Global Emissions of Air Pollutants and Greenhouse Gases

John van Aardenne

Climate Change Unit

Acknowledgements: Valerio Pagliari (Italy), Suvi Monni (Finland), Jos Olivier (Netherlands), Jeroen Peters (Netherlands), Lorenzo Orlandini (Italy),Fulgencio SanMartin (Spain), Ulrike Doering (Germany).

Overview

1. Introduction: Global emission Inventory research at European Commission

2. Task Force on Hemispheric Transport of Air Pollution

3. Large scale emissions inventories: calculation of emissions for ~240 countries

4. Overview of existing knowledge

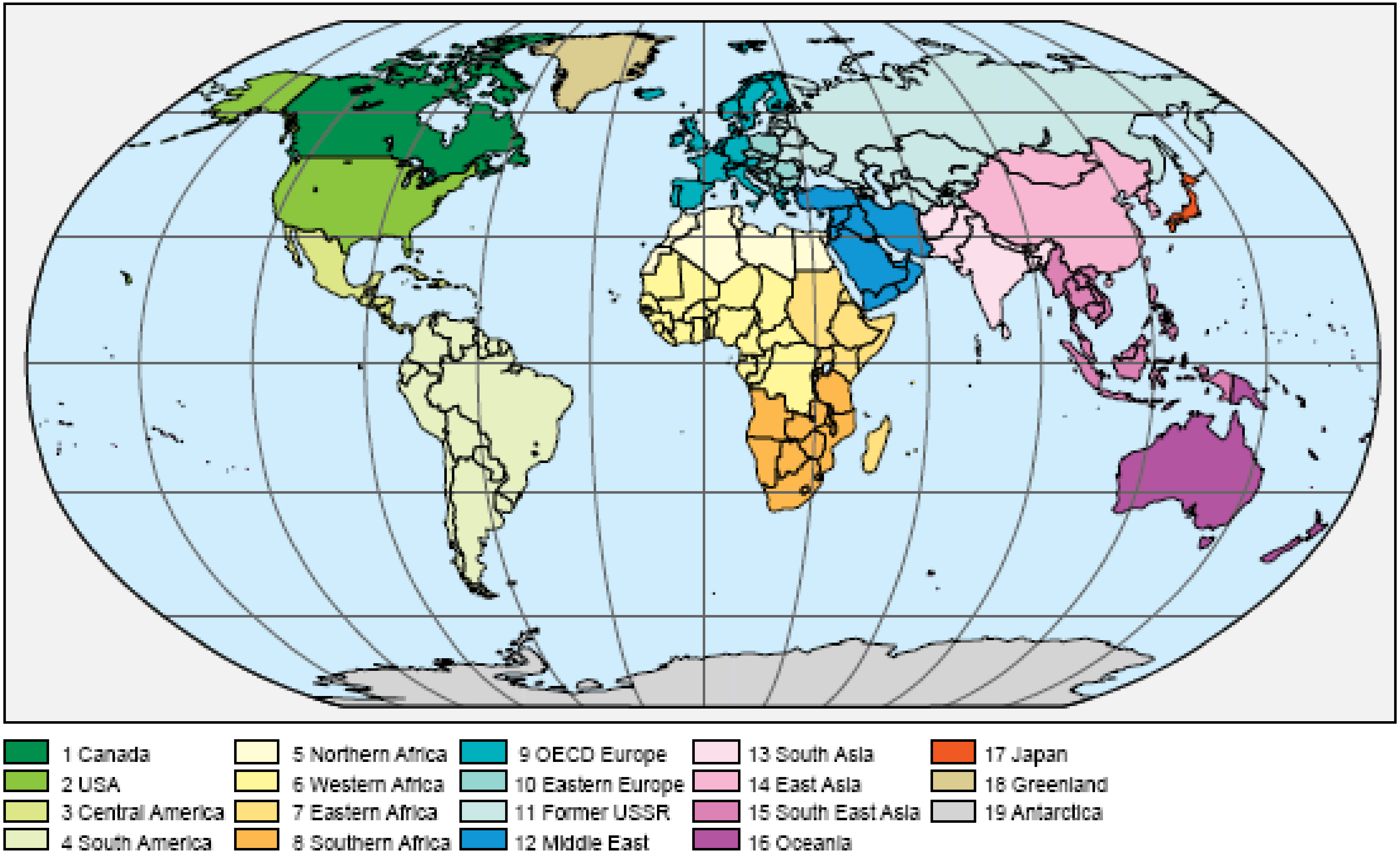
5. Special case: emissions from international marine transport

Discussion

- Can insights from global emission inventories help you in compiling your emission inventory?

- Your inventory will provide us with insights on the “local” situation (validation)

Study domain

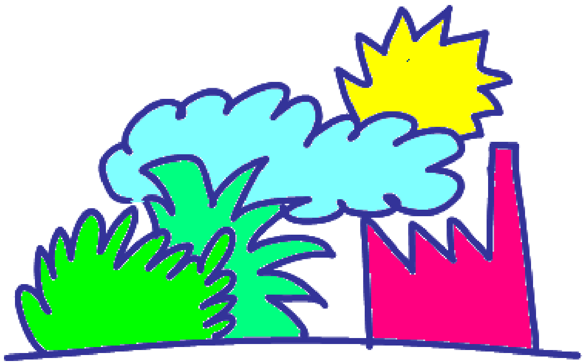


Courtesy: MNP

Unit head: Frank Raes
~ 45 staff members

Global Air Pollution and Climate

Frank Dentener



Integrated Climate Policy Assessment

John van Aardenne

Greenhouse Gases - Agriculture, Forestry and other Land Uses

Guenther Seufert

Different uses of emission inventories

Inventories for policy purposes:
- monitoring the progress/compliance in meeting specific emission targets (National, Kyoto, LRTAP)
- deciding which activities should be regulated to reduce emissions

Inventories for scientific purposes:
- understanding the processes that lead to anthropogenic and natural emissions
- understanding past, present and future change in atmospheric composition due to emissions (through atmospheric dispersion modeling)

Science for policy:
- impact modeling (inventories used to calculate impact on health, ecosystems)
- assessment of transport of air pollutants across country borders and continents (e.g. HTAP modeling).

CLRTAP
Task Force on Hemispheric Transport of Air Poluttion

Task Force on Hemispheric Transport of Air Pollution

- Parties of the Convention on Long-range Transboundary Air Pollution (CLRTAP) decided to create a new task force to develop a fuller understanding of the intercontinental transport of air pollutants in the Northern Hemisphere and to produce estimates of the intercontinental flows of air pollutants for consideration in the review of protocols under the Convention.

Emissions Inventories and Projections for Assessing Hemispheric or Intercontinental Transport

Assessment for hemispheric transport of air pollution requires global gridded emission inventories of (SO_2, NO_x, NMVOC, NH_3, CH_4, OC, BC, PM, and CO)

- The quality of emission inventories varies widely
  - For developed countries, some sector inventories are of high quality, as they have been crosschecked by field studies and laboratory tests and through air quality modeling (e.g. emissions power plants)

- For developing and newly industrializing countries, the quality of emission inventories is lower and sometimes poor:
  - lack of actual emissions measurements and intensive ambient observations,
  - incompleteness of the activity data, and absence of test-based emission factors.
  - A shorter history of inventory development lack of expertise and capable institutions.

Recommendations of Emission workshop (Beijing, 2006) and Interim Assessment report 2007.

- improve the quality of emission methodology and inventories for sources that are poorly known:
  - biomass burning (agricultural waste, biomass for heating and cooking, and forest fires)
  - small and medium scale industry and energy production,
  - transport
  - domestic use of coal.

- Improvements can only be achieved through improved data capture in cooperation with experts from different countries and regions bringing in knowledge of the local conditions governing the emissions in various regions.

- Emissions are changing rapidly in many regions and particularly in Asian countries with rapidly economic growth (emerging economies). There is thus a strong need to update any emission data base to hold as recent data as possible.

20 experts from different world regions

Main issues in inventory construction:

- Land based transport
  - fraction of 'super-emitters' and their emission factors
  - unregistered vehicles (missing fuel statistics/mileage data)
  - mixture of vehicle types and car maintenance

- Small scale stationary combustion
  - local knowledge is essential on technologies in use
  - biofuel emission factors
  - registration of non-commercial biofuel use
  - non-registered fossil fuel use

- Large scale stationary combustion
  - exact location of large point sources
  - penetration and actual efficiency of abatement measures
  - data availability of technological splits
  - activities in Industrial processes

Large scale emission inventories

Simplified equation of emission factor approach

EMISSION = AD x EF (1-(IC x RE))

AD = activity data by sector and technology
EF = uncontrolled emission factor by sector, technology, compound
IC = installed capacity of abatement measure by sector, technology
RE = removal efficiency of abatement measure, by compound

2b. Emitted by?

Classification independent of sector/compound

IPCC
1 Energy
1A1 Energy industries
1A2 Manufacturing industries
1A3 Transport
1A4 Other sectors
1A5 Not specified (military)
1B1 Solid fuels
1B2 Oil and natural gas
1C CO_2 transport, injection, storage
2 Industrial process
2A Mineral products
2B Chemical industry
2C Metal production
2D Non energy, solvents
2E Electronics industry
2F Substitutes ozone depletion sub.
2G Other product use
3 Agriculture, forestry, other land use
3A Land
3B Agriculture, livestock
3C Aggregated sources, non-CO_2
3D Other
4 Waste
4A Solid waste
4B Wastewater
4C Waste incineration
4D Other
5 Other
5A Indirect N_2O from deposition
5B Other

EDGAR
Energy
B10-F10: Industrial combustion
B20-F20: Power generatoin
B30-F30: Transformation
B40-F40: Residential, othr
B50-F50: Transport
F60: Non-energy
F70: Coal production
F80: Oil production
F90 Gas production
Industrial processes
I10: Iron and steel production
I20: Non-ferro production
I30: Chemical industry
I40: Building materials
I50: Food industry
I70: Solvents
I90: Misc. Industry
Agriculture/land use
L10: Arable land
L15: Rice cultivation
L20: Enteric fermentation
L30: Animal waste management
L40: Biomass burning
L50: Crop production
L60: Animal waste to soil
L70: Indirect N_2O
L80: A forestation
Waste
W10: Landfills
W20: Wastewater treatment
W30: Human wastewater disposal
W40: Waste incineration
W50: Misc. waste

