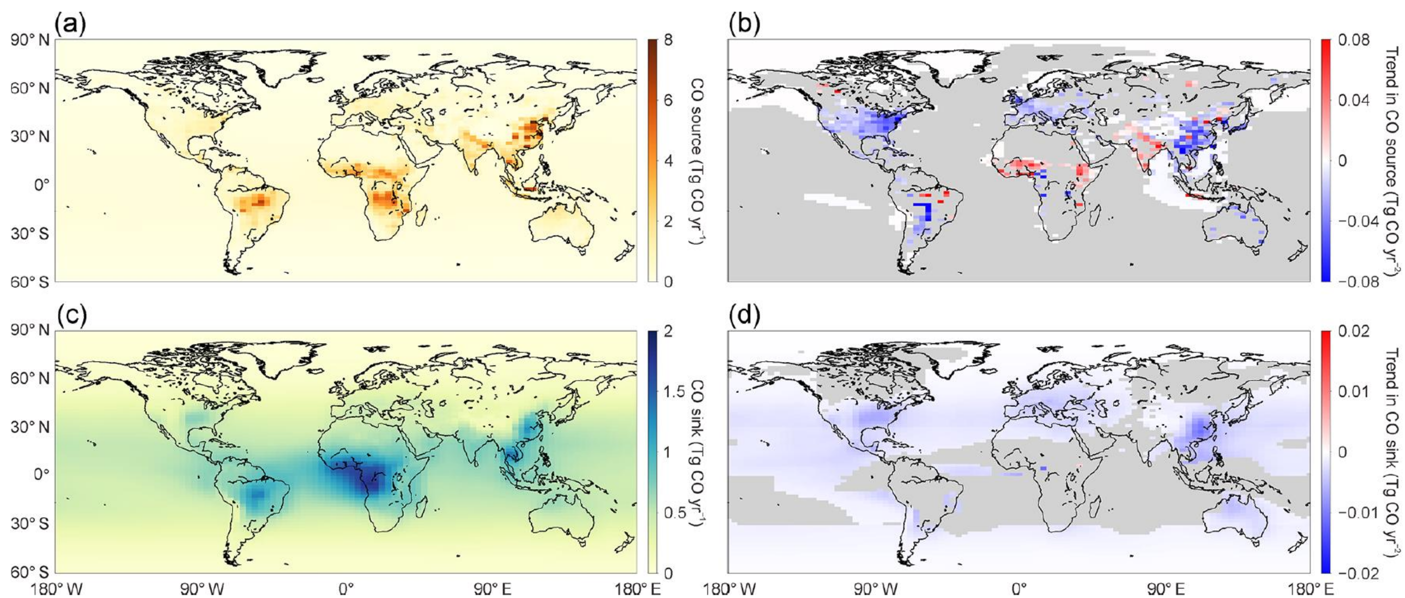
Tropospheric CO Column: 2000-2017



Zheng et al., 2019, ESSD

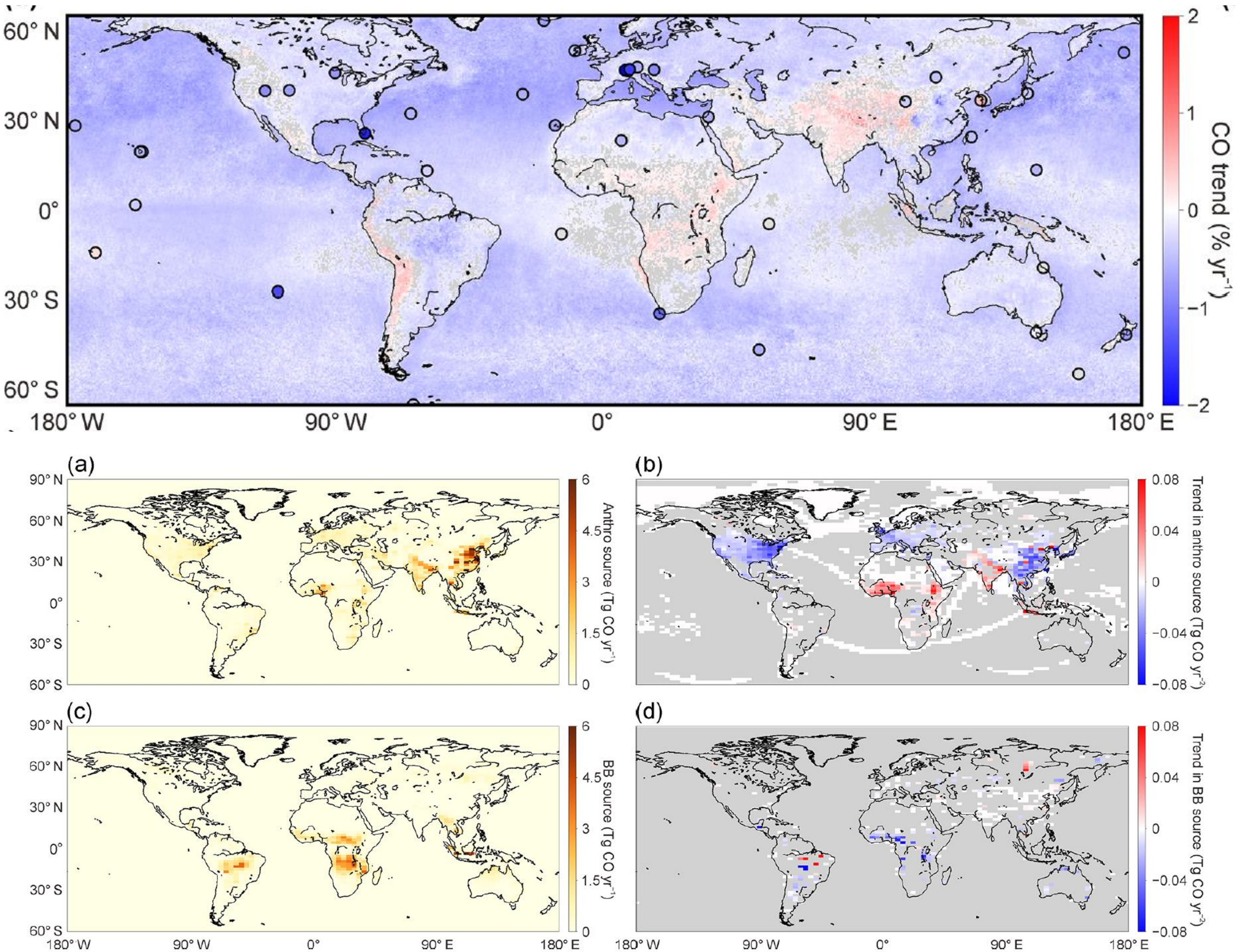
Trends of Tropospheric CO, Sources and Sinks: 2000-2017





Zheng et al., 2019, ESSD

Trends of Tropospheric CO and Emissions: 2000-2017



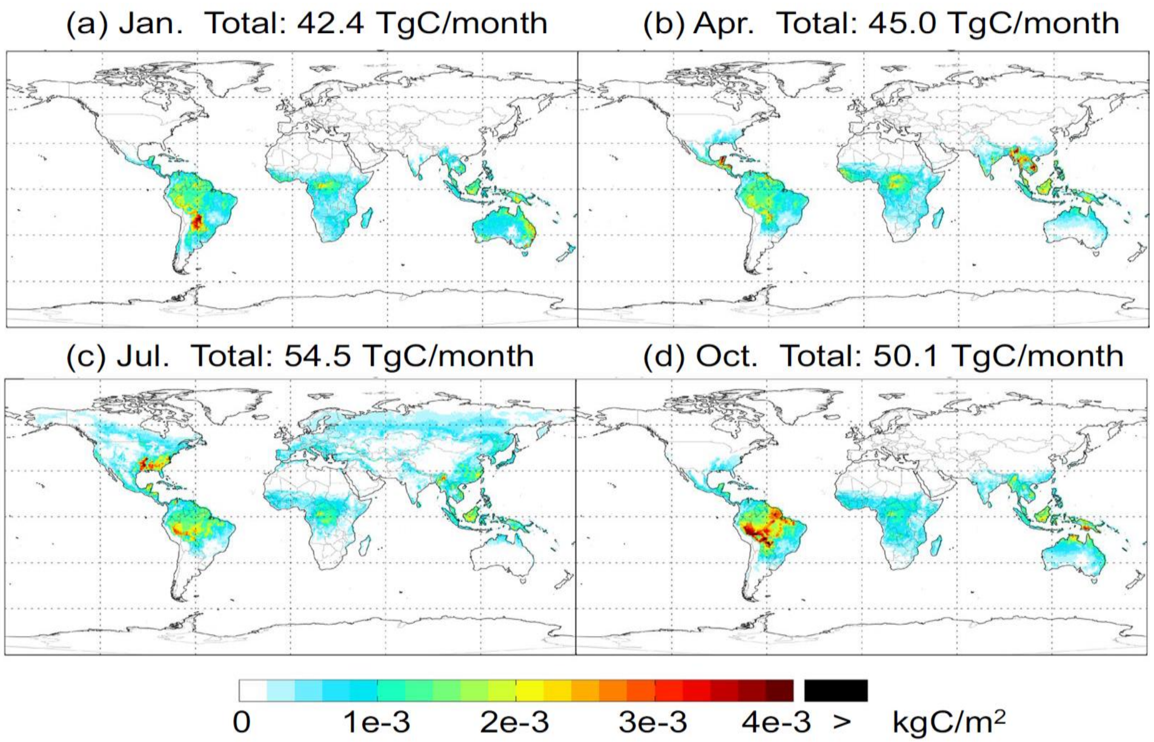
Zheng et al., 2019, ESSD

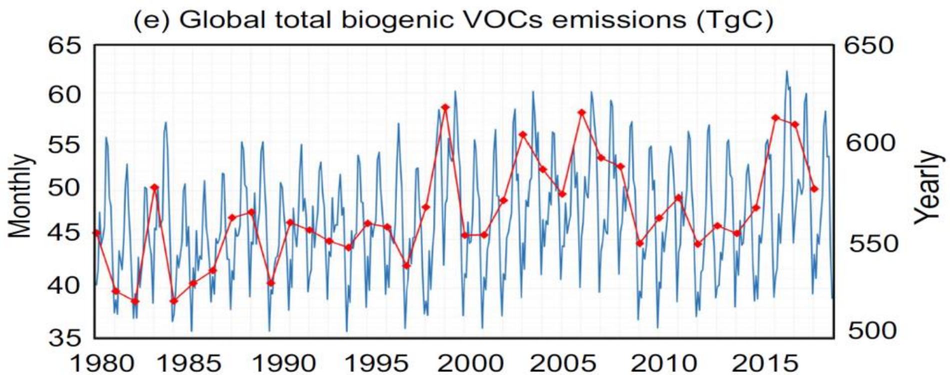
Sources of Non-Methane Volatile Organic Compounds

Human Sources			**~100 TgC/yr**
	Energy use and transfer		43 TgC/yr
	Biomass burning		45 TgC/yr
	Organic solvents		15 TgC/yr
Natural Sources			**~1170 TgC/yr**
	Emissions from vegetation		
	异戊二烯	*isoprene* (C_5H_8)	200-600*TgC/yr*
	单萜烯	monoterpenes	125 TgC/yr
		other VOC	520 TgC/yr
	Oceanic emissions		6-36 TgC/yr

Brasseur et al., 1998; Weng HJ et al., SD, 2020

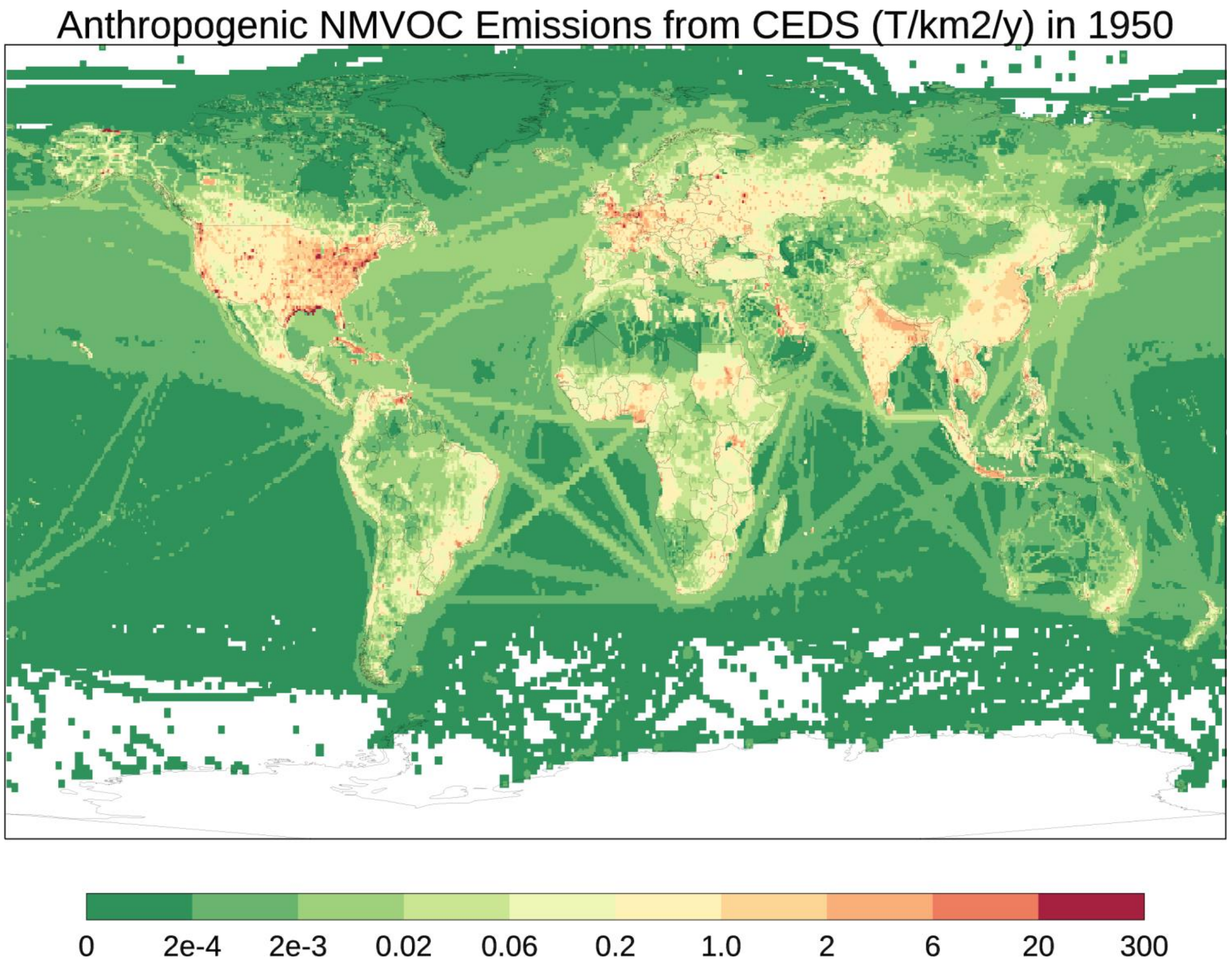
Biogenic NMVOC Emissions: 1980–2017





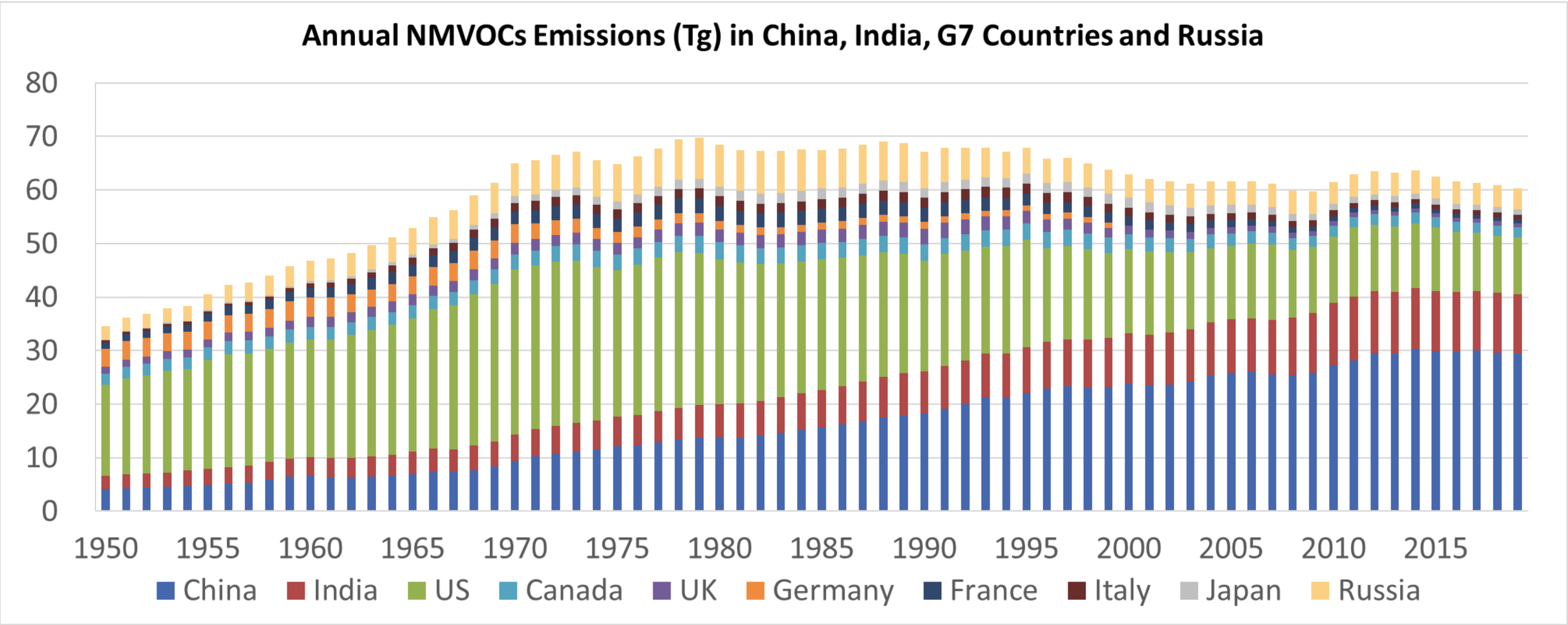
Weng HJ et al., SD, 2020

Anthropogenic NMVOC Emissions: 1950-2014



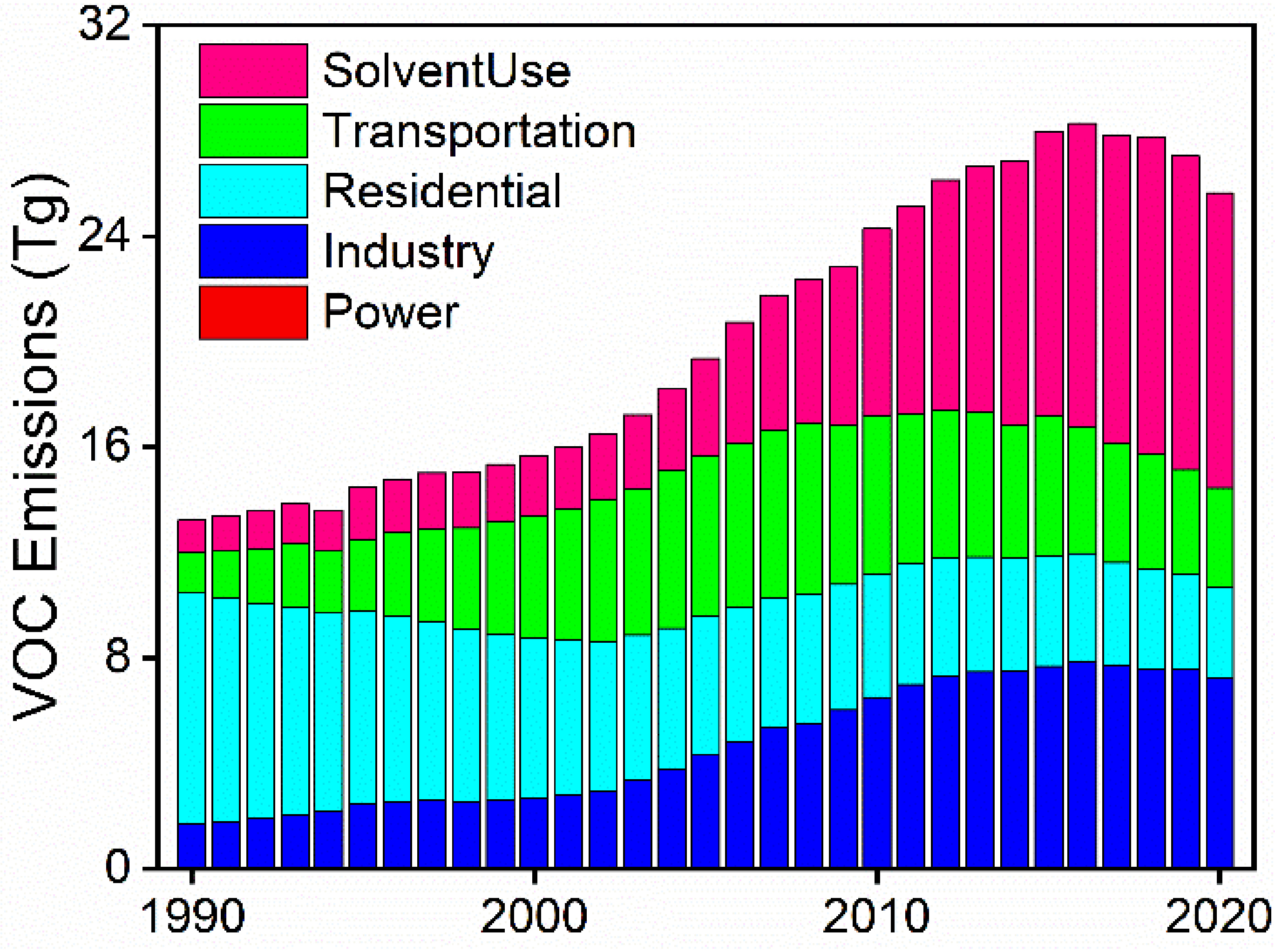
CEDS inventory

Anthropogenic Emissions of NMVOC: 1950-2019



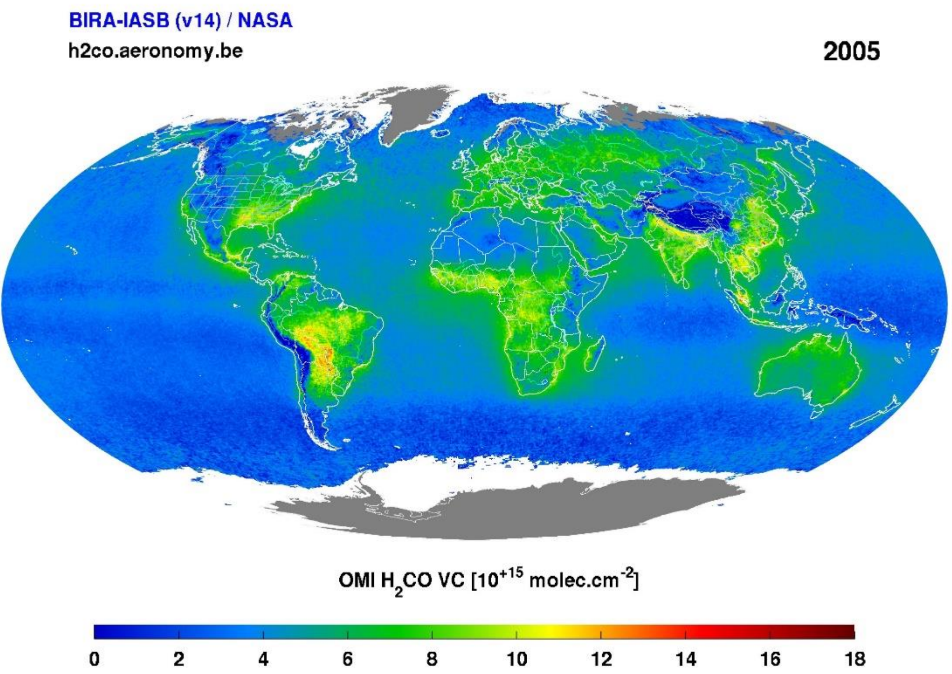
CEDS v2 inventory

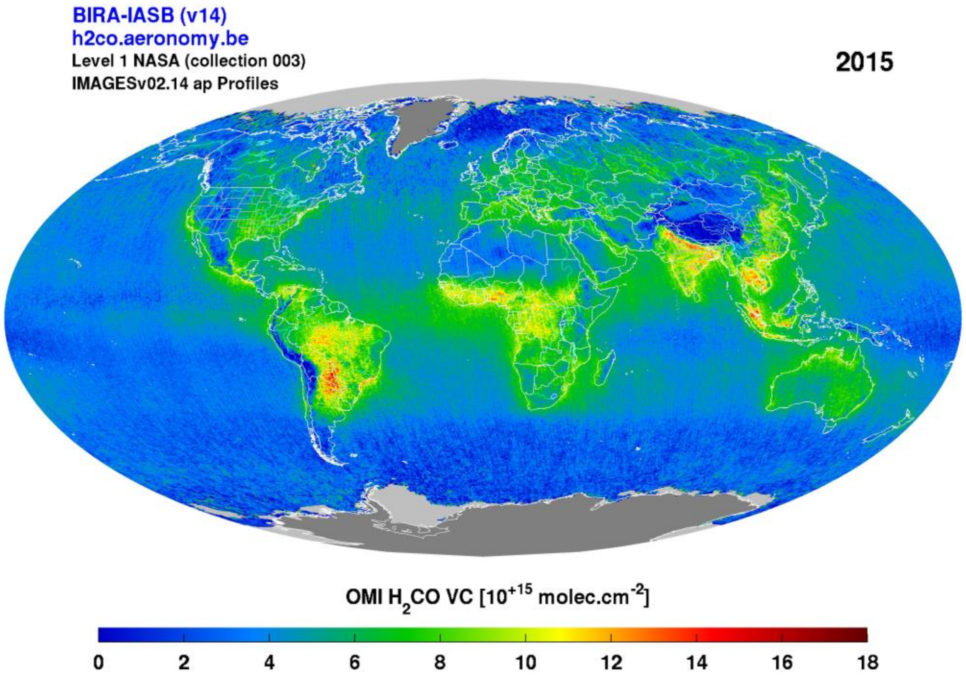
Anthro. Emission Trends of NMVOC in China: 1990-2020



Source: MEIC data from Bo Zheng

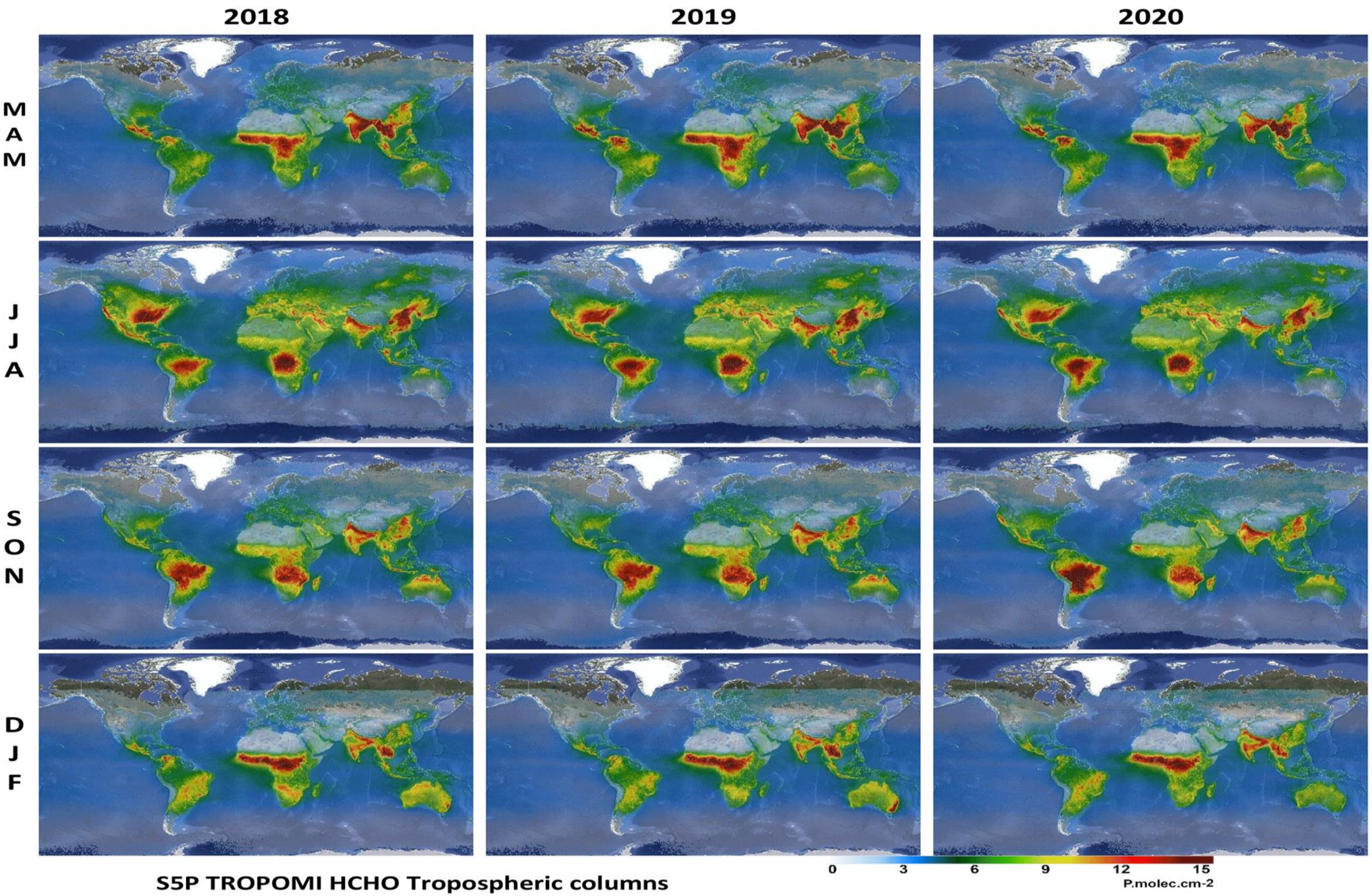
Tropospheric HCHO Columns from OMI: 2005-2015





www.temis.nl

Tropospheric HCHO Column from TROPOMI: 2018-2020

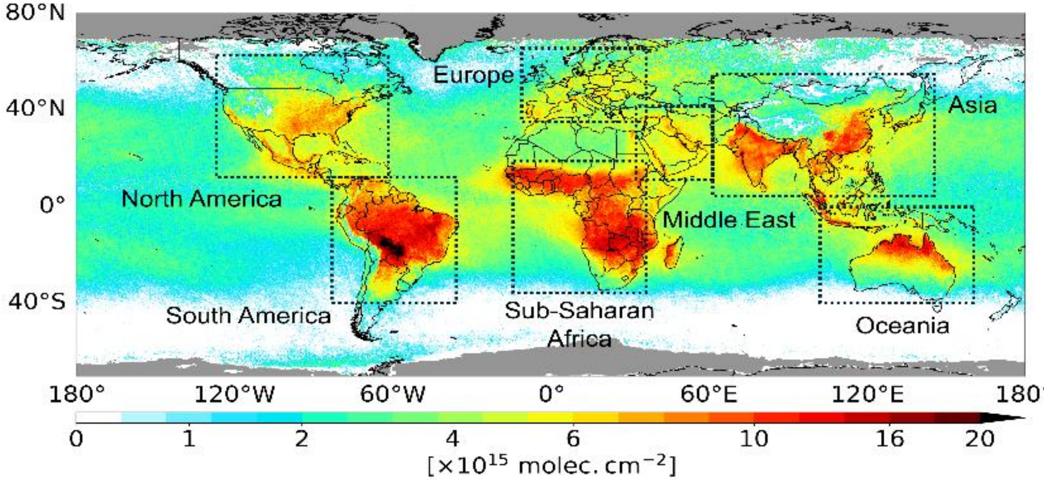


De Smedt et al., ACP, 2021

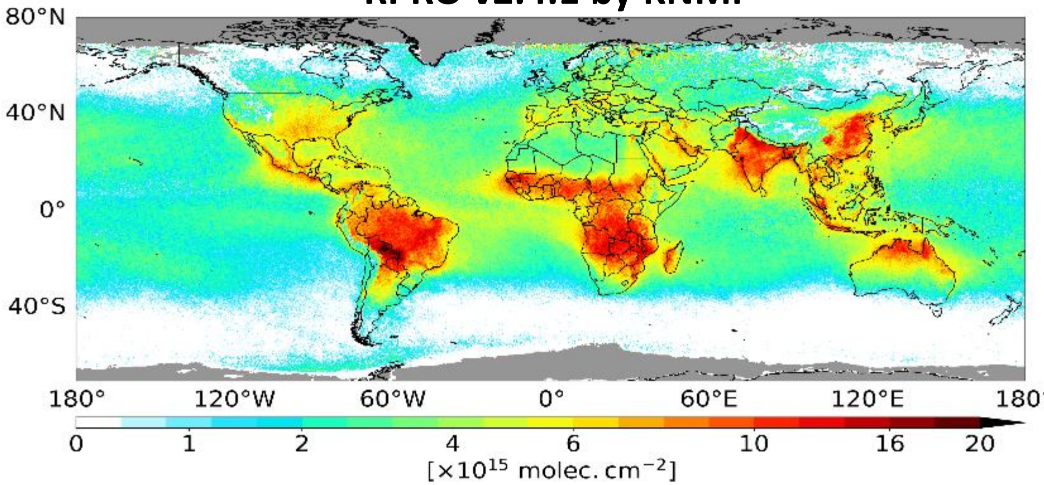
Global POMINO-TROPOMI HCHO VCDs

Tropospheric HCHO VCDs (April, July, October 2021, and January 2022)

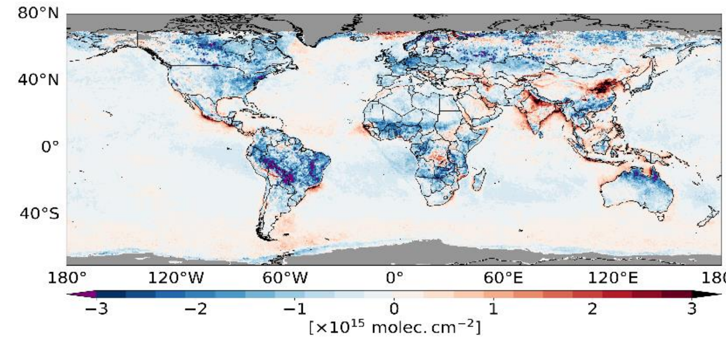
POMINO



RPRO v2.4.1 by KNMI

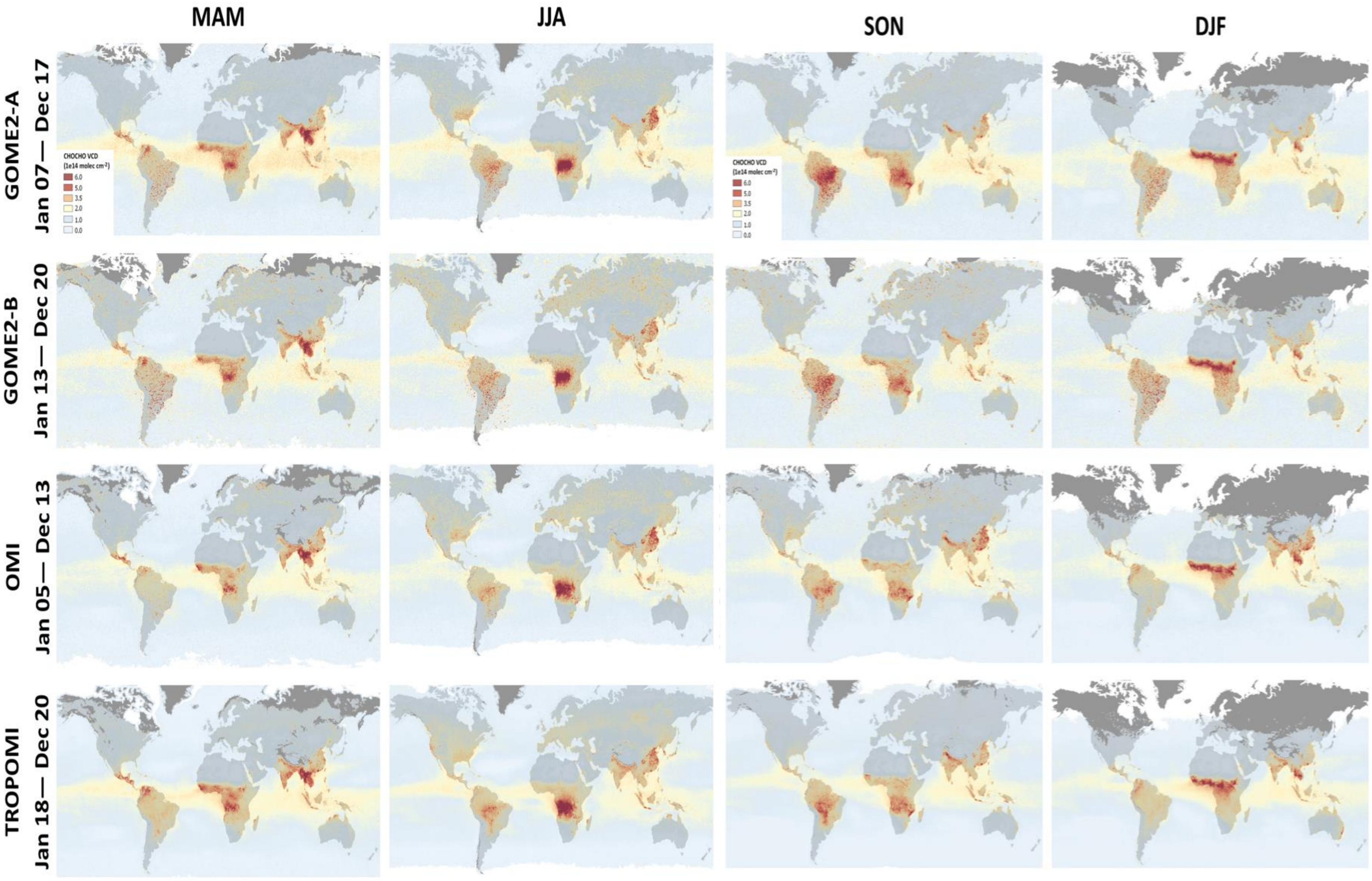


RPRO minus POMINO



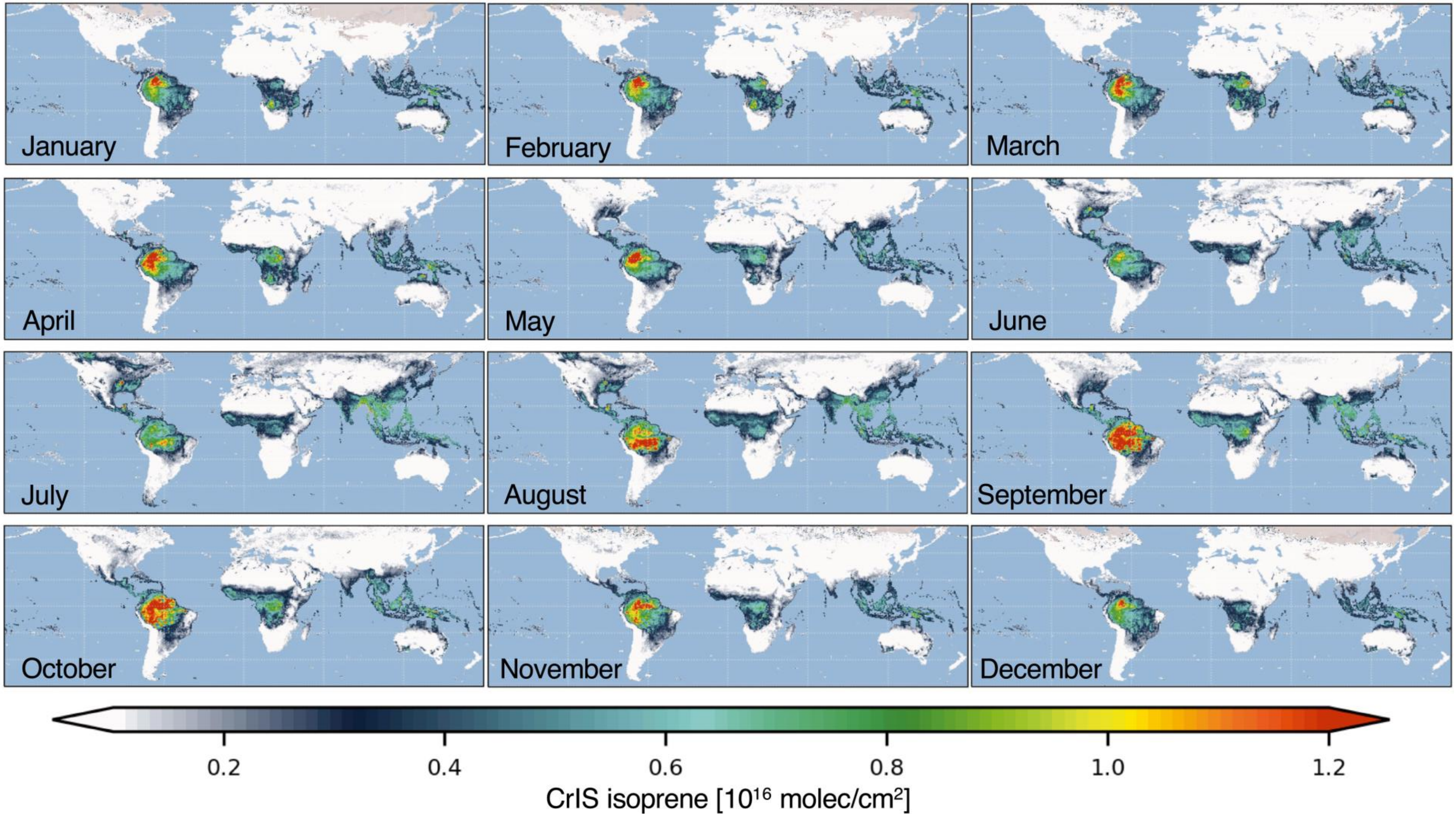
Zhang et al., AMT, 2025

Tropospheric CHOCHO Columns: 2005-2020



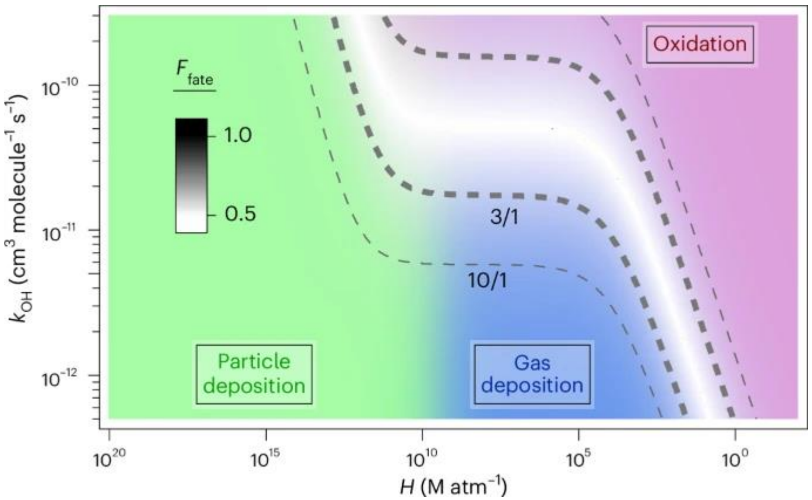
Lerot et al., AMT, 2021

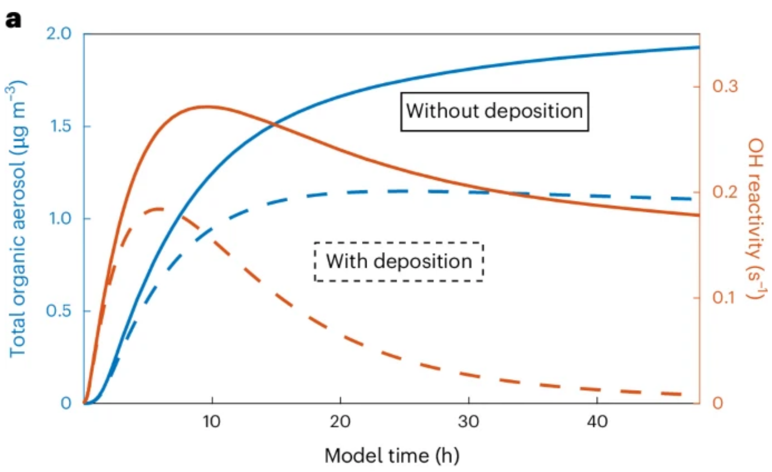
Tropospheric Isoprene Columns from CrIS: 2012-2020

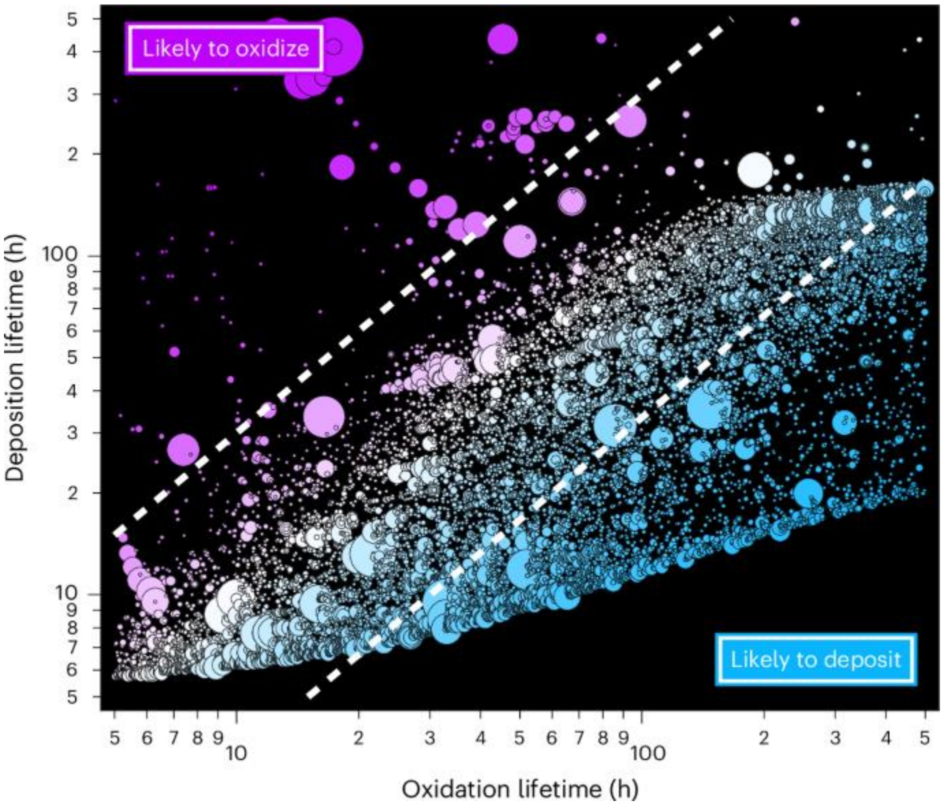


Wells et al., JGR, 2022

Formation of Late-Generation Atmospheric Compounds Inhibited by Rapid Deposition of Organics





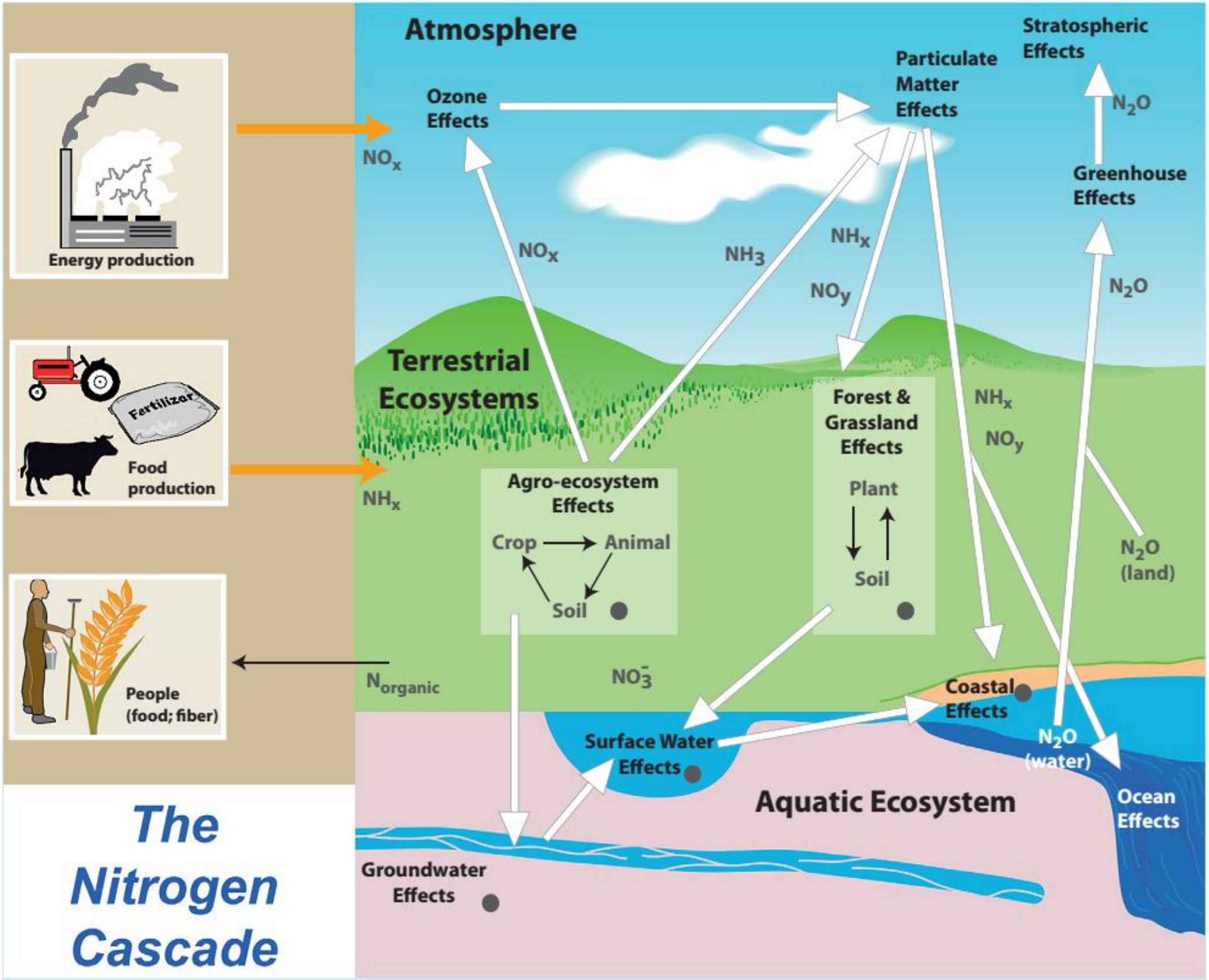


Bi and Isaacman-VanWertz, Nature Geoscience, 2025

Global Nitrogen Cycle: Why Should We Care?

- **Good: Important nutrition for agriculture, ecosystem**
- **Bad: Precursor of ozone, aerosols**
- **Bad: Adverse effects on air quality, climate, acid deposition, eutrophication, biodiversity threat**
- **Species: NOx, NOy, NH_3, NH_4, N_2O**

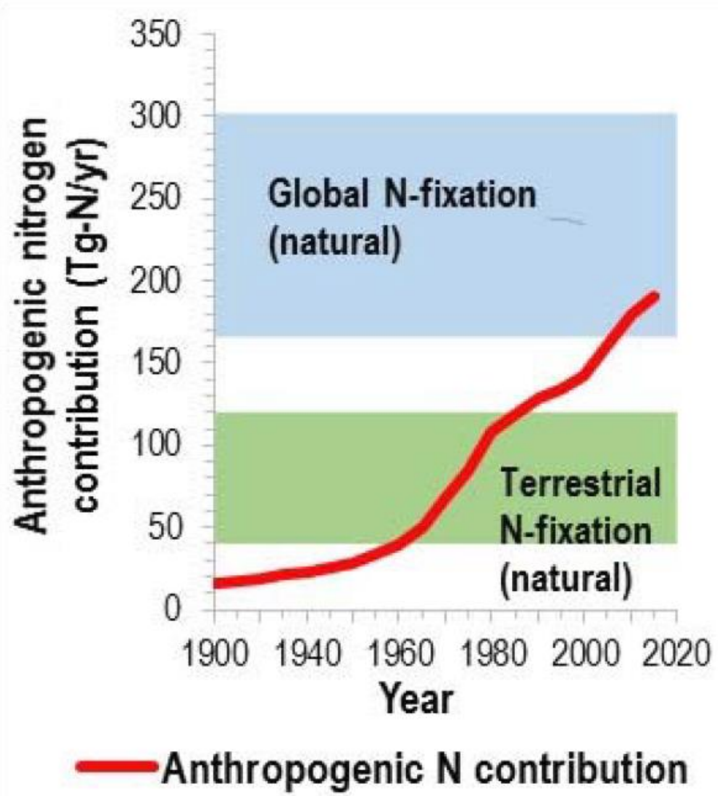
Global Nitrogen Cascade

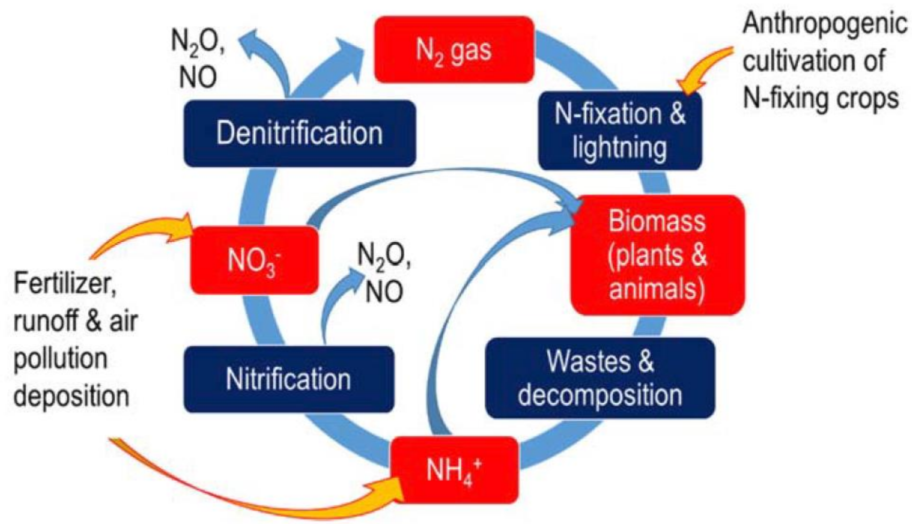


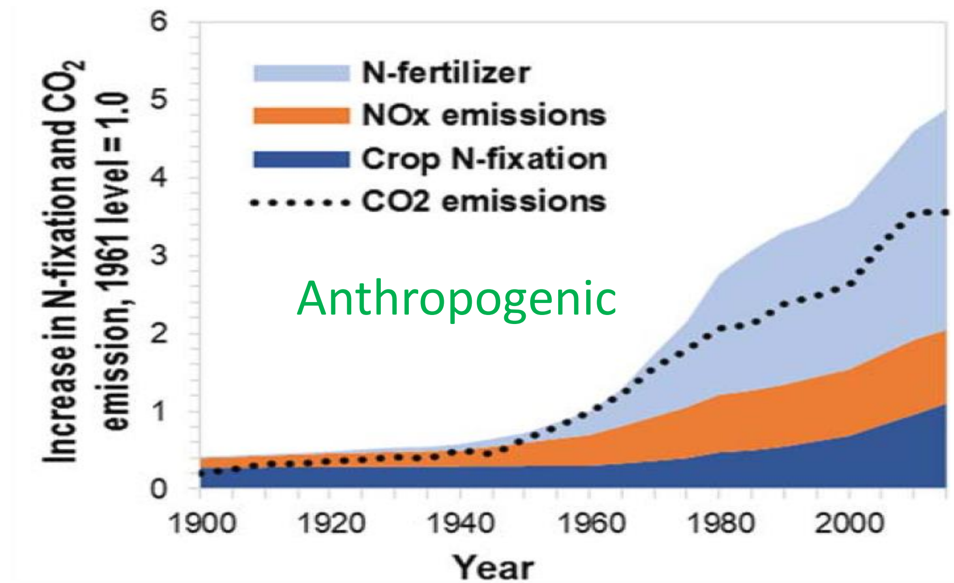
Haber-Bosch Process: $N_2 + 3H_2$ (+ Catalyst) ↔ $2NH_3$

IPCC, 2013

Global Reactive Nitrogen Creation







Battye et al., 2017

NOx Emissions by Source

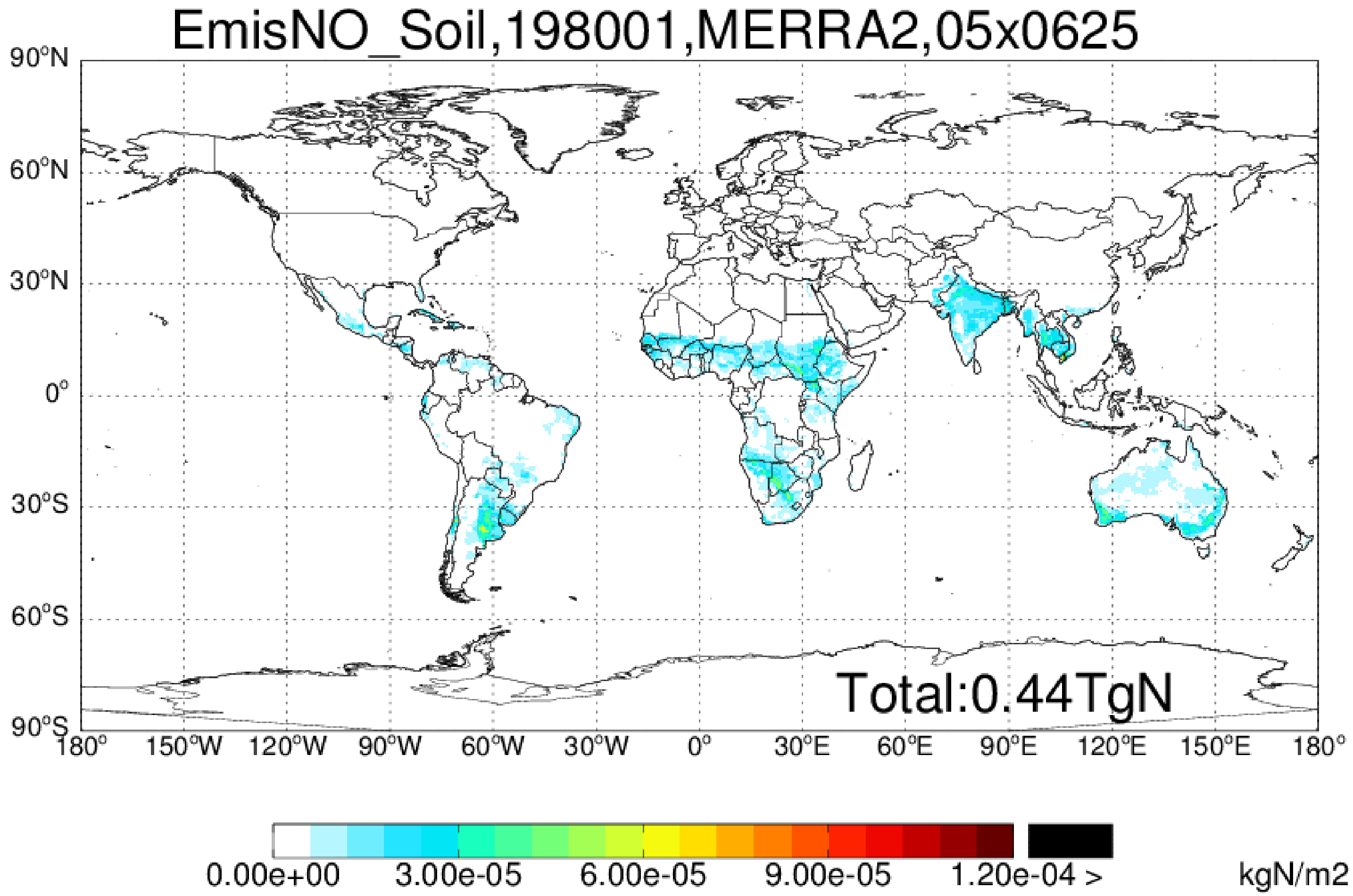
NOx Budget

Table 4.8: Estimates of the global tropospheric NO_x budget (in TgN/yr) from different sources compared with the values adopted for this report.

Reference:	TAR	Ehhalt (1999)	Holland *et al.* (1999)	Penner *et al.* (1999)	Lee *et al.* (1997)
Base year	**2000**	**~1985**	**~1985**	**1992**	
Fossil fuel	33.0	21.0	20 - 24	21.0	22.0
Aircraft	0.7	0.45	0.23 -0.6	0.5	0.85
Biomass burning	7.1	7.5	3 - 13	5 - 12	7.9
Soils	5.6	5.5	4 - 21	4 - 6	7.0
Lightning	5.0	7.0	3 - 13	3 - 5	5.0
Stratosphere	<0.5	0.15	0.1 - 0.6	-	0.6
Total	**51.9**	**44.6**			**44.3**

China has used excessive fertilizer in agriculture (32.6 vs 11.6 in US in 2010), leading to significant emis of nitrogen from soil

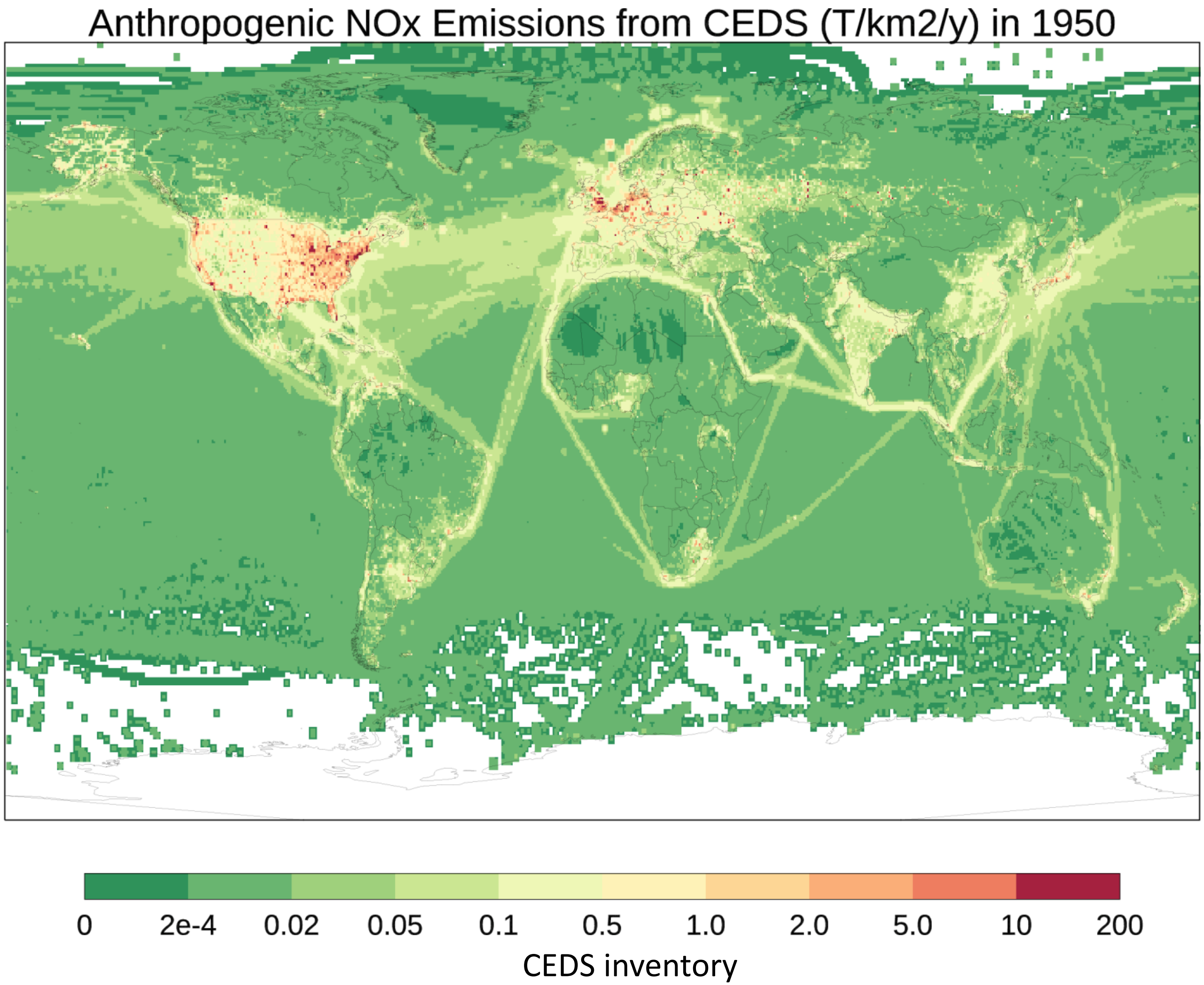
Soil NOx Emissions Since 1980



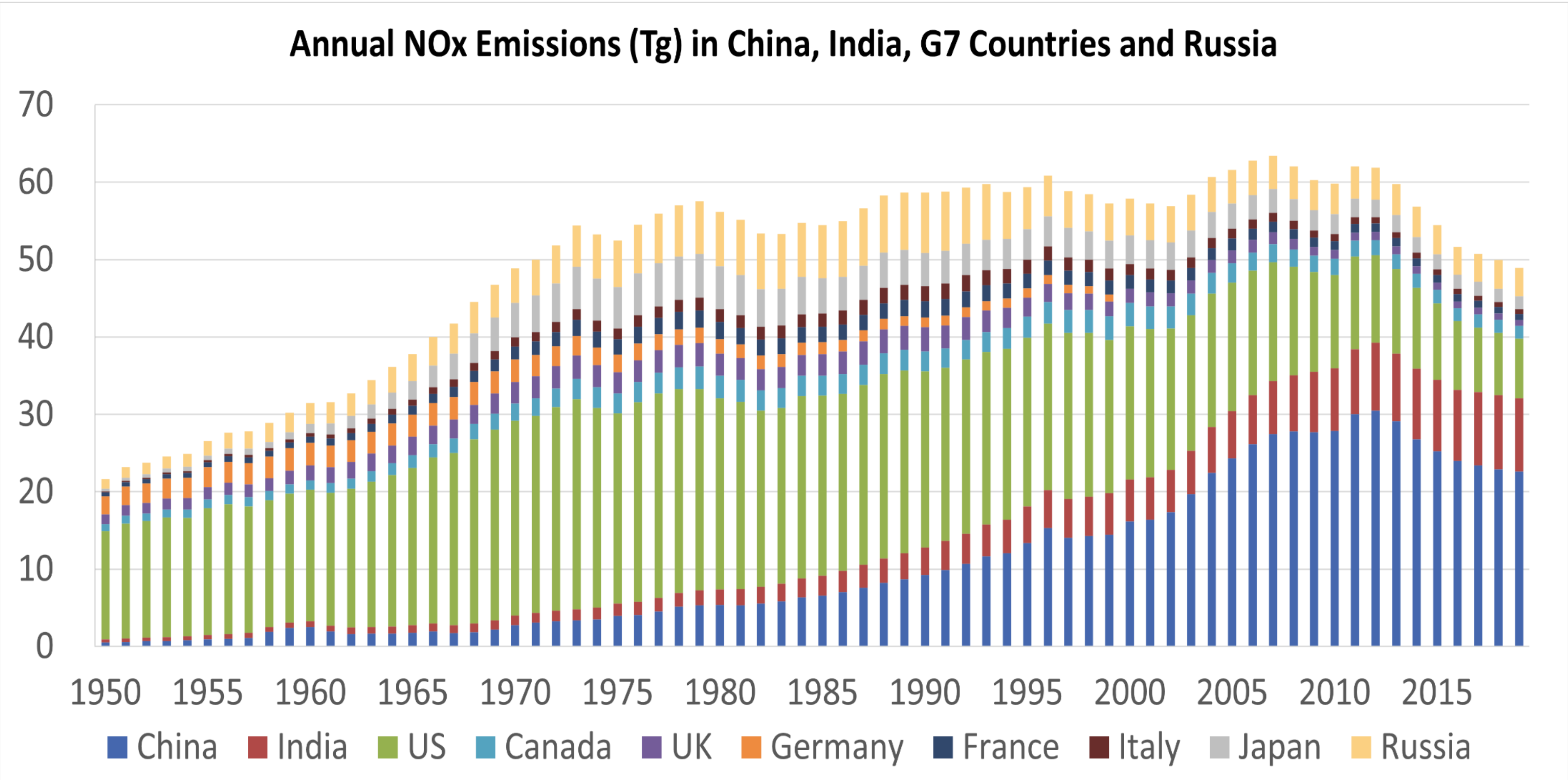
Temporal res : hourly
Horizontal res: 25 or 50 km

Weng HJ et al., 2020, SD

Anthropogenic NOx Emissions: 1950-2014

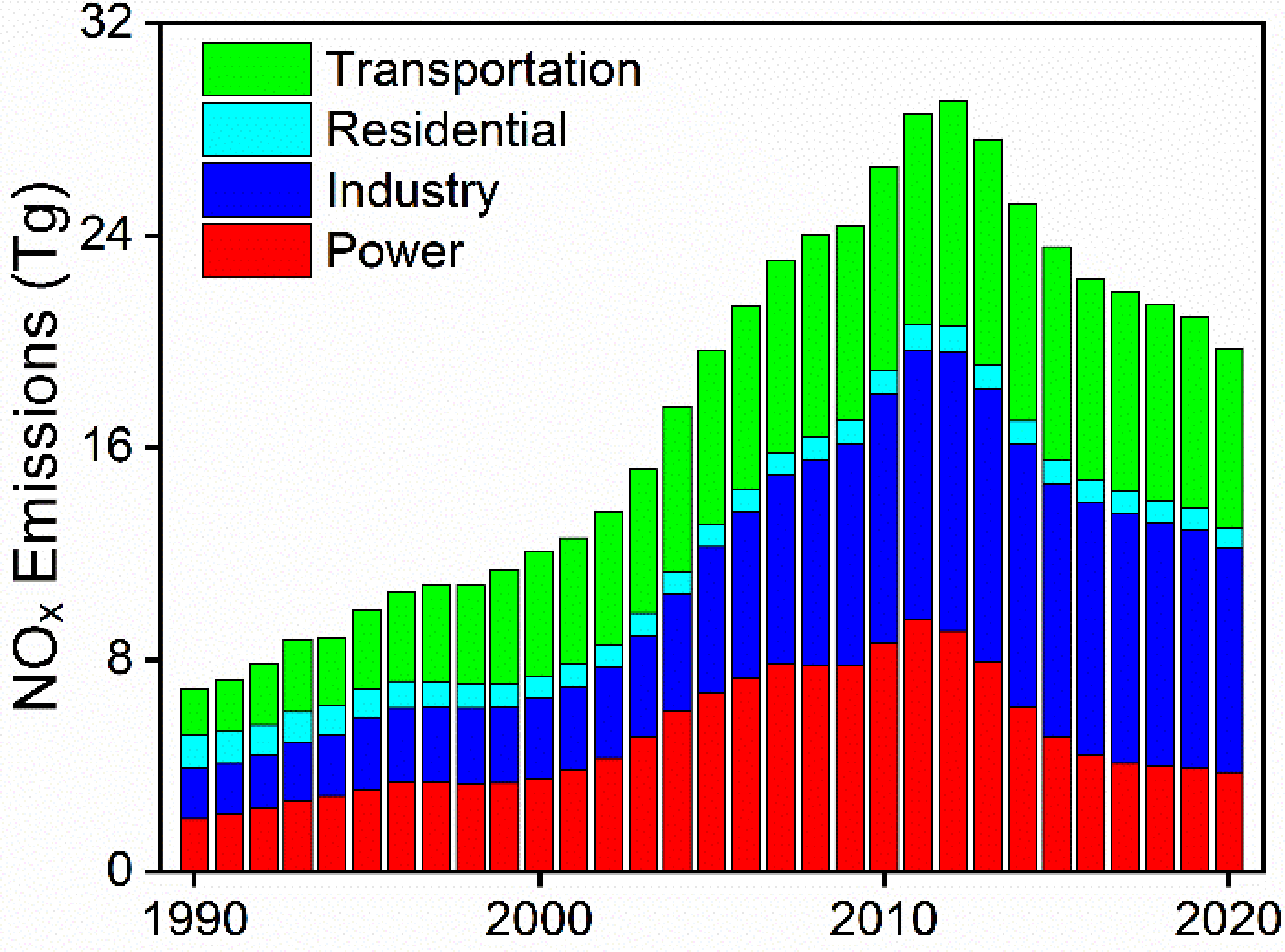


Anthropogenic Emissions of NOx: 1950-2019



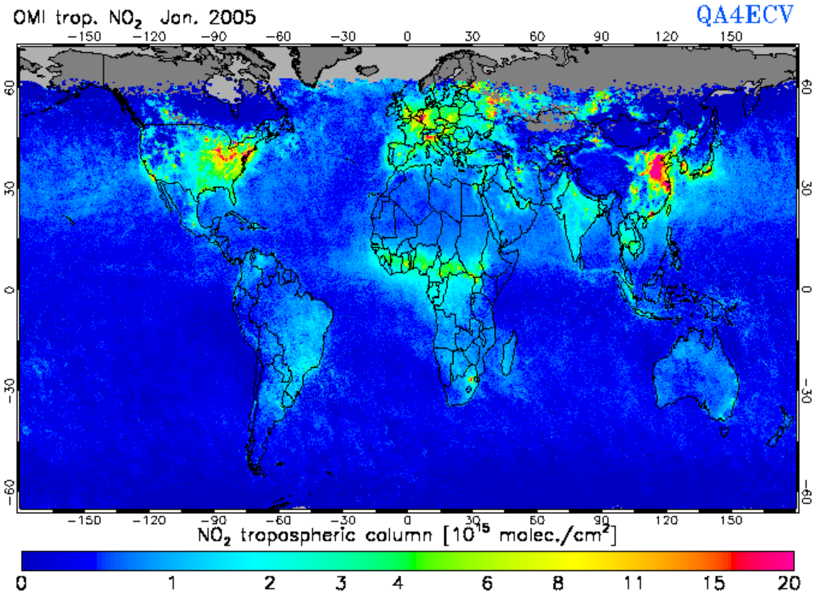
CEDS v2 inventory

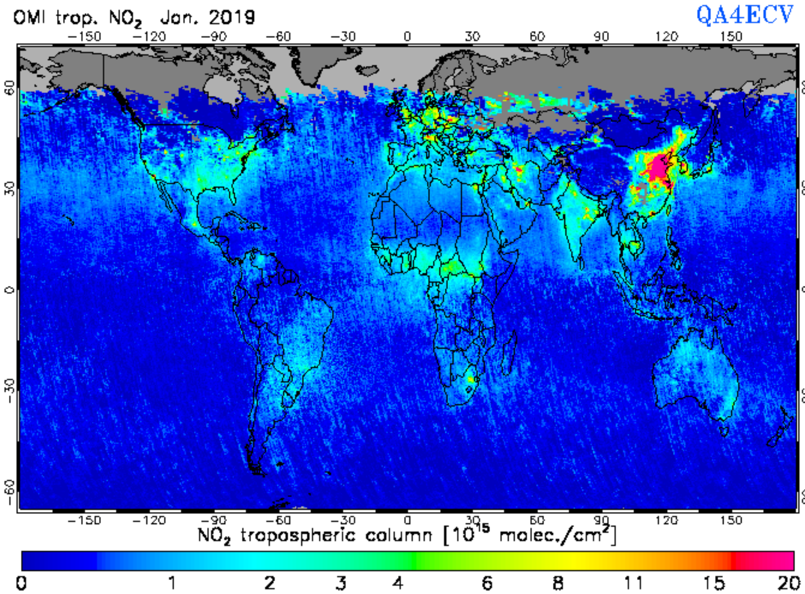
Anthro. Emission Trends of NOx in China: 1990-2020