Classification dependent on compound

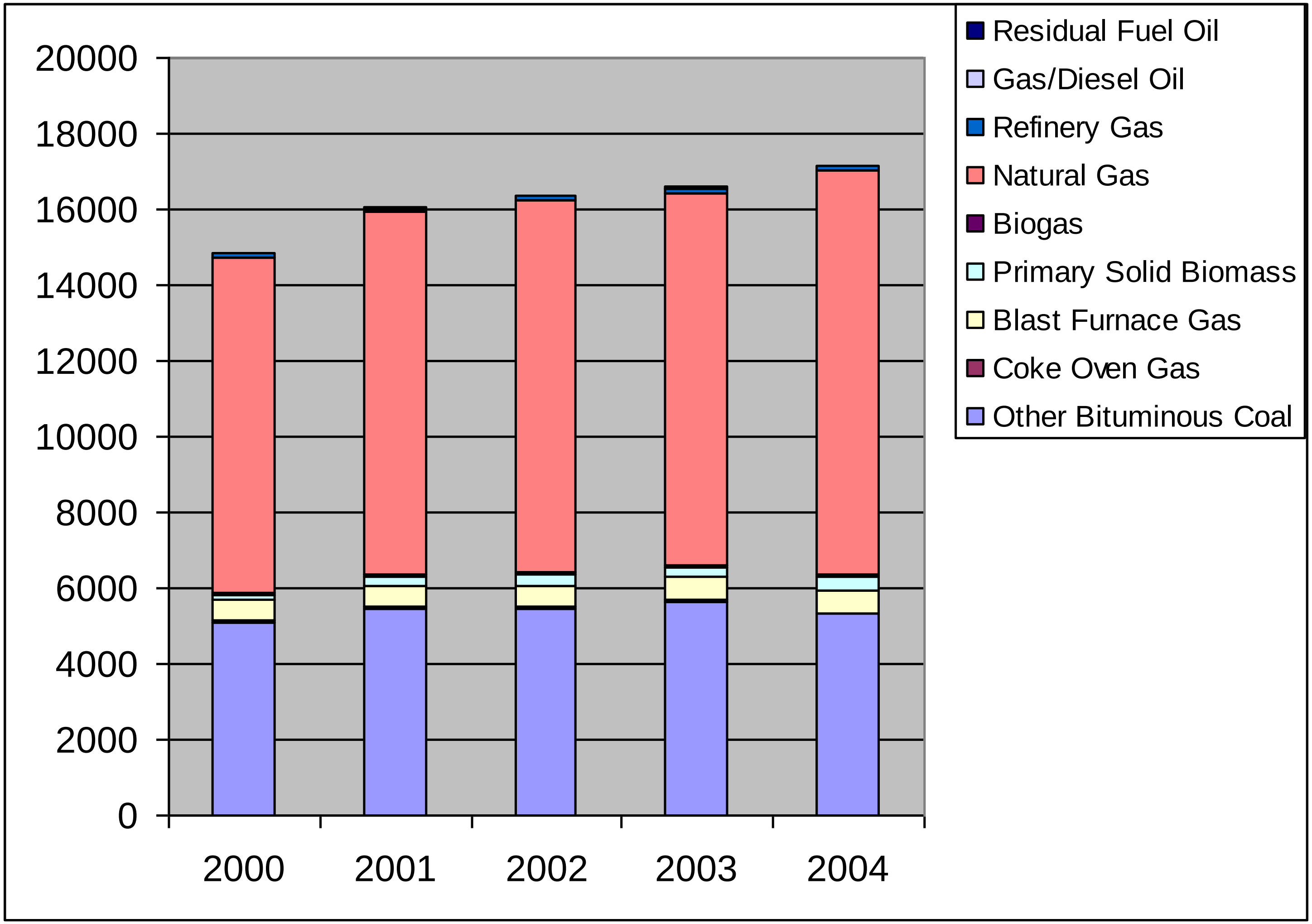
GEIA NH_3 emission dataset
- **Domestic animals**
- Synthetic fertilizers
- Crops
-Humans
- Biofuel
- Savannah burning
- Deforestation
- Agricultural residual bruning
- Fossil fuel processes
- Oceans

Other classifications:
- EMEP/CORINAIR (SNAP)
- GEIA v1
- US EPA
- etc.

Methodology: typical sources of activity data by sector

Energy	Source of information
Fossil fuel combustion Biofuel combustion Fuel production	IEA: Energy balances of OECD and non-OECD countries (e.g. IEA/OECD, year). UN: Energy Statistics Yearbook (UN, year) Hall et al (1994) additional info on biofuel Olivier et al. 1996: Country studies on split surface/underground mining
International shipping	(a) Bunker statistics (IEA/OECD, year) (b) Eyring et al. (2005).
Industrial processes	UN industrial commodity statistics USGS Geological Survey Minerals Yearbook
Solvent use	Olivier et al. 1996: estimates made by EDGAR team
Fertilizer application Animals Crop production	FAOSTAT: agricultural data (e.g. FAO, year) " "
Agricultural waste burning	FAOSTAT: agricultural data (FAO, year). Smill (1999)
Landfills	Based on waste generation figures per capita for 1990 (IPCC, 1997 and Adler, 1994)
Wastewater	Based on per capita organics loading and industrial waste water generation selected by Doorn et al. (1997)
Waste incineration	Olivier et al. 1996: per capita waste burning assumption
Biomass burning	v32: FAOSTAT: forestry data (FAO, year). FT200: Global Fire Emissions Database (Van der Werf et al., 2003)

AD: Fuel combusted in public power plants (ktoe) in The Netherlands (IEA, 2006)



Main technologies in power plant sector:

Grate firing
Pulverized coal (wet bottom)
Pulverized coal (dry bottom)
Fluidized bed combustion
Oil/gas boiler
Internal combustion engine
Gas Turbine

Example: Technologies in NL power plants (IEA)

Fuel type	Technology	%
Solid fuels	Grate firing	4
	Pulverized coal (dry)	85
	Fluidized bed	11
Gaseous fuels	Gas turbine	37
	Gas turbine in combin	42
	NS boiler	21

Uncontrolled emission factors

Example from US.EPA boiler emission inventory (NO_x as NO_2)

Other bituminous coal:

- grate firing:	192 kg/TJ
- pulverized coal (wet)	540 kg/TJ
- pulverized coal (dry)	380 kg/TJ
- fluidized bed	88 kg/TJ

Coke oven gas:

- steam boiler:	38 kt/TJ
- internal combustion engine	1180 kg/TJ
- gas turbine	140 kg/TJ

Control measures

Primary: suppress formation compound that is emitted (combustion modification)

Secondary: end-of-pipe techniques to reduce compound emission already formed

Example: Selective catalytic reduction (SCR) for NO_x

a) with NH3

$4\ NO + 4\ NH_3 + O_2 = 4\ N_2 + 6\ H_2O$

$6\ NO_2 + 8\ NH_3 = 7\ N_2 + 12\ H_2O$

b) with urea

$4\ NO + 2\ (NH_2)2CO + 2\ H_2O + O_2 = 4\ N_2 + 6\ H_2O + 2\ CO_2$

$6\ NO_2 + 4\ (NH_2)2CO + 4\ H_2O = 7\ N_2 + 12\ H_2O + 4\ CO_2$

Removal efficiency: 80-95%

Cost: 2000-3000 Euro/year, depending on flue gas volume

Reference: Integrated Pollution Prevention and Control Reference Document on Best Available Techniques for Large Combustion Plants, European Commission July 2006

Selection of emissions data as typically found in literature

Capacity (MW_{th})	Comb. Tech.	Emission reduction measures	Emissions to air (mg/Nm^3)							Remarks
			SO_2	NO_X	Dust	CO	HF	HCl	NH_3	
50 – 100	GF									
	PC		52 – 128	154 – 158		18 – 31	10			
	AFBC									
	PFBC	Limestone injection		214 – 257						
	PFBC	2 x 70 MWe with SCR (+district heating)	170	50		20 – 40				Fuel: 0.7% sulphur bituminous coal.
100 – 300	GF									
	PC									
	AFBC	Limestone injection at the level of secondary air	200 – 800	150 – 300	30 – 50	100 – 150				Hot-type, grate firing combustion technique
	AFBC	FF/FGD (wet)/SCR	40 - 110							
	AFBC	FGD (sds)/FF/SCR	75	322	14	5.7	0.05	0.7		
	PFBC	Limestone/SCR		43 – 114						Plant in Japan
	PFBC	Limestone/SNCR		29 – 143						
	CFBC	Limestone/ESP	100 – 200	60 – 160						
>300	PC	No abatement	2000 – 3000							1 % sulphur content standard coal
	PC	ESP/FGD(wet)/SCR	20 – 252	90 – 190	3 – 11	12 – 25	0.2 – 3	1.7 – 30	0.16 – 0.5	Dry bottom boiler Several LCPs
	PC	ESP/FGD(wet)/SCR	185	200	8	27	7	7	0.5	Wet bottom boiler
	PC	Pm/FGD (sds)/ESP/SCR	130	140	5 – 10					
	PC	Pm/FGD(dsi)/ESP	170	270	20					
	PC	Pm (LNB)/FGD(dsi)/FF	170	250	20					
	PC	Pm (reburning gas-coal)		250 - 350						
	PC	Pm (reburning coal-coal)		300 - 430						
	CFBC	limestone+ESP	100 – 200	100 – 250	30 – 50					plants in France, US and Poland

Notes:
GF (Grate firing)
PFBC (Pressurised fluidised bed combustion)
FGD(dsi) (Flue-gas desulphurisation by dry sorbent injection)
Pm(..) (Primary measures to reduce NO_X)
PC (Pulverised coal combustion)
FGD(wet) (Wet flue-gas desulphurisation)
ESP (Electrostatic precipitator)
SCR (Selective catalytic reduction of NO_X)
AFBC (Atmospheric fluidised bed combustion)
FGD(sds) (Flue-gas desulphurisation by using a spray drier)
FF (Fabric filter)
SNCR (Selective non catalytic reduction of NO_X)

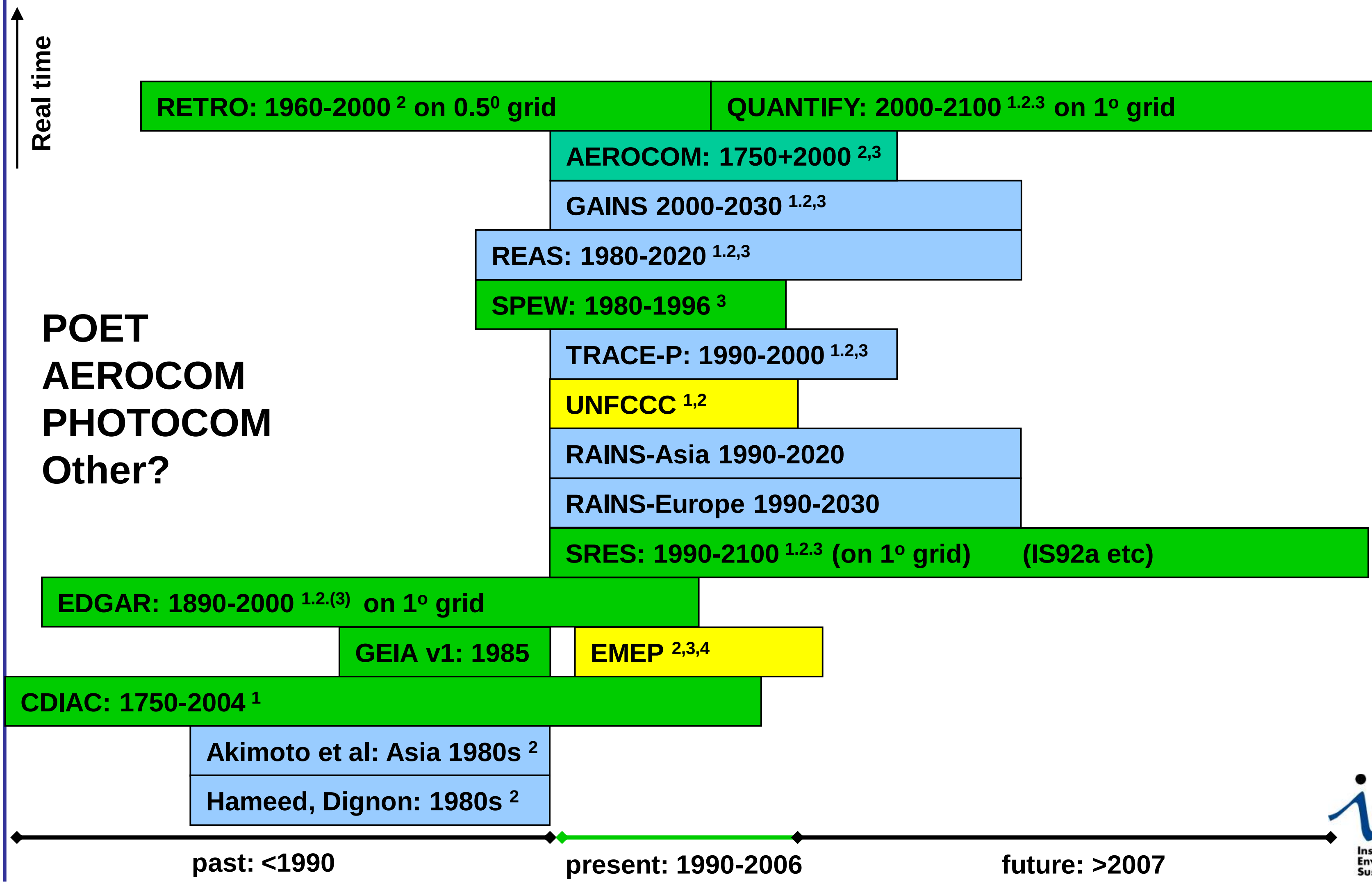
Variety in (large scale) emission inventories