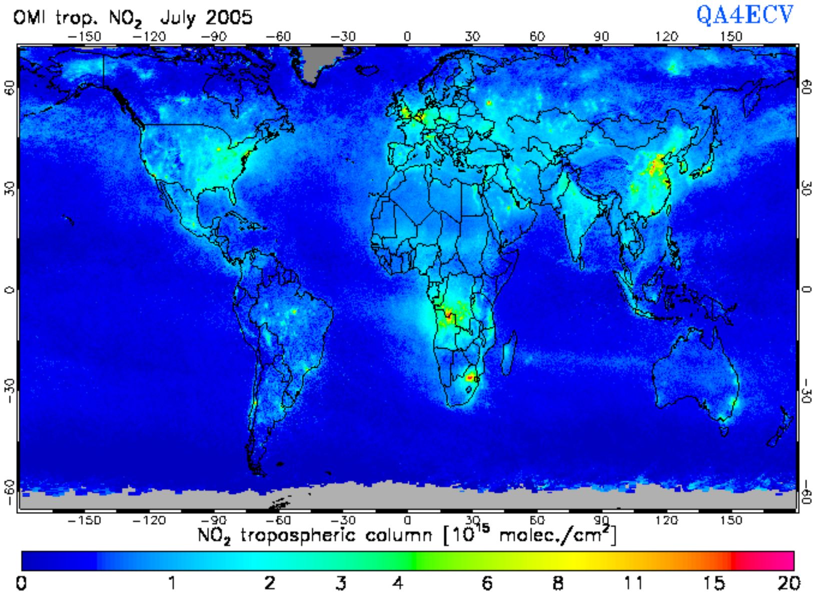


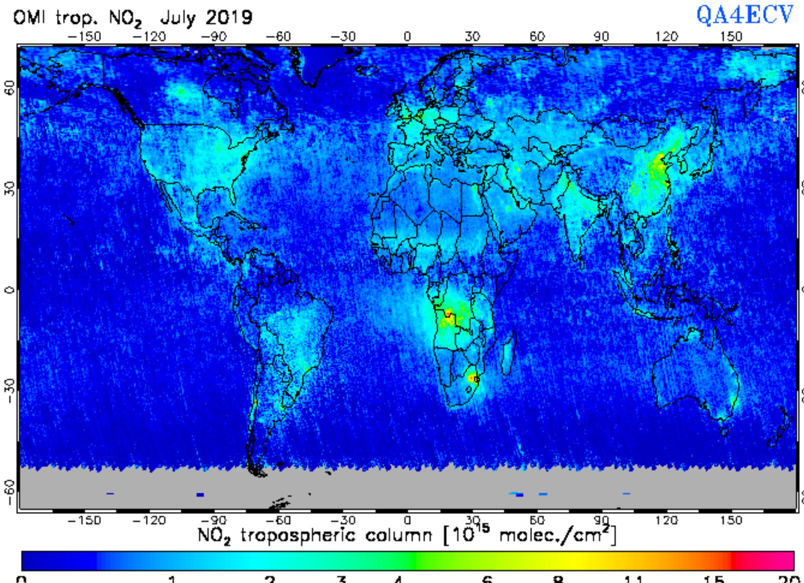
Source: MEIC data from Bo Zheng

Tropospheric NO_2 Column: 2005-2019



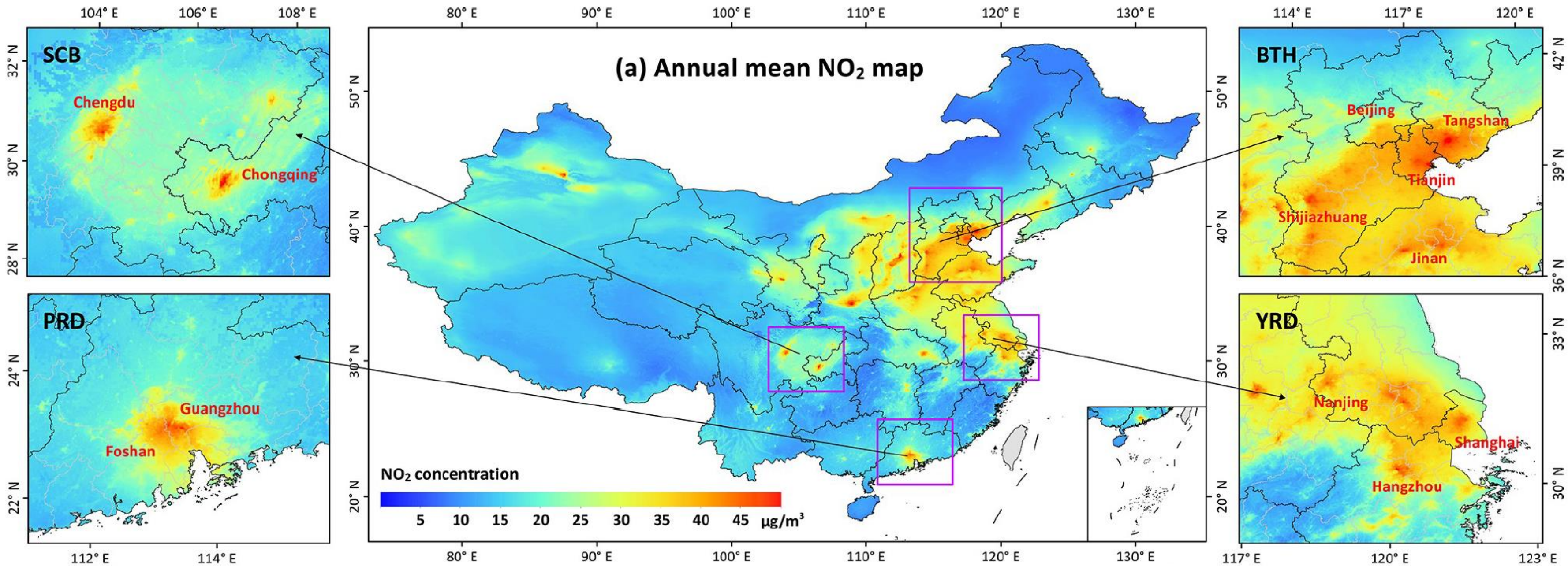






Near Surface NO_2 Concentrations Over China: 2019-2020

Estimated based on satellite NO_2 VCDs and machine learning

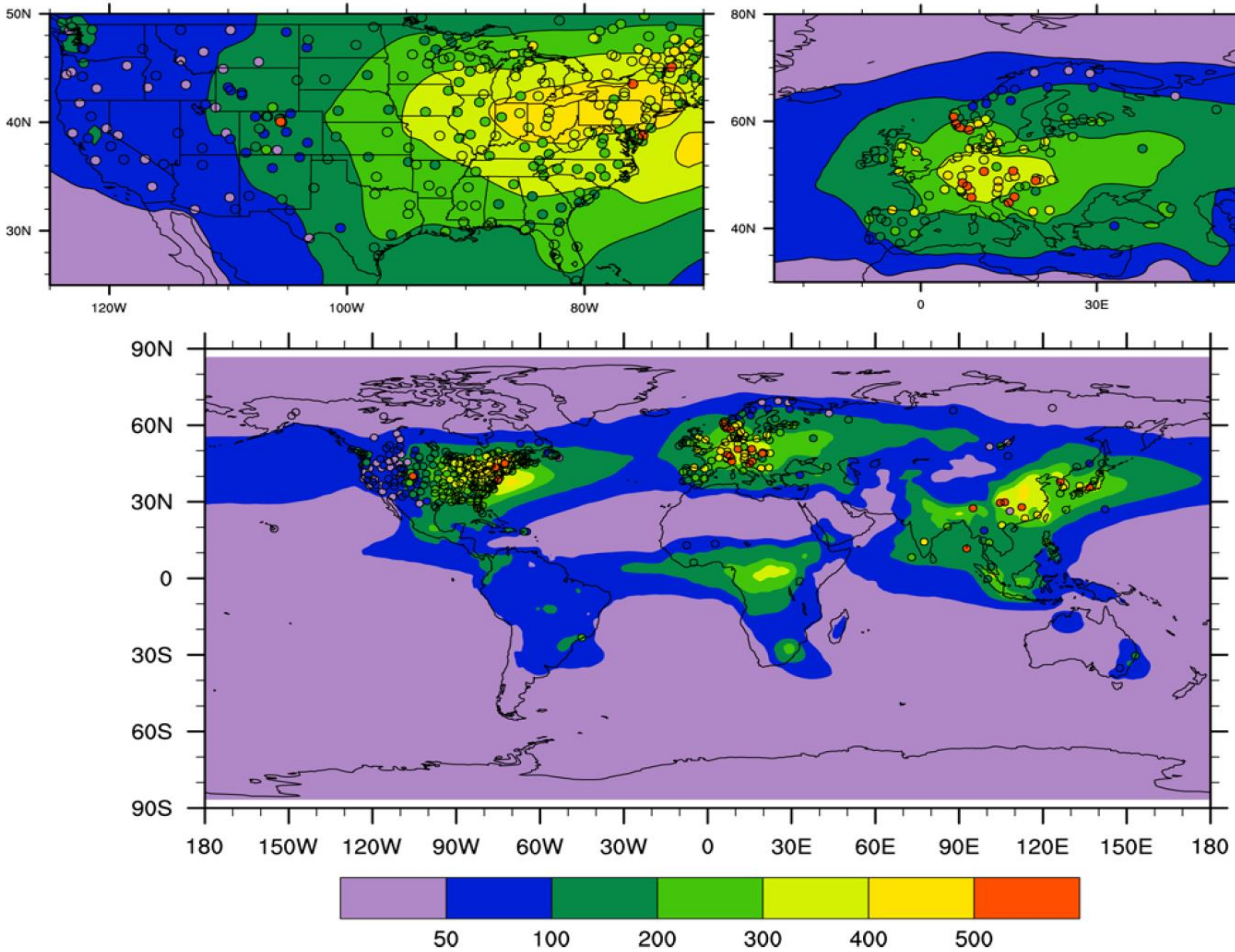


Wei et al., EST, 2022

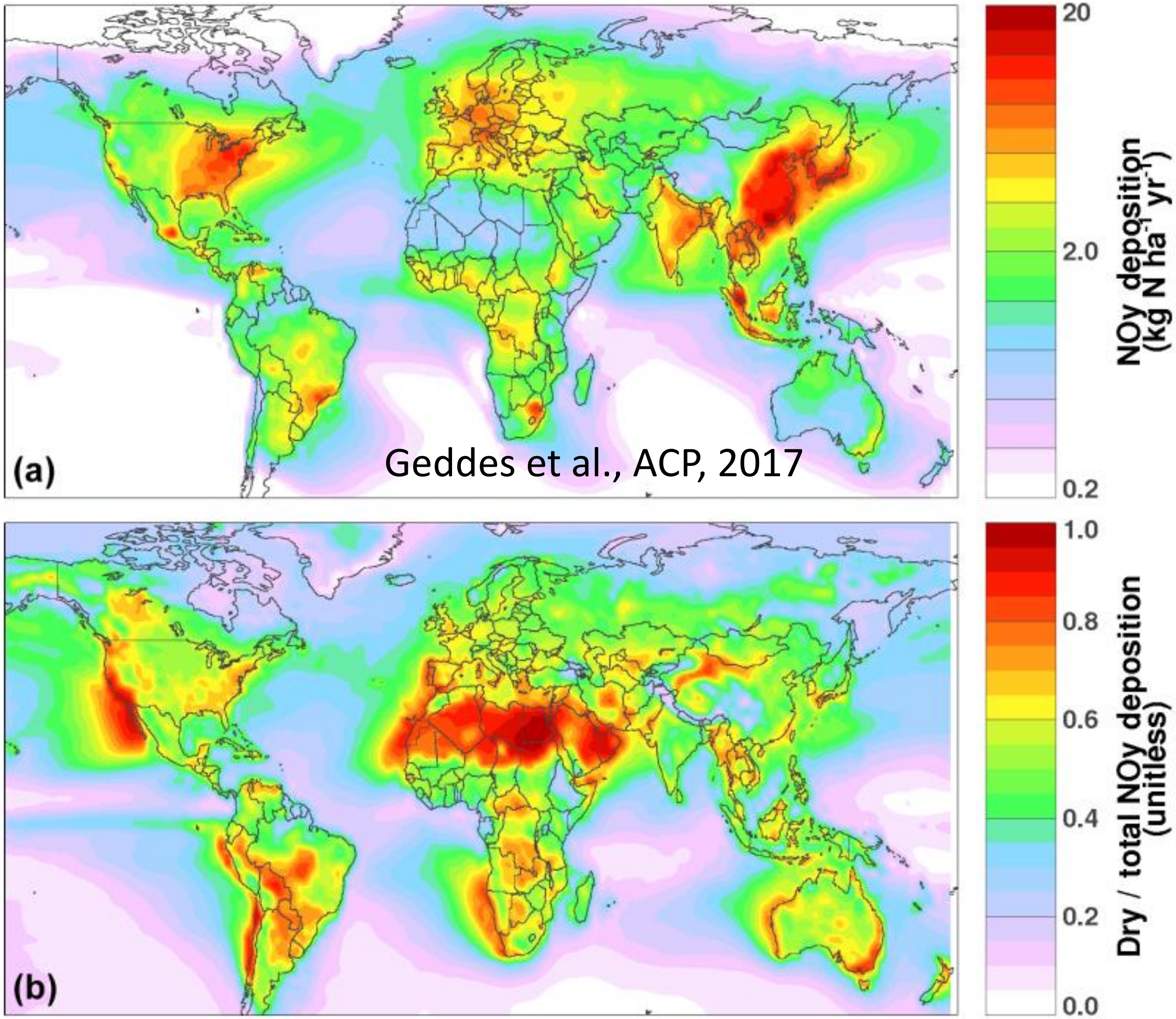
国家标准：40（年均），80（24小时），200（1小时）
WHO指导值：10（年均），25（24小时）

NO_3^- Wet Deposition in 2000

Lamarque et al., 2013, ACP, Multi-model mean

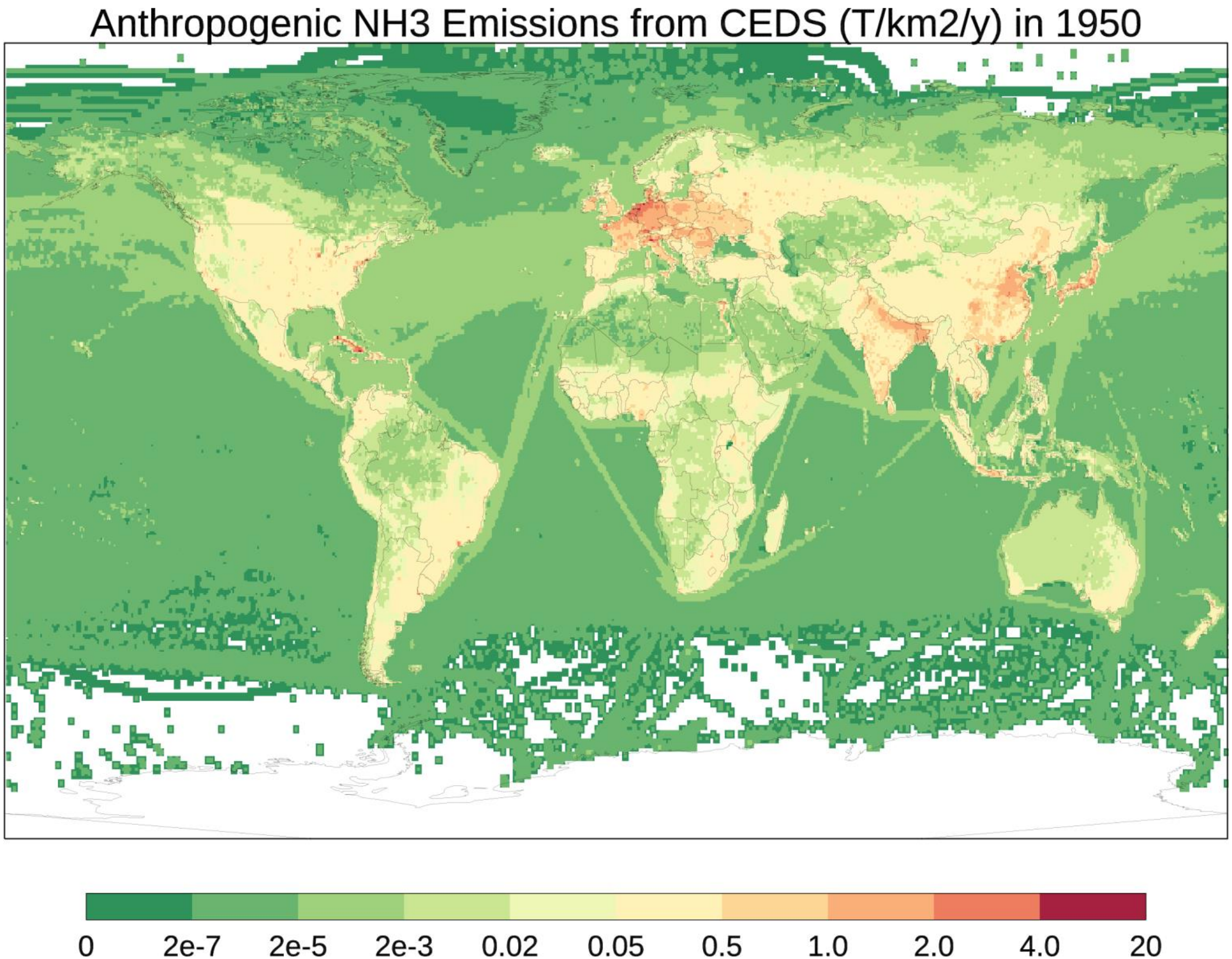


NOy Deposition in 1996-2014



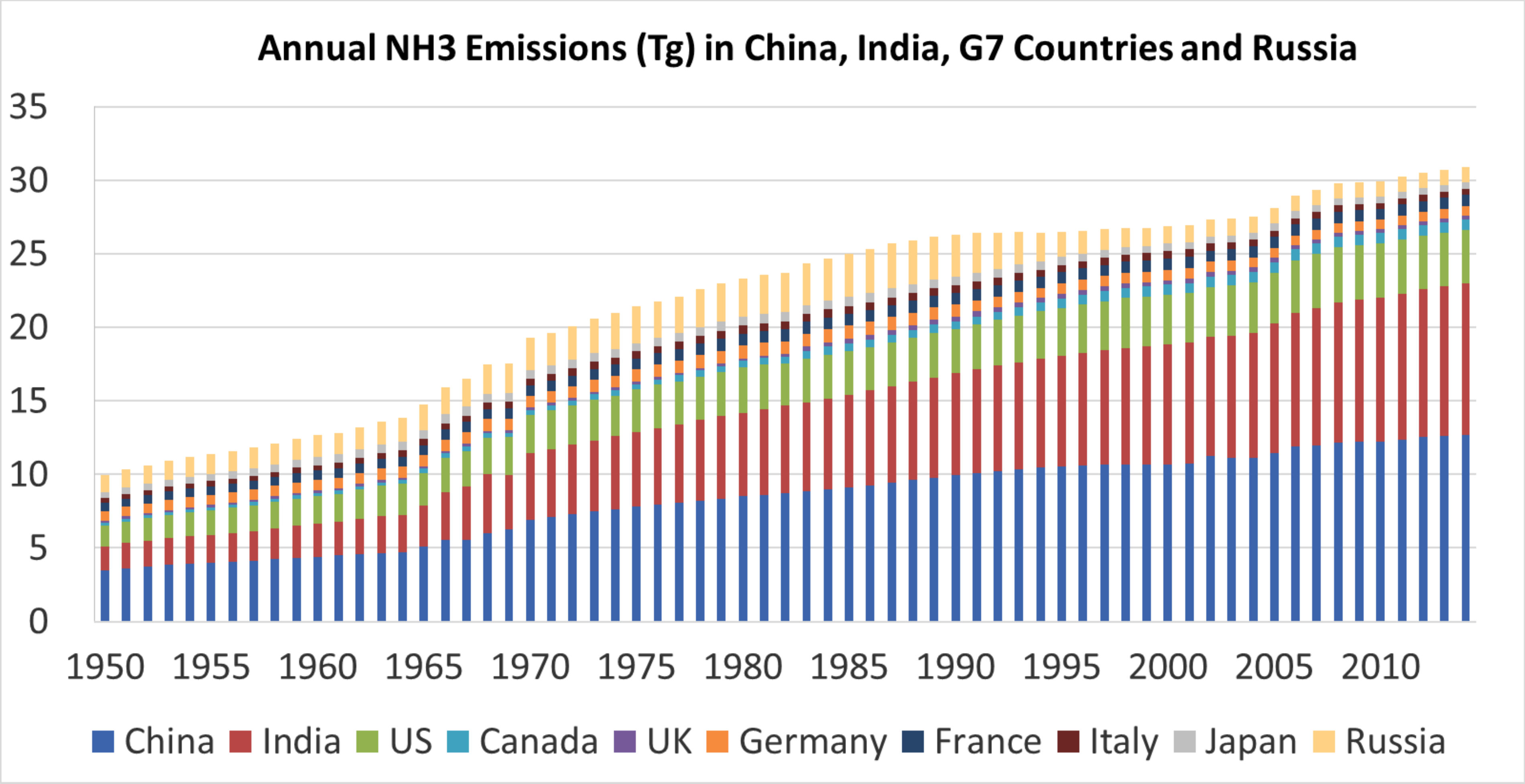
Here, $NO_y = NO + NO_2 + HNO_3 + HONO$ + organic nitrate molecules + aerosol nitrate

Anthropogenic NH_3 Emissions: 1950-2014



CEDS inventory

Anthropogenic Emissions of NH_3: 1950-2014



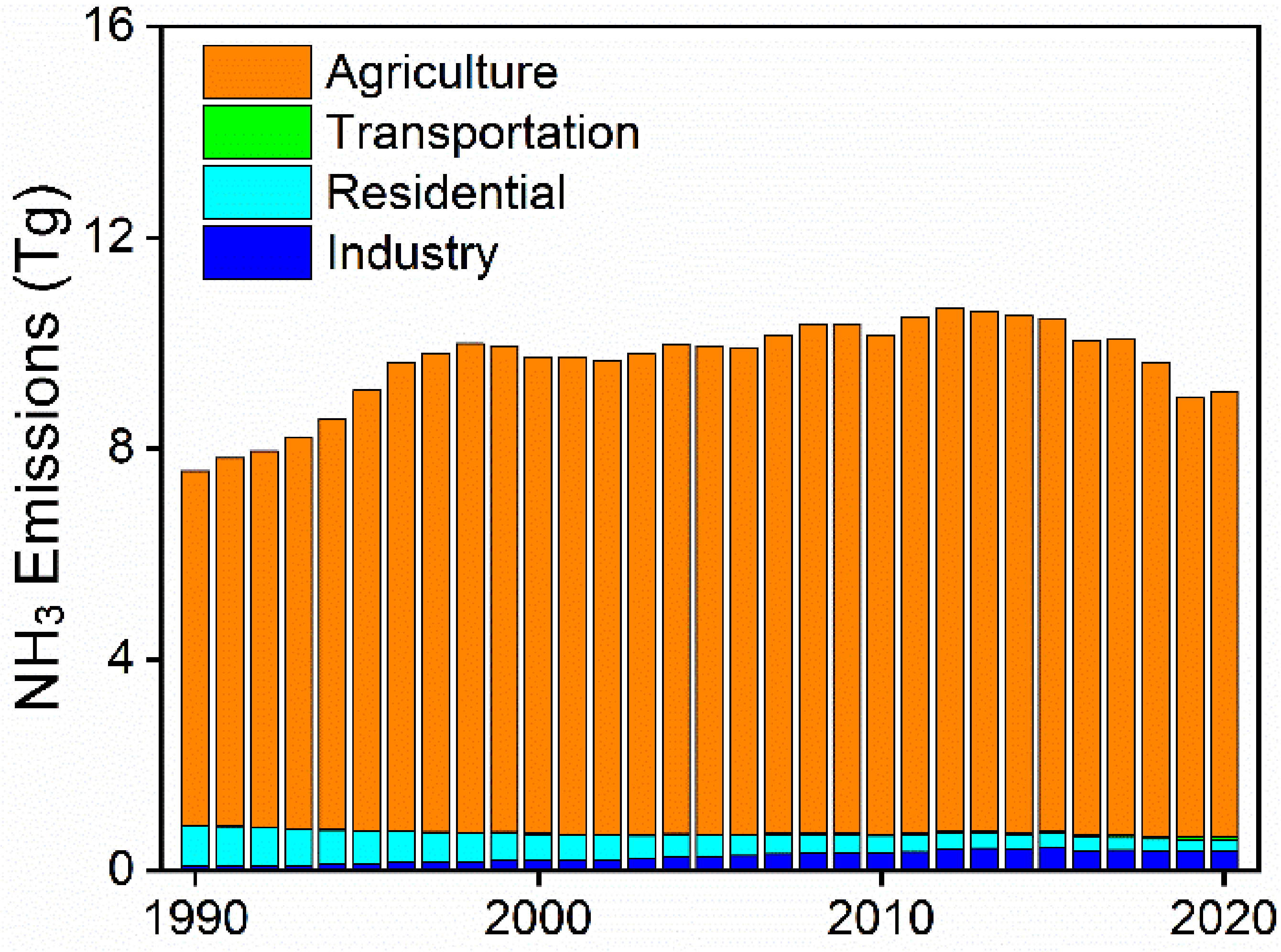
CEDS Inventory

Large Uncertainty in Chinese Anthropogenic NH_3 Emissions

References	Base year	Fertilizer application	Livestock waste	Human	Others[2]	Total
Yan et al. (2003)	1995	4.32	2.48[3]	0.21		7.01
Streets et al. (2003)	2000	6.8	5.17	1.63		13.6
Li and Li (2012)	2004	1.82	8.30	1.67	0.21	12.0
Wang et al. (2009)	2005	4.3	8.82	0.26		13.38
Zhang et al. (2011)	2005	4.31				
Dong et al. (2010)	2006	8.68	6.61	0.65	0.14	16.08
Huang et al. (2012)	2006	3.2	5.3	0.2	1.1	9.8
Cao et al. (2010)	2007	3.62	9.58		2.8	16.0
EDGAR	2008	8.1	3.1	0.1		11.3
Xu et al. (2016)	2008	3.3	3.8[3]	0.7	0.6	8.4
Paulot et al. (2014) (MASAGE)	2008	3.6	5.8	0.8		10.2
Kurokawa et al. (2013) (REAS v2)	2008	9.46	2.88	1.81	0.85	15.0
Zhao et al. (2013)	2010	9.82	7.36	1.12		18.3
Fu et al. (2015)	2011	3				
Kang et al. (2016)	2012	2.8	4.99	0.12	1.71	9.62
Zhang et al. (2017)	2008	5.05	5.31	1.30[4]		11.7

Zhang et al., 2017, ACP

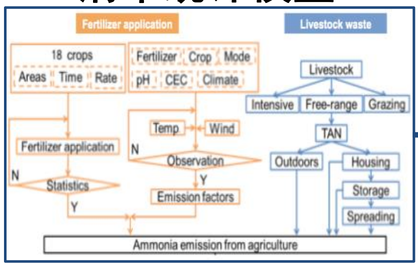
Anthro. Emission Trends of NH_3 in China: 1990-2020



Source: MEIC data from Bo Zheng

Agricultural NH_3 Emissions in China

清单统计模型



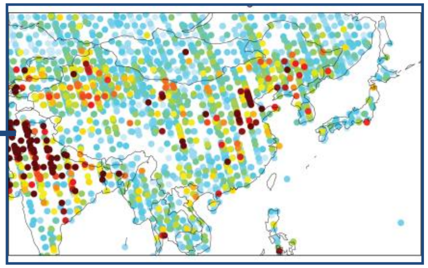
排放过程信息约束

源输入

GEOS-Chem伴随模型的氨资料同化系统

伴随算法排放反演

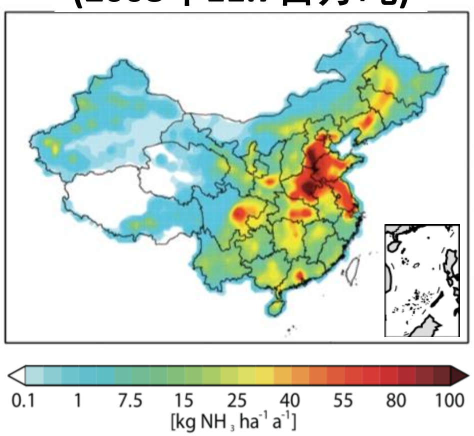
卫星氨浓度



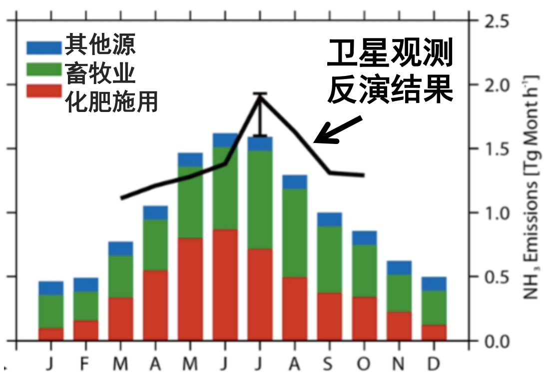
总量约束

地面观测验证

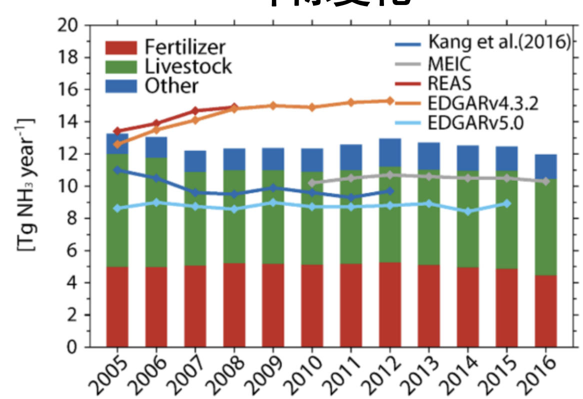
氨排放空间分布
(2008年11.7百万吨)



季节变化



年际变化

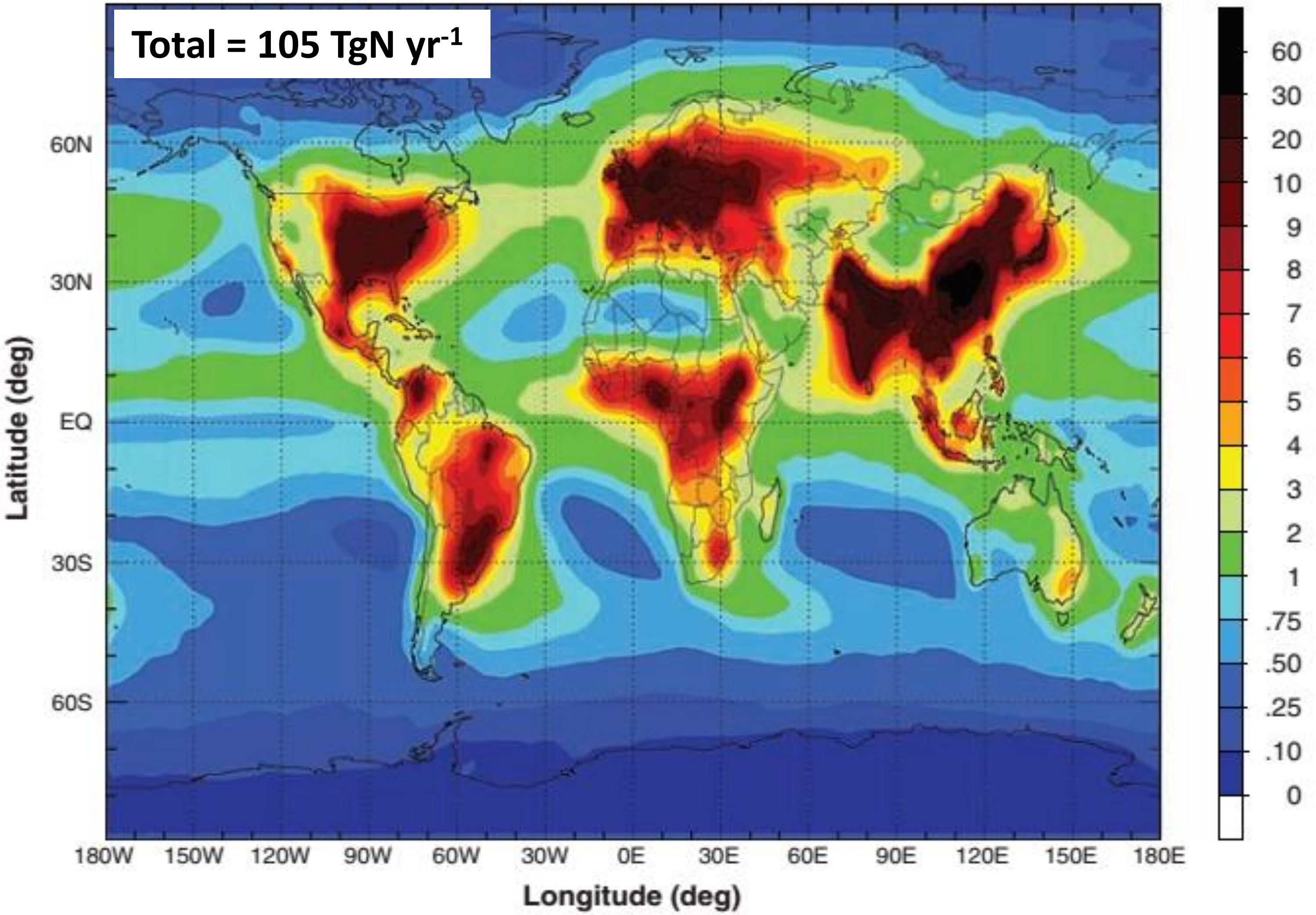


地面观测验证模拟偏差由40%降至<5%

Zhang* et al., ACP, 2018; ERL, 2021; ES&T, 2023

Global Nitrogen (NOy+NHx) Deposition

NOy+NHx deposition in 2000 (kg N ha^{-1} yr^{-1})



Dentener et al., 2006, GBC; Galloway et al., 2008, Science

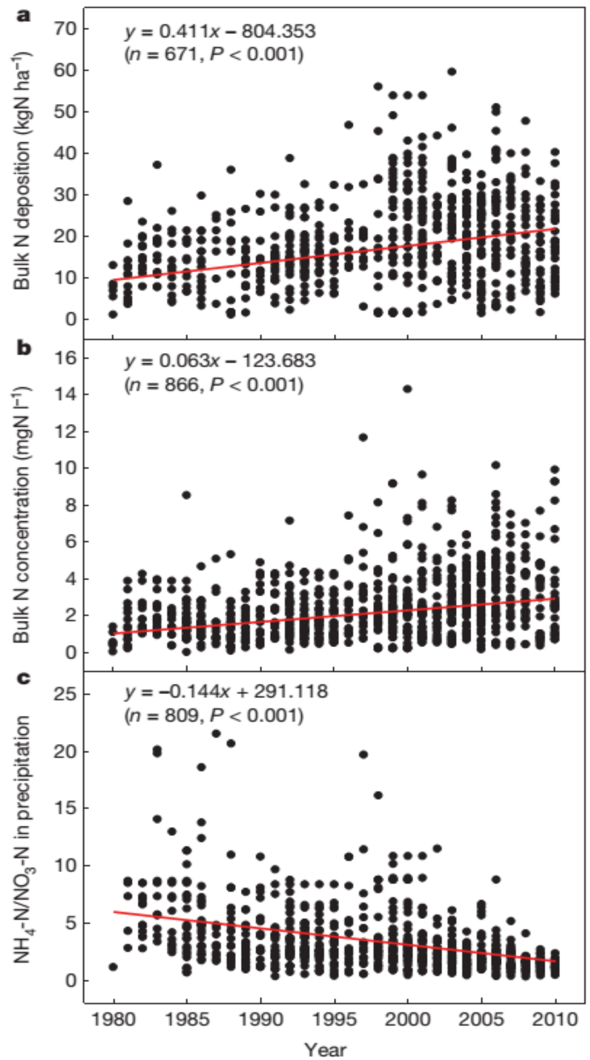
Increasing Bulk N Deposition in China

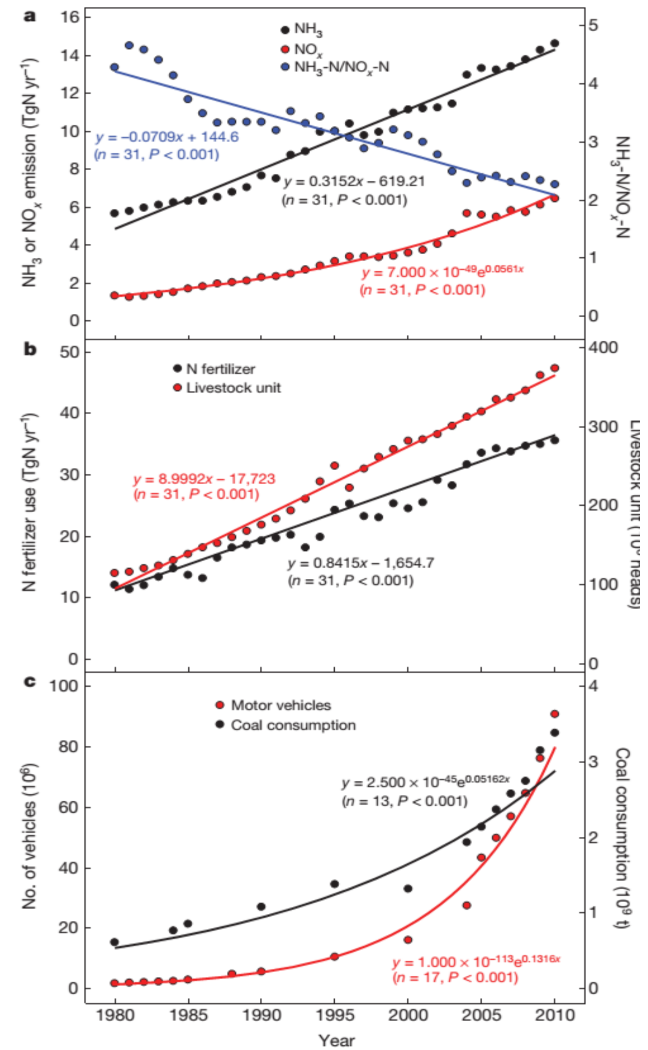
Deposition

Emissions

Wet + some Dry

Mostly inorganic

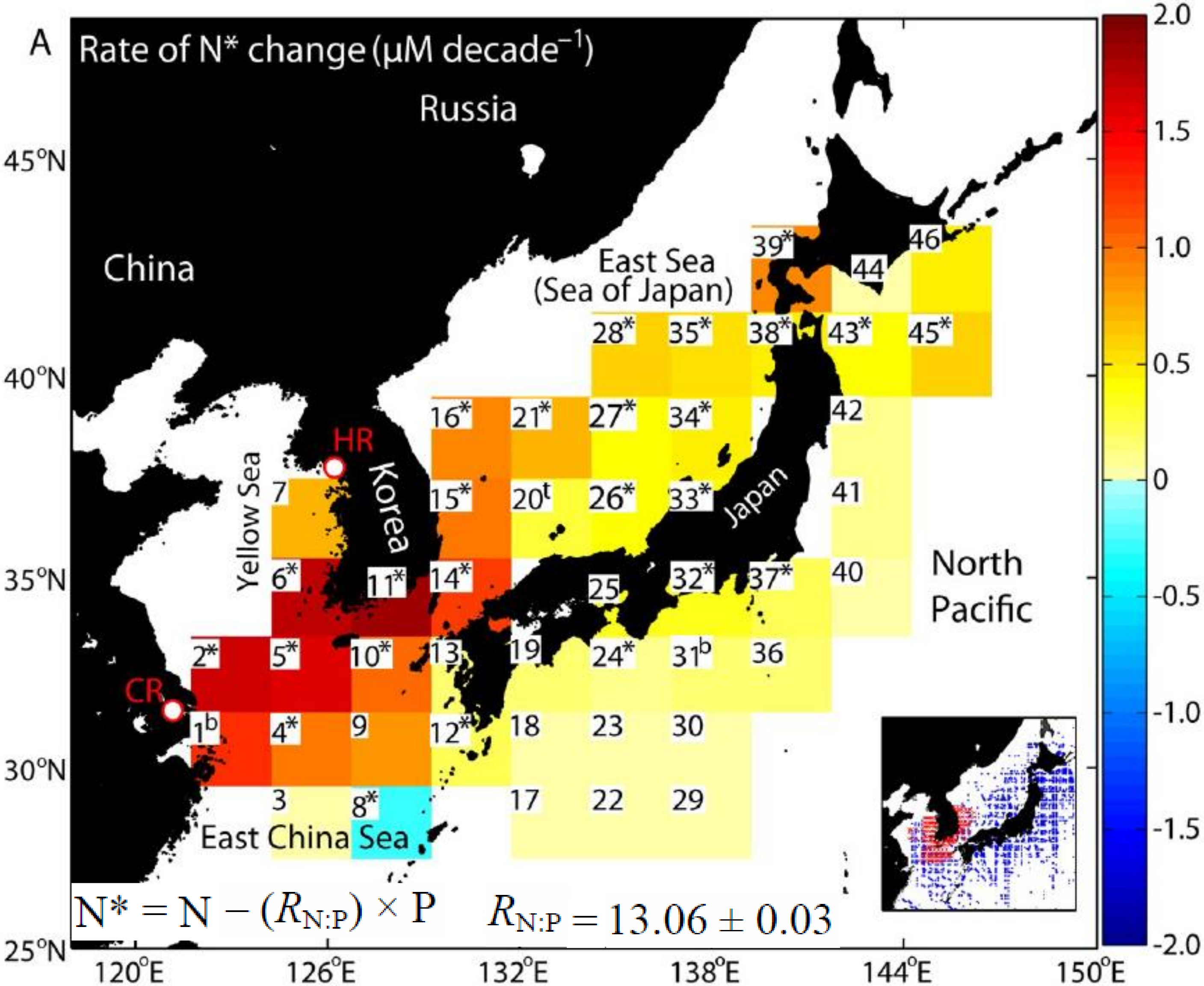




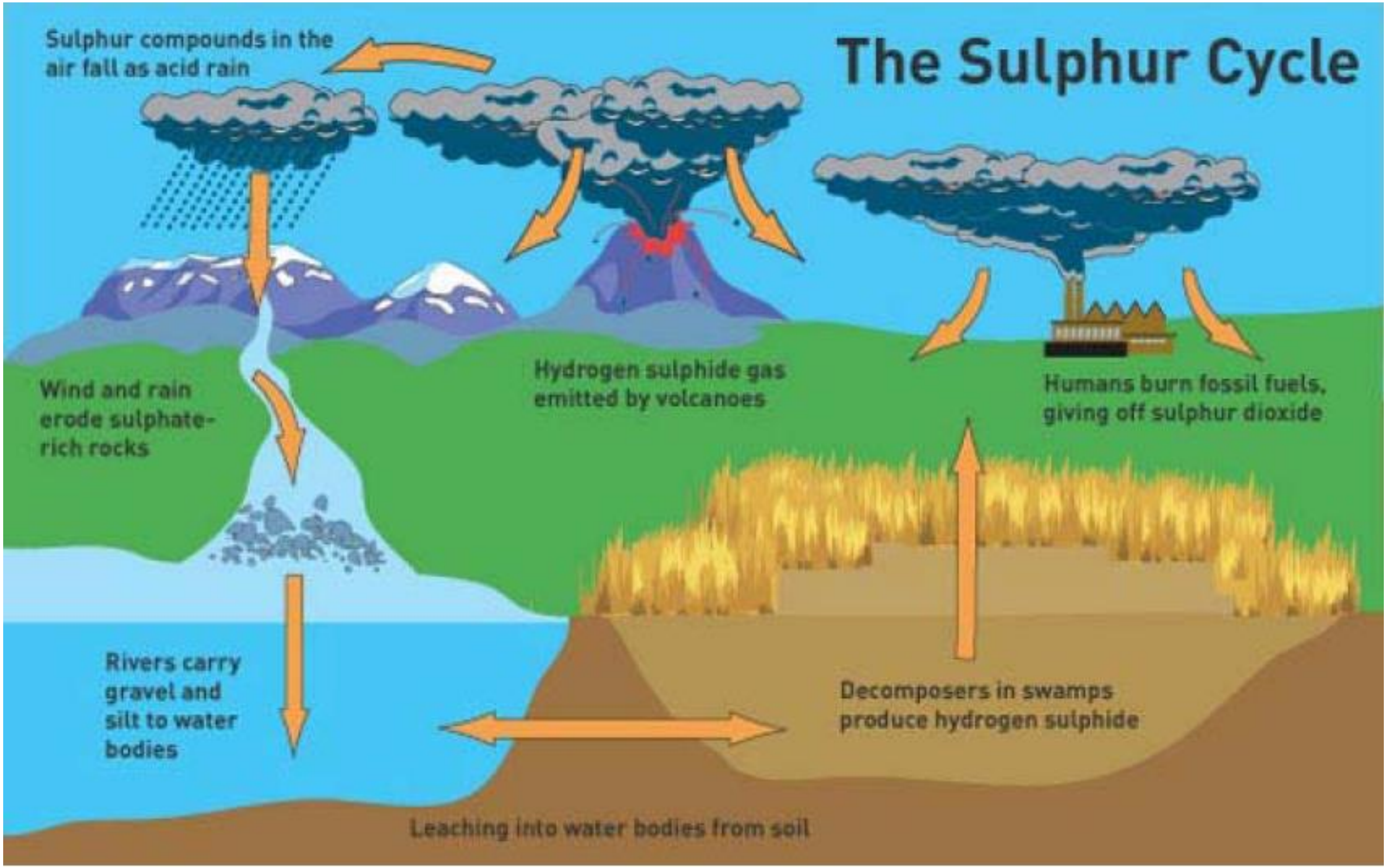
Liu et al., 2013, Nature

N* Concentration in the Ocean: 1980-2010

Kim et al., 2011, Science



Global Sulfur Cycle

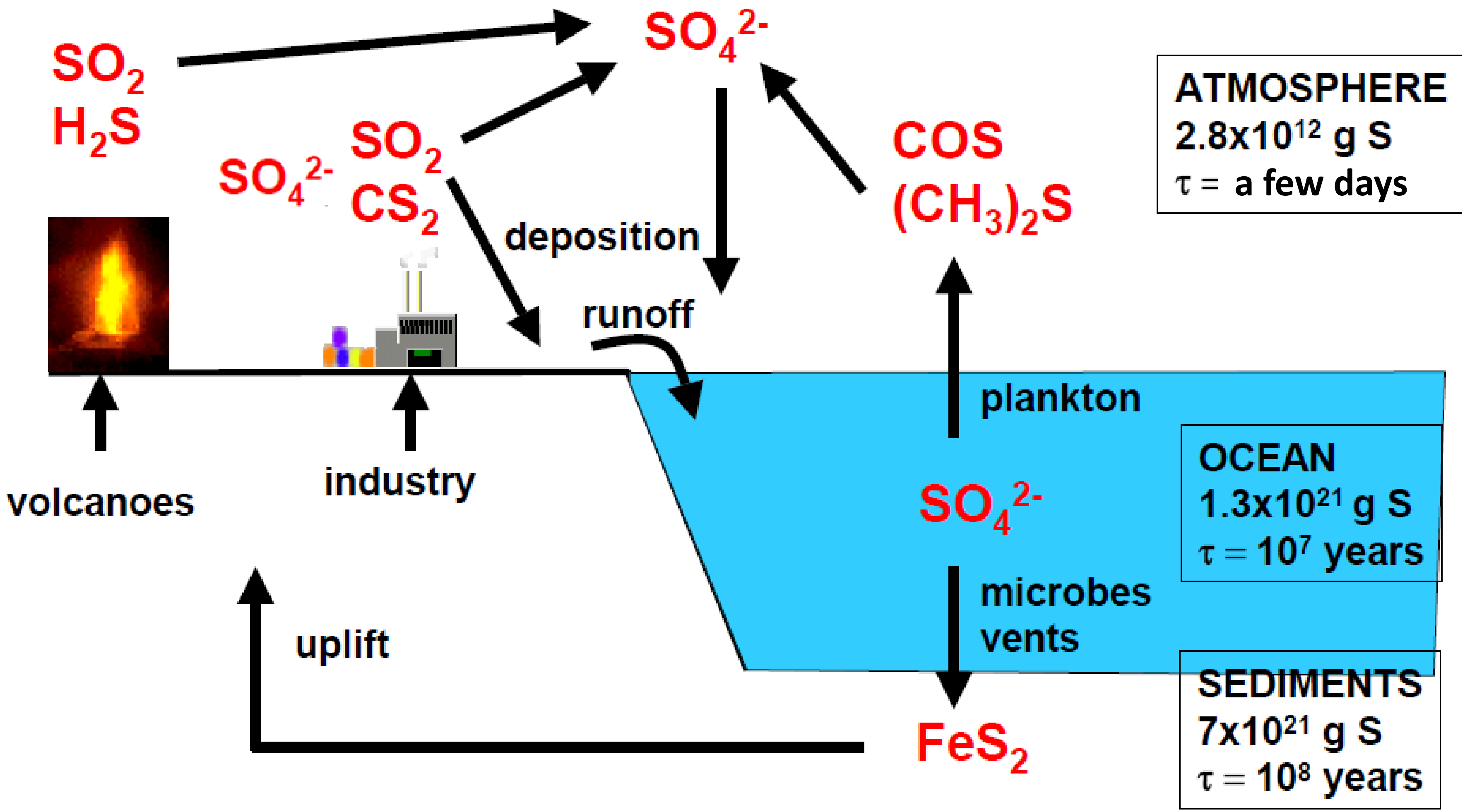


Oxidation States of Sulfur

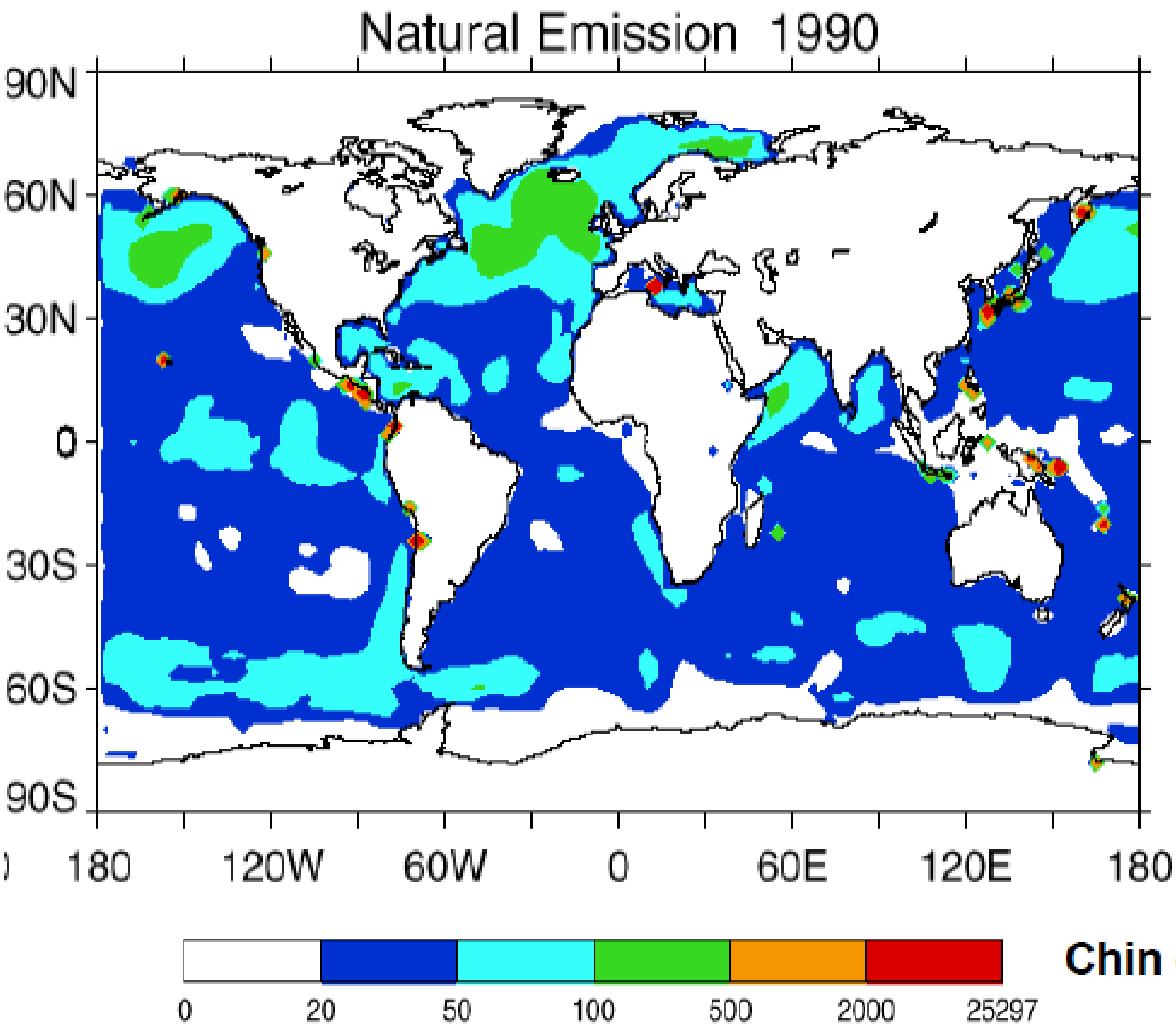
Increasing oxidation number (oxidation reactions) →

-2	+4	+6
FeS_2 二硫化铁 Pyrite H_2S Hydrogen sulfide $(CH_3)_2S$ 二甲基硫醚 Dimethylsulfide (DMS) CS_2 二硫化碳 Carbon disulfide COS 羰基硫 Carbonyl sulfide	SO_2 Sulfur dioxide	H_2SO_4 Sulfuric acid SO_4^{2-} Sulfate

Global Sulfur Cycle

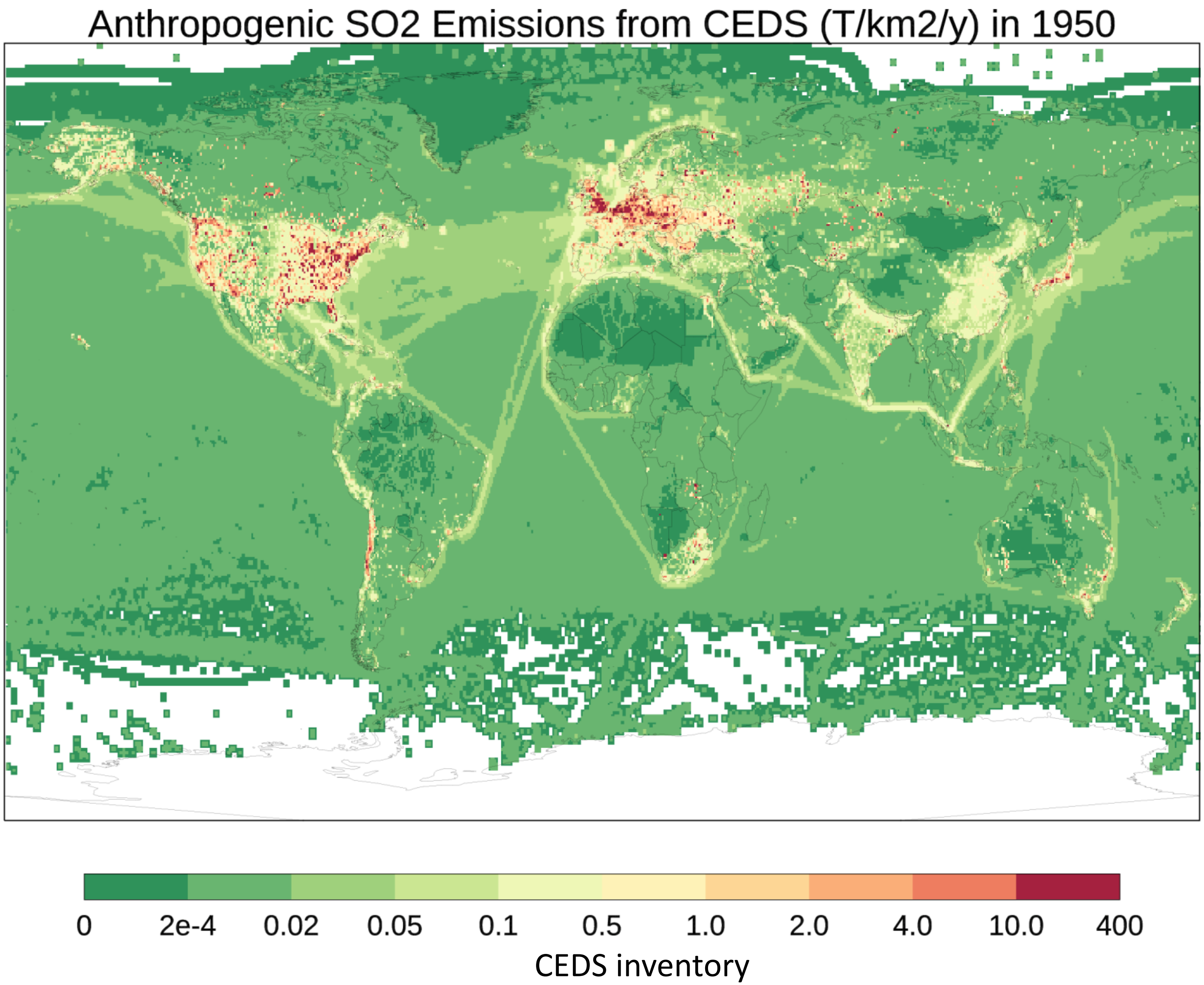


Natural Sulfur Emissions

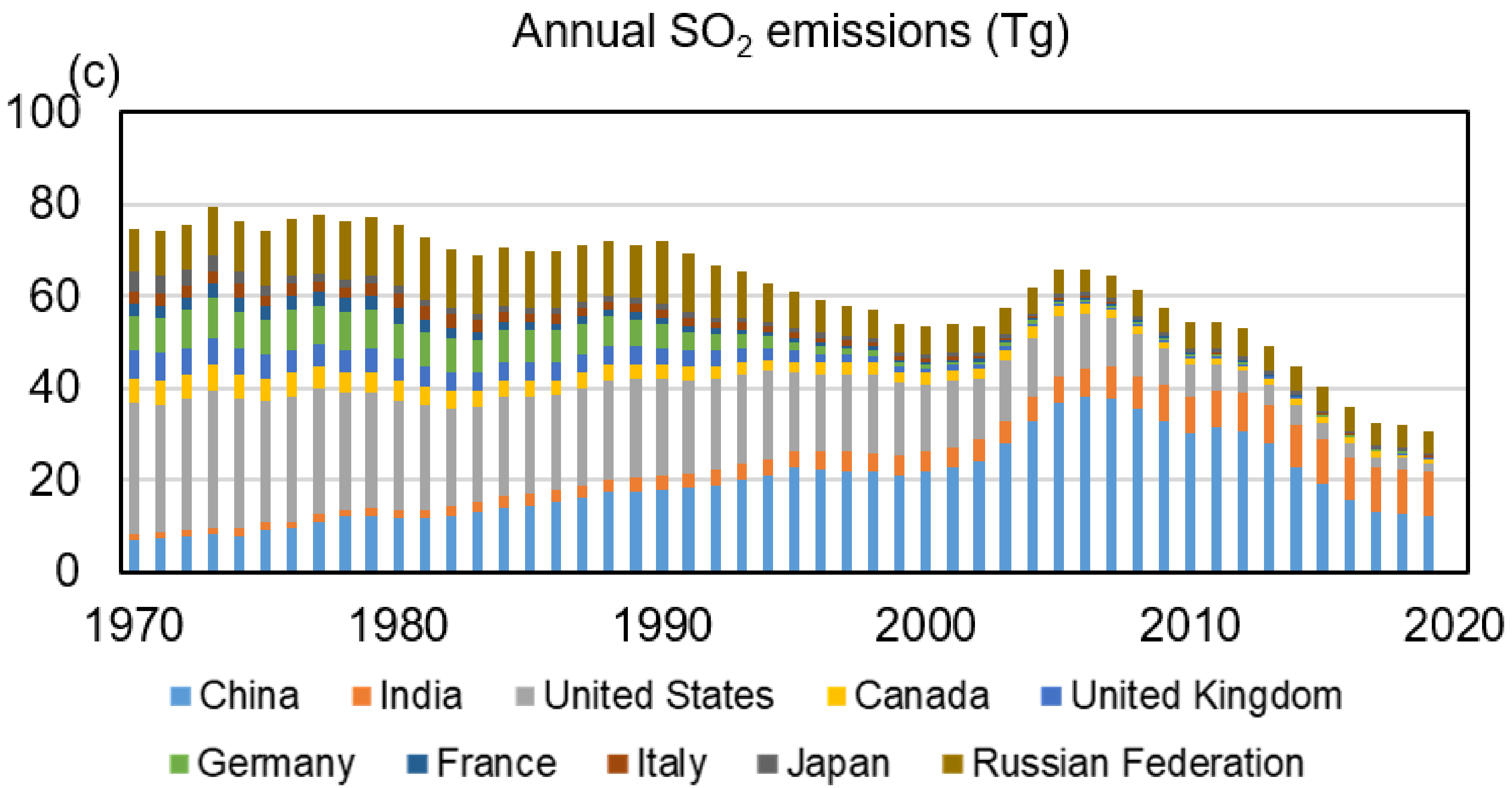


Chin et al. [2000]

Anthropogenic SO_2 Emissions: 1950-2014

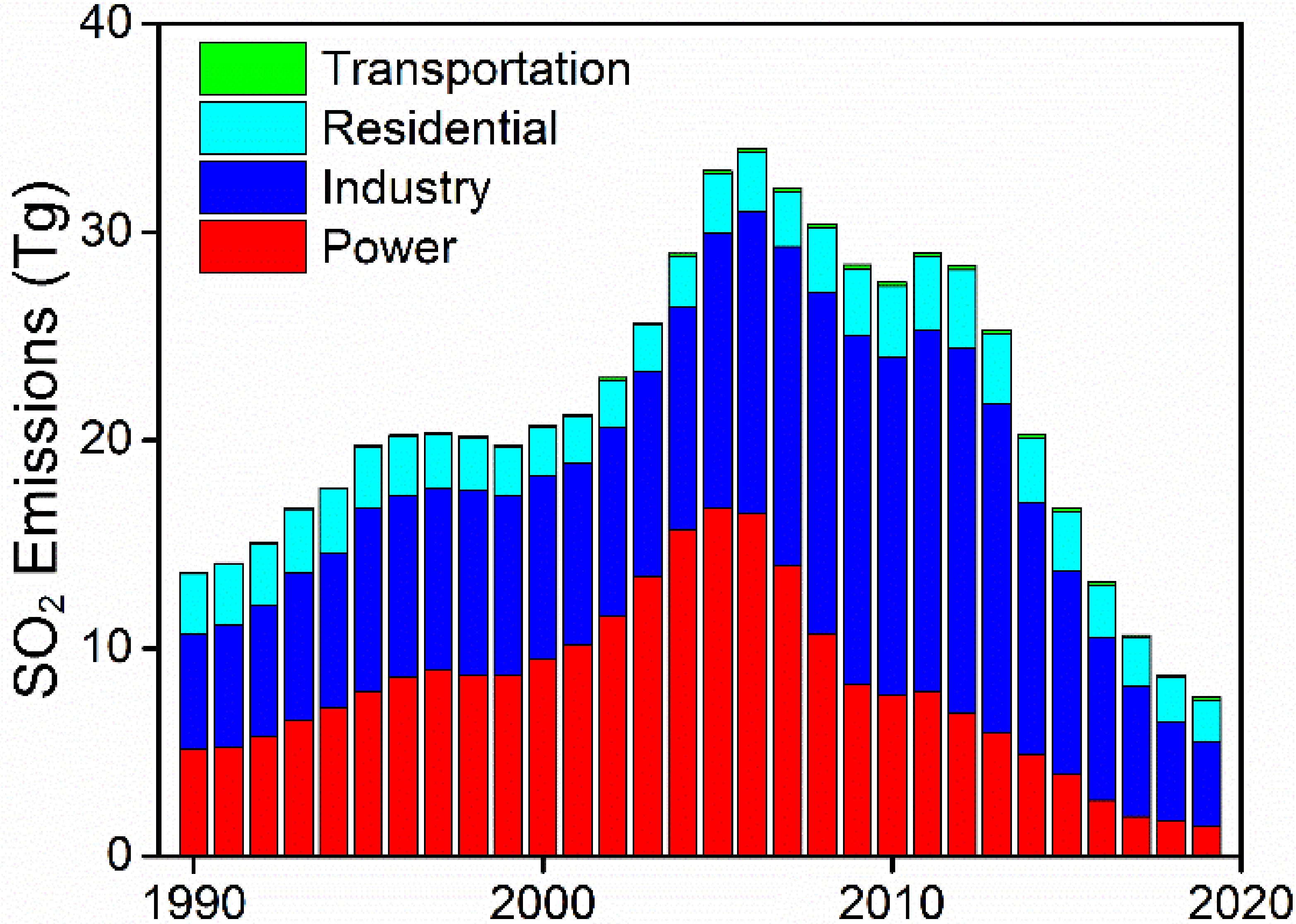


Anthropogenic Emissions of SO_2: 1970-2019



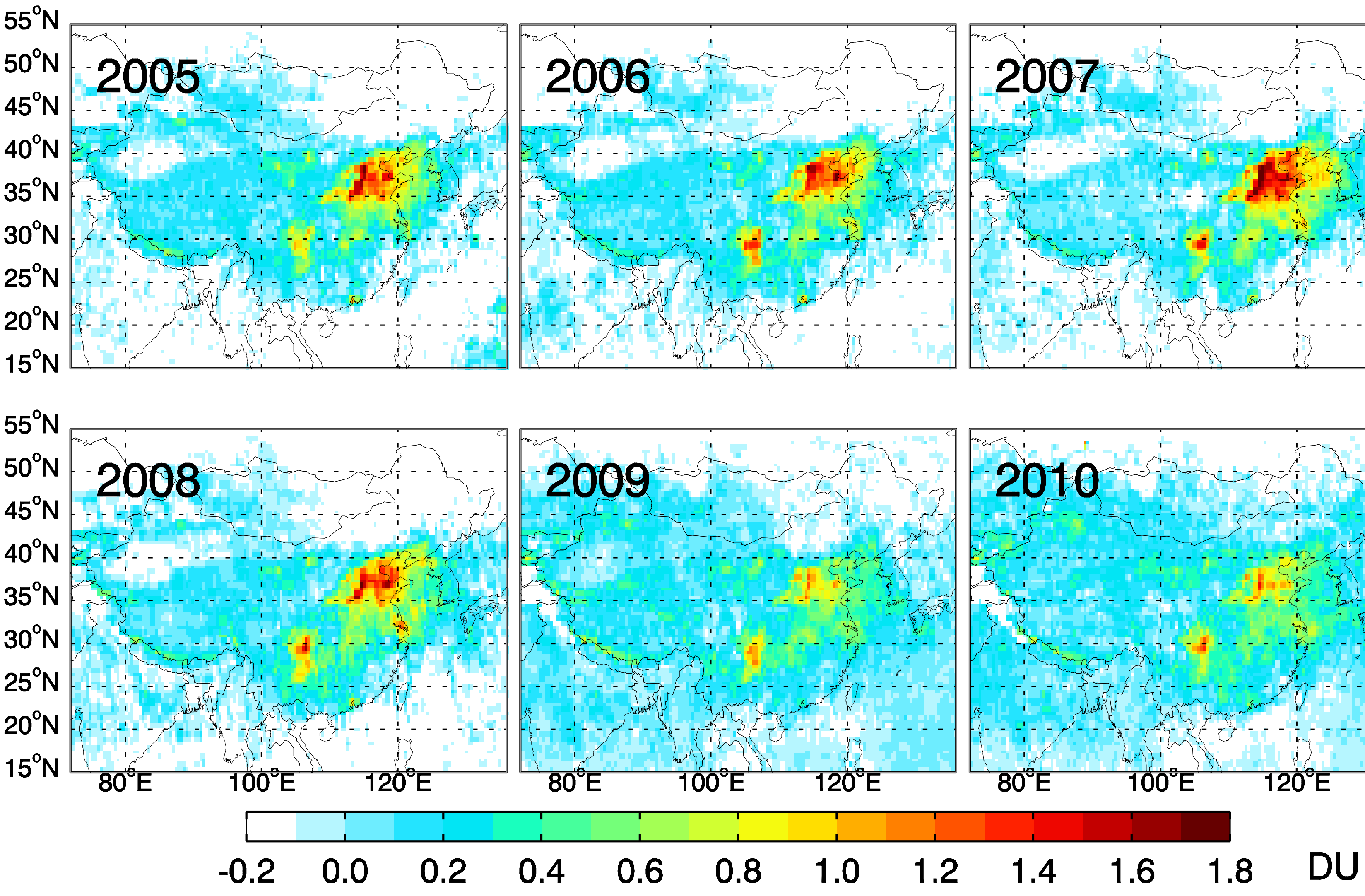
CEDS-GBD-Map

Anthro. Emission Trends of SO_2 in China: 1990-2020

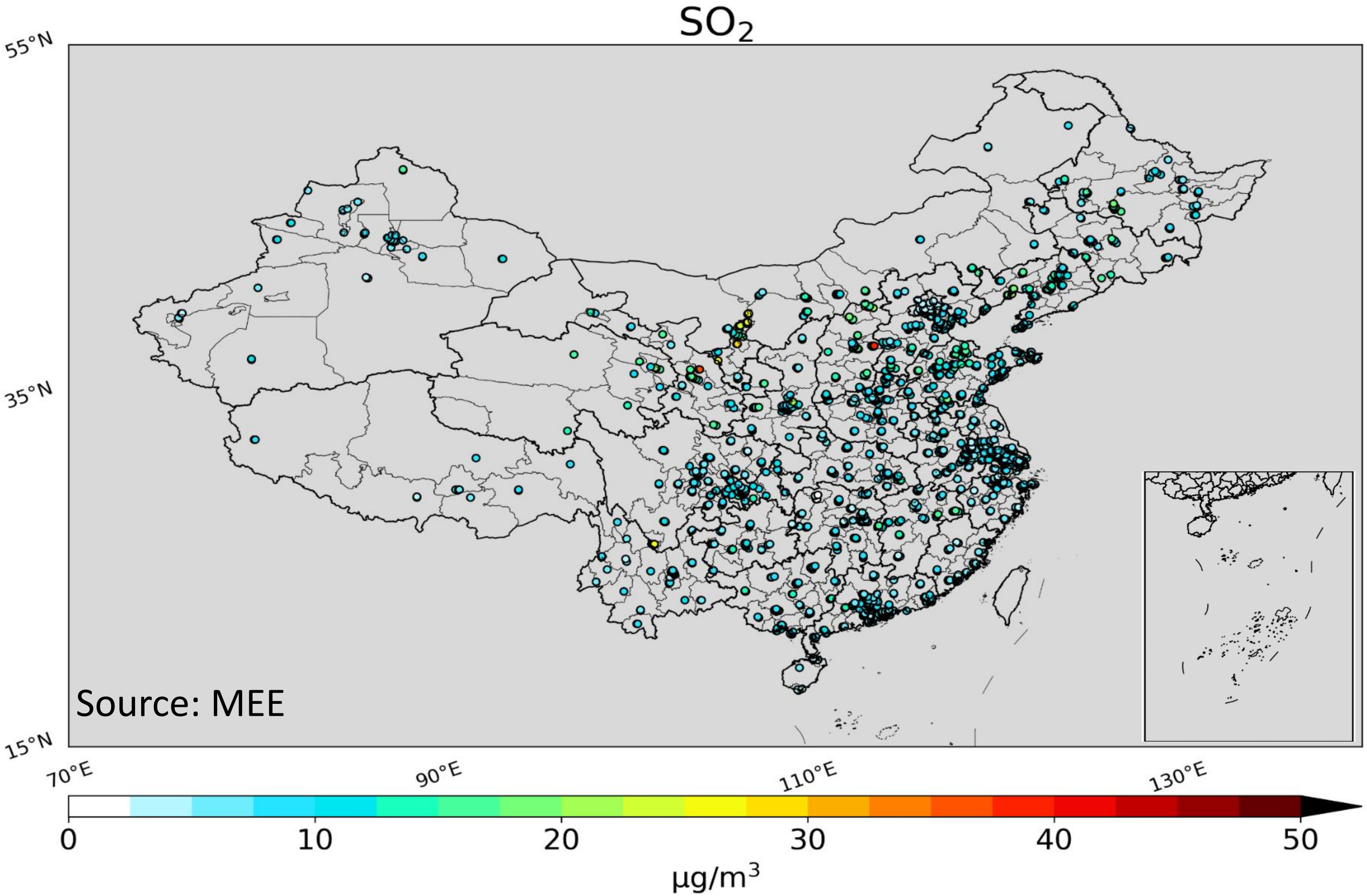


Source: MEIC data from Bo Zheng

Trends of SO_2 VCD from OMI: 2005-2010



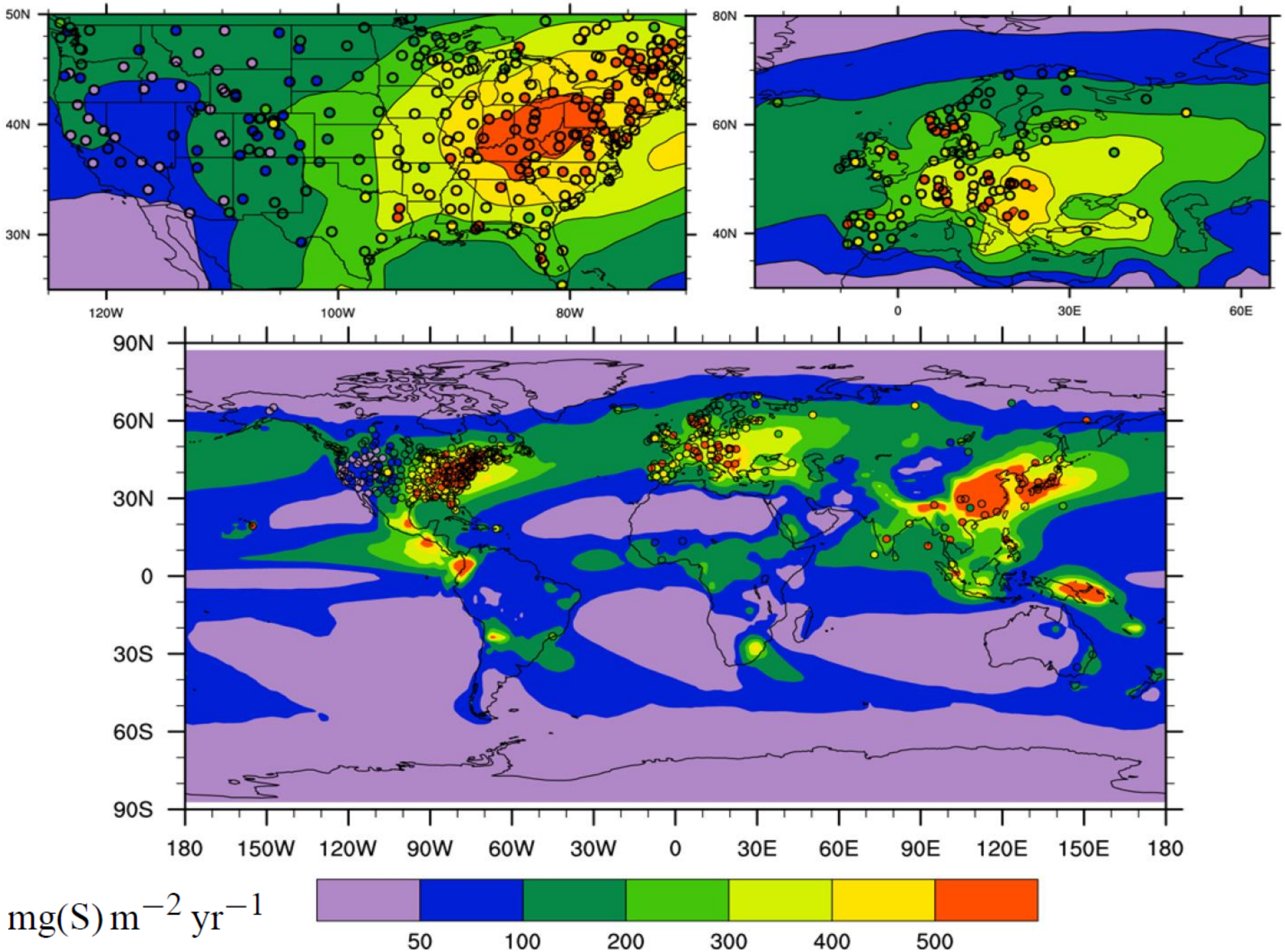
Near Surface SO_2 Concentrations over China: 2021



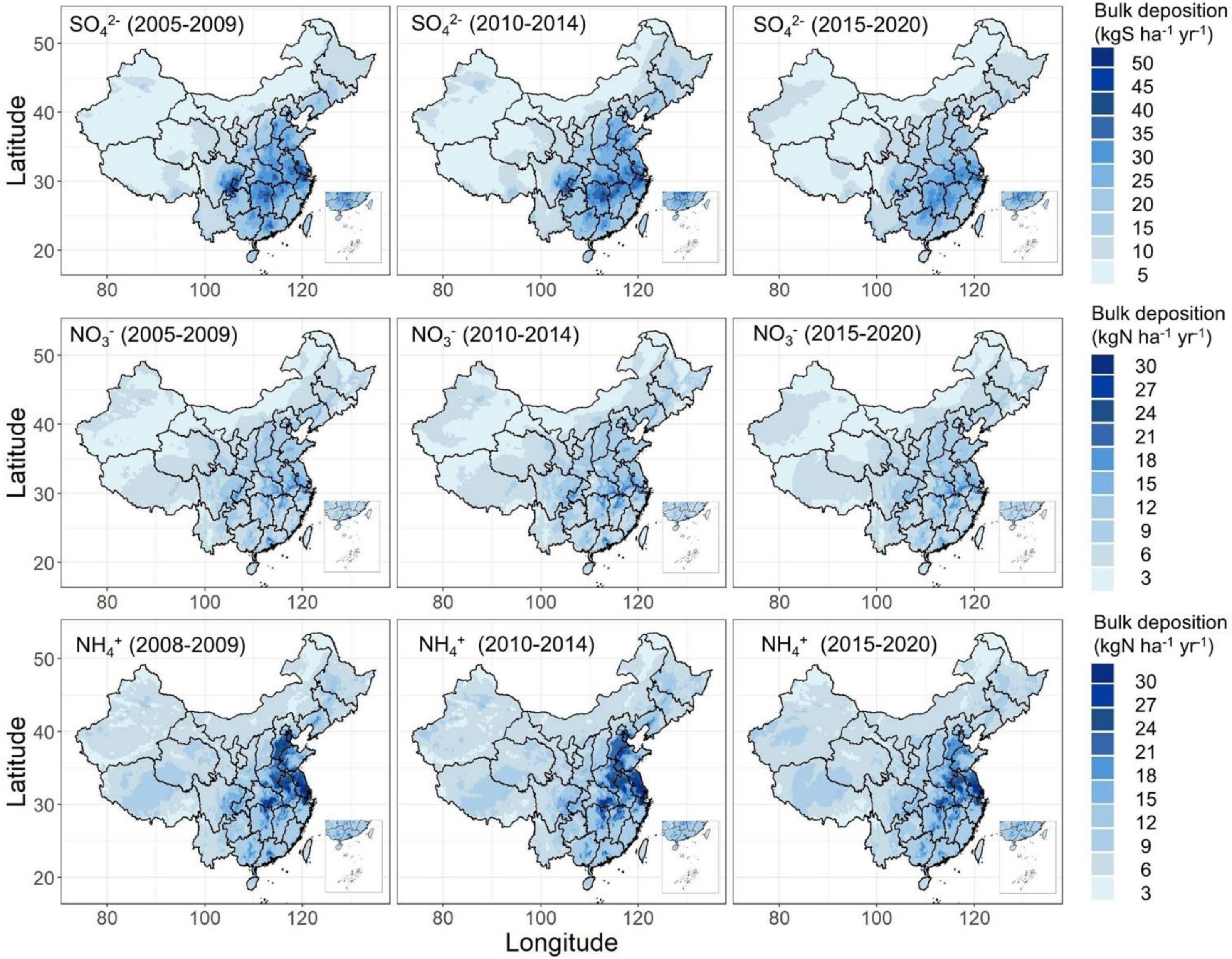
国家标准：60（年均），150（24小时），500（1小时）
WHO指导值：40（24小时）

SO_4^{-2} Wet Deposition in 2000

Lamarque et al., 2013, ACP, Multi-model mean

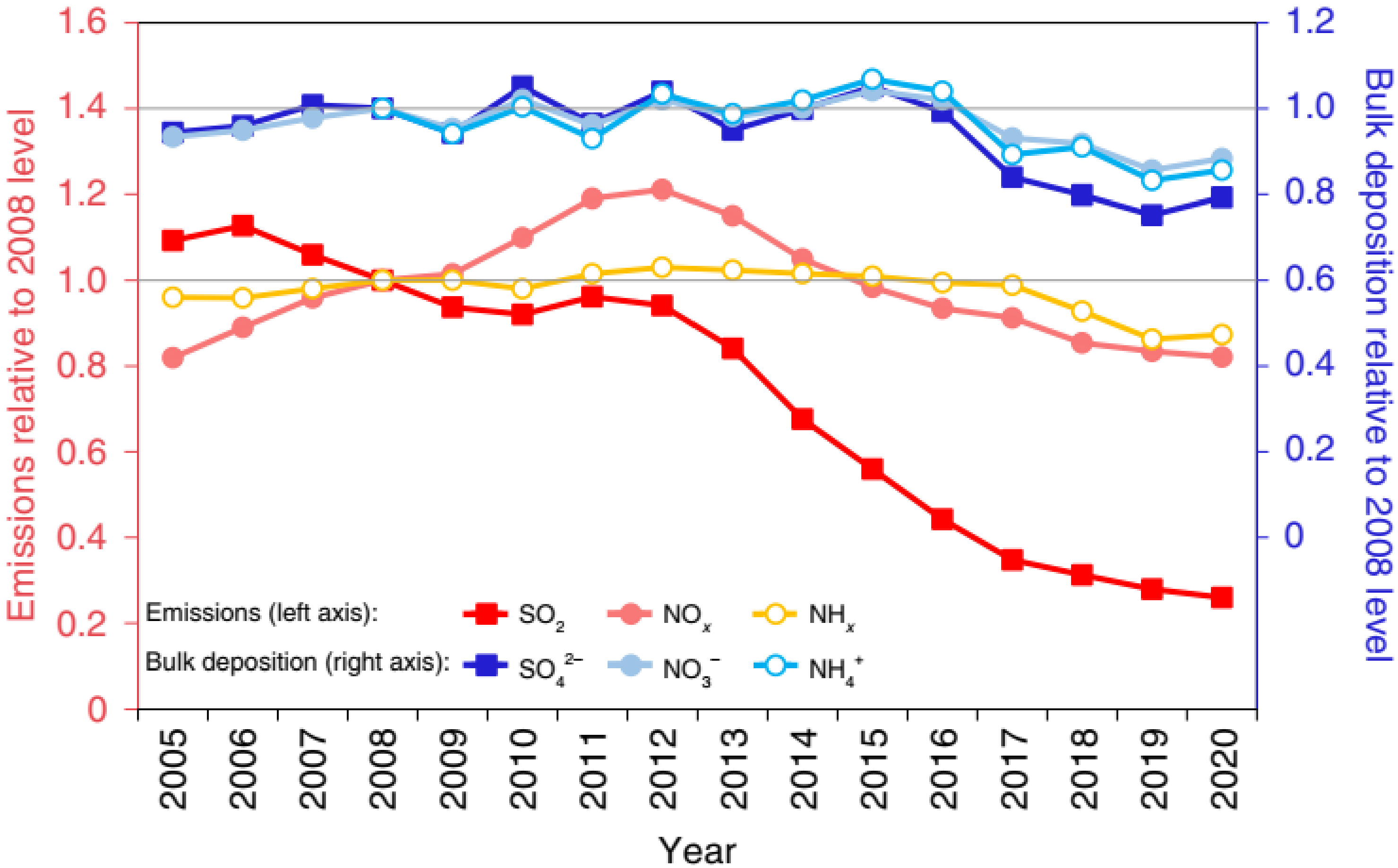


Lagged Decline of N and S Deposition in China: 2005–2020



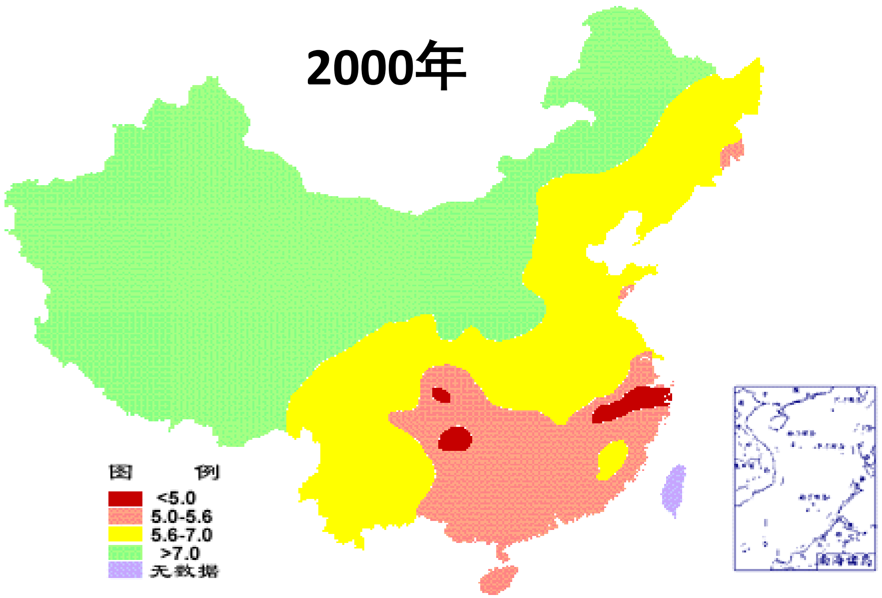
Zhao et al., Nature Geoscience, 2022

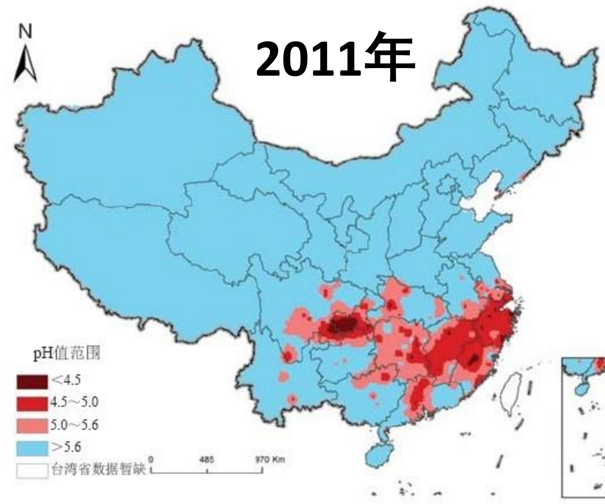
Lagged Nitrogen and Sulfur Deposition in China: 2005–2020