Websites with global data:
- GEIA
- WRI (CAIT/WRI Earth-trends)

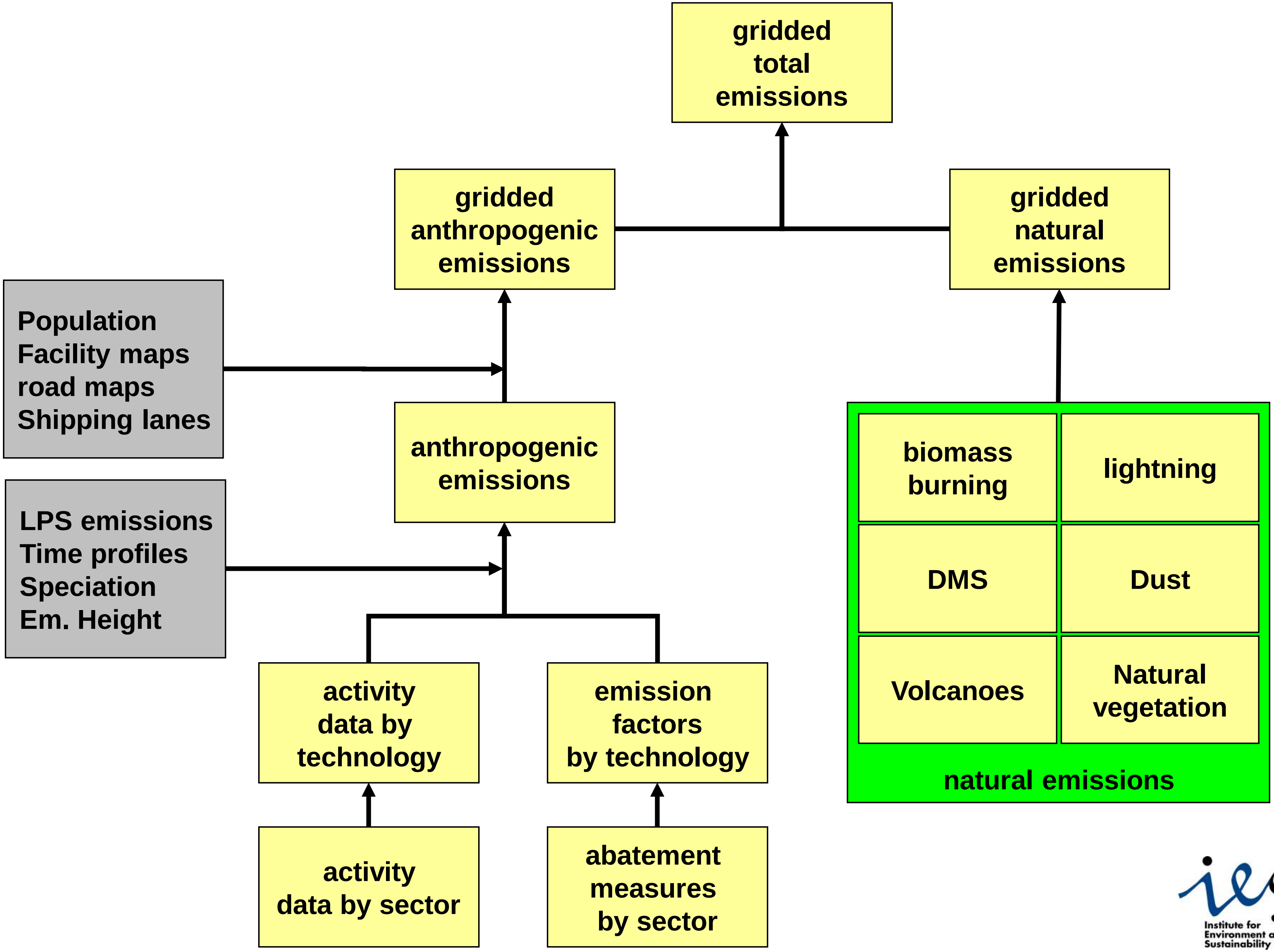
Websites with LPS data:
- EPER
- NEIT

National inventories
Regional inventories
Global inventories

[1] Greenhouse gas
[2] Air pollutants
[3] Aerosol
[4] Other



Methodology: constructing gridded global emission inventories



2c. Importance of different sector

The relative importance for global emissions of different sectors and fuel types is presented in Table 4.2. The contributions shown in this table can be markedly different, however, for individual countries and regions. The estimates are based on EDGAR FT2000 (Olivier et al., 2005), Bond et al. (2004), EDGARv2 (Olivier et al., 1996), and Bouwman et al. (1997).

Species	Large stationary combustion		Small stationary combustion		Transport		Industrial processes	Agriculture	Waste	Biomass Burning
	Fossil fuel	Biofuel	Fossil fuel	Biofuel	Road	Non-road				
CO	2	1	3	24	19	1	4	0	0	46
NH_3	0	0	0	3	0	0	1	82	6	8
NO_x	28	1	2	5	22	13	5	0	0	23
NMVOC	23[a]	2	1	16	20	3	16	0	2	17
SO_2	62	0	5	2	2	6	19	0	0	2
BC	3	2	15	22	14	5	0	0	0	38
OC	1	3	2	21	4	0	0	0	0	69
CH_4	30	0	1	4	0	0	0	40	18	6

CO: ~ 900 Tg

NOx: ~ 130 Tg

NMVOC: ~ 165 Tg

SO_2: ~150 Tg

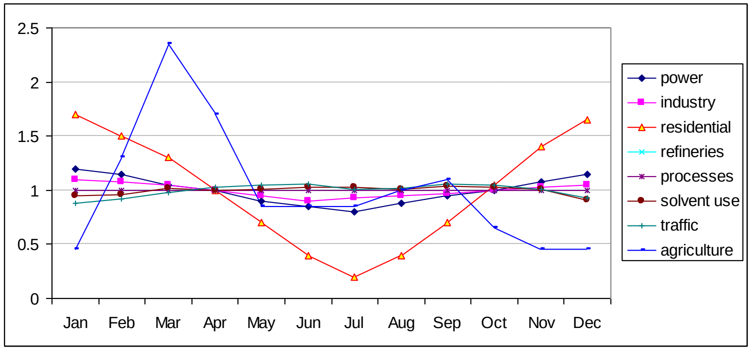
BC: ~ 8 Tg

OC: ~33 Tg

CH4: ~320 Tg

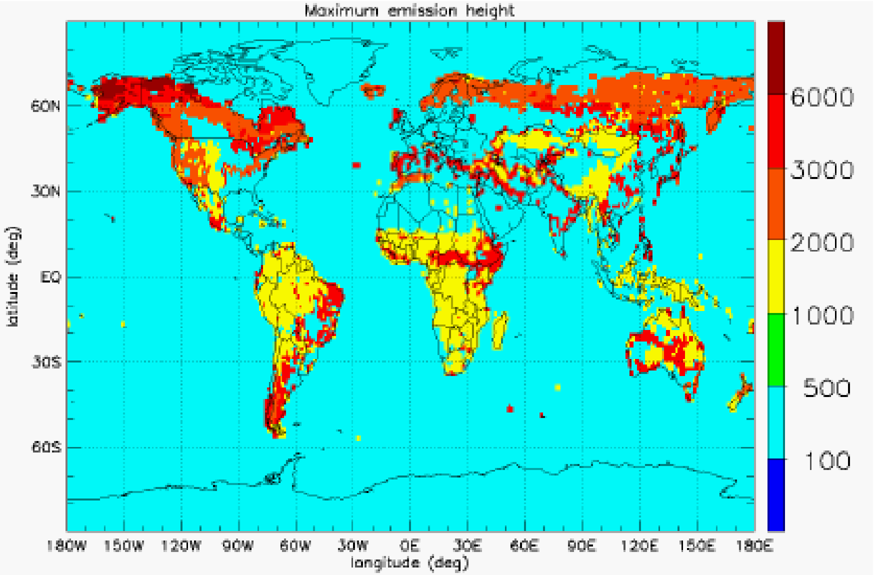
Methodology: post-processing of emission calculation

- Correct country totals with LPS emissions data (e.g. from EPER)
- Speciation of total NMVOC (alcohols, ethane, etc.)
- Time profiles