Zhao et al., Nature Geoscience, 2022

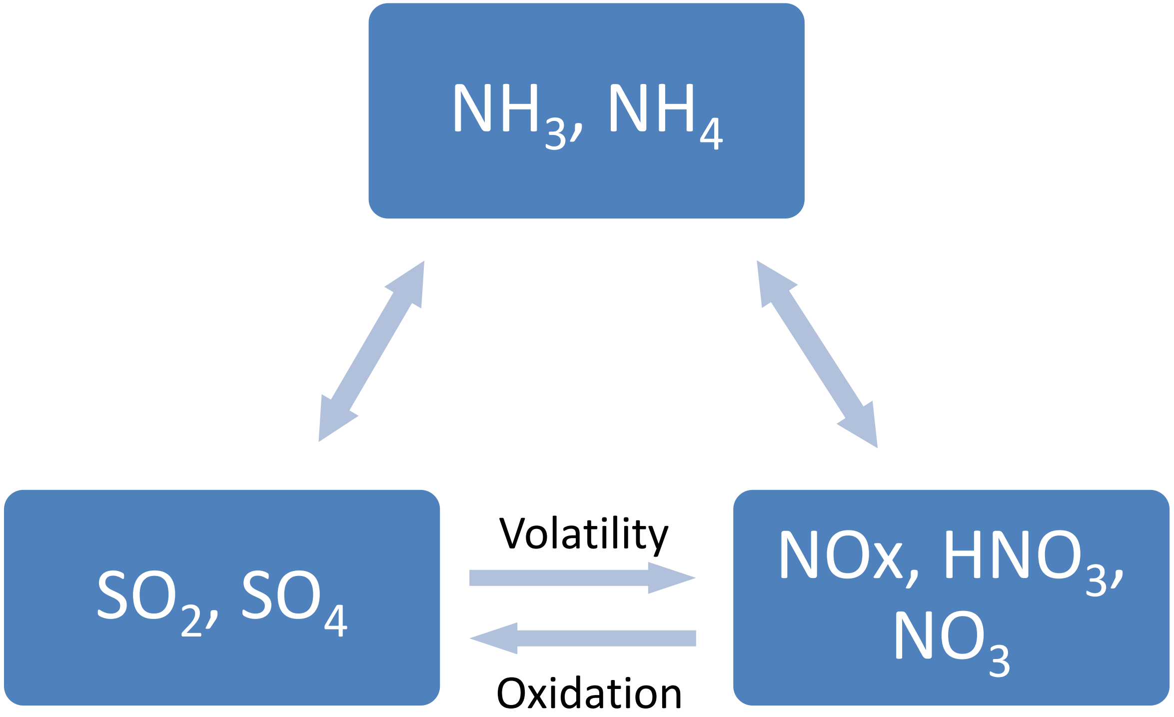
pH Value in Precipitation



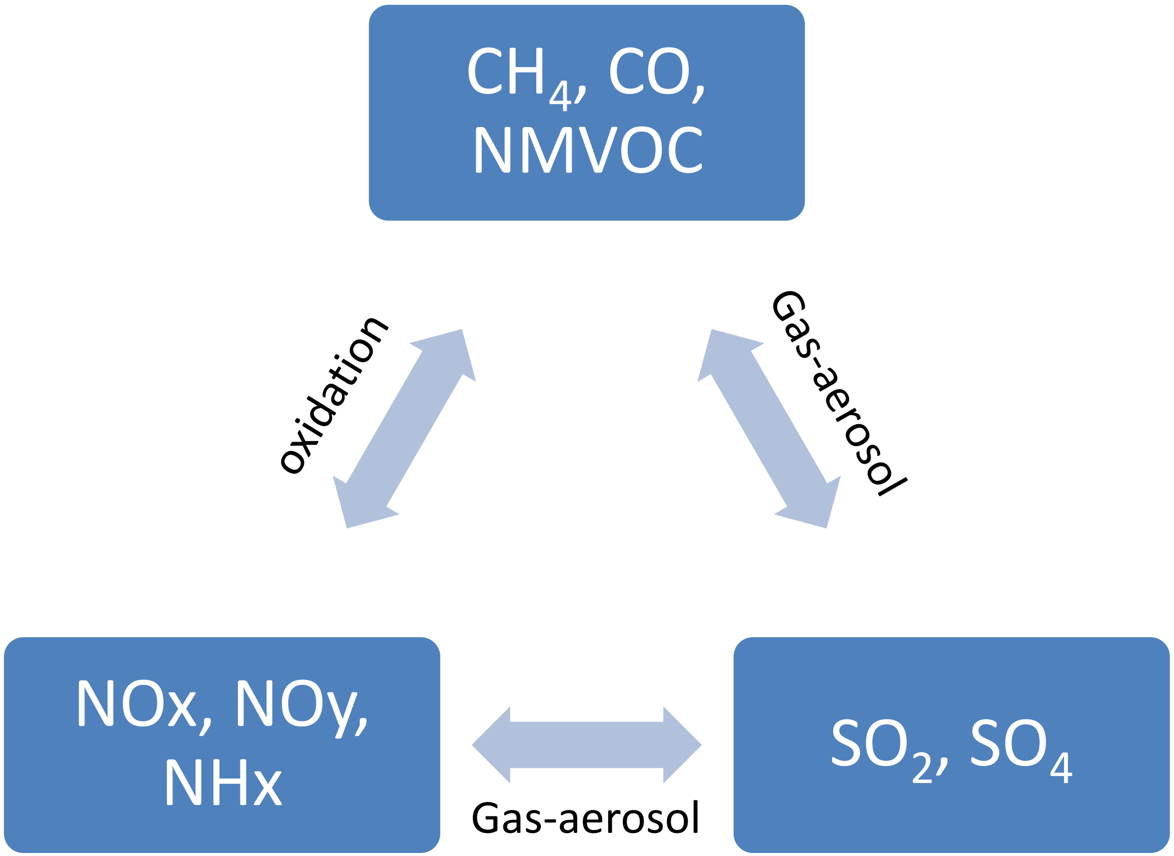


中国生态环境状况公报

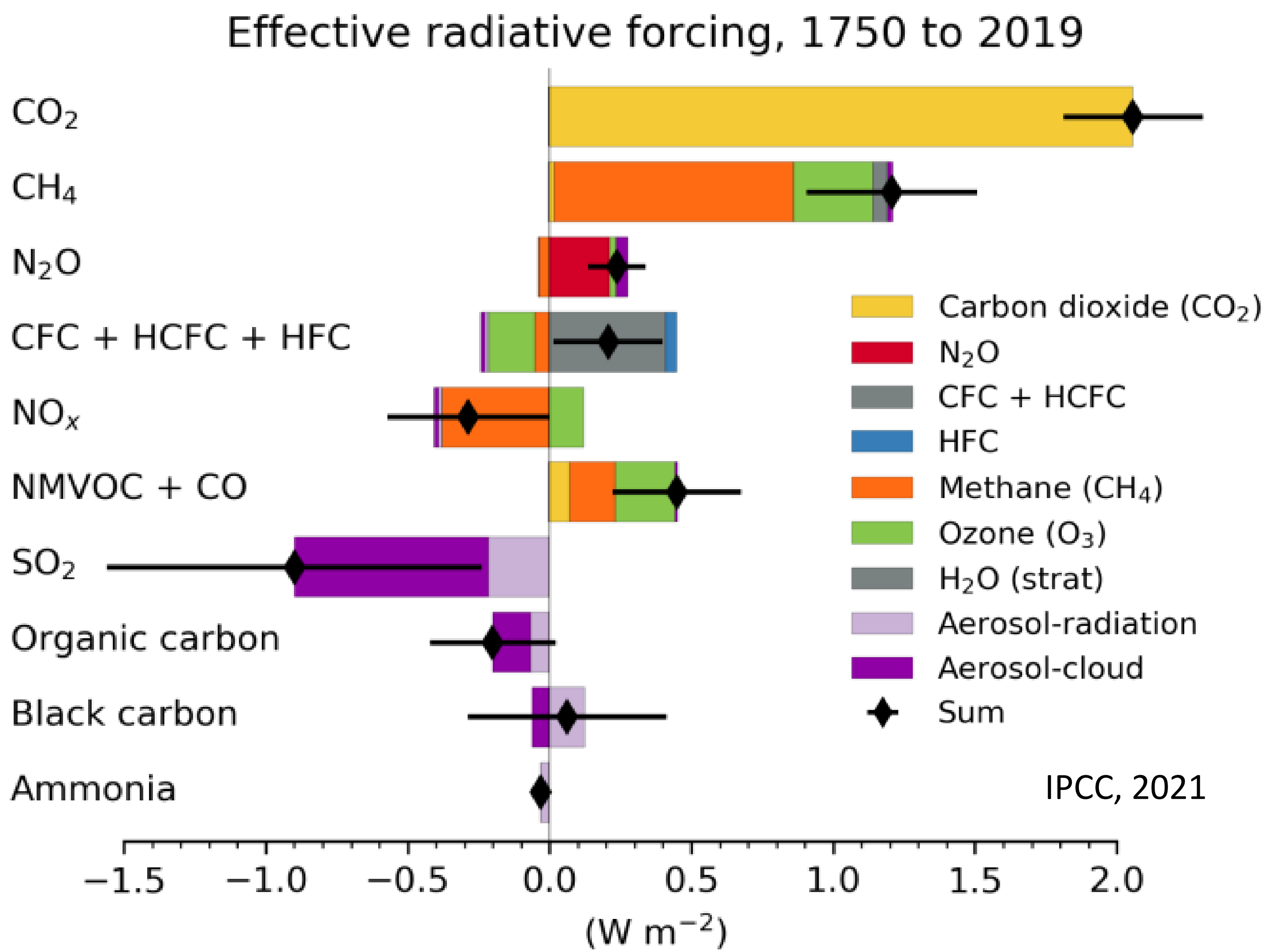
Sulfate-Nitrate-Ammonium Interactions



Carbon-Nitrogen-Sulfur Interactions



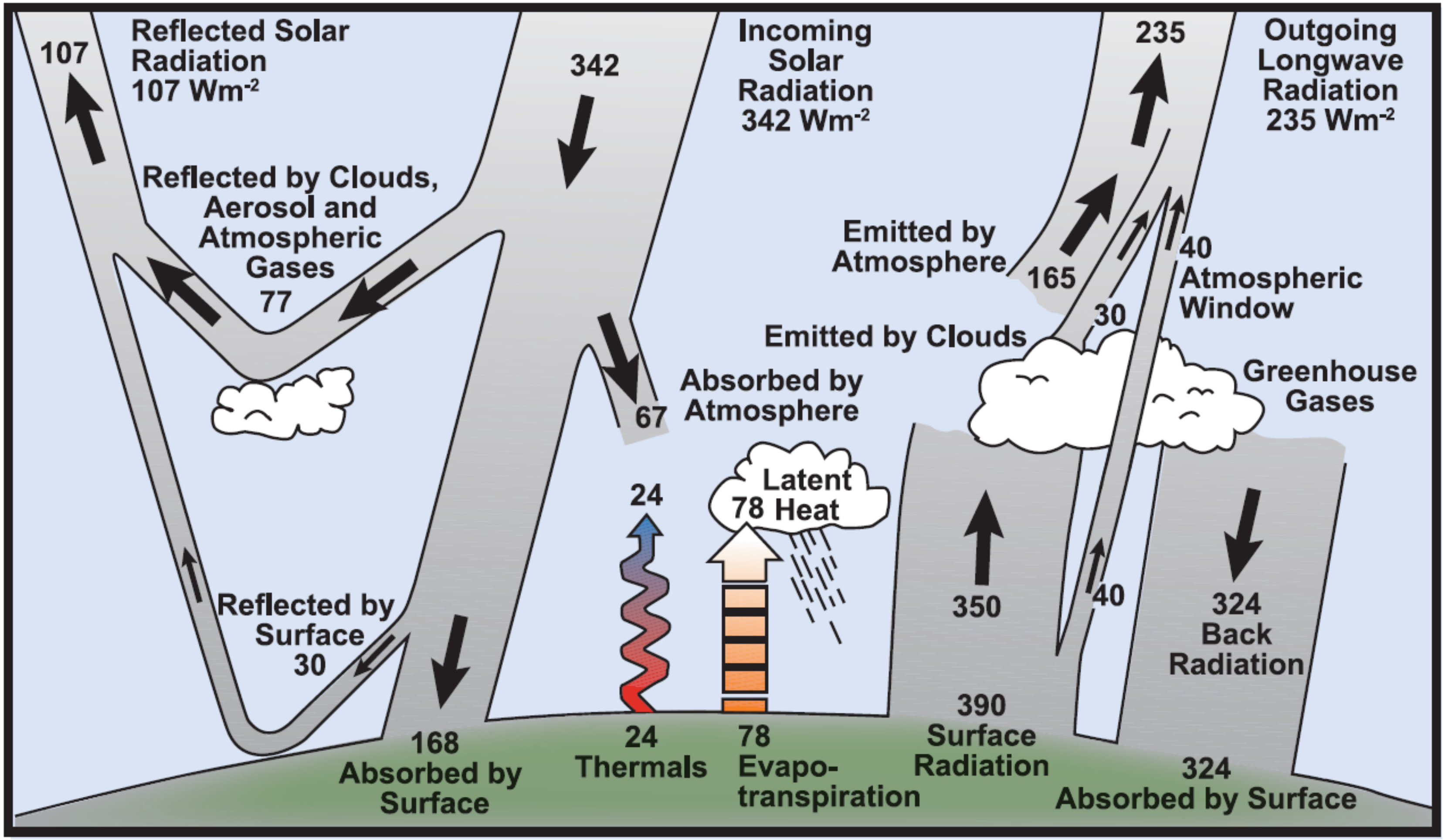
Radiative Forcing of Emitted C, N and S

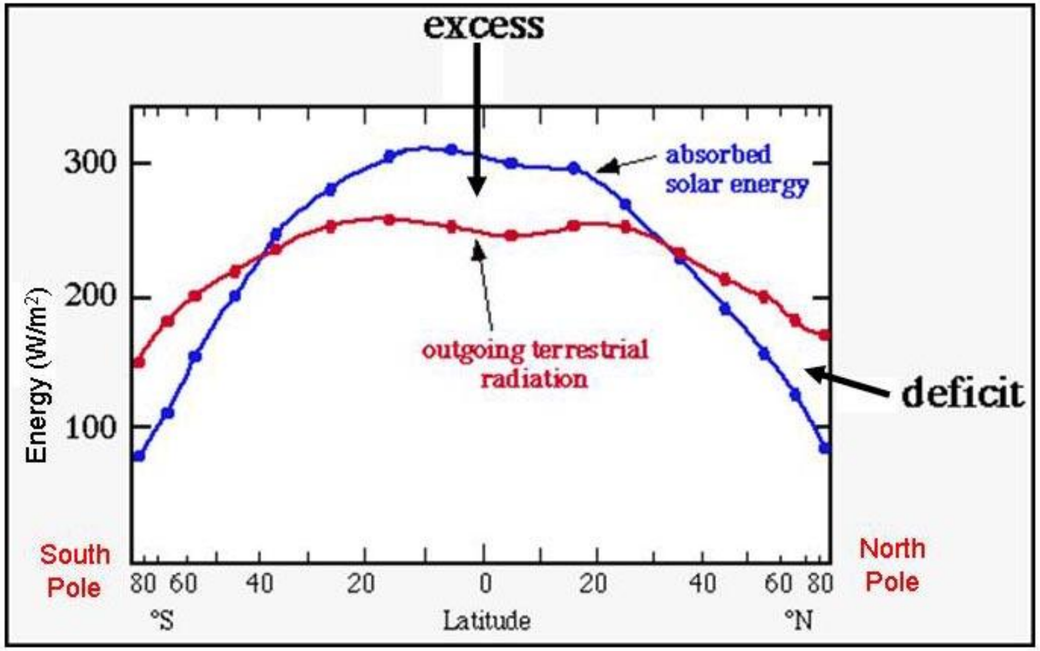


Quiz

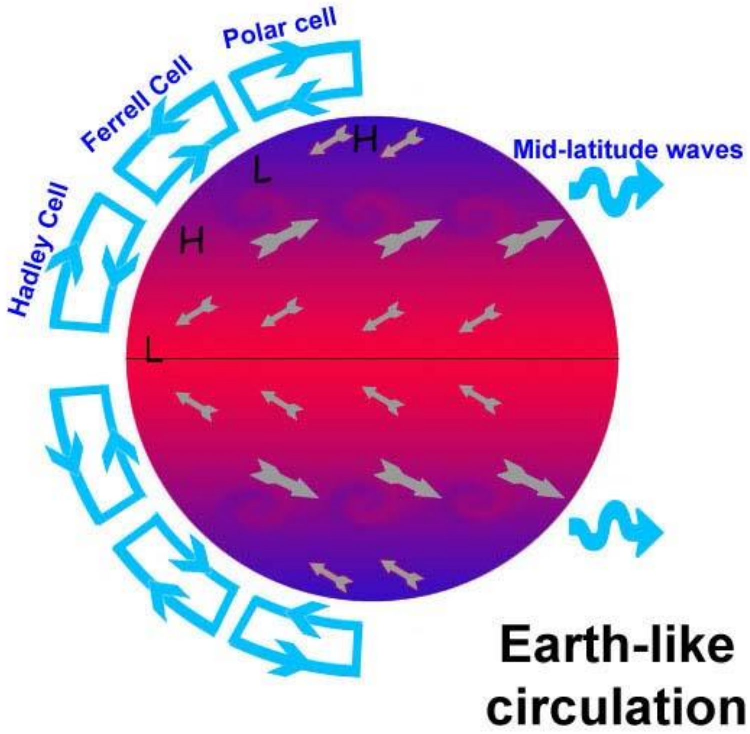
1. **Causes of slowdown and resumption of CH_4 growth**
2. **Project the future changes in biomass burning emissions under human influences and climate change**
3. **Given the wind fields and NO_2 columns, estimate the lifetime of NOx**
4. **Given CO and/or NOx emissions, estimate emissions of other species such as CO_2 and N_2O**
5. **Causes of horizontal distribution in sulfur emissions from oceans**
6. **Why does deposition of N and S resemble their emissions**

Energy Budget of Earth Climate

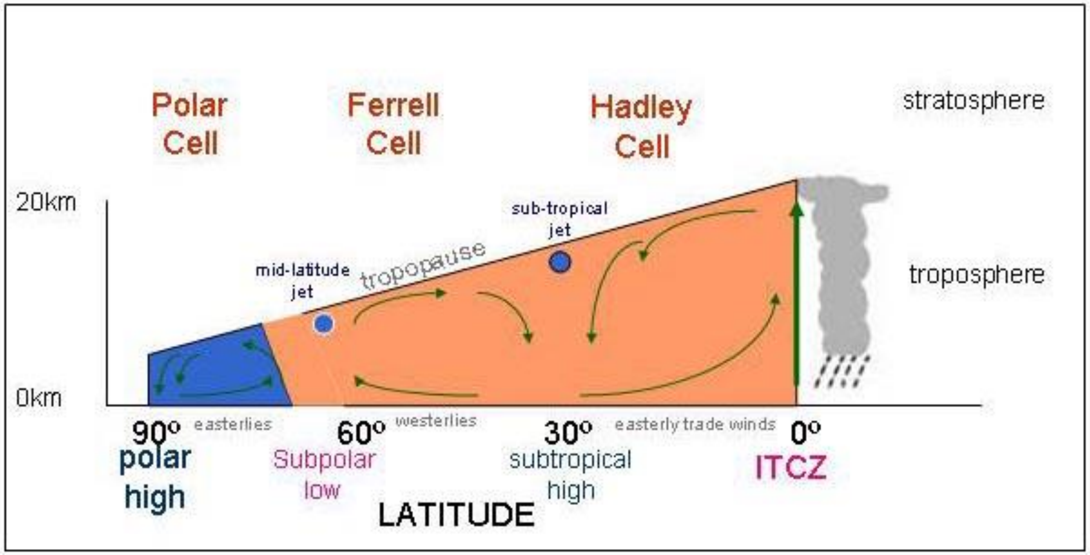




excess
absorbed solar energy
outgoing terrestrial radiation
deficit
Energy (W/m^2)
300
200
100
South Pole
North Pole
80 60 40 20 0 20 40 60 80
°S
Latitude
°N



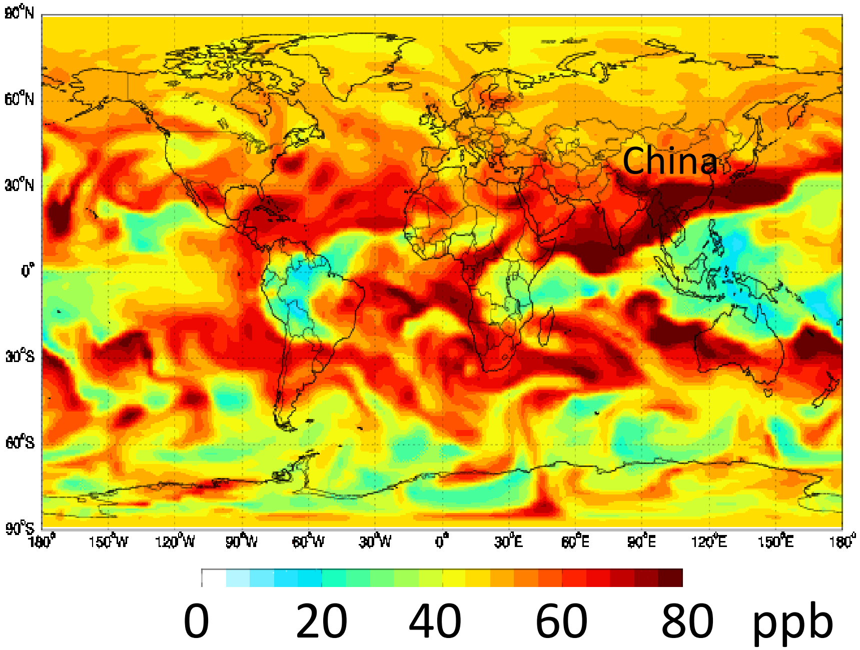
Polar cell
Ferrell Cell
Hadley Cell
Mid-latitude waves
H
L
H
L
Earth-like circulation



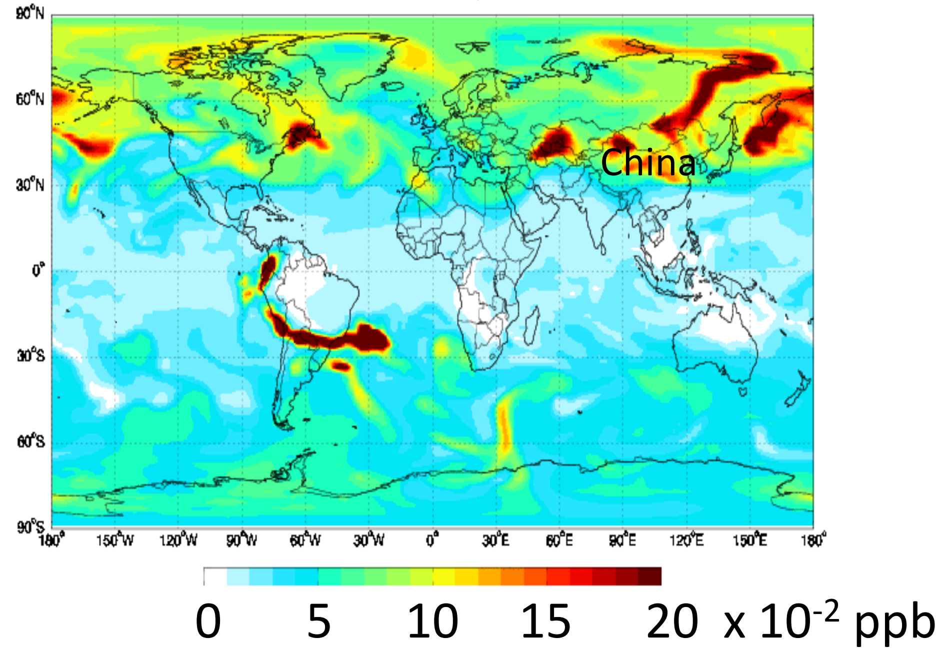
Polar Cell
Ferrell Cell
Hadley Cell
stratosphere
20km
sub-tropical jet
mid-latitude jet
tropopause
troposphere
0km
easterlies
westerlies
easterly trade winds
90° polar high
60° Subpolar low
30° subtropical high
0° ITCZ
LATITUDE

Atmospheric Pollution Transport

Ozone in Mid-Trop. in Jan 2009



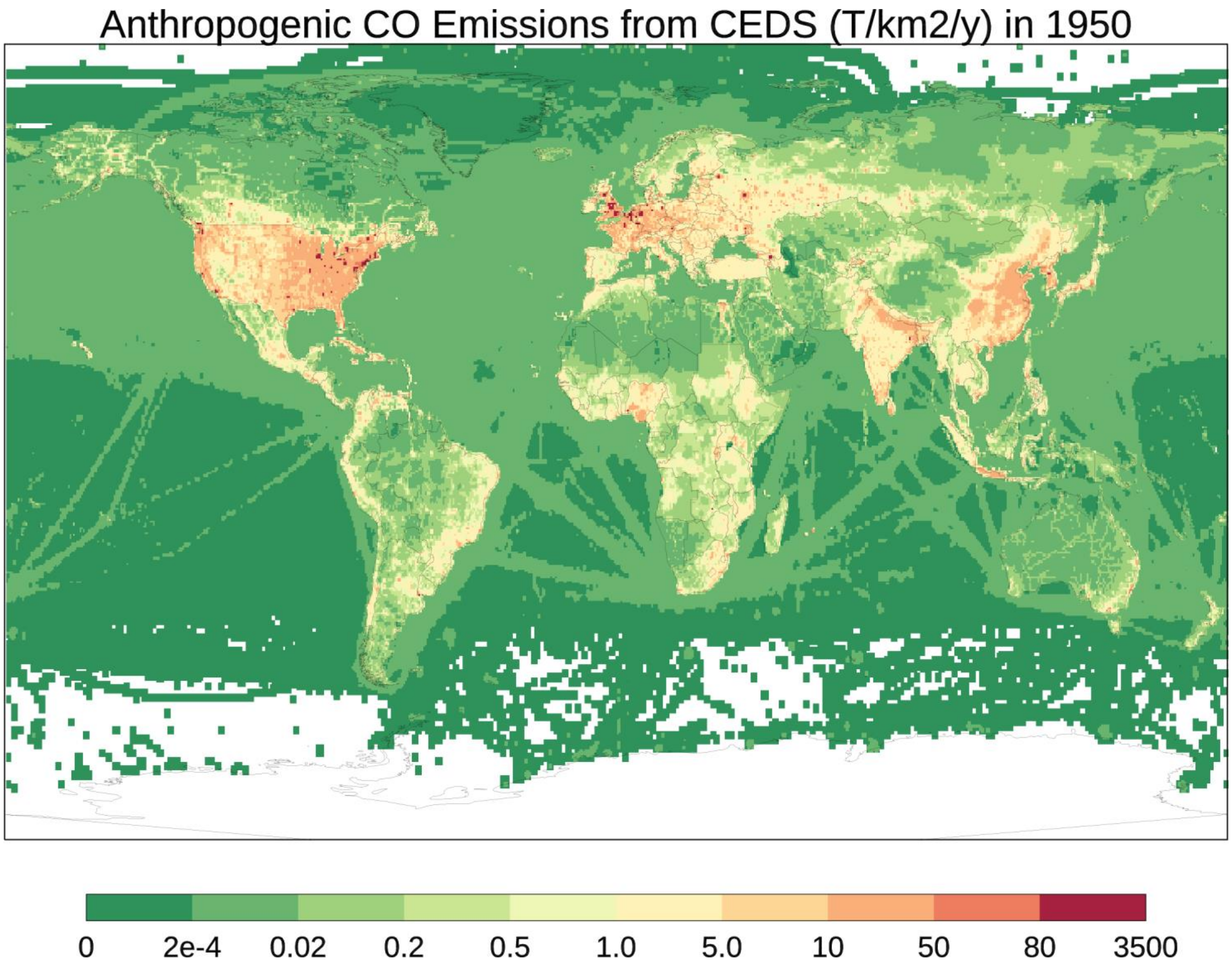
Sulfate in Mid-Trop. in Jan 2009



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

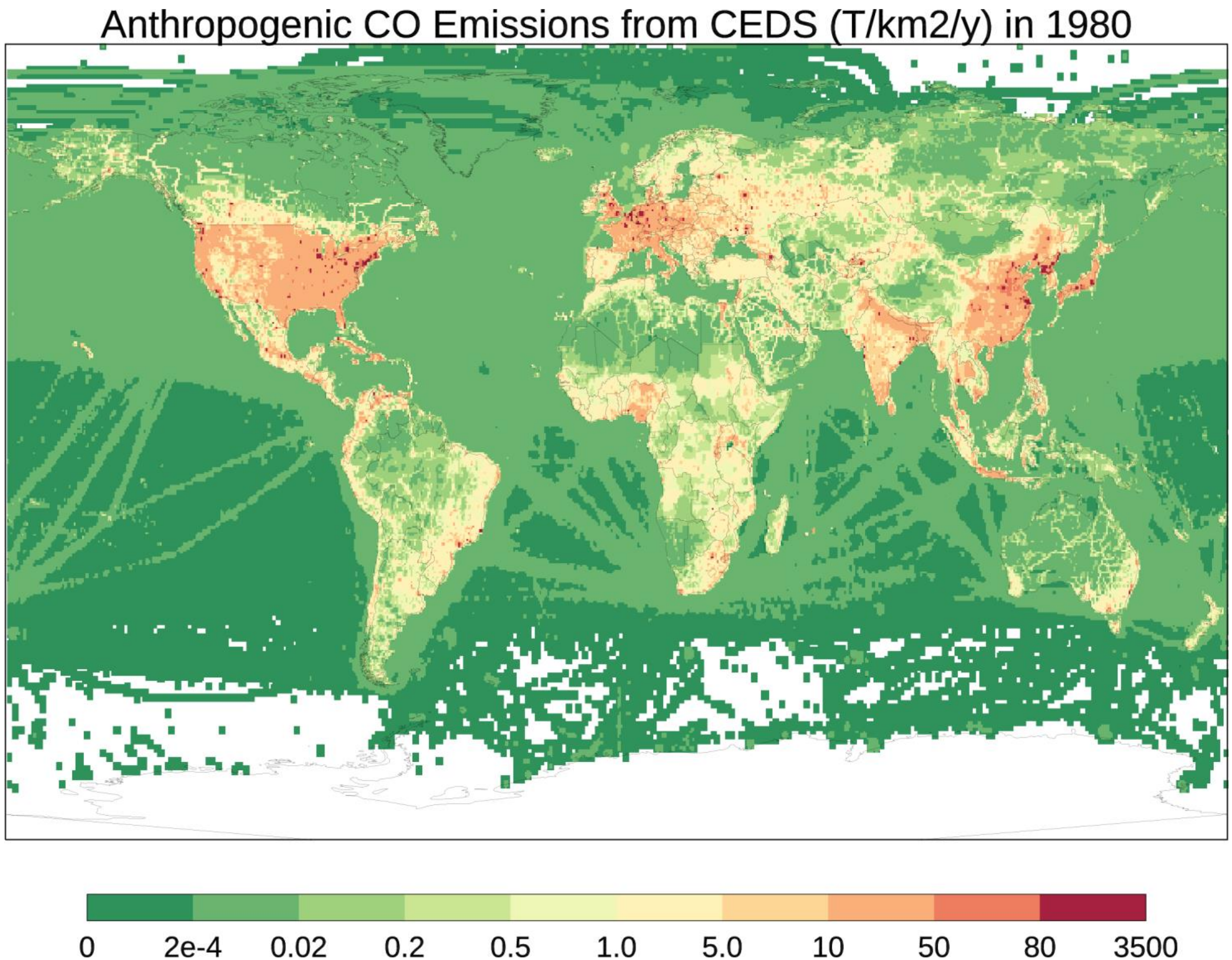
Yan et al., 2014 ACP; 2016 ACP

Anthropogenic Emissions of CO: 1950-2014



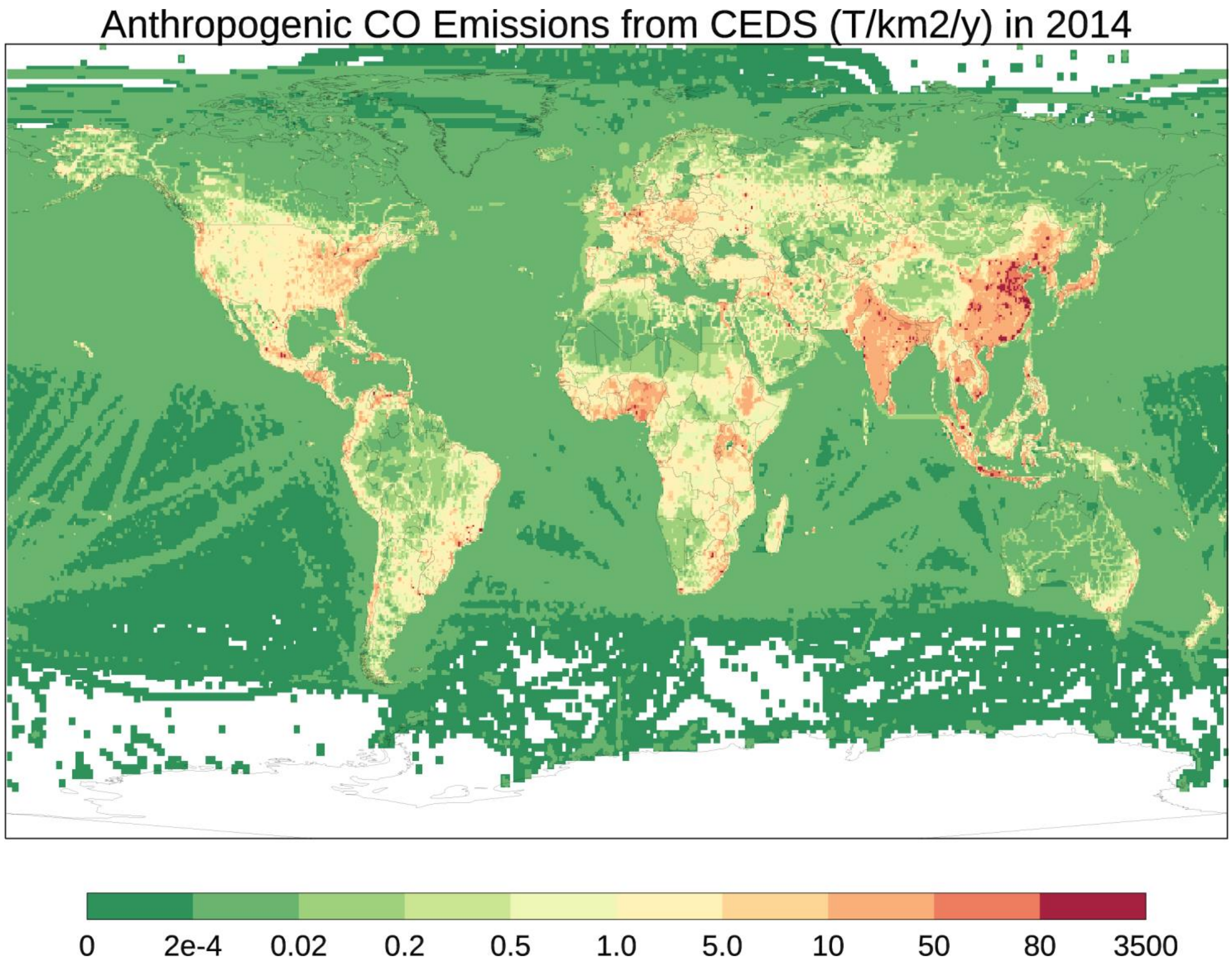
CEDS inventory

Anthropogenic Emissions of CO: 1950-2014



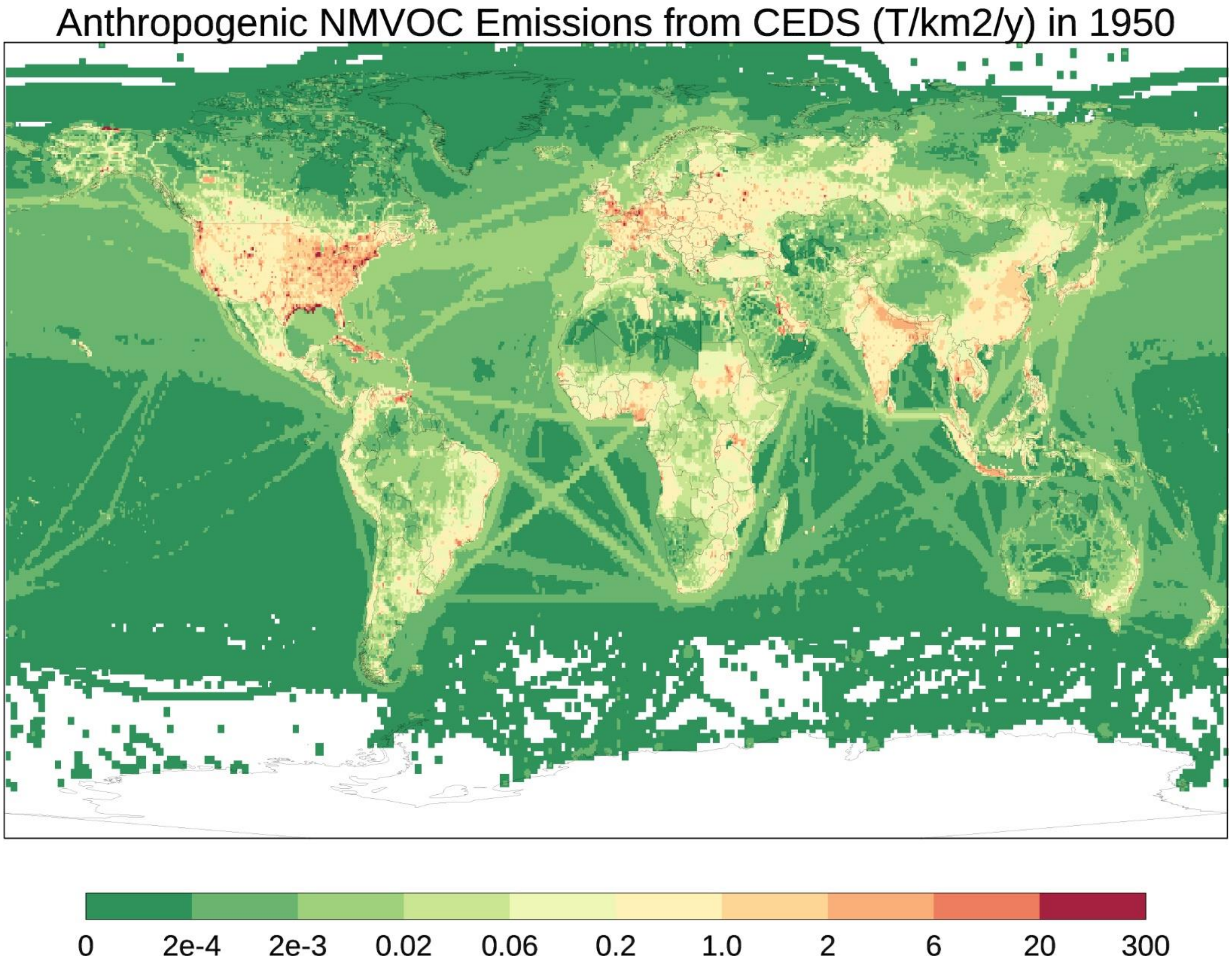
CEDS inventory

Anthropogenic Emissions of CO: 1950-2014



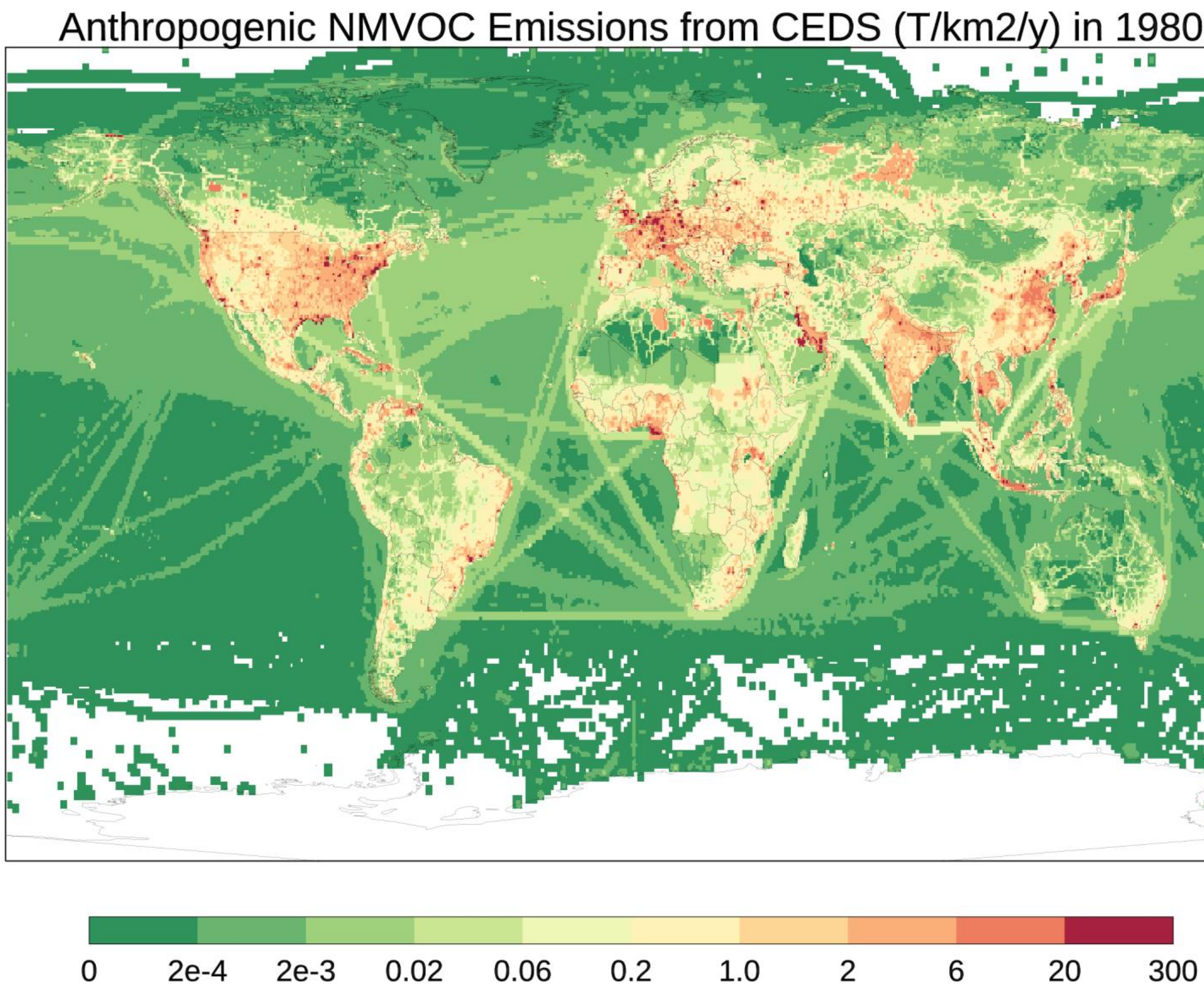
CEDS inventory

Anthropogenic NMVOC Emissions: 1950-2014



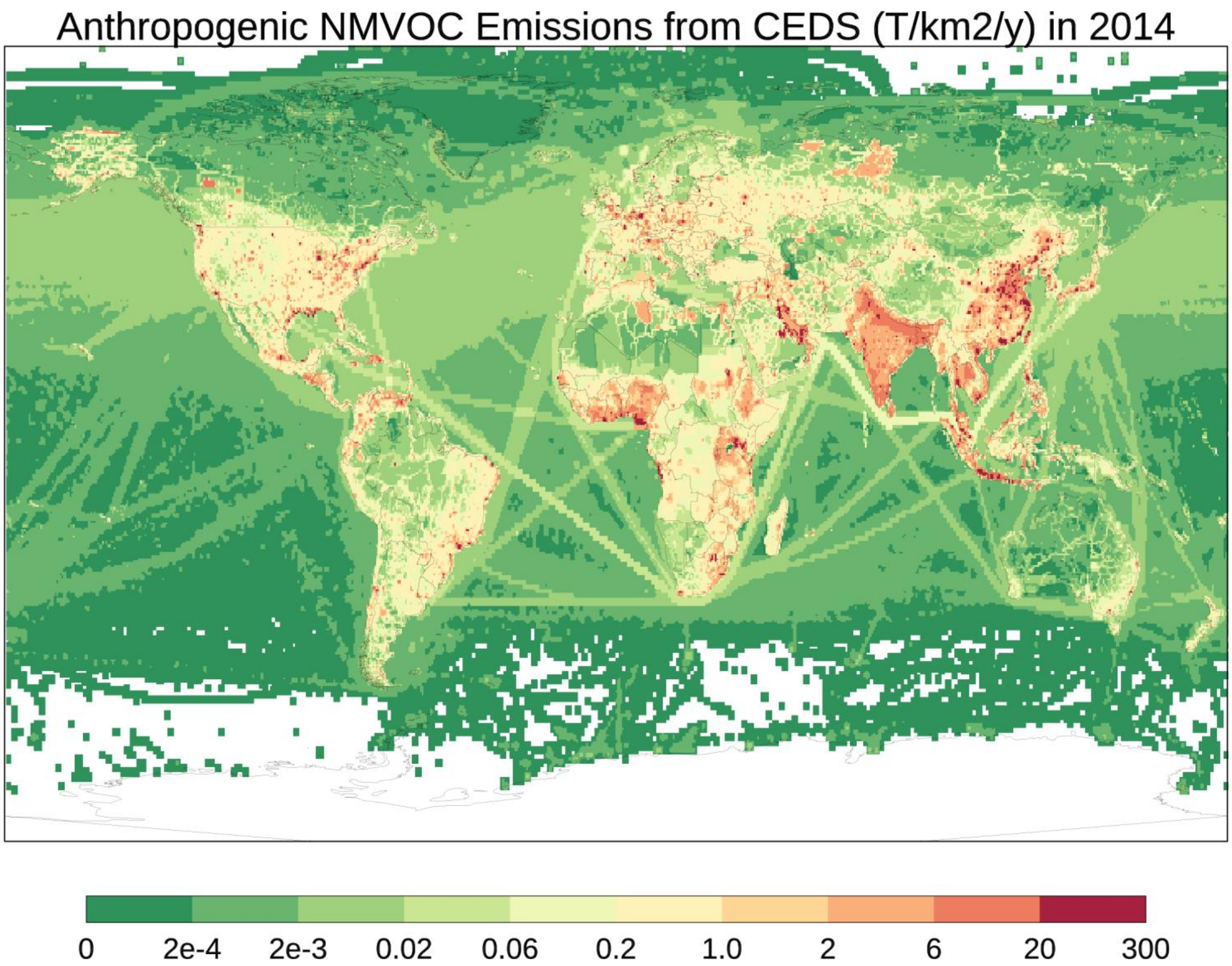
CEDS inventory

Anthropogenic NMVOC Emissions: 1950-2014



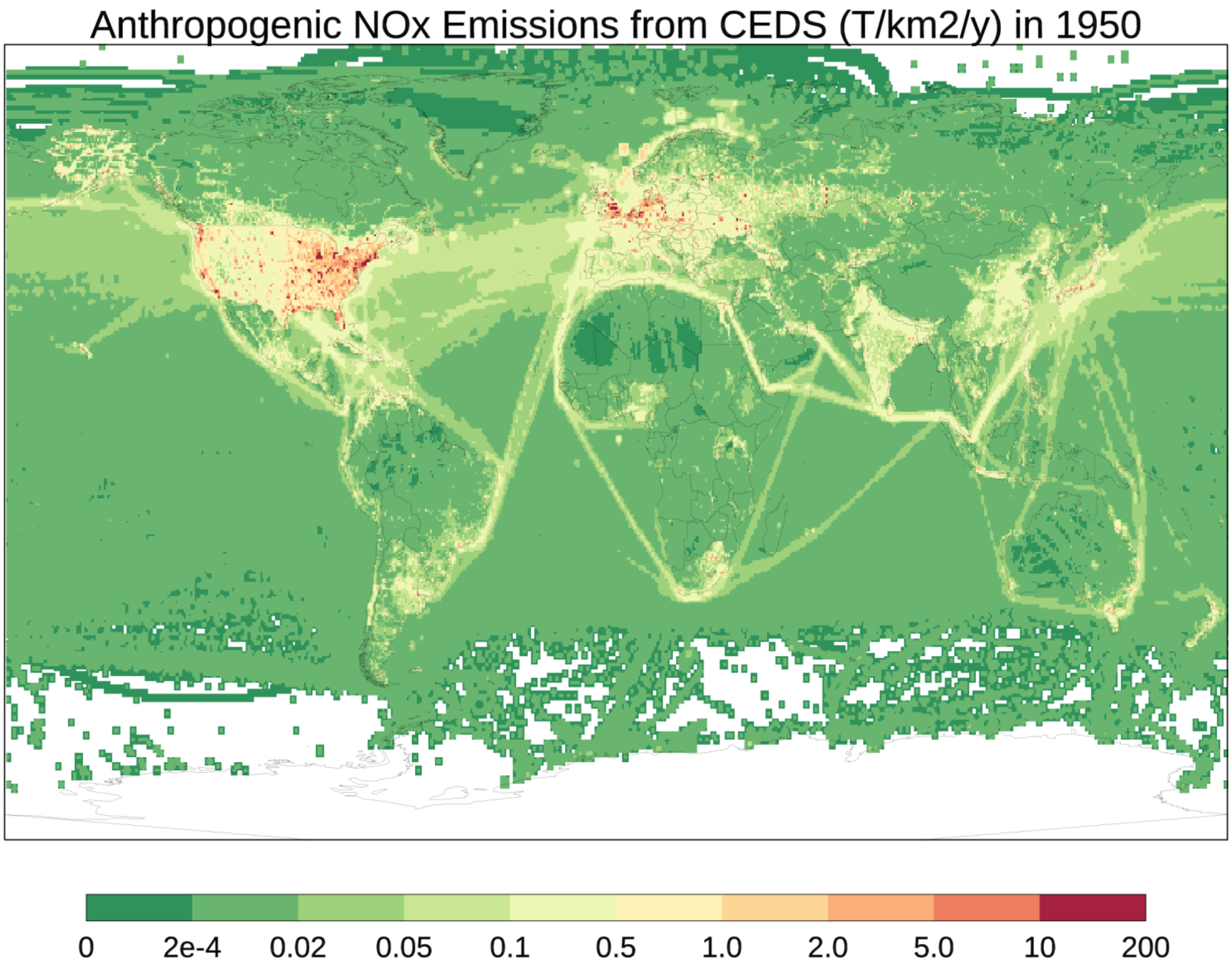
CEDS inventory

Anthropogenic NMVOC Emissions: 1950-2014



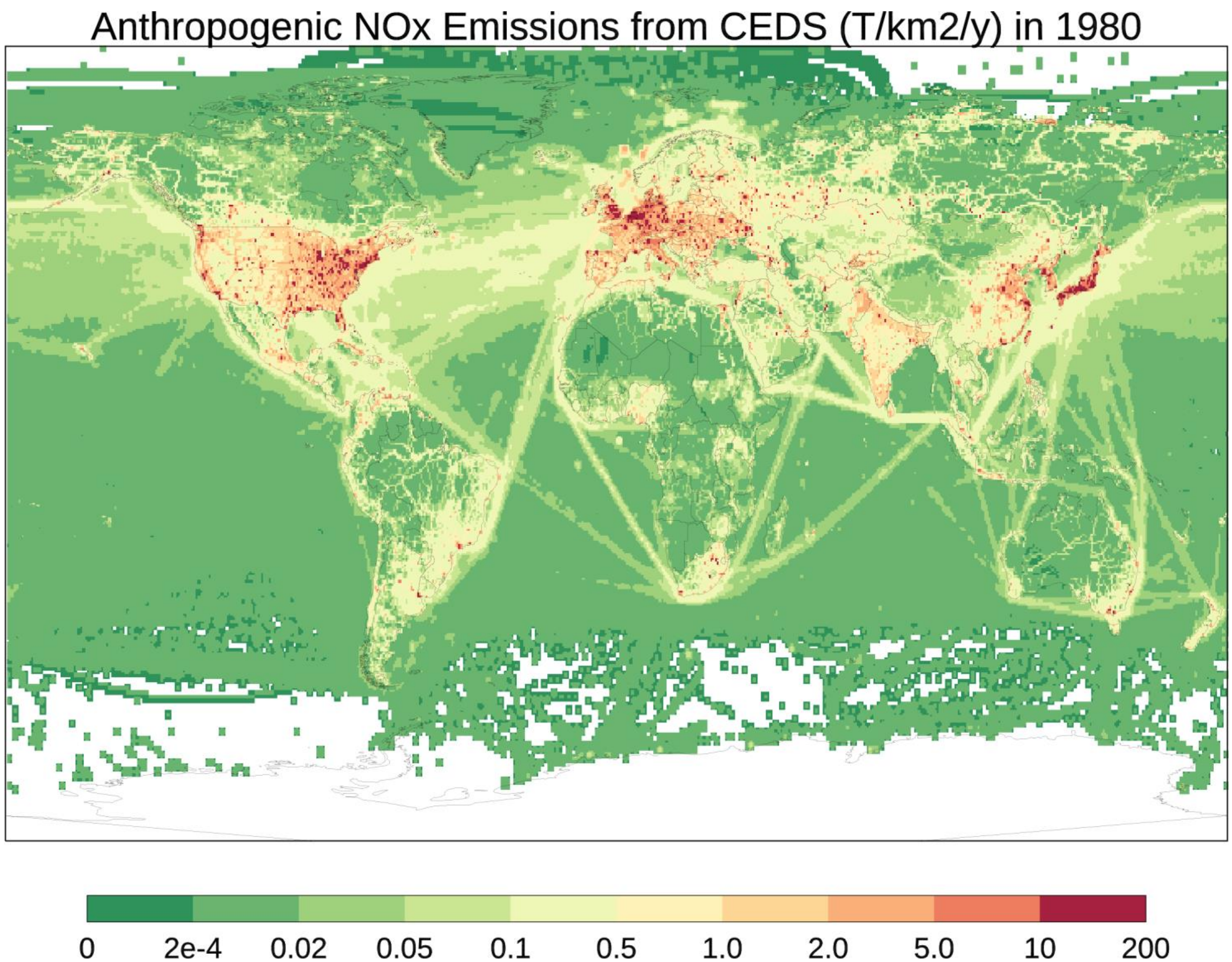
CEDS inventory

Anthropogenic NOx Emissions: 1950-2014



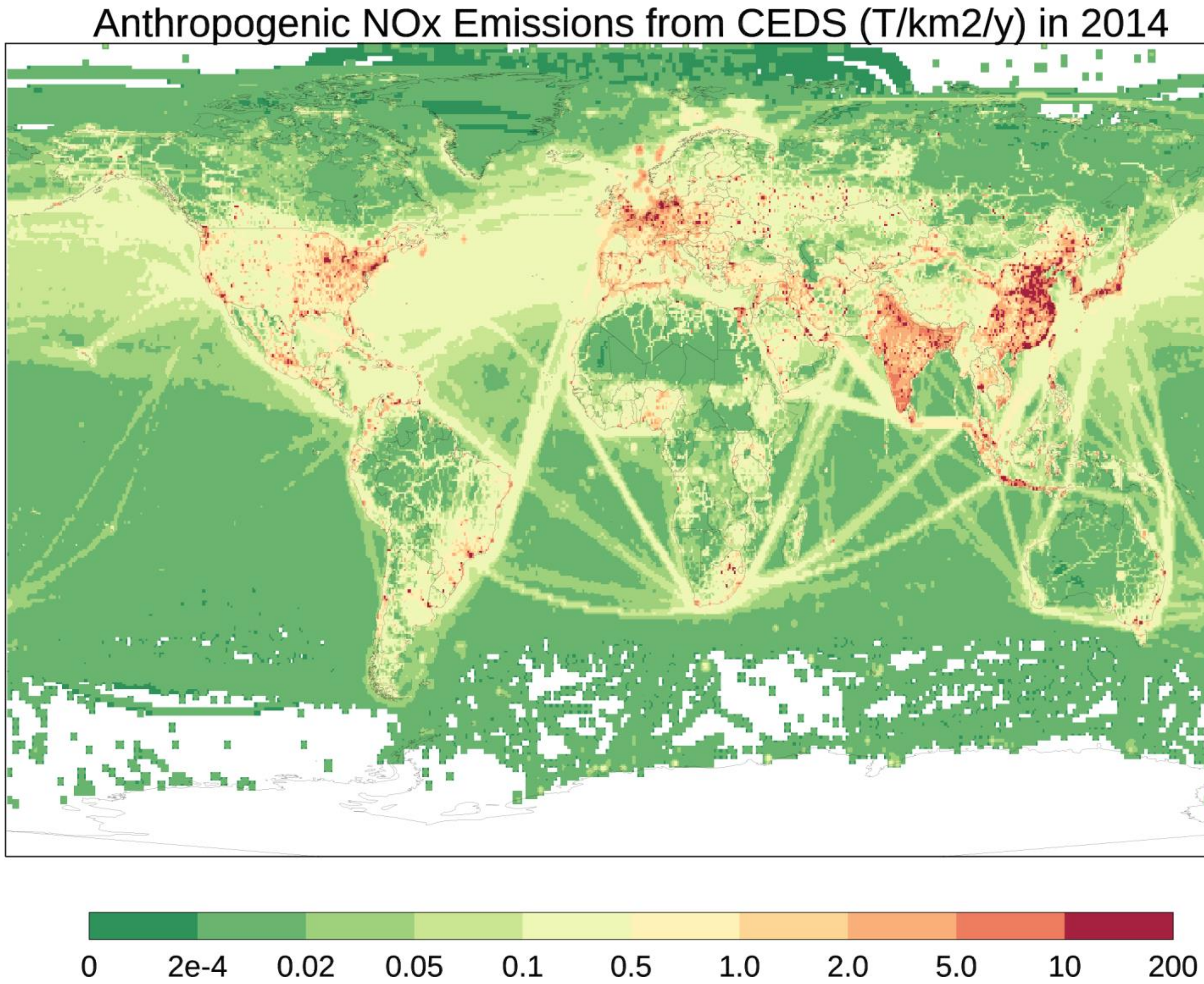
CEDS inventory

Anthropogenic NOx Emissions: 1950-2014



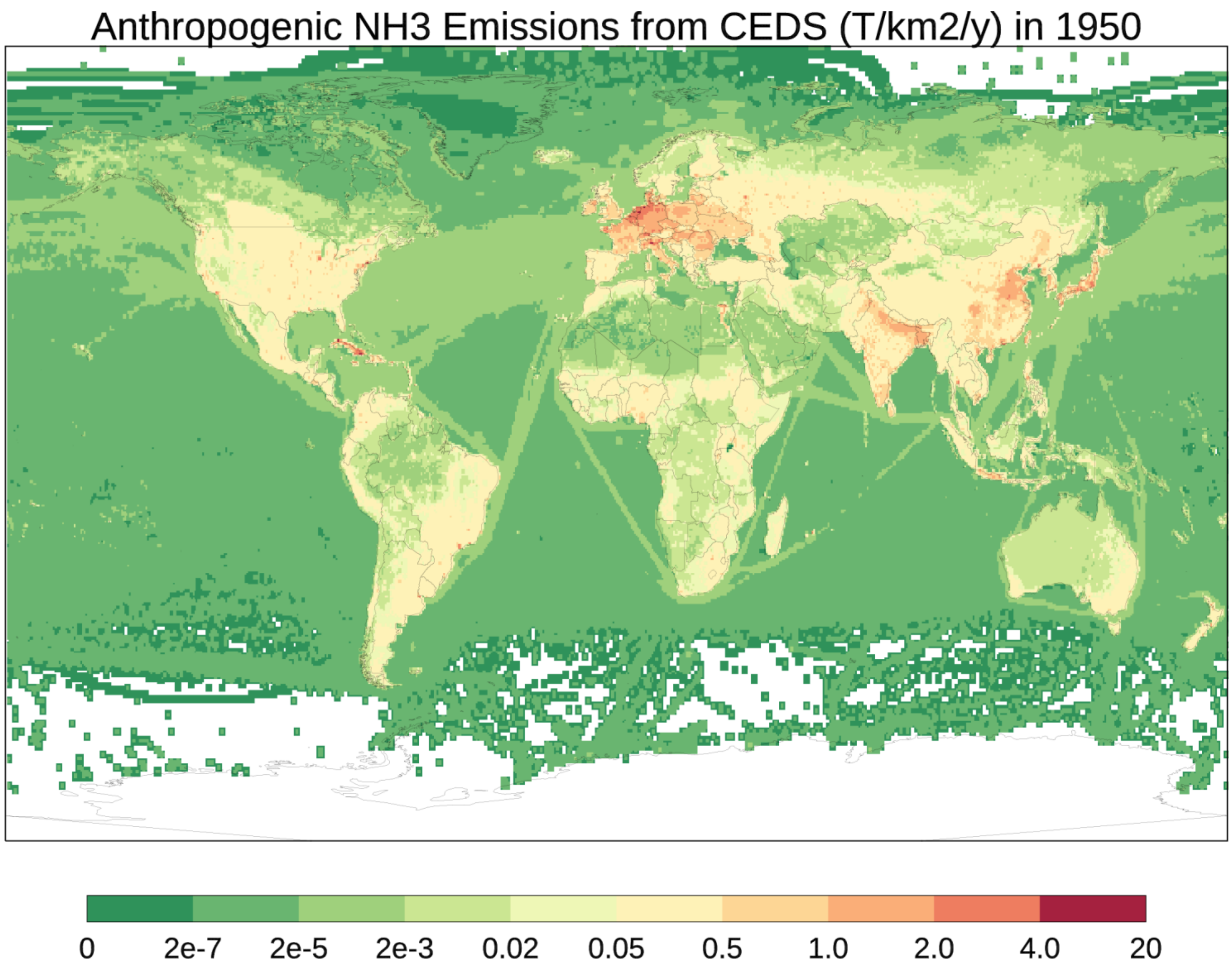
CEDS inventory

Anthropogenic NOx Emissions: 1950-2014



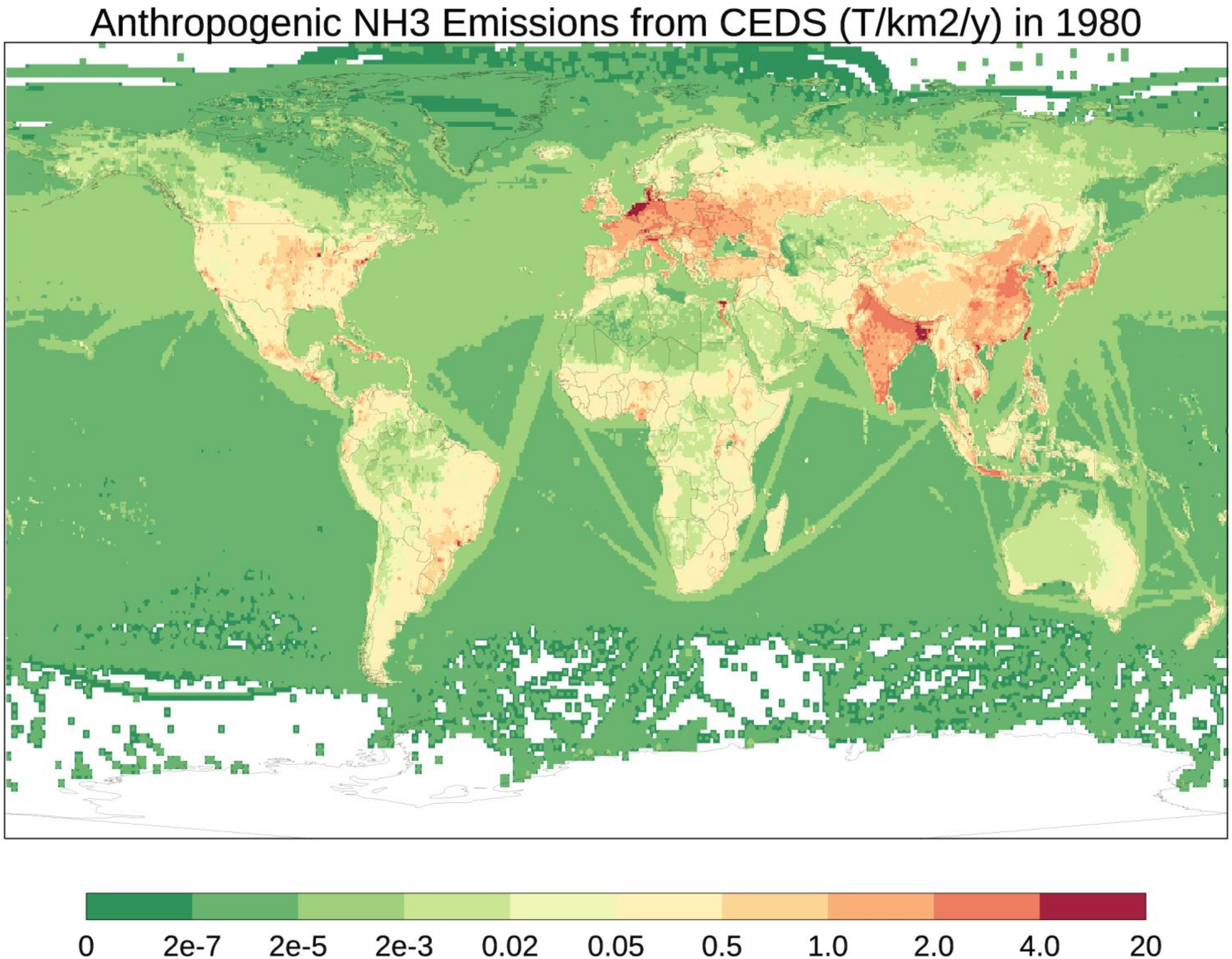
CEDS inventory

Anthropogenic NH_3 Emissions: 1950-2014



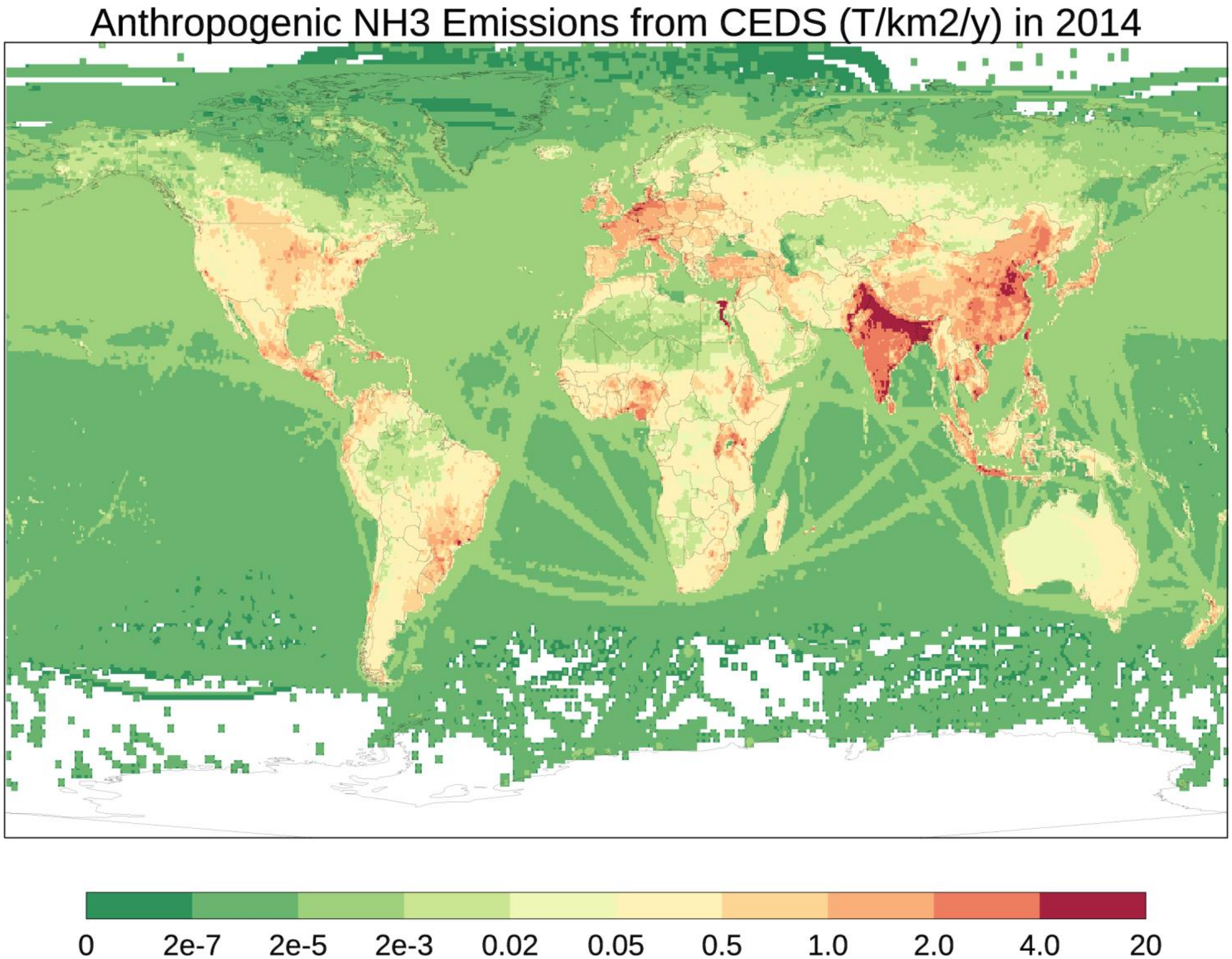
CEDS inventory

Anthropogenic NH_3 Emissions: 1950-2014



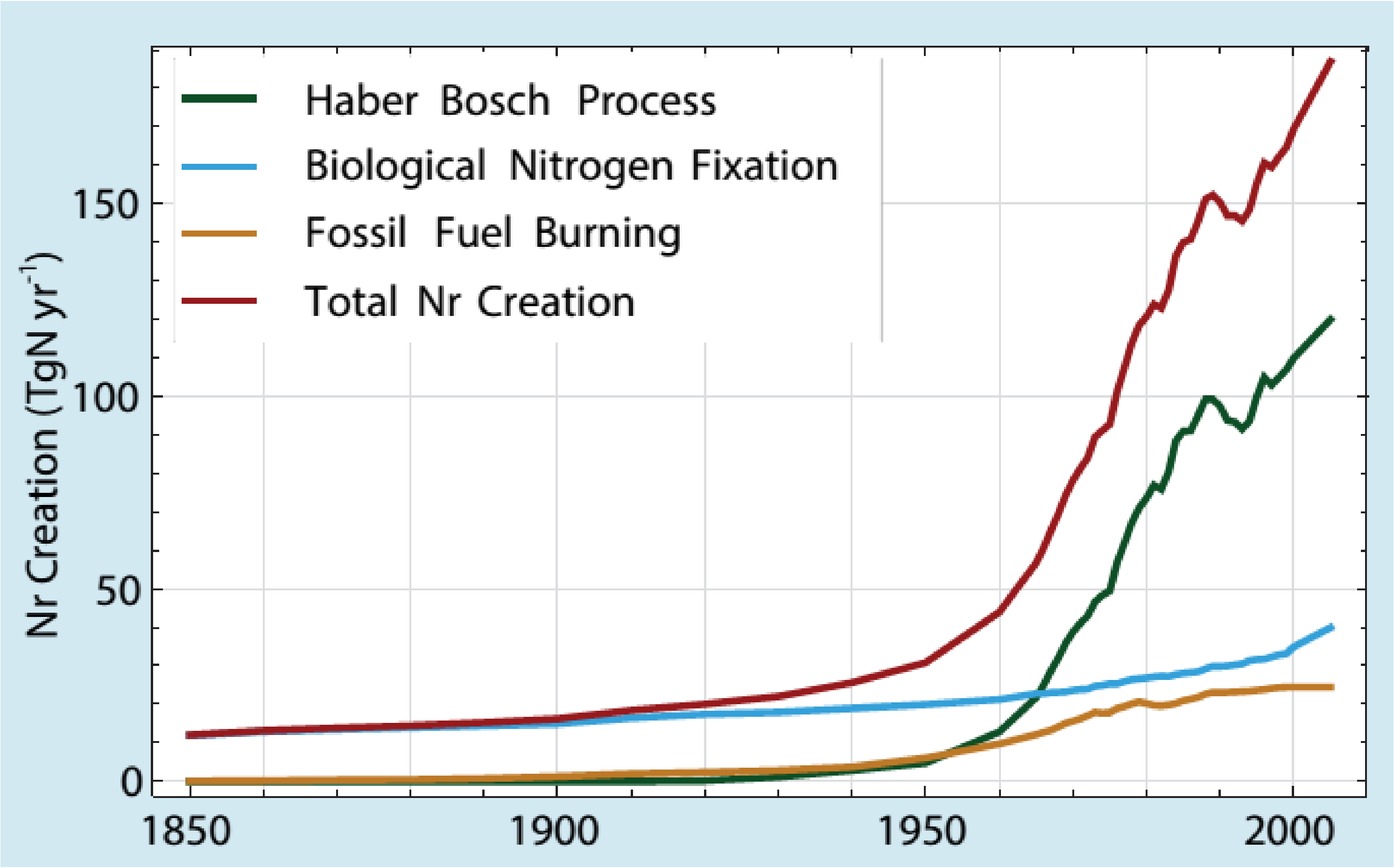
CEDS inventory

Anthropogenic NH_3 Emissions: 1950-2014



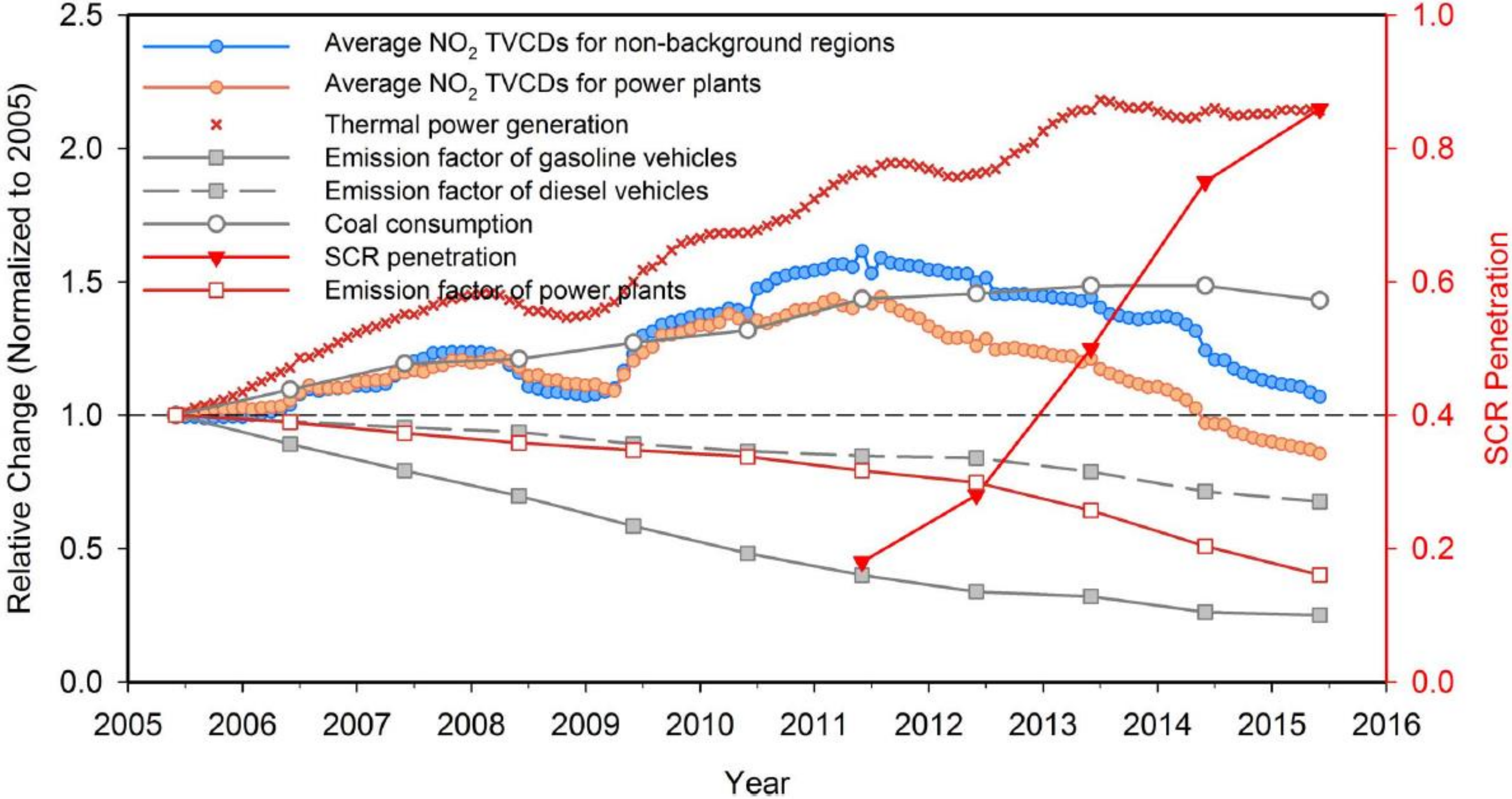
CEDS inventory

Global Reactive Nitrogen Creation by Human



IPCC, 2013

Recent Reduction in NOx Emissions Over China



Liu et al., 2016, ERL

Global Nitrogen Cycle: Past, Present and Future

Inorganic N deposition

mg N m^{-2} yr^{-1}

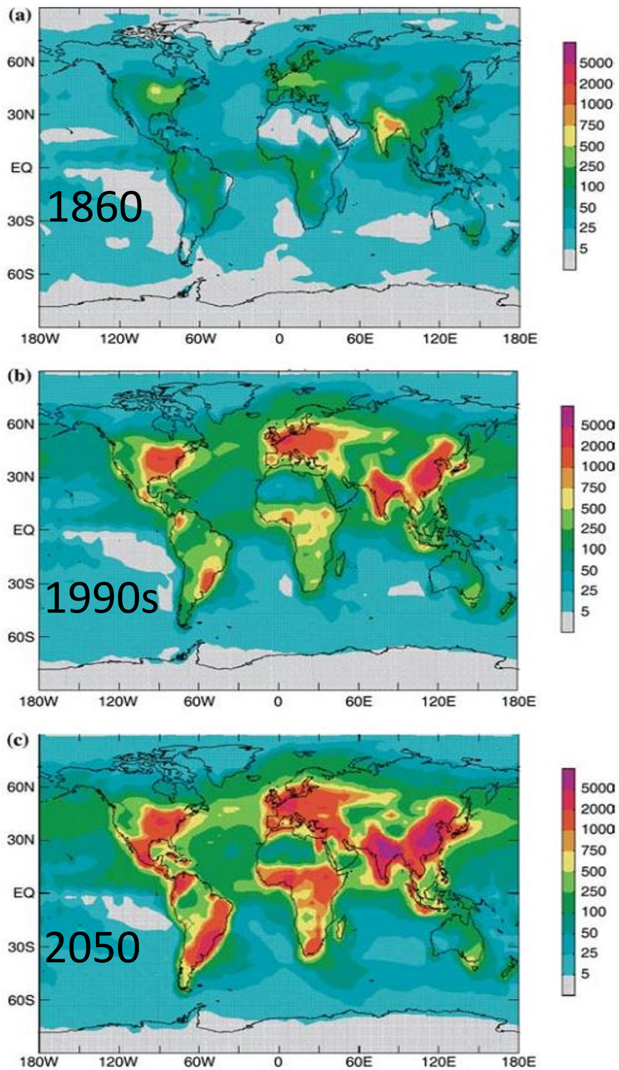


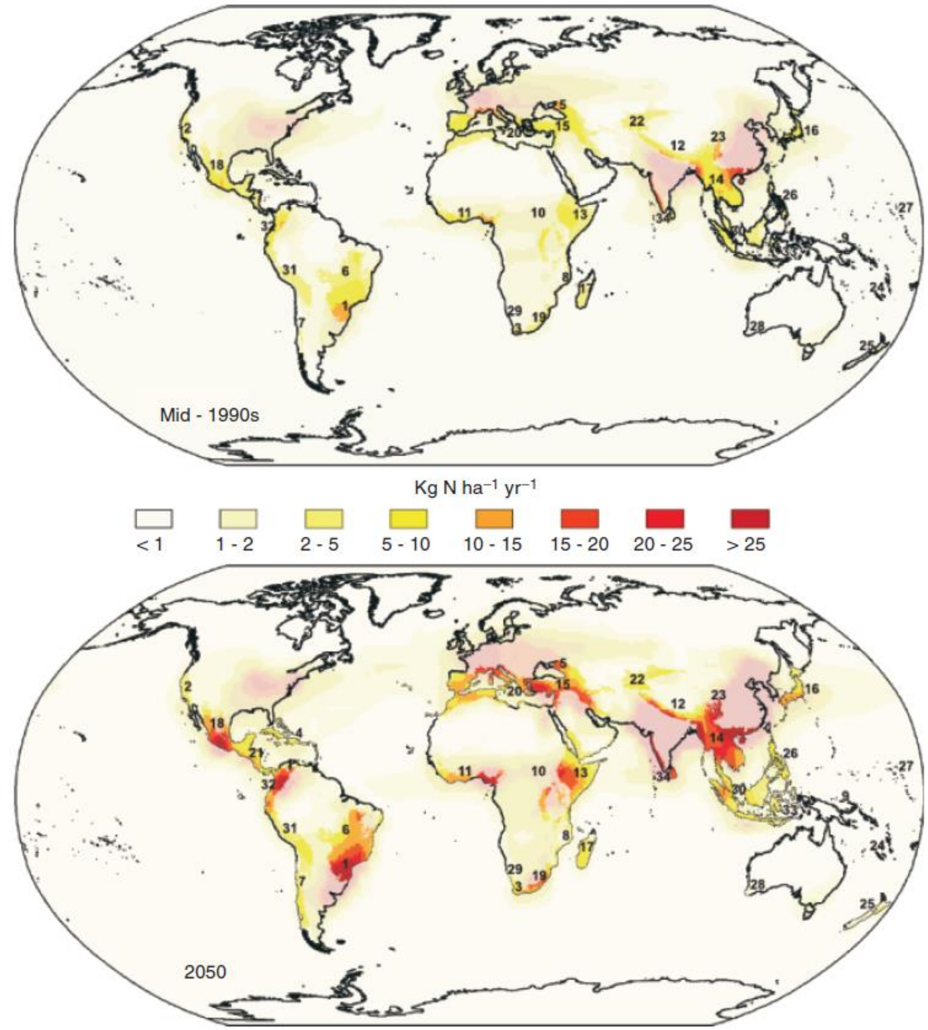
Table 1. Global Nr creation and distribution, Tg N yr^{-1}

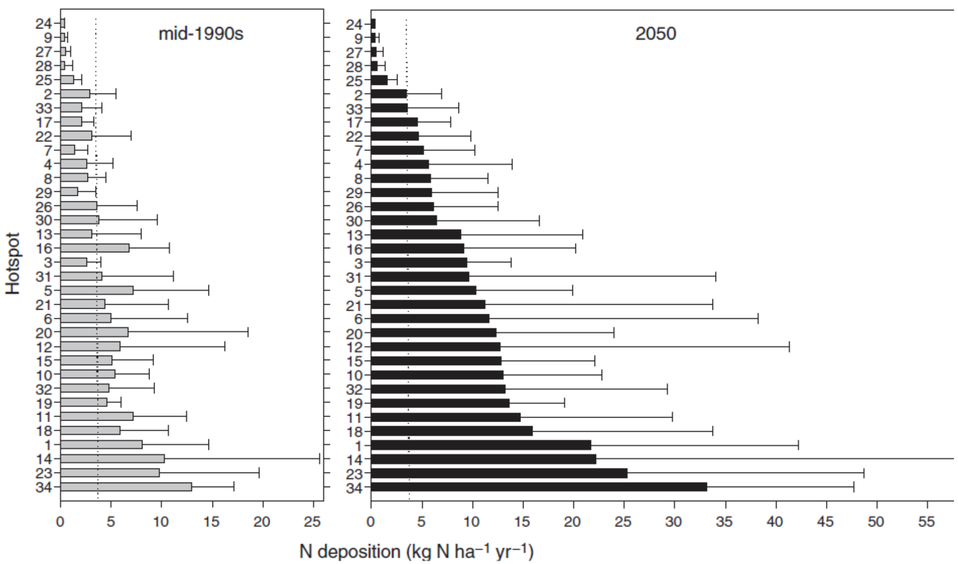
	1860	Early-1990s	2050
Nr creation			
Natural			
Lightning	5.4	5.4	5.4
BNF-terestrial	120	107	98
BNF-marine	121	121	121
Subtotal	246	233	224
Anthropogenic			
Haber-Bosch	0	100	165
BNF-cultivation	15	31.5	50