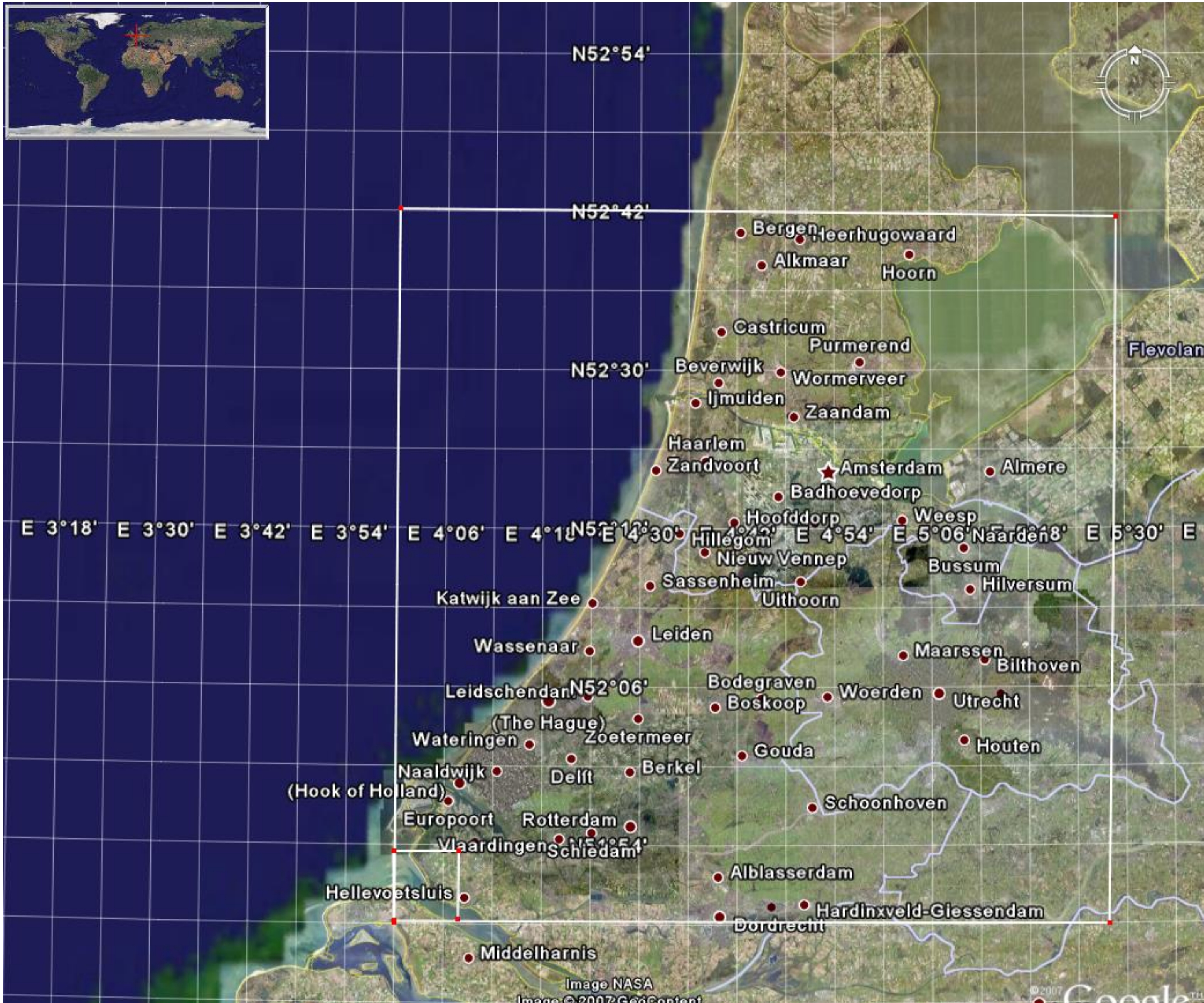


LOTOS time profiles, Veldt (1992)

- Emission height



Allocation of emissions on grid (1x1 vs 0.1x0.1 grid)



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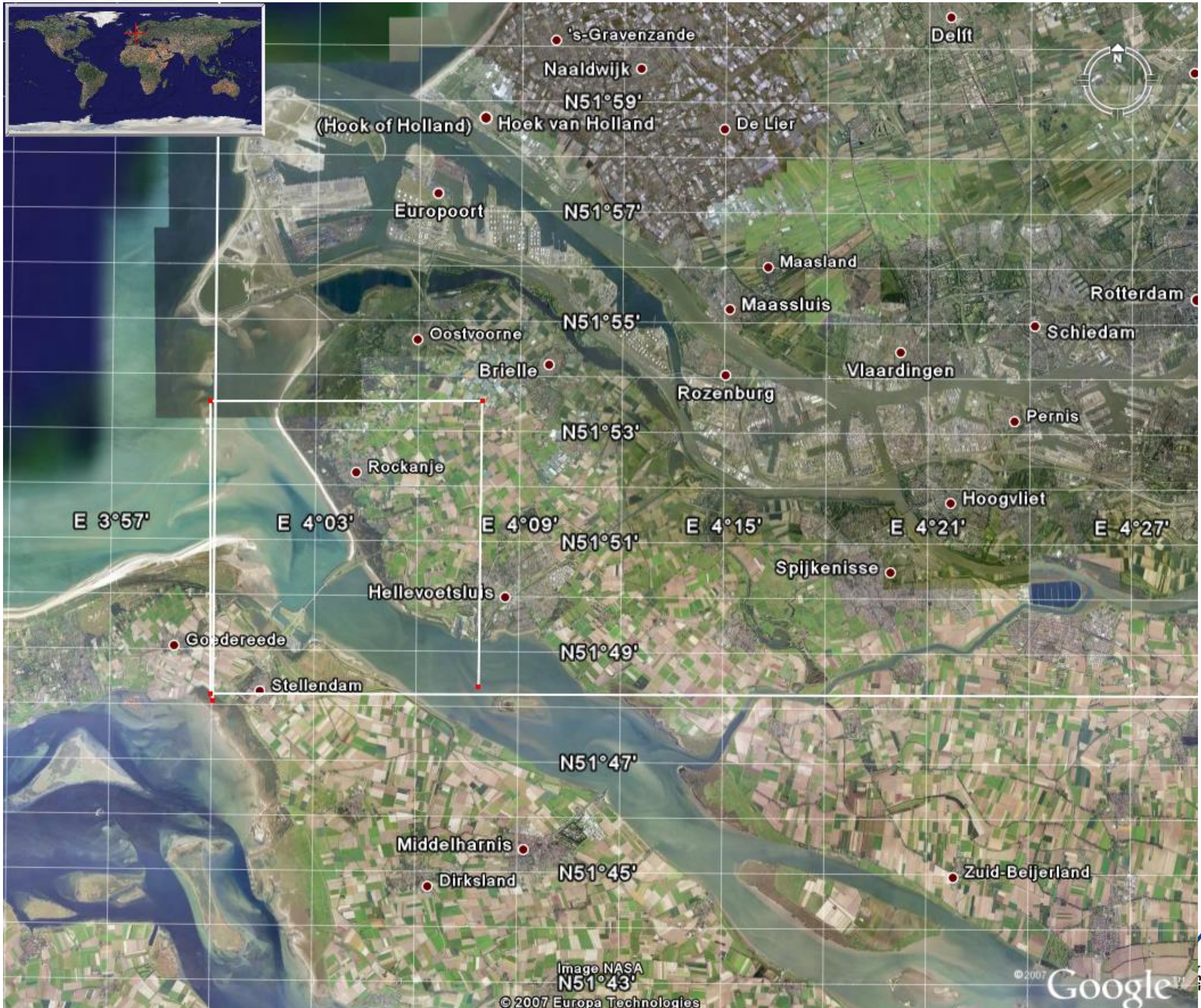
Allocation of emissions on grid (1x1 vs. 0.1x0.1 grid)



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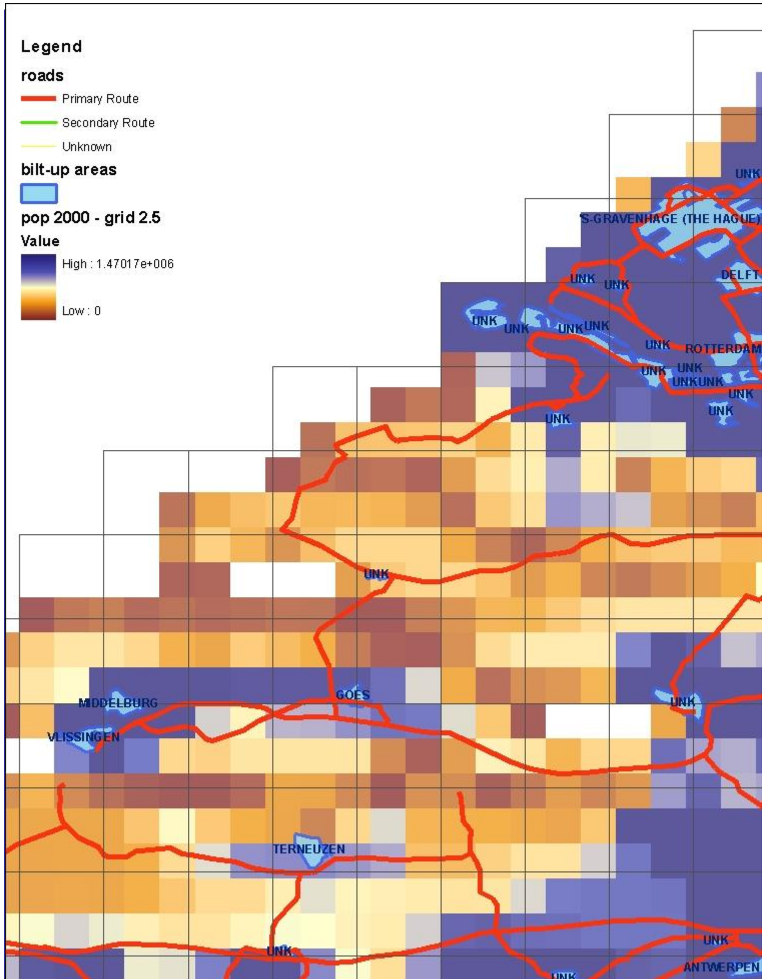
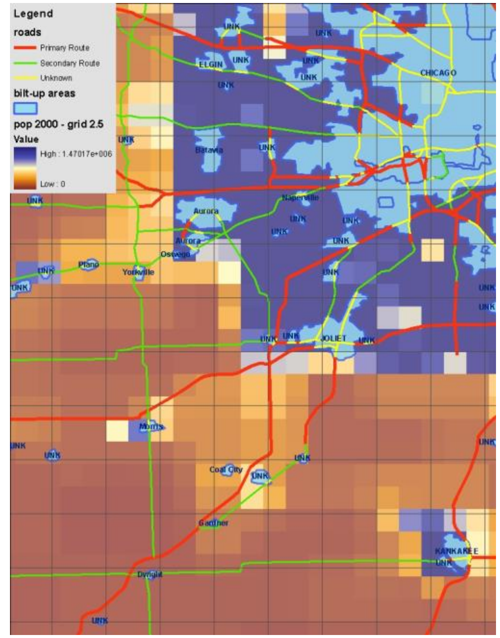
Allocation of emissions on grid (0.1x0.1 grid)





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Resulting data distributed to modelers