Fossil fuel combustion	0.3	24.5	52.2
Subtotal	15	156	267
Total	262	389	492
Atmospheric emission			
NO_x			
Fossil fuel combustion	0.3	24.5	52.2
Lightning	5.4	5.4	5.4
Other emissions	7.4	16.1	23.9
NH_3			
Terrestrial	14.9	52.6	113
Marine	5.6	5.6	5.6
N_2O			
Terrestrial	8.1	10.9	13.1 ±
Marine	3.9	4.3	5.1
Total (NO_x and NH_3)	13.1	46	82
Atmospheric deposition			
NO_y			
Terrestrial	6.6	24.8	42.2
Marine	6.2	21	36.3
Subtotal	12.8	45.8	78.5
NH_x			
Terrestrial	10.8	38.7	83
Marine	8	18	33.1
Subtotal	18.8	56.7	116.1
Total	31.6	103	195
Riverine fluxes			
Nr input into rivers	69.8	118.1	149.8
Nr export to inland systems	7.9	11.3	11.7
Nr export to coastal areas	27	47.8	63.2
Denitrification			
Continental			
Terrestrial		67	95
Riverine		47.8	63.2
Subtotal	98	115	158
Estuary and shelf			
Riverine nitrate	27	47.8	63.2
Open ocean nitrate	145	145	145
Subtotal	172	193	208

Galloway et al., 2004, Biogeochemistry

Nitrogen Deposition in Biodiversity Hotspots

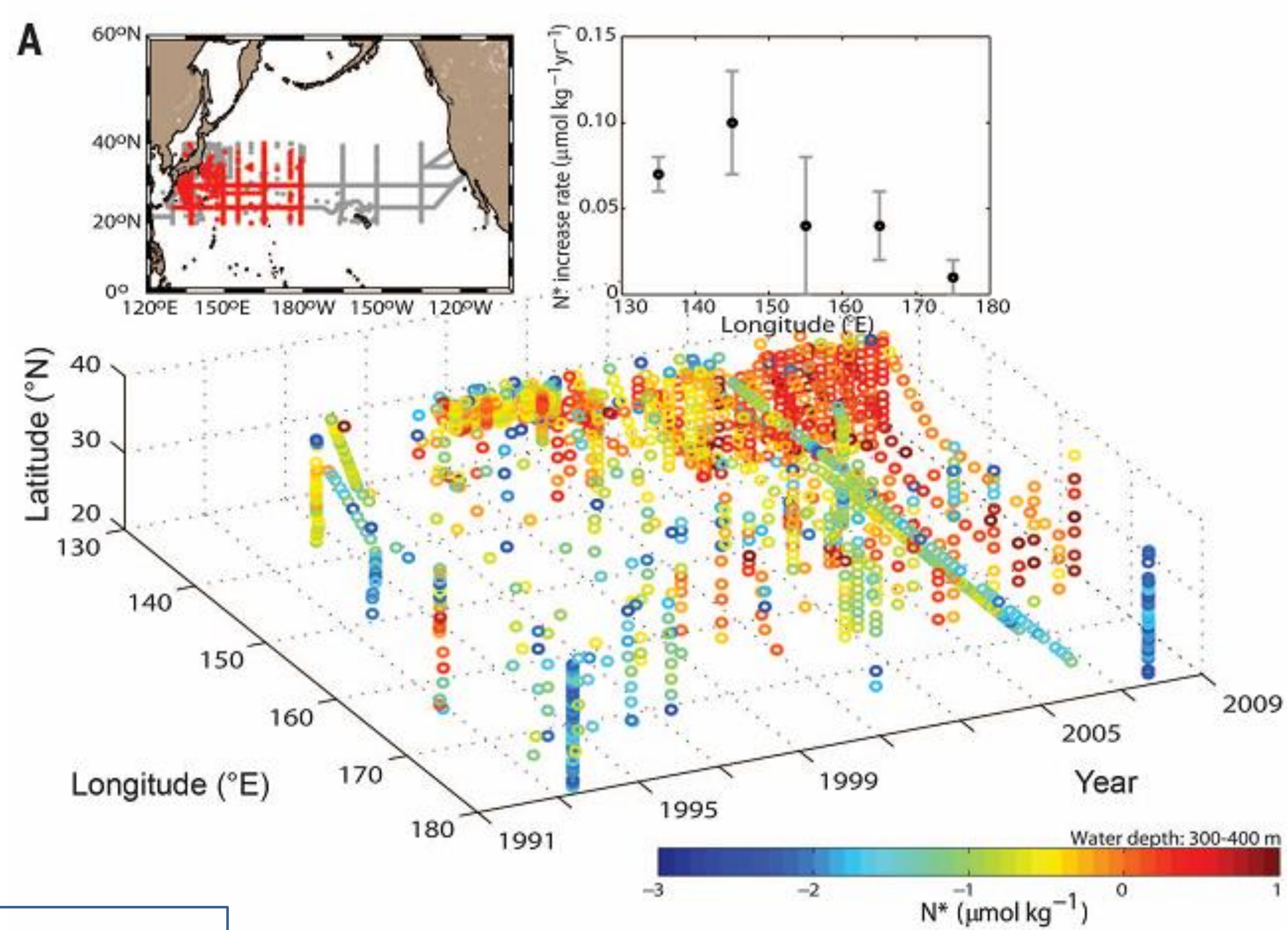
- **Setting a threshold of N deposition(15 kg N ha^{-1} yr^{-1}), Phoenix et al. simulated the impacts of atmospheric N deposition on the 34 world biodiversity hotspots in 1990s and 2050 (based on TM3)**





Phoenix et al., 2006, GCB

Increasing Atmospheric N Deposition in the Pacific Ocean

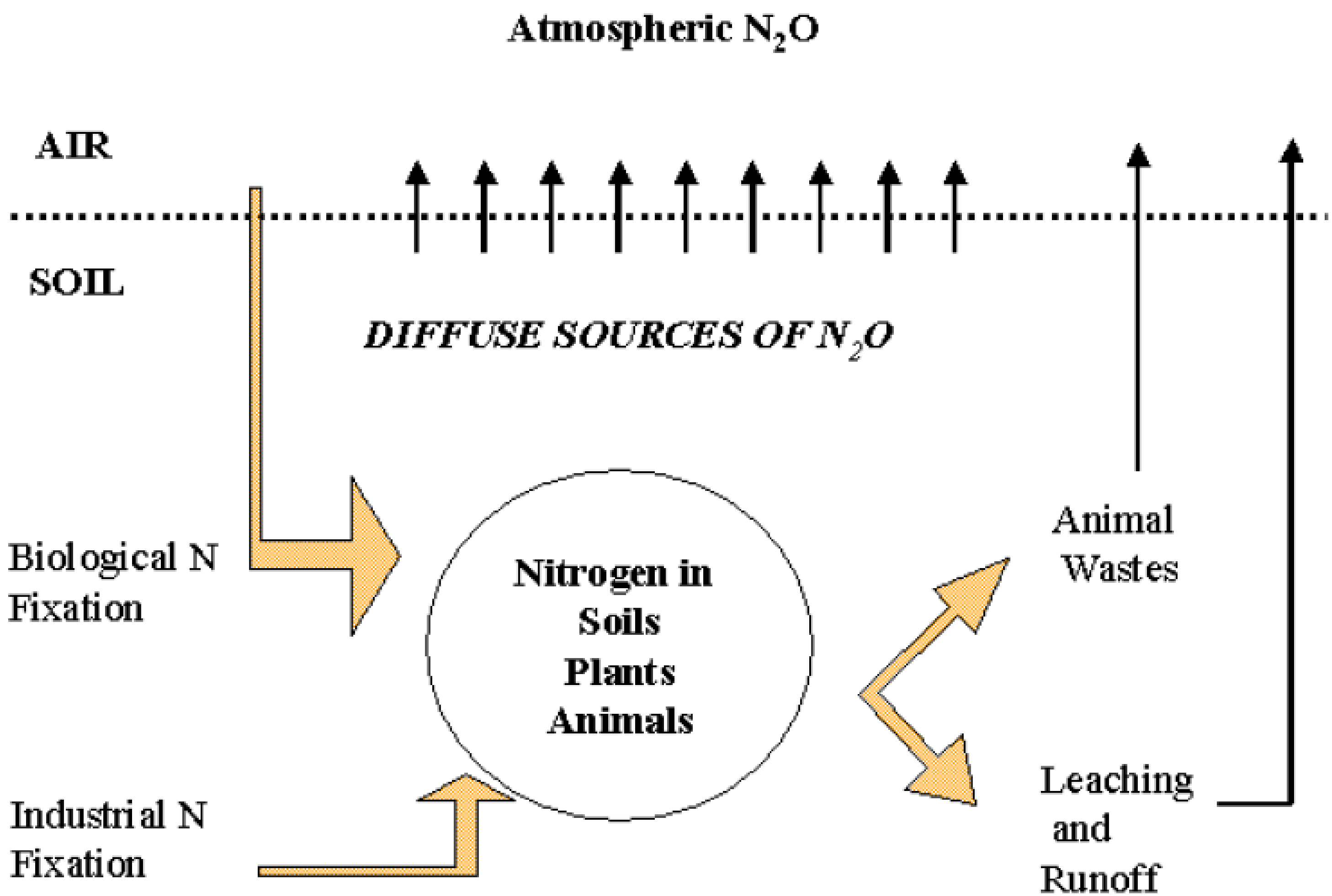


$$N^* = N - R_{N:P} \times P$$

$R_{N:P}$ = Redfield ratio = 16

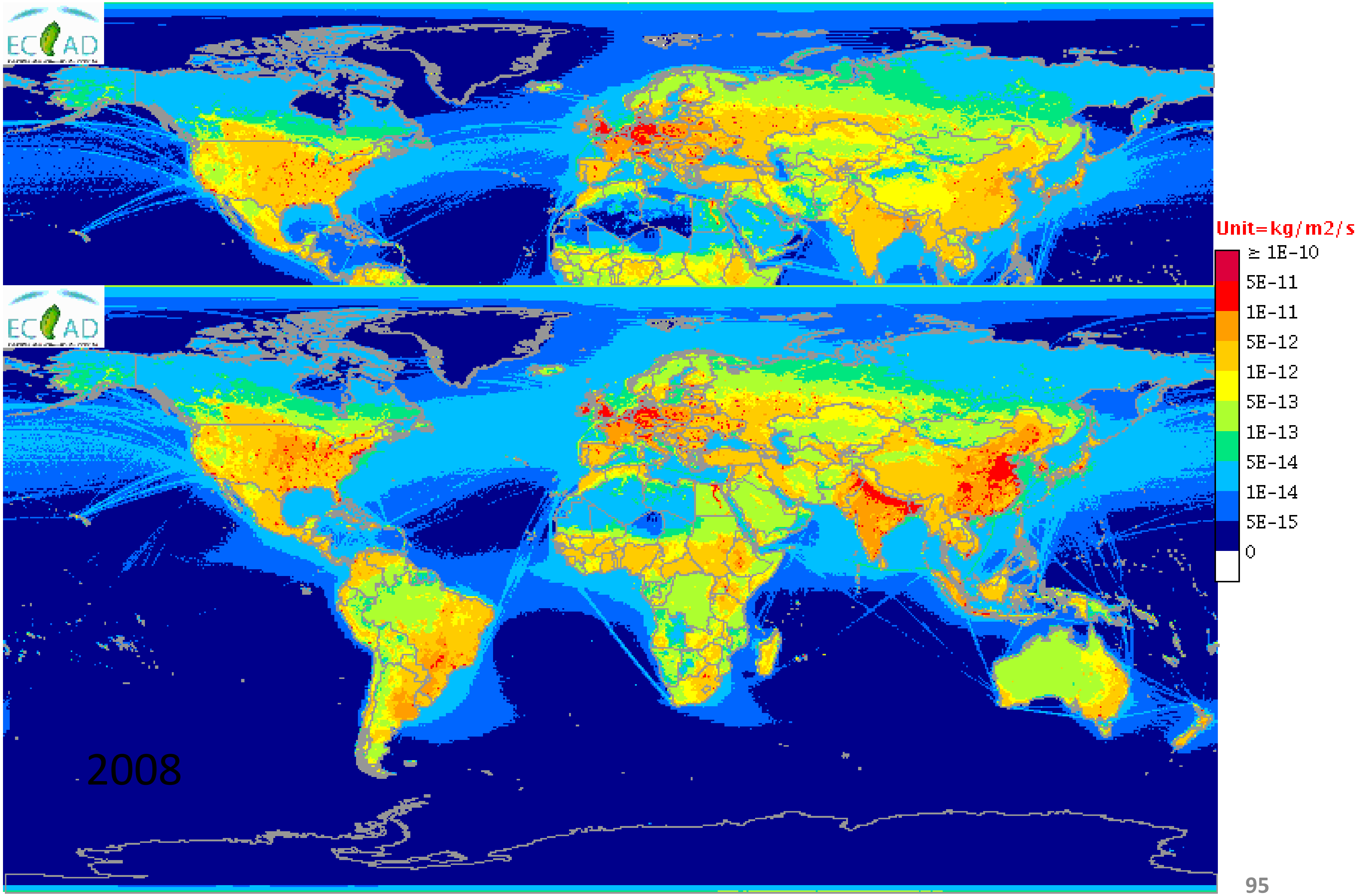
Kim et al., 2014, Science

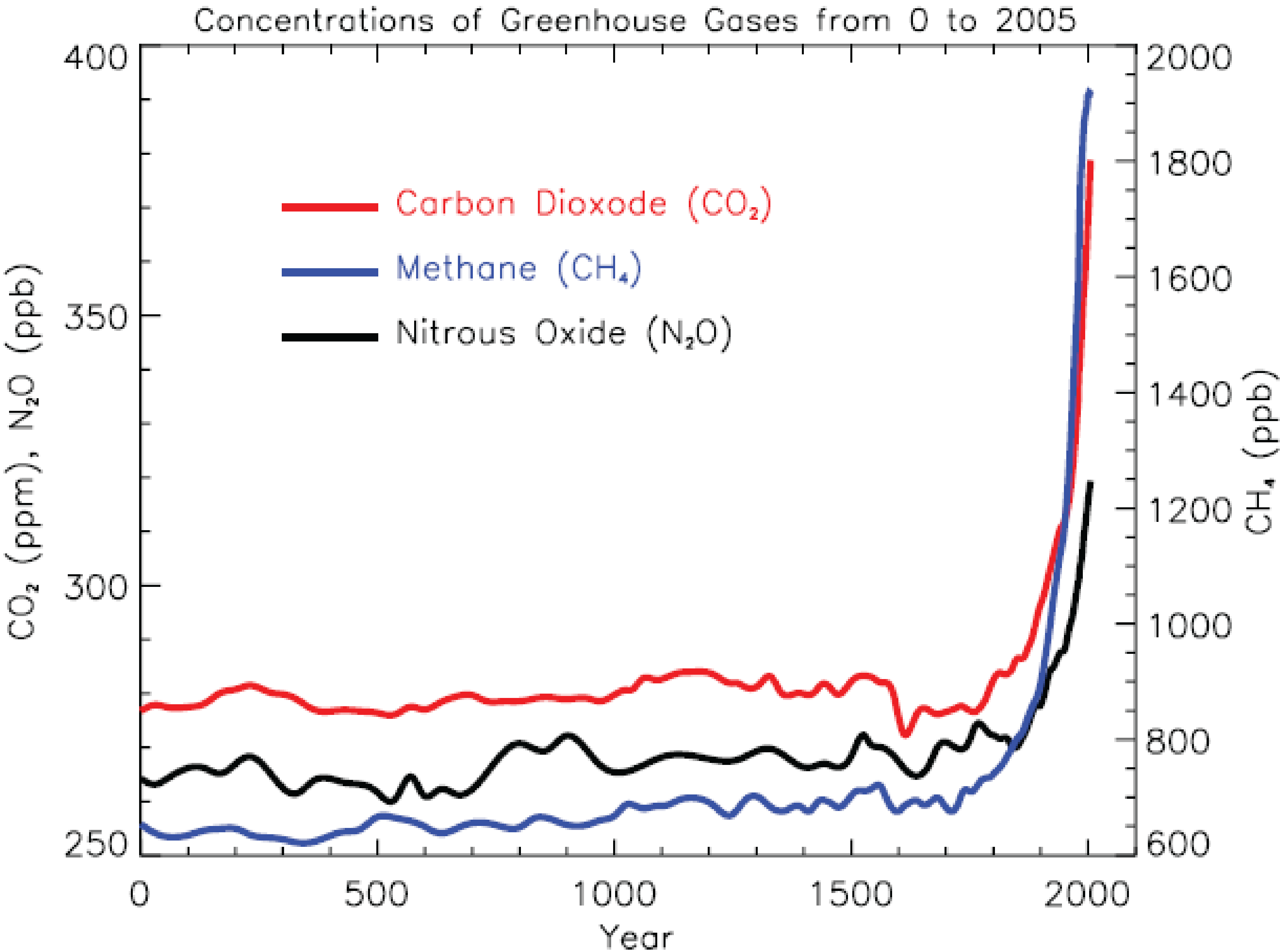
N_2O Emitted from Agriculture and Biosphere



Soil processes involved in the formation of N_2O from agriculture

N_2O Emissions: 1970-2008 (EDGAR v4.2)

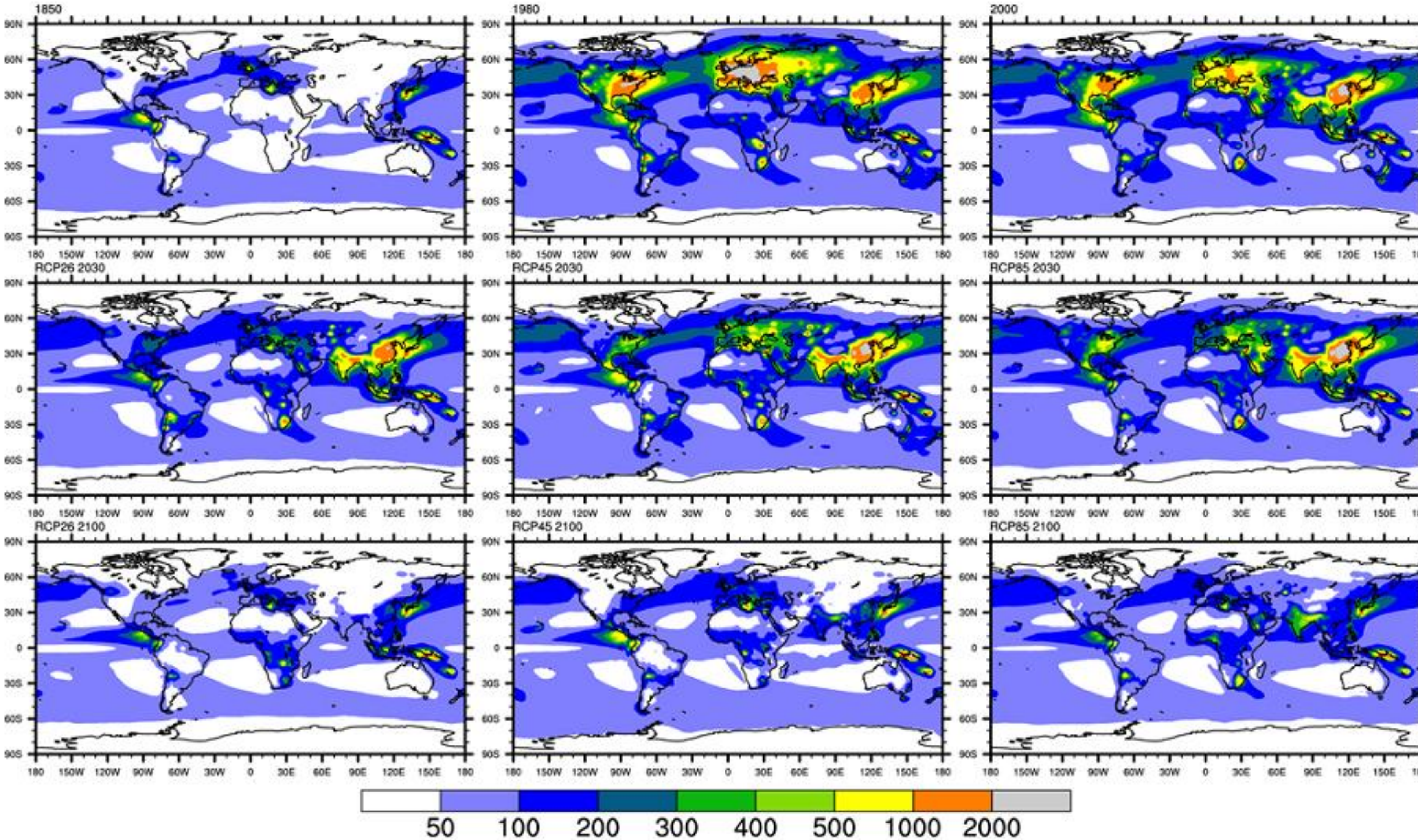




Concentrations of Greenhouse Gases from 0 to 2005
Carbon Dioxode (CO2)
Methane (CH4)
Nitrous Oxide (N2O)
CO2 (ppm), N2O (ppb)
CH4 (ppb)
Year
400
350
300
250
2000
1800
1600
1400
1200
1000
800
600
0
500
1000
1500
2000

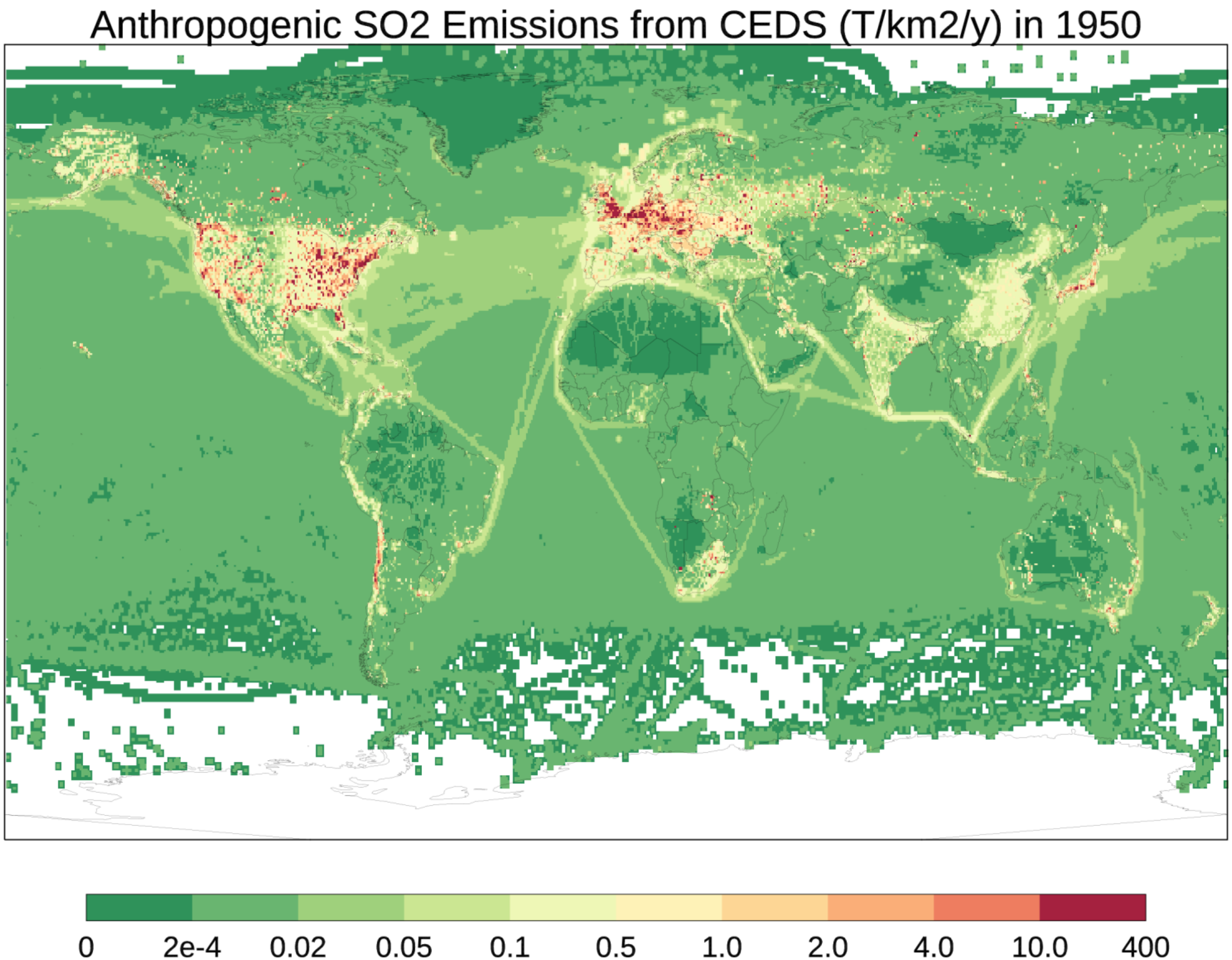
Global Sulfur Deposition: Past, Present and Future

SOx deposition in 1850, 1980, 2000, 2030 and 2100 (mg S m^{-2} yr^{-1})



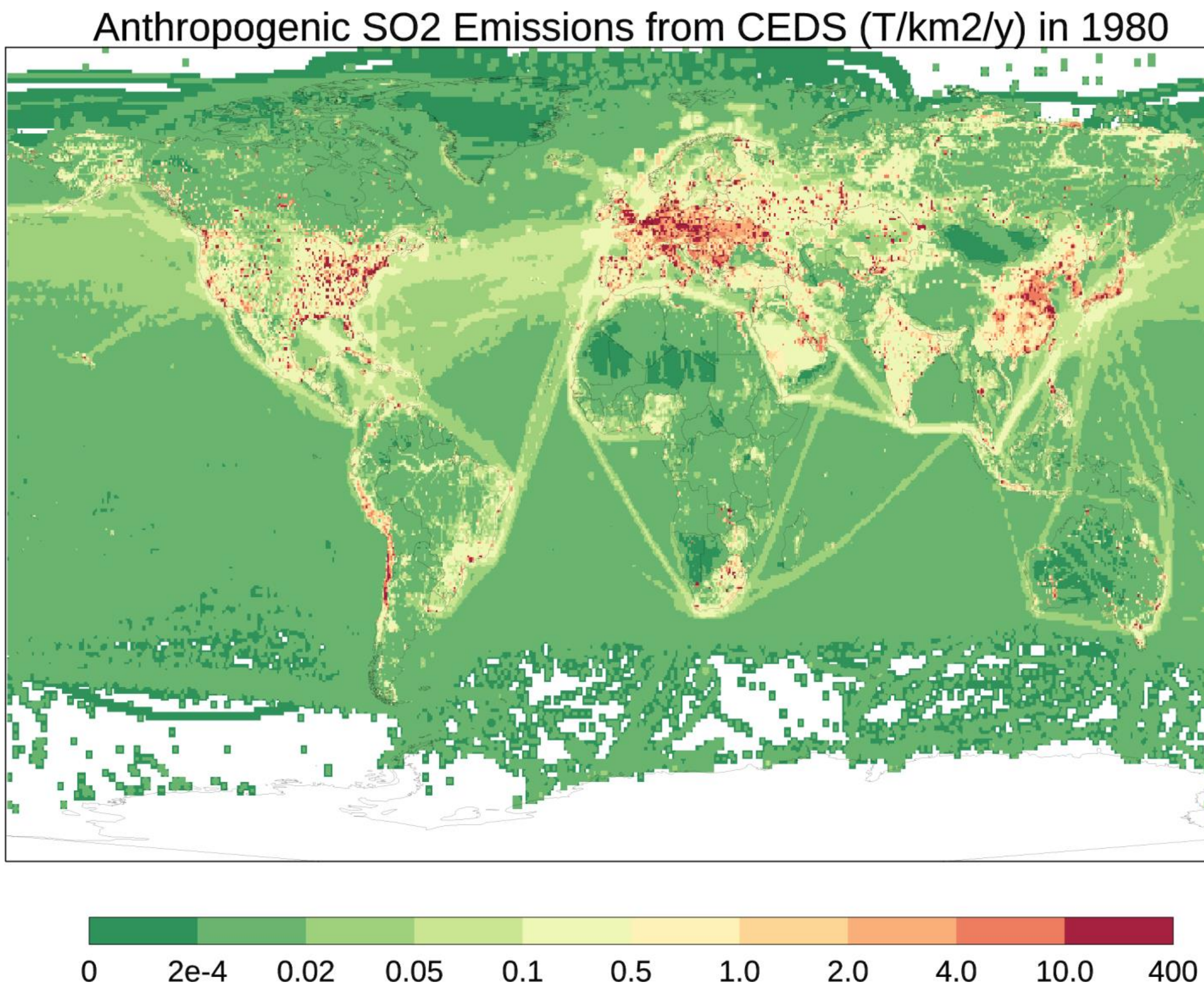
Lamarque et al., 2013, ACP

Anthropogenic SO_2 Emissions: 1950-2014



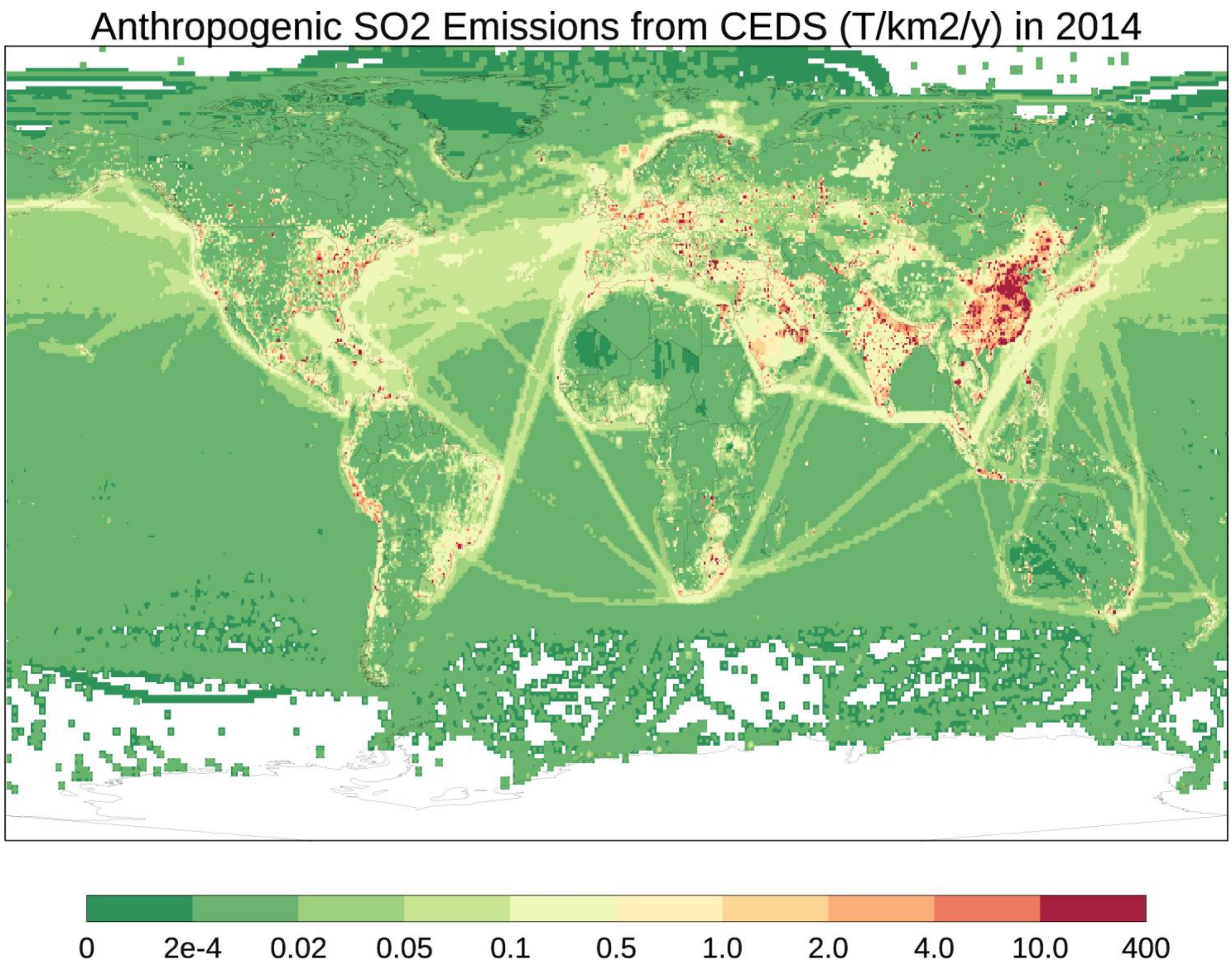
CEDS inventory

Anthropogenic SO_2 Emissions: 1950-2014



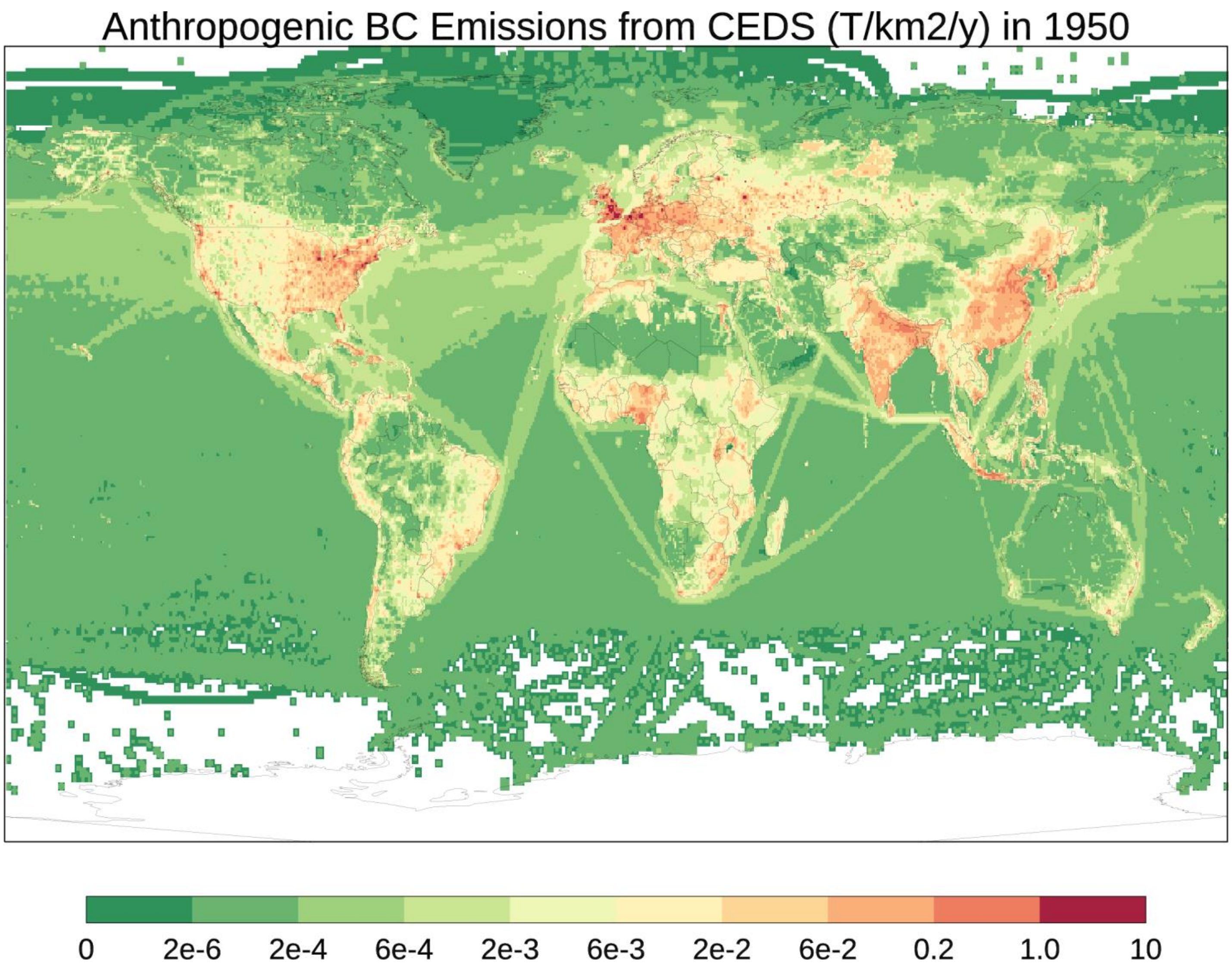
CEDS inventory

Anthropogenic SO_2 Emissions: 1950-2014



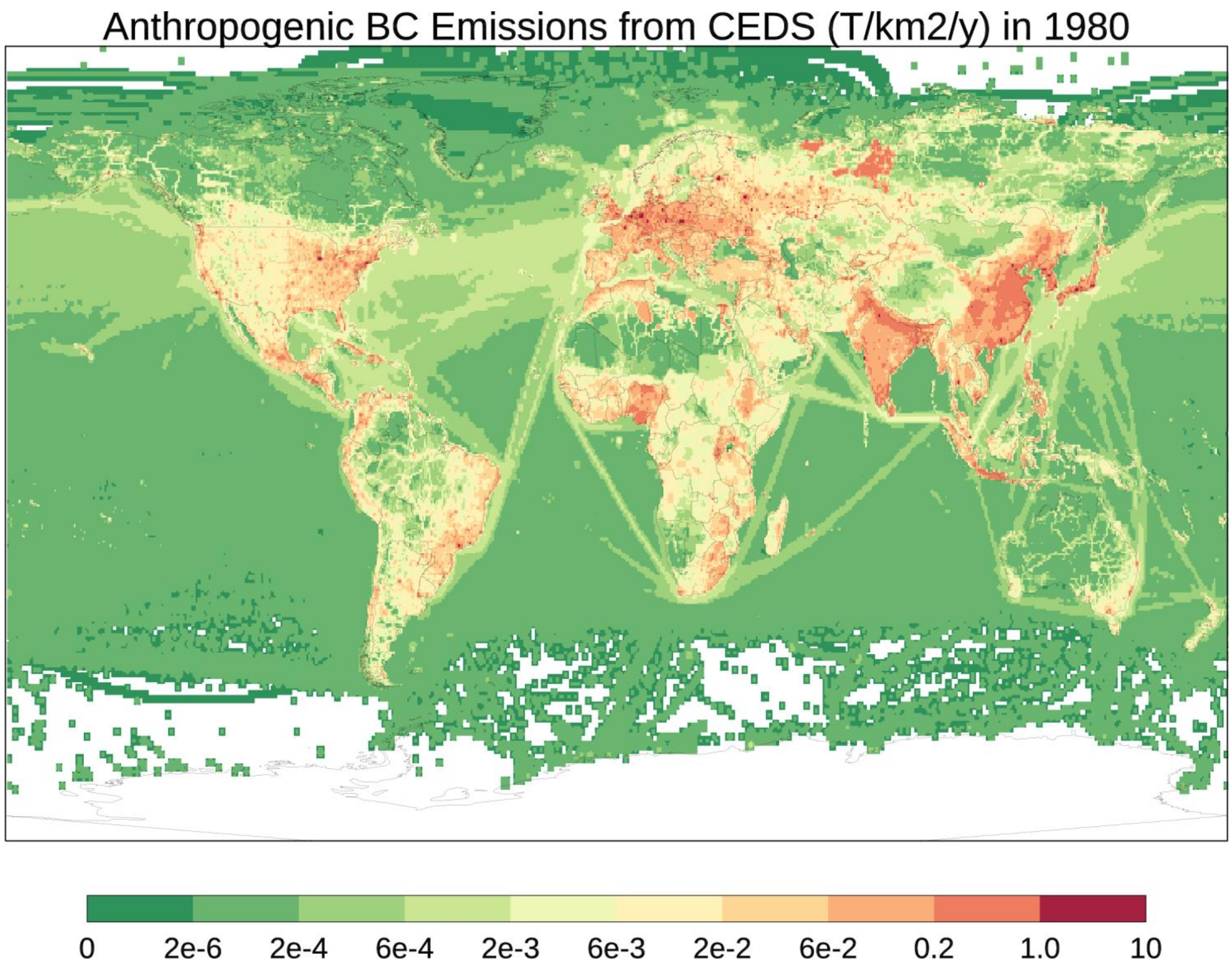
CEDS inventory

Anthropogenic BC Emissions: 1950-2014



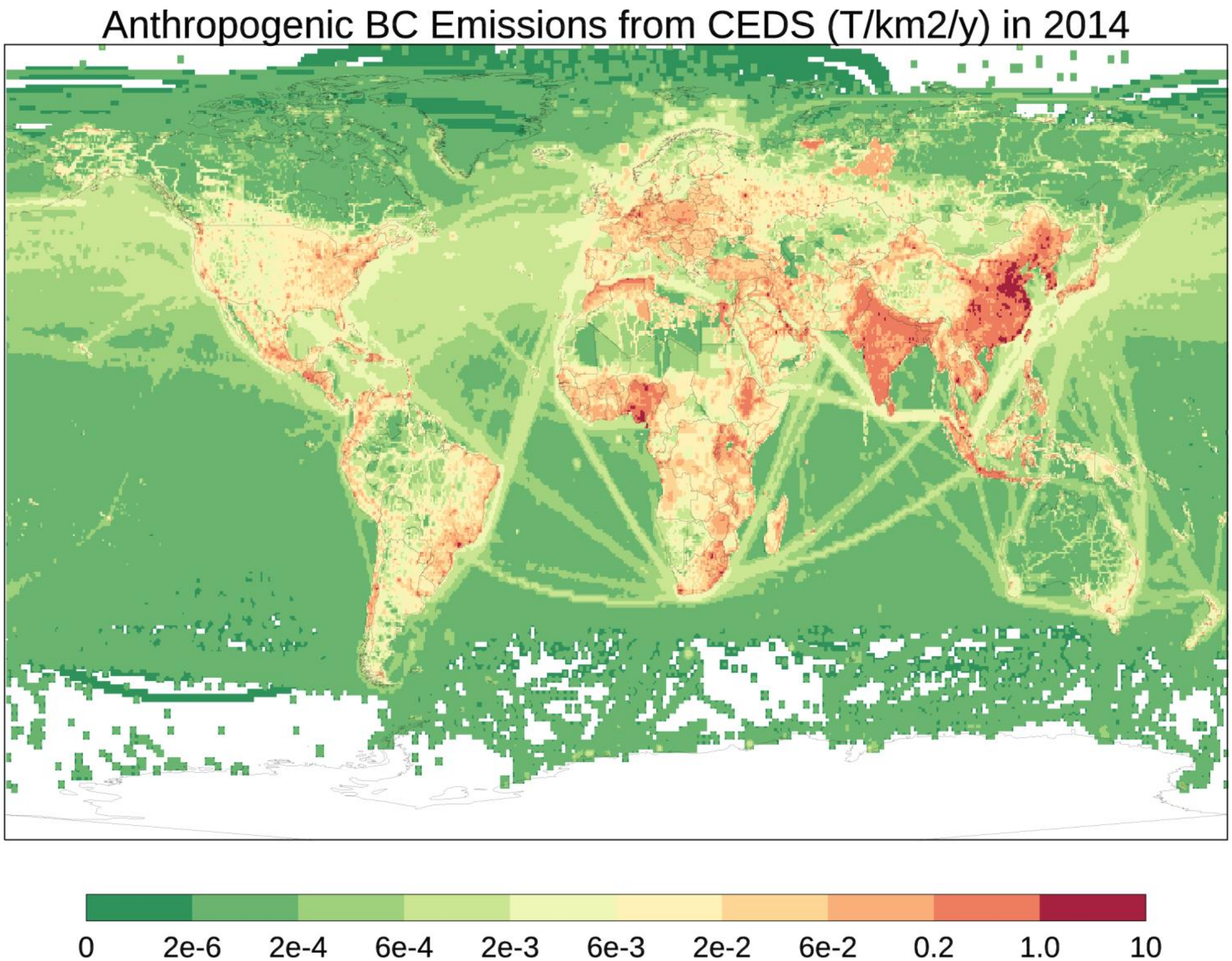
CEDS inventory

Anthropogenic BC Emissions: 1950-2014



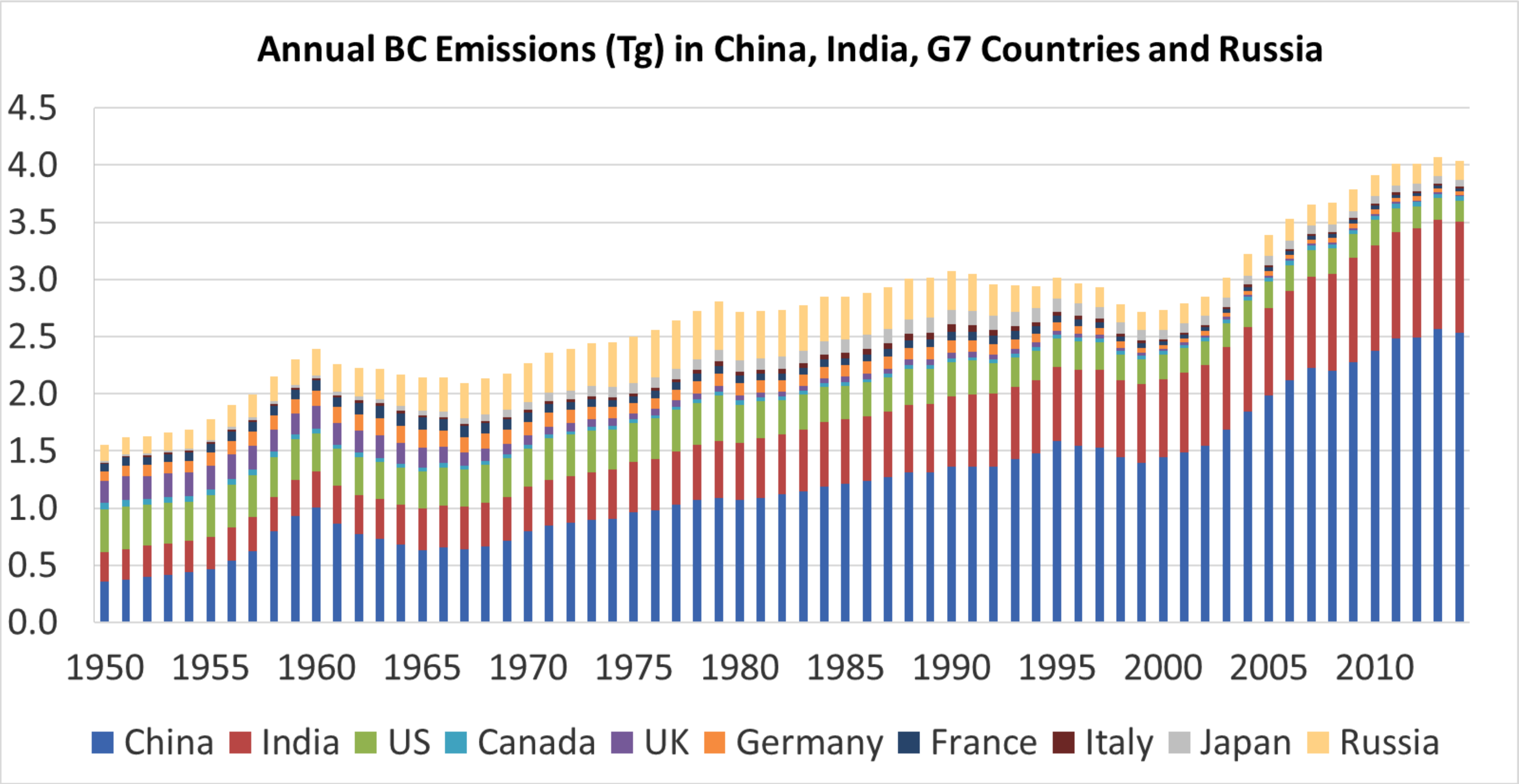
CEDS inventory

Anthropogenic BC Emissions: 1950-2014



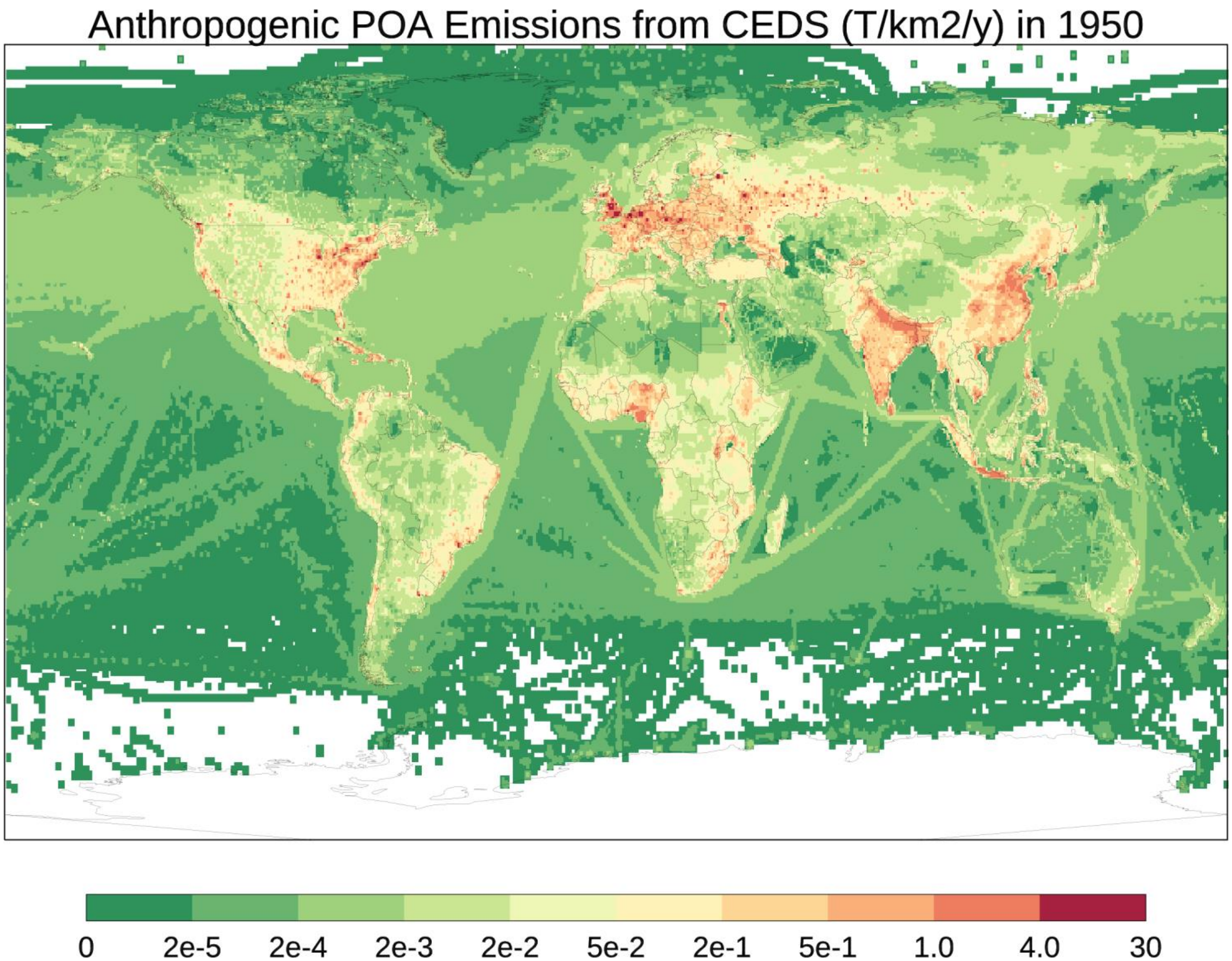
CEDS inventory

Anthropogenic Emissions of BC: 1950-2014



CEDS inventory

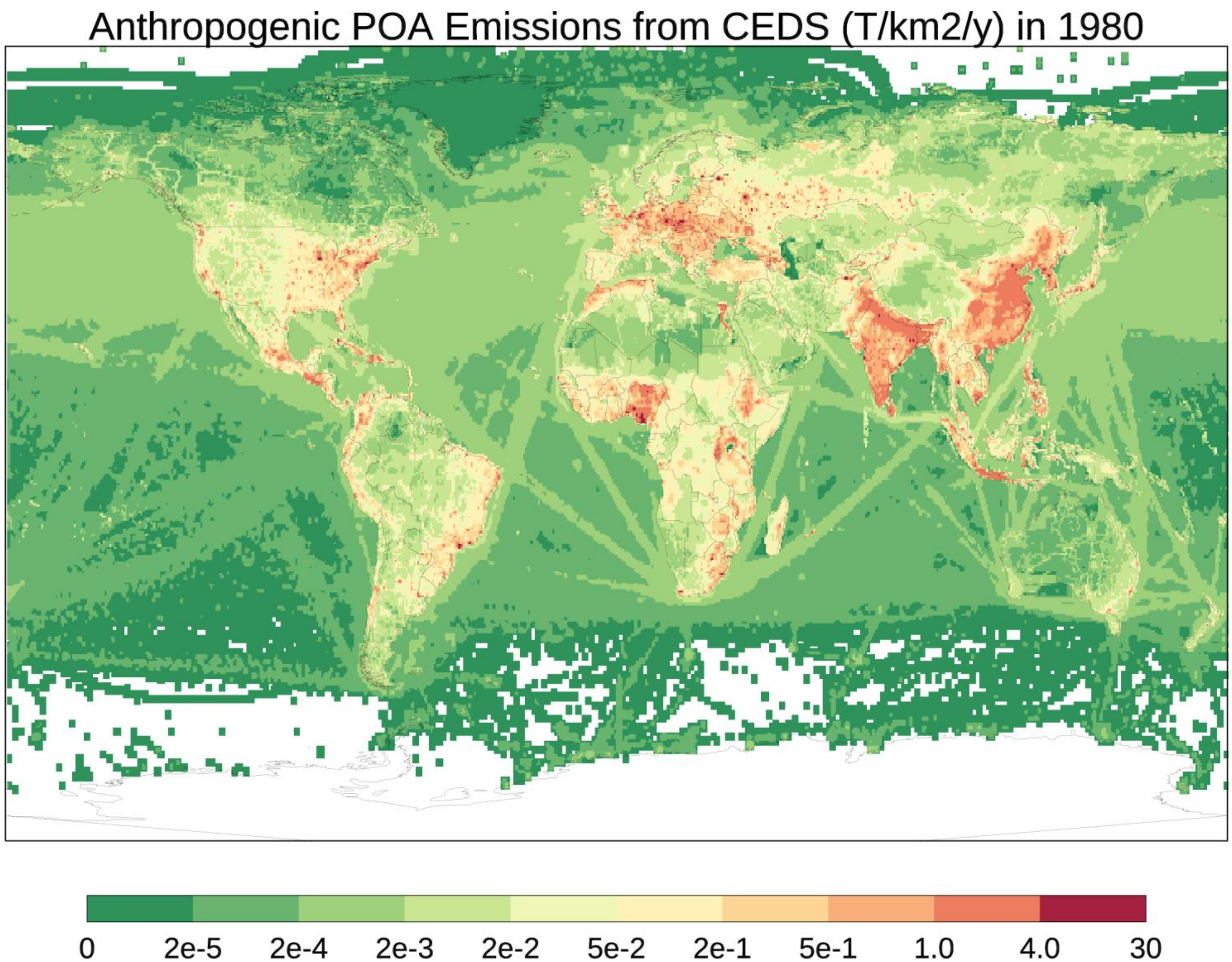
Anthropogenic POA Emissions: 1950-2014



CEDS inventory

POA = 2.1 * POC

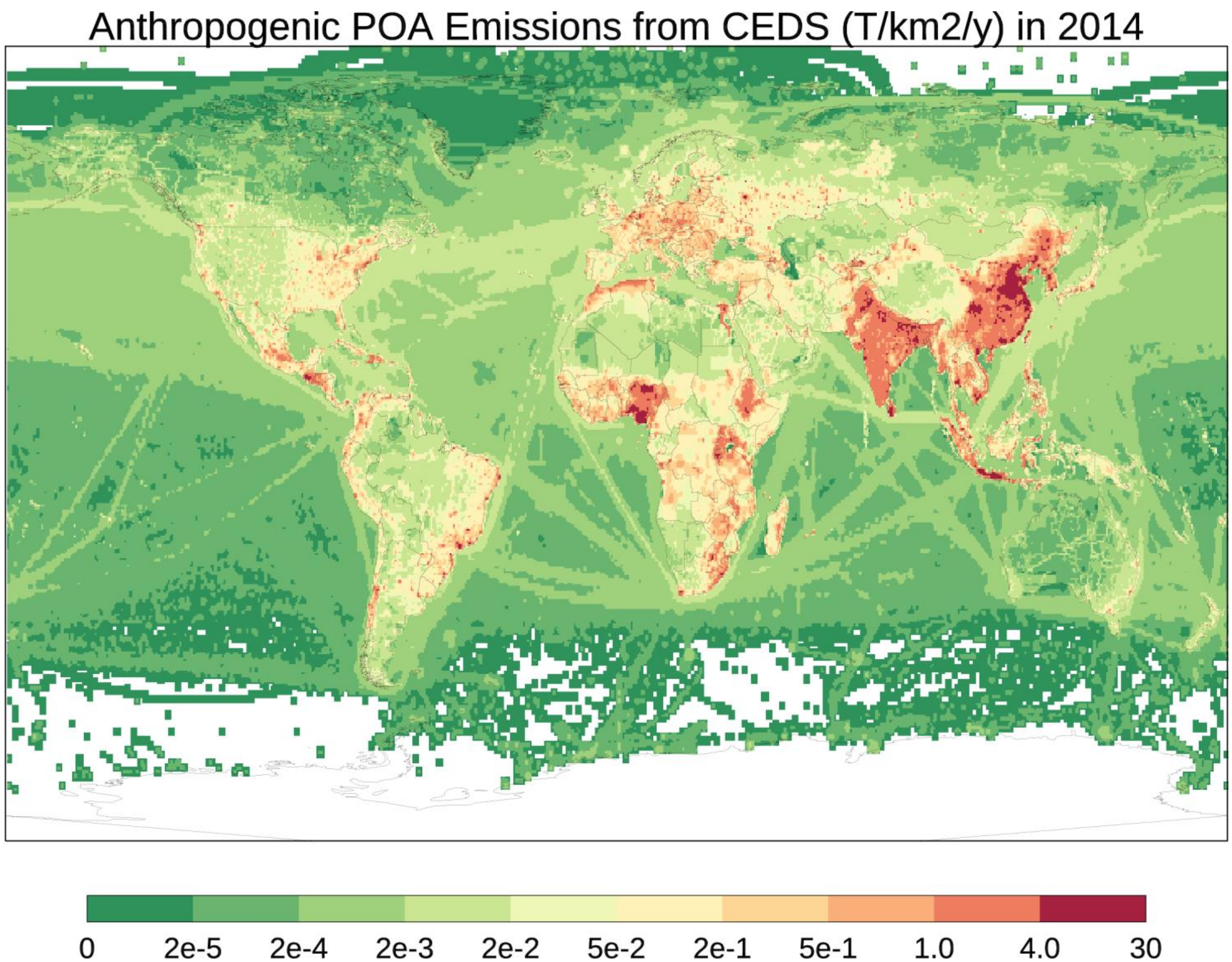
Anthropogenic POA Emissions: 1950-2014



CEDS inventory

POA = 2.1 * POC

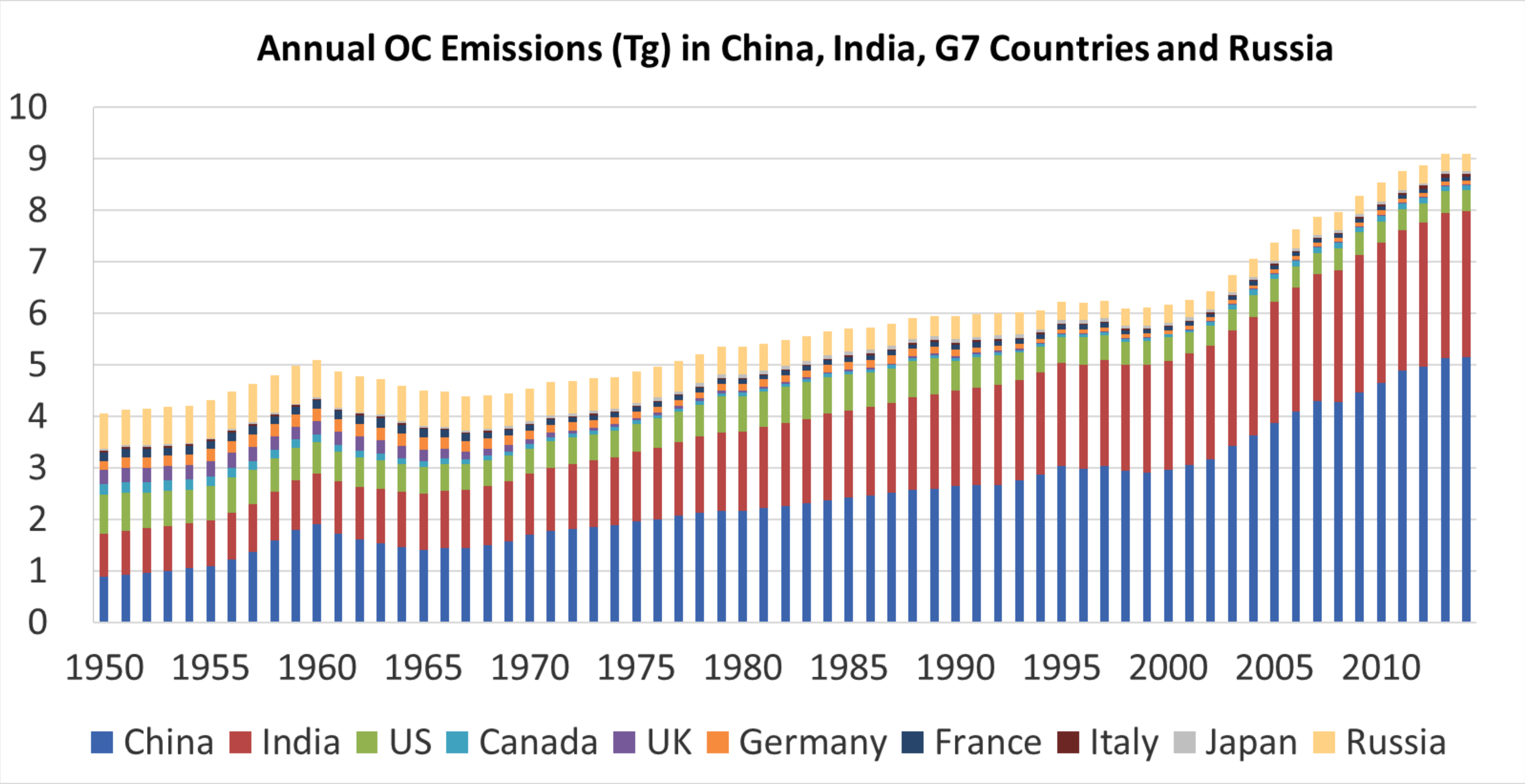
Anthropogenic POA Emissions: 1950-2014



CEDS inventory

POA = 2.1 * POC

Anthropogenic Emissions of POC: 1950-2014

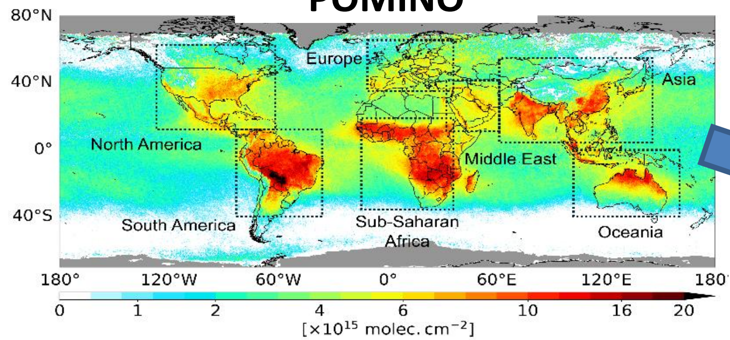


CEDS inventory

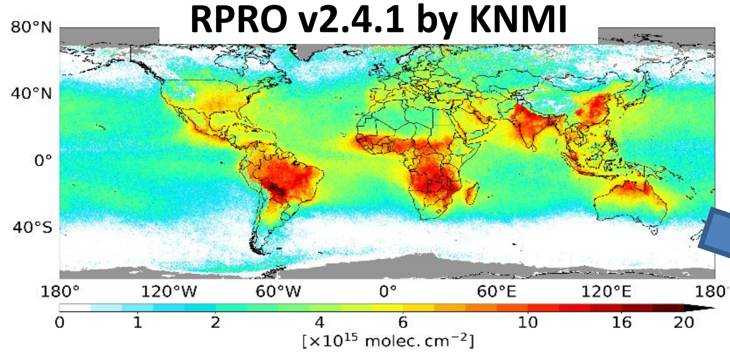
Global POMINO-TROPOMI HCHO VCDs

Tropospheric HCHO VCDs (April, July, October 2021, and January 2022)

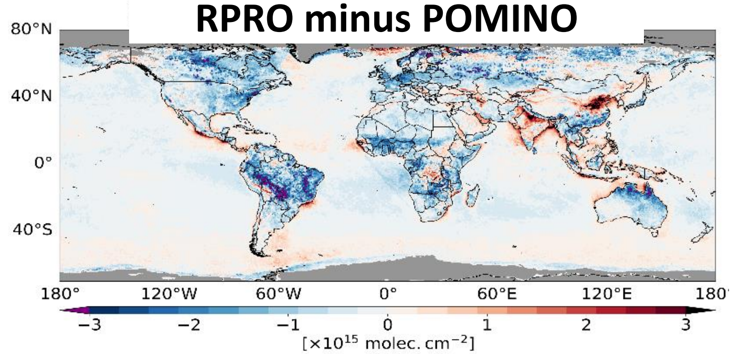
POMINO



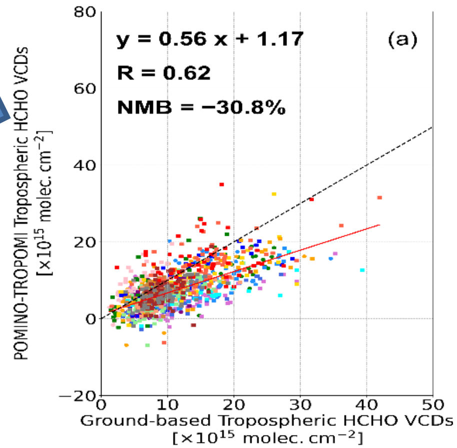
RPRO v2.4.1 by KNMI



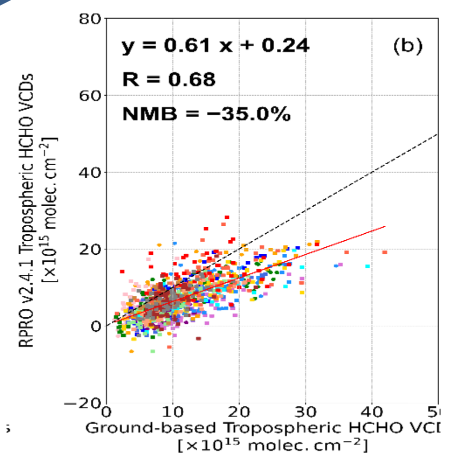
RPRO minus POMINO



POMINO vs. Ground obs



RPRO vs. Ground obs

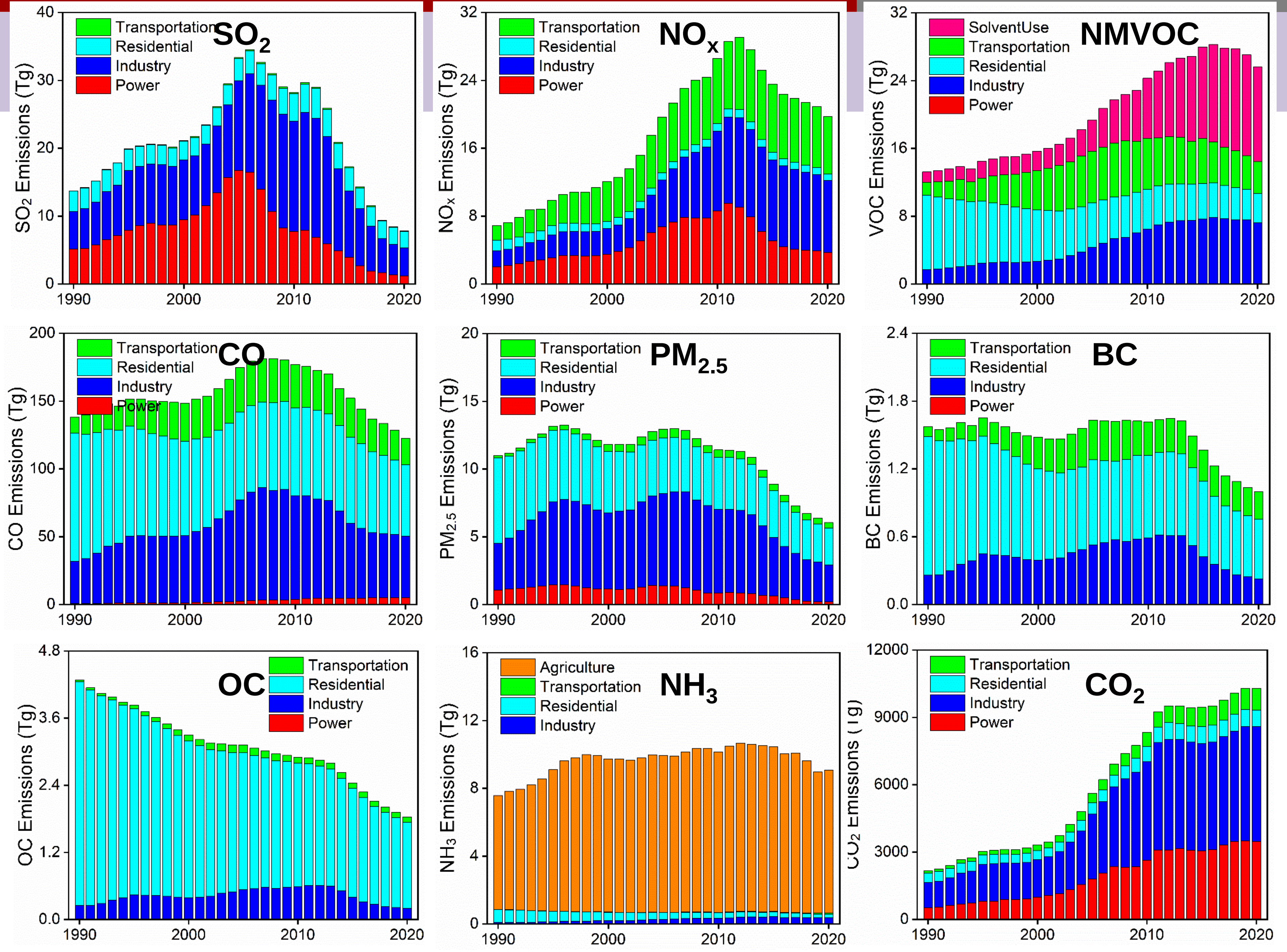


Ground obs. globally

MAX-DOAS	PGN
Bremen	Altzomoni
Cabauw	Athens
De Bilt	Bremen
Kinshasa	Bristol PA
Mohali	Busan
Xianghe	Houston TX
	La Porte TX (GSFC063)
	Londonderry NH
	Mountain View CA
	New Brunswick NJ
	Philadelphia PA
	Tel Aviv
	Tsukuba (JAXA193)
	Unam
	Vallejo
	Wakkerstroom
	Yokosuka

Sampling radius: 20 km, 2.5 h

Zhang et al., AMT, 2025



SO2
Transportation
Residential
Industry
Power
SO2 Emissions (Tg)
NOx
NOx Emissions (Tg)
NMVOC
SolventUse
VOC Emissions (Tg)
CO
CO Emissions (Tg)
PM2.5
PM2.5 Emissions (Tg)
BC
BC Emissions (Tg)
OC
OC Emissions (Tg)
NH3
Agriculture
NH3 Emissions (Tg)
CO2
CO2 Emissions (Tg)
1990
2000
2010
2020