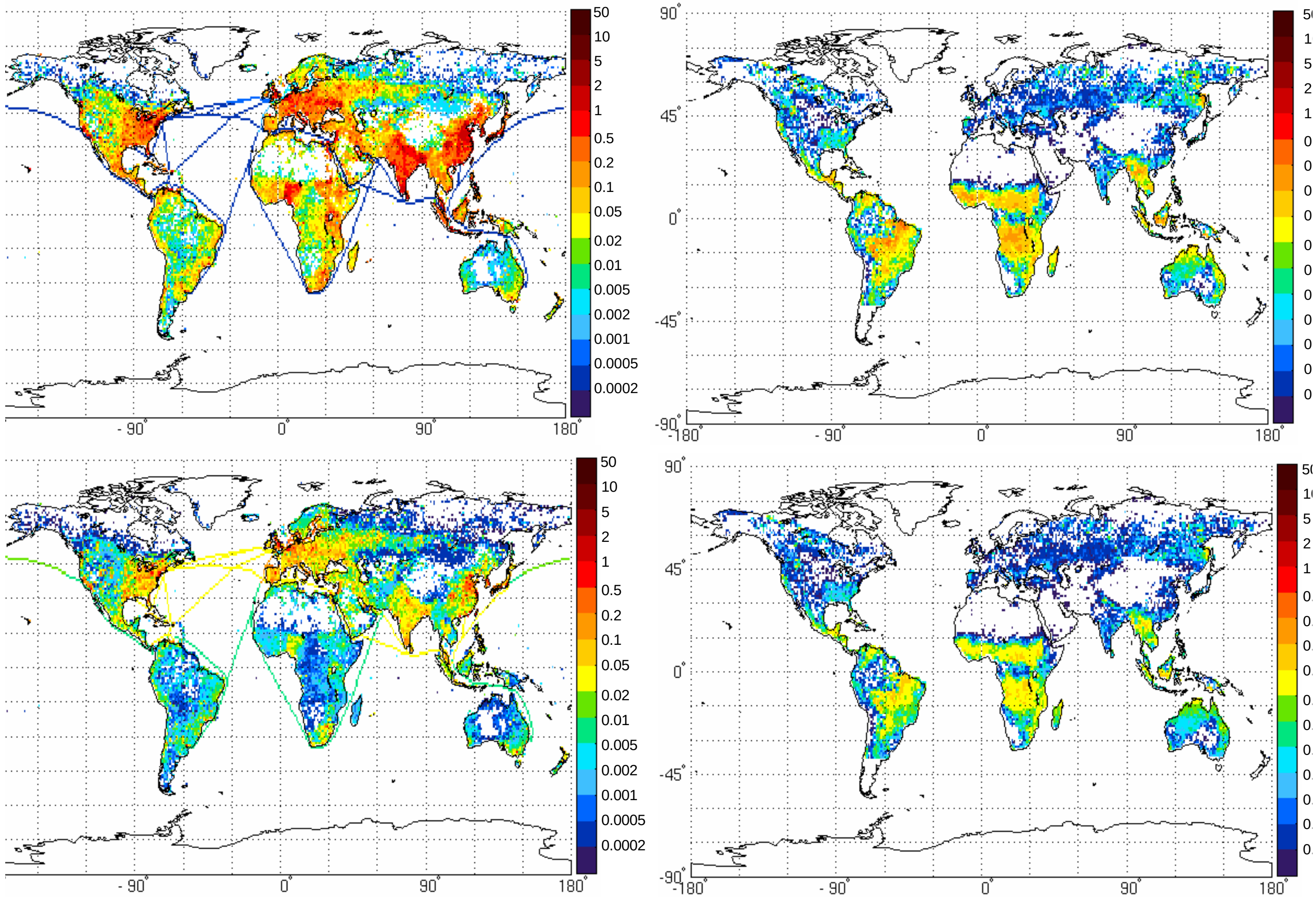
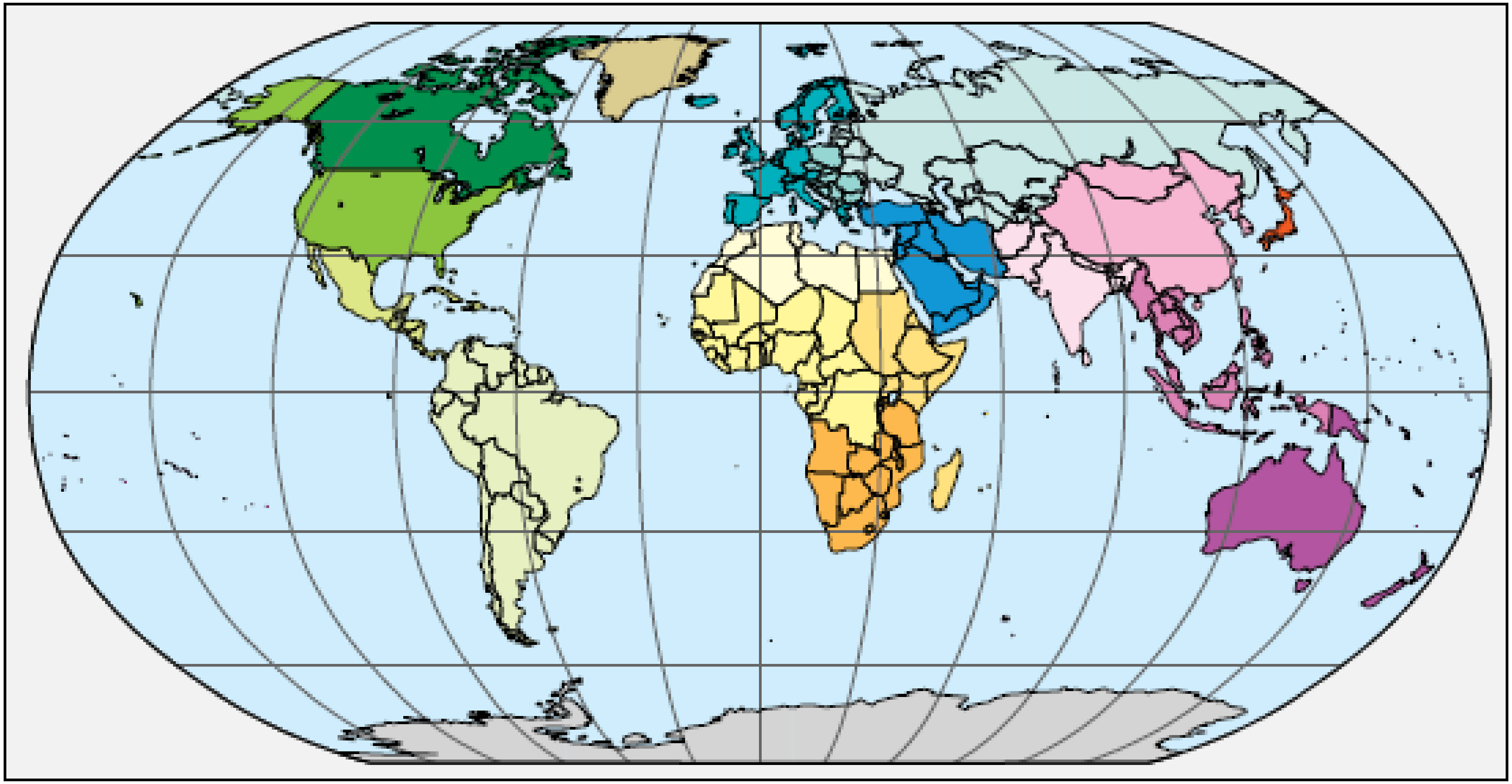


Figure 4-2. Geographical distribution of global emissions. Global emissions of carbon monoxide (top panels) and nitrogen oxides (bottom panels) from anthropogenic sources (left panels) and biomass burning (right panels), gridded at 1° × 1° resolution, taken from the EDGARv32FT2000 dataset (units 10^9 kg m^{-2} s^{-1}).

Overview of regional emissions

Emission trends: world regions



1 Canada	5 Northern Africa	9 OECD Europe	13 South Asia	17 Japan
2 USA	6 Western Africa	10 Eastern Europe	14 East Asia	18 Greenland
3 Central America	7 Eastern Africa	11 Former USSR	15 South East Asia	19 Antarctica
4 South America	8 Southern Africa	12 Middle East	16 Oceania	

Courtesy: MNP

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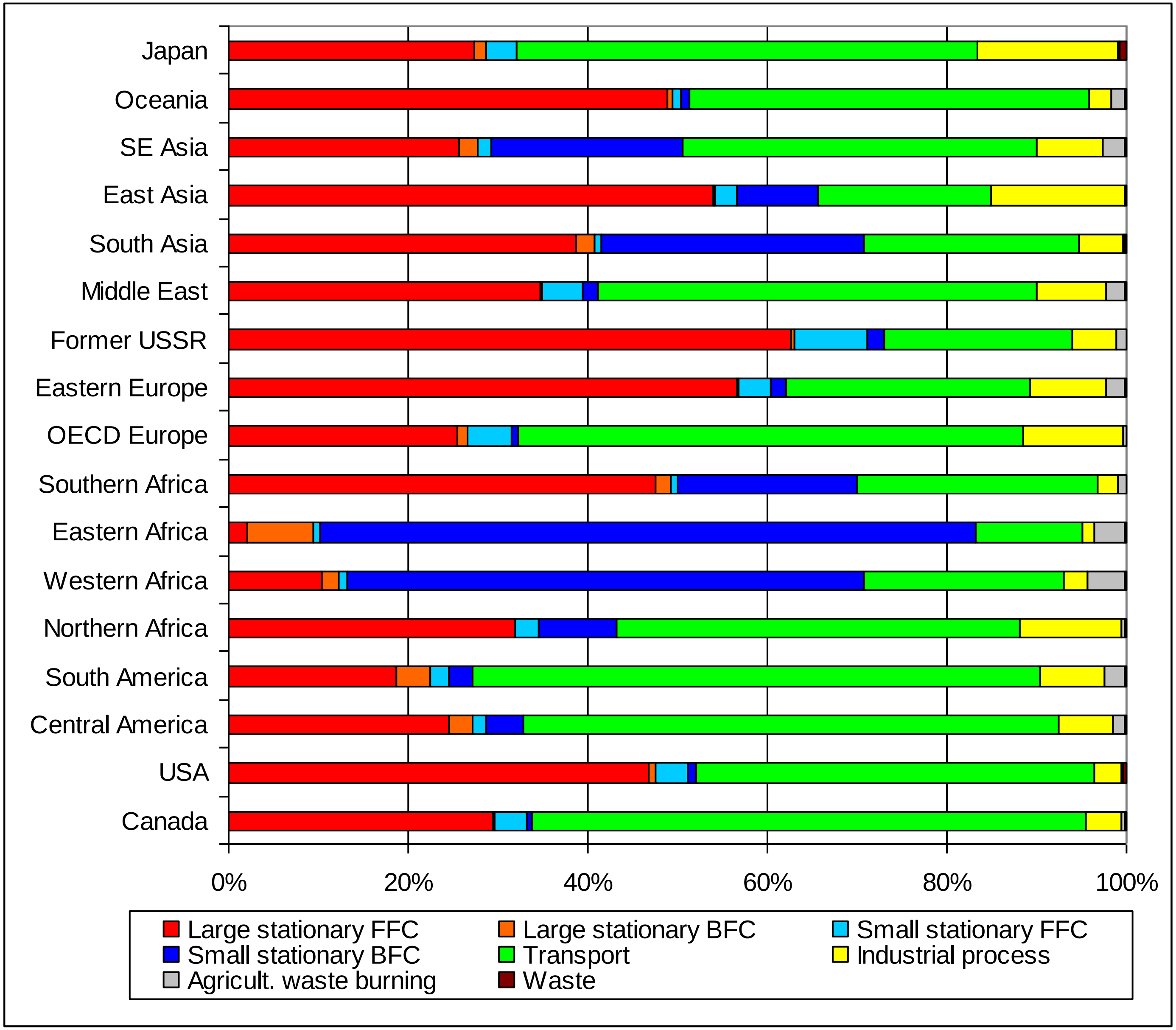
NOx emissions in 2000 (excluding international shipping and aviation)



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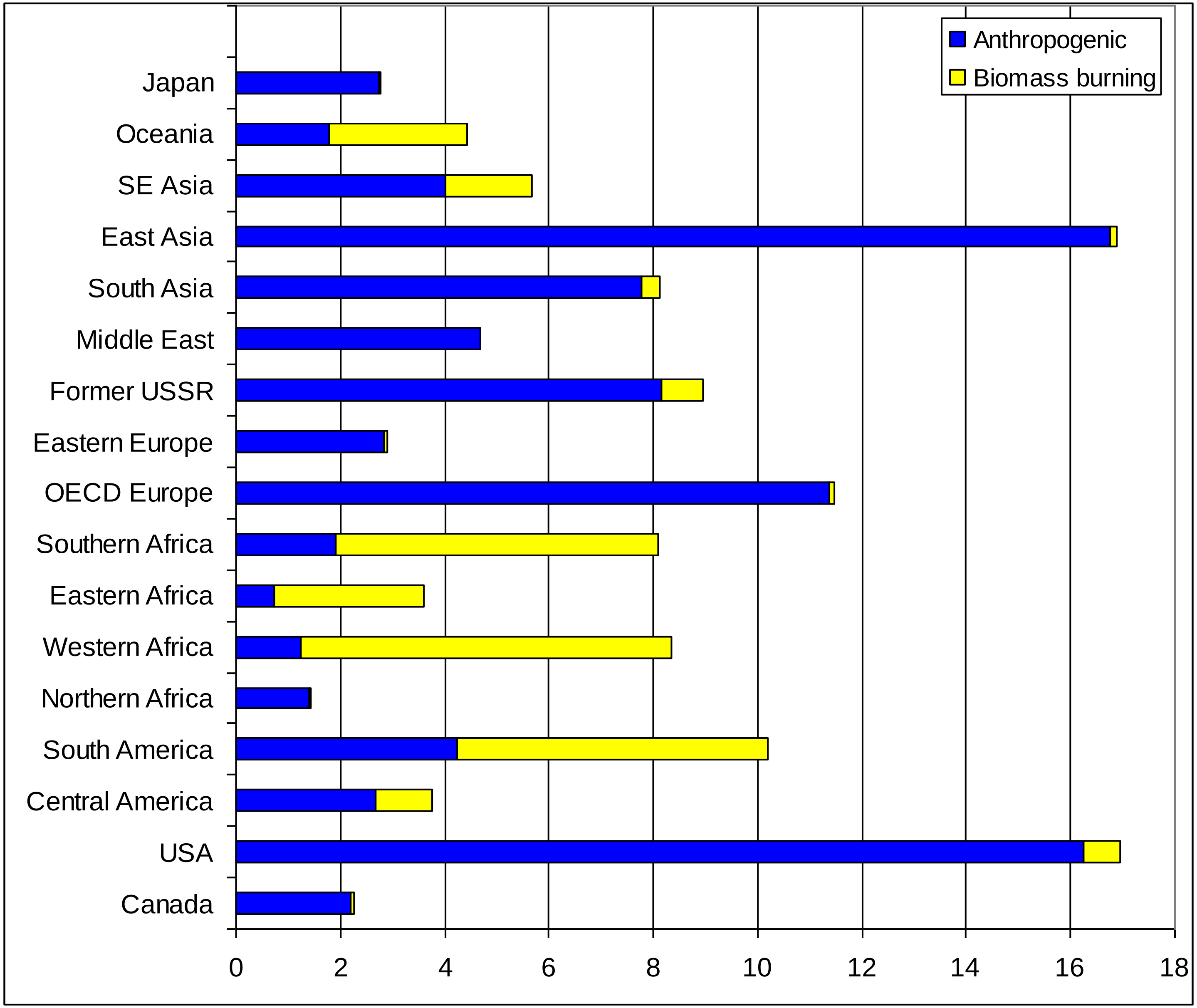
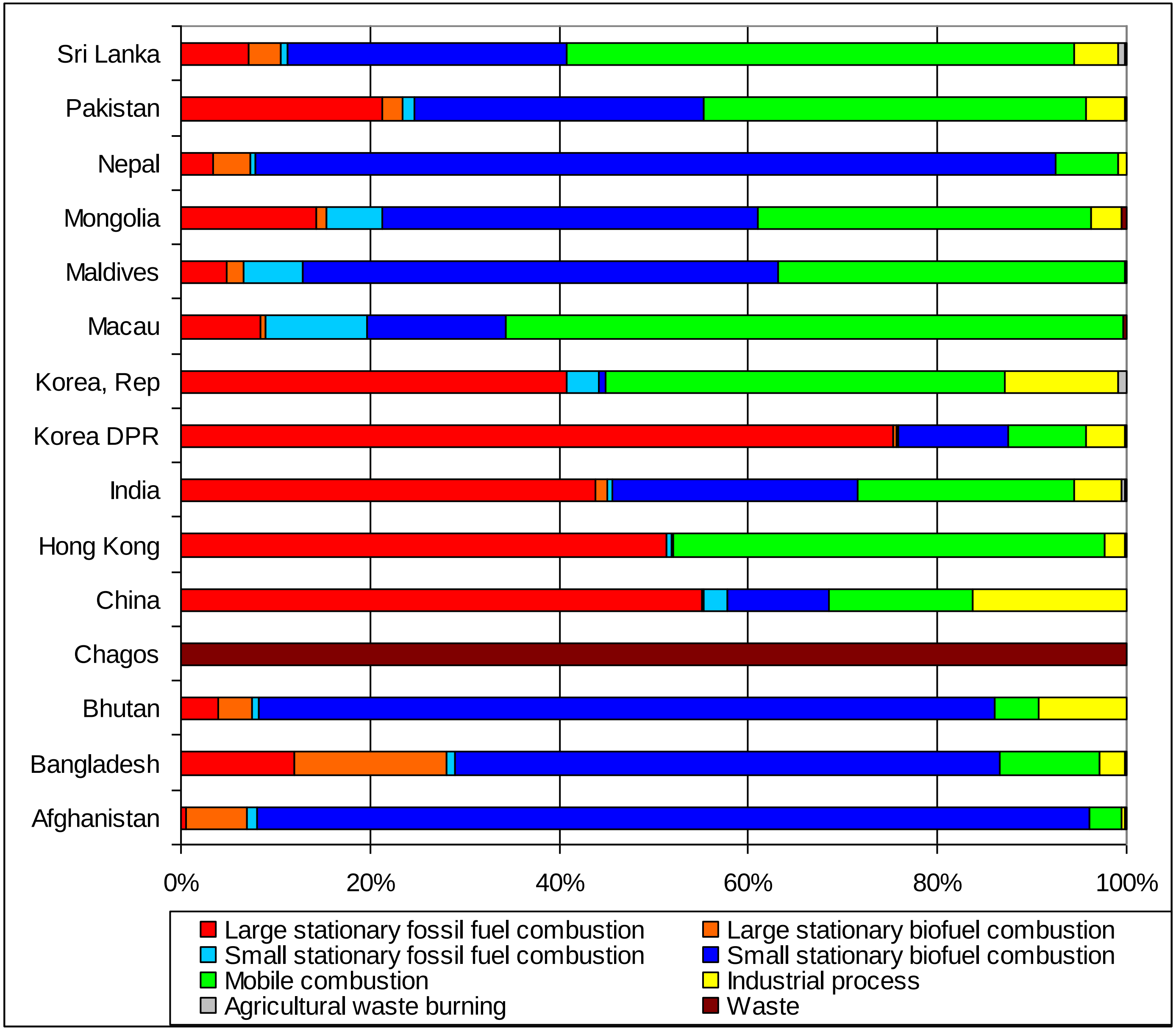
NOx emissions Tg NO_2 (including biomass burning, excl shipping/aviation)

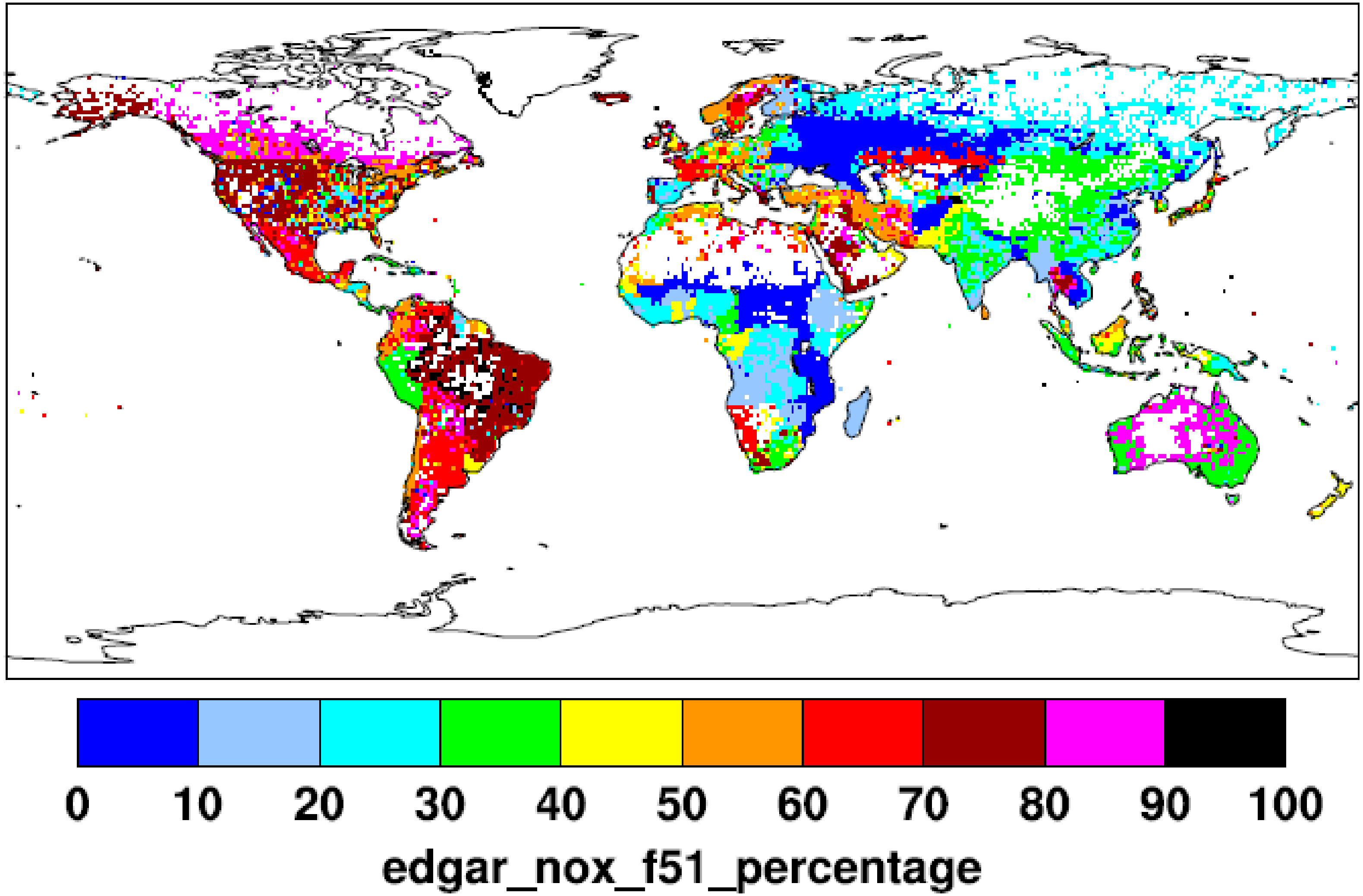


Shipping: 9.6 Tg
Aviation: 2.3 Tg

NOx emissions Tg NO_2 (example South Asia and East Asia)

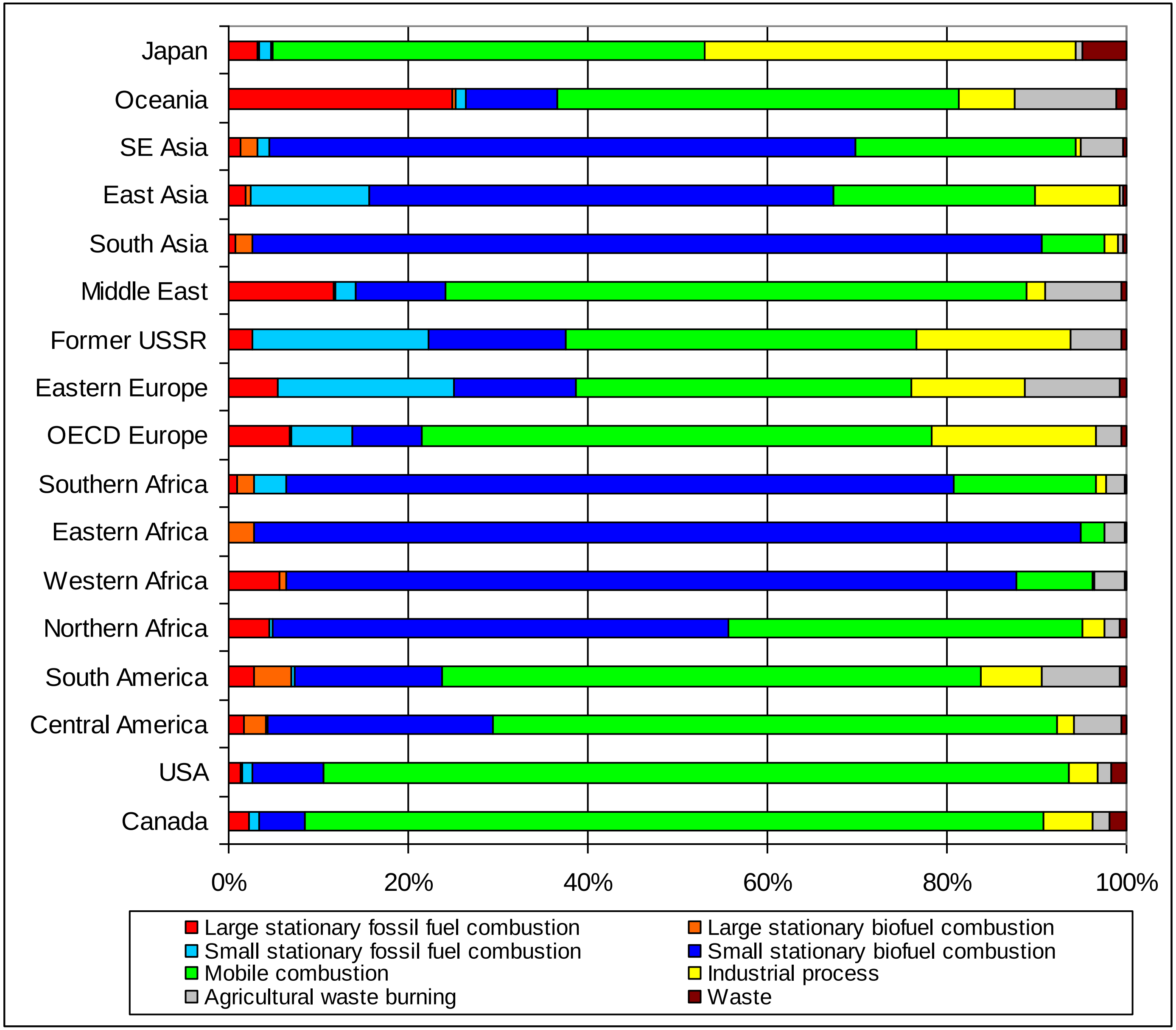


NOx Contribution of road transport to grid cell emission

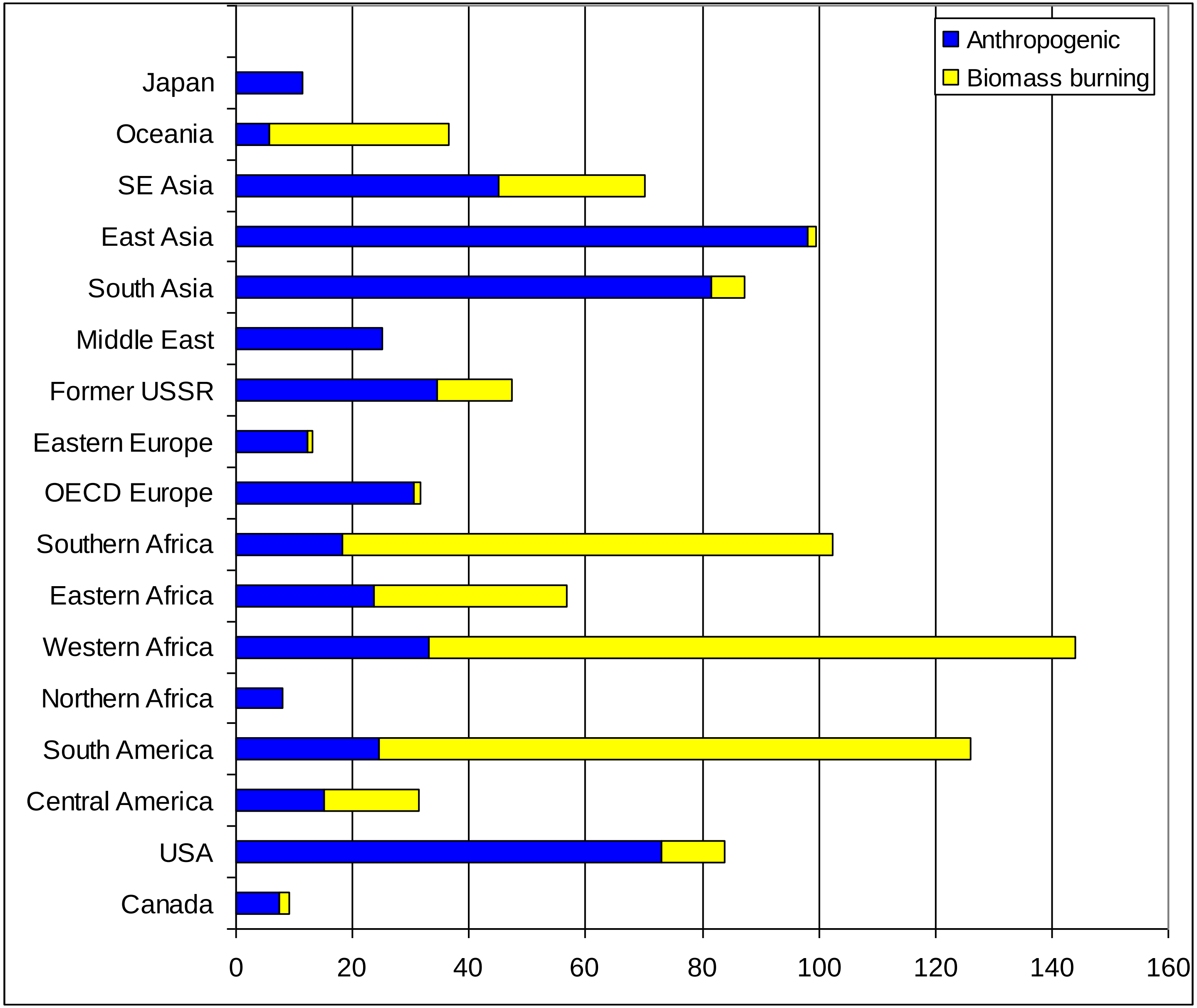


Butler, Lawrence, Gurjar, van Aardenne, Schultz and Lelieveld, the representation of megacities in global emission inventories, submitted to Atmospheric Environment, 2007

CO emissions in 2000 (excluding international shipping and aviation)



CO emissions Tg CO (including biomass burning, excl shipping/aviation)



Shipping: 0.1 Tg
Aviation: 1.8 Tg

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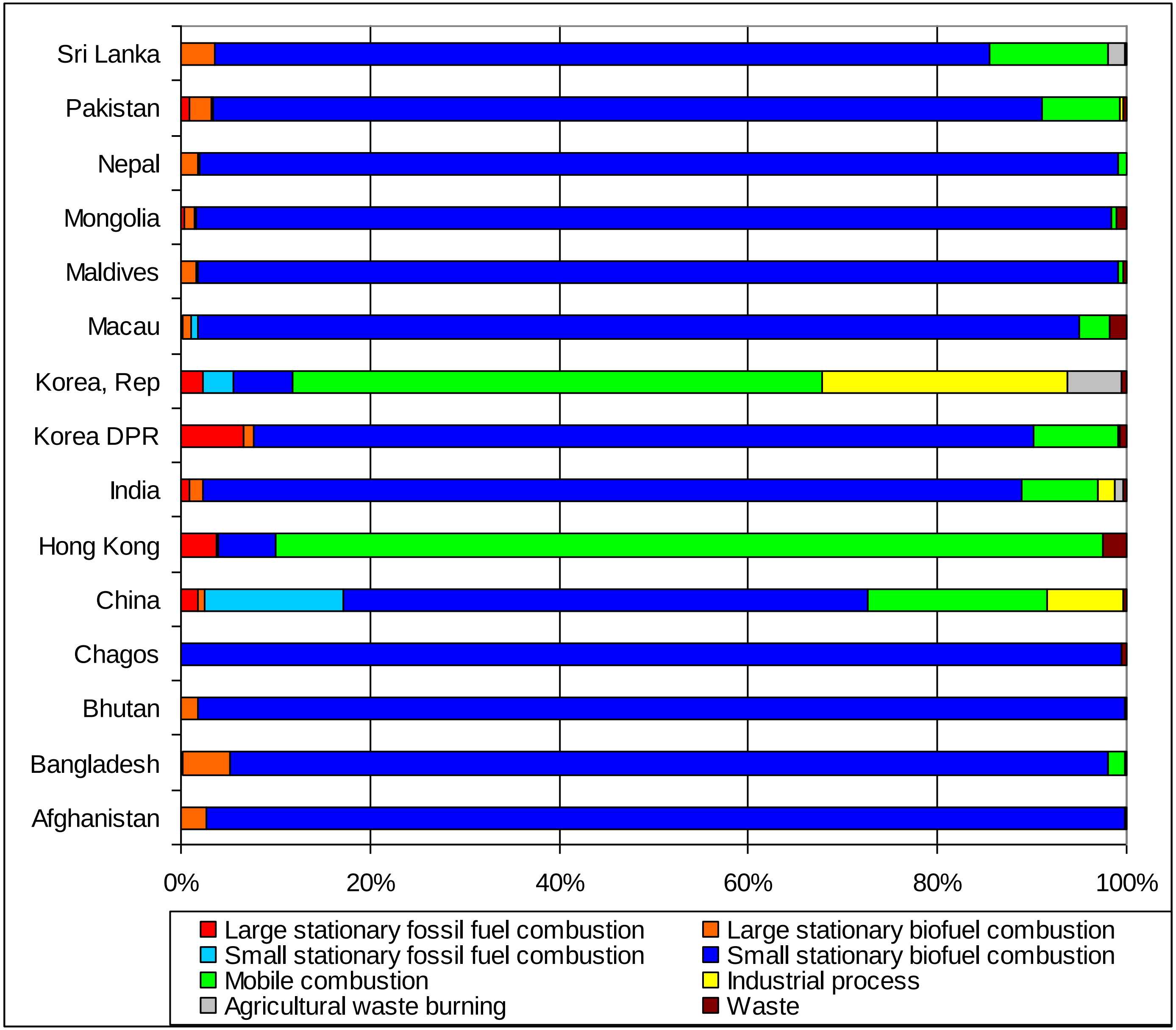
CO emissions Tg CO (example South Asia and East Asia)



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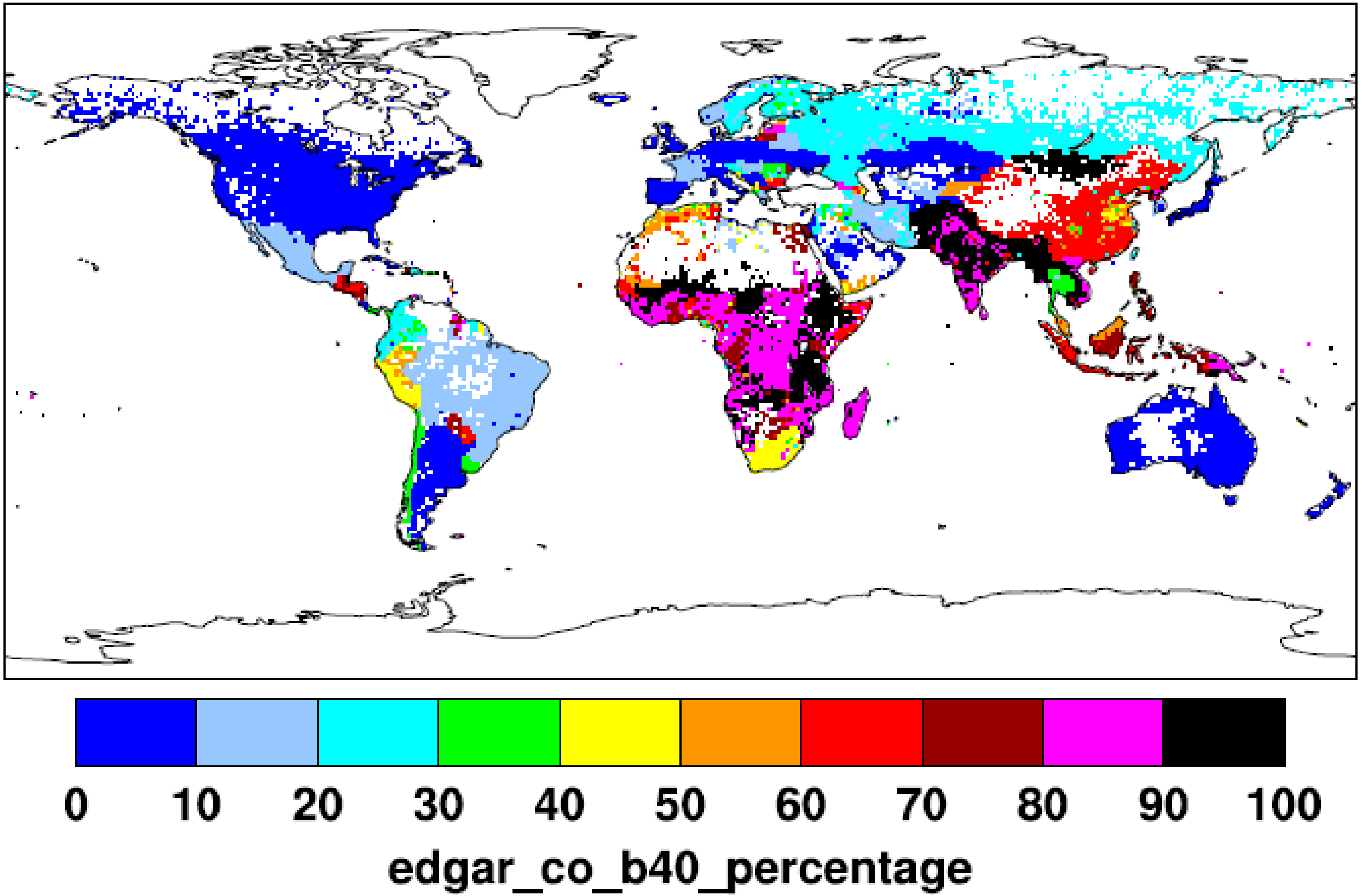
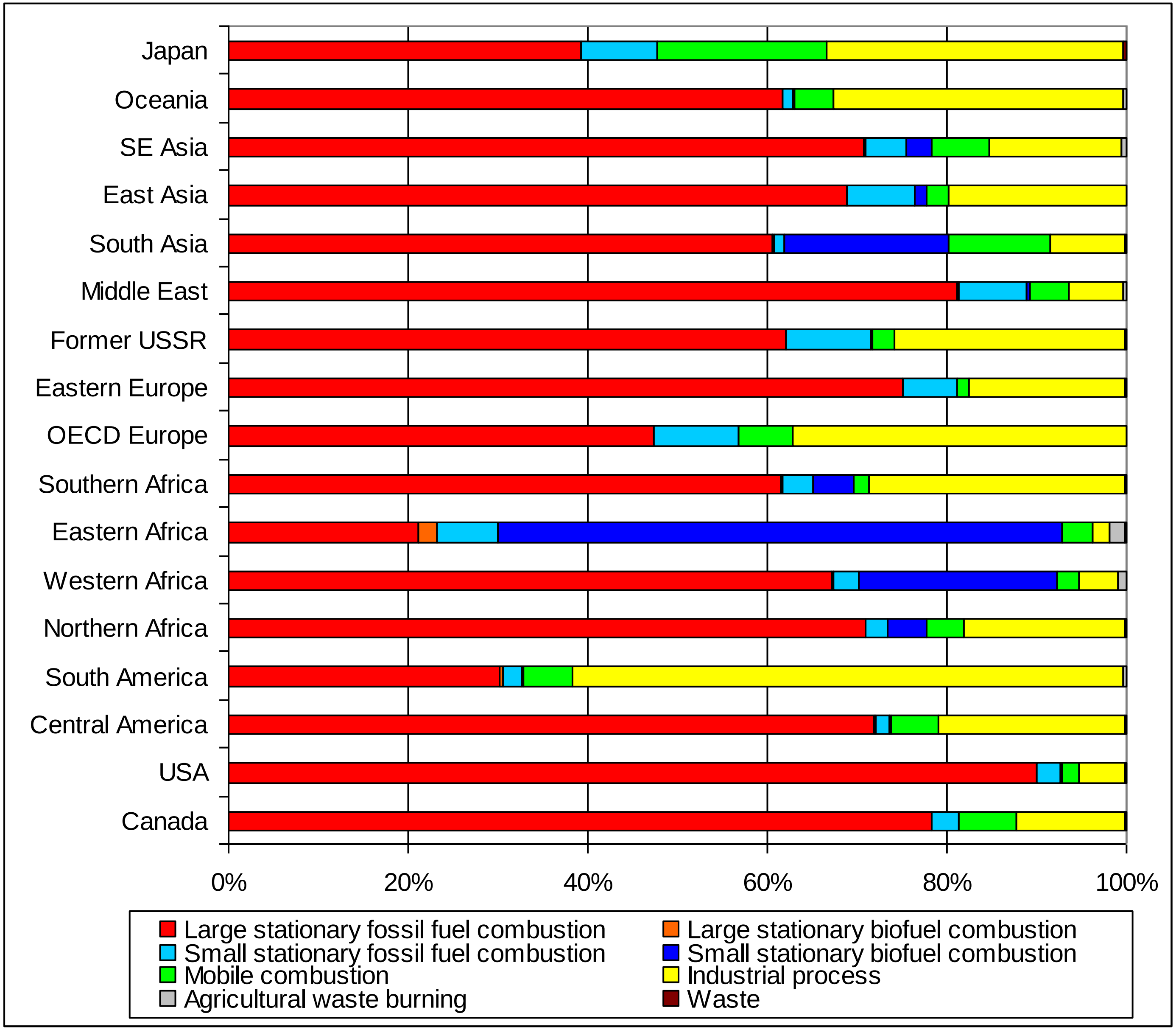
CO: Contribution of residential biofuel combustion to grid cell emission



Butler, Lawrence, Gurjar, van Aardenne, Schultz and Lelieveld, the representation of megacities in global emission inventories, in preparation.

SO_2 emissions in 2000 (excluding international shipping and aviation)



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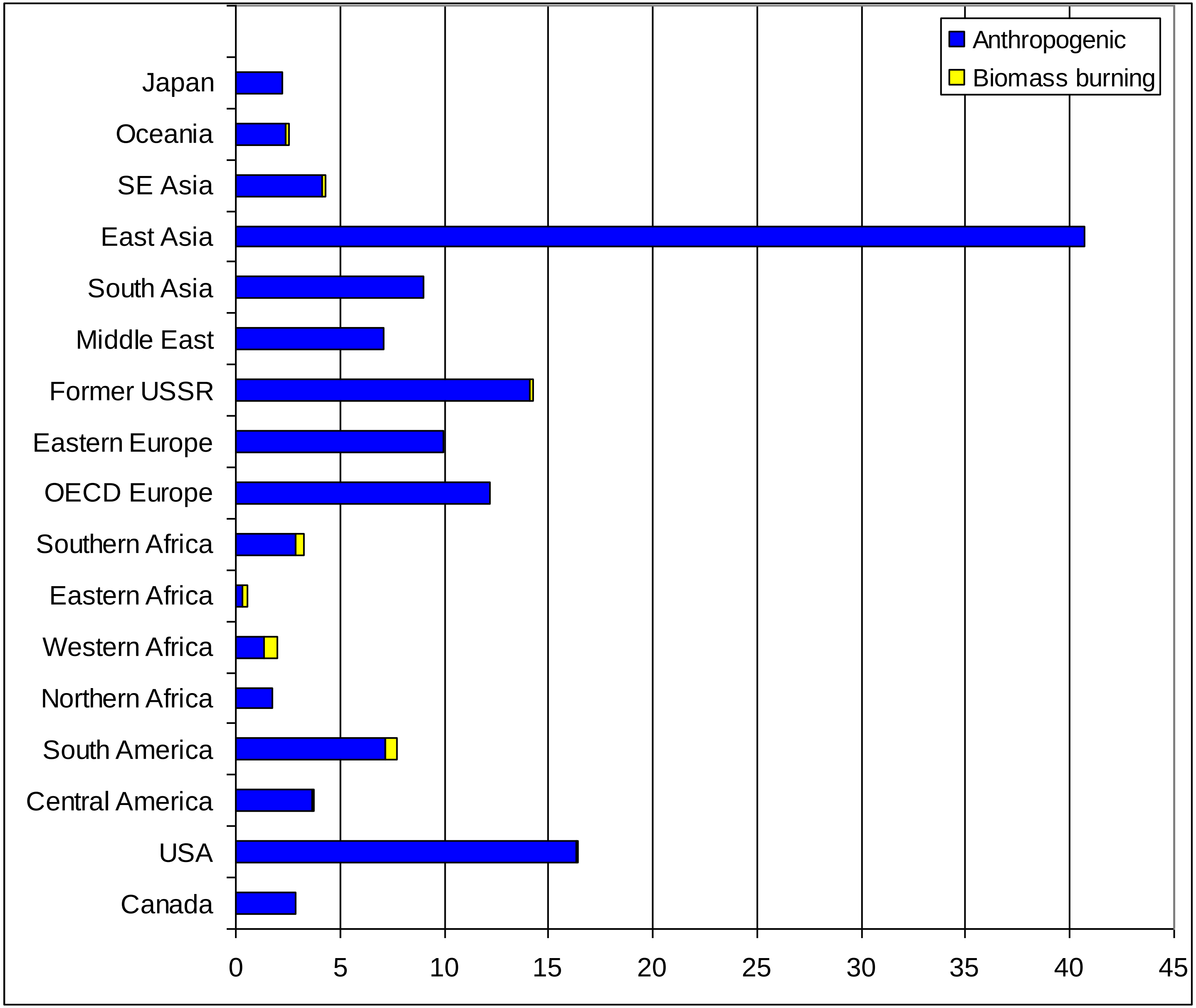
SO_2 emissions Tg SO_2 (including biomass burning, excl shipping/aviation)



Shipping: 7.3 Tg
Aviation: 0.2 Tg

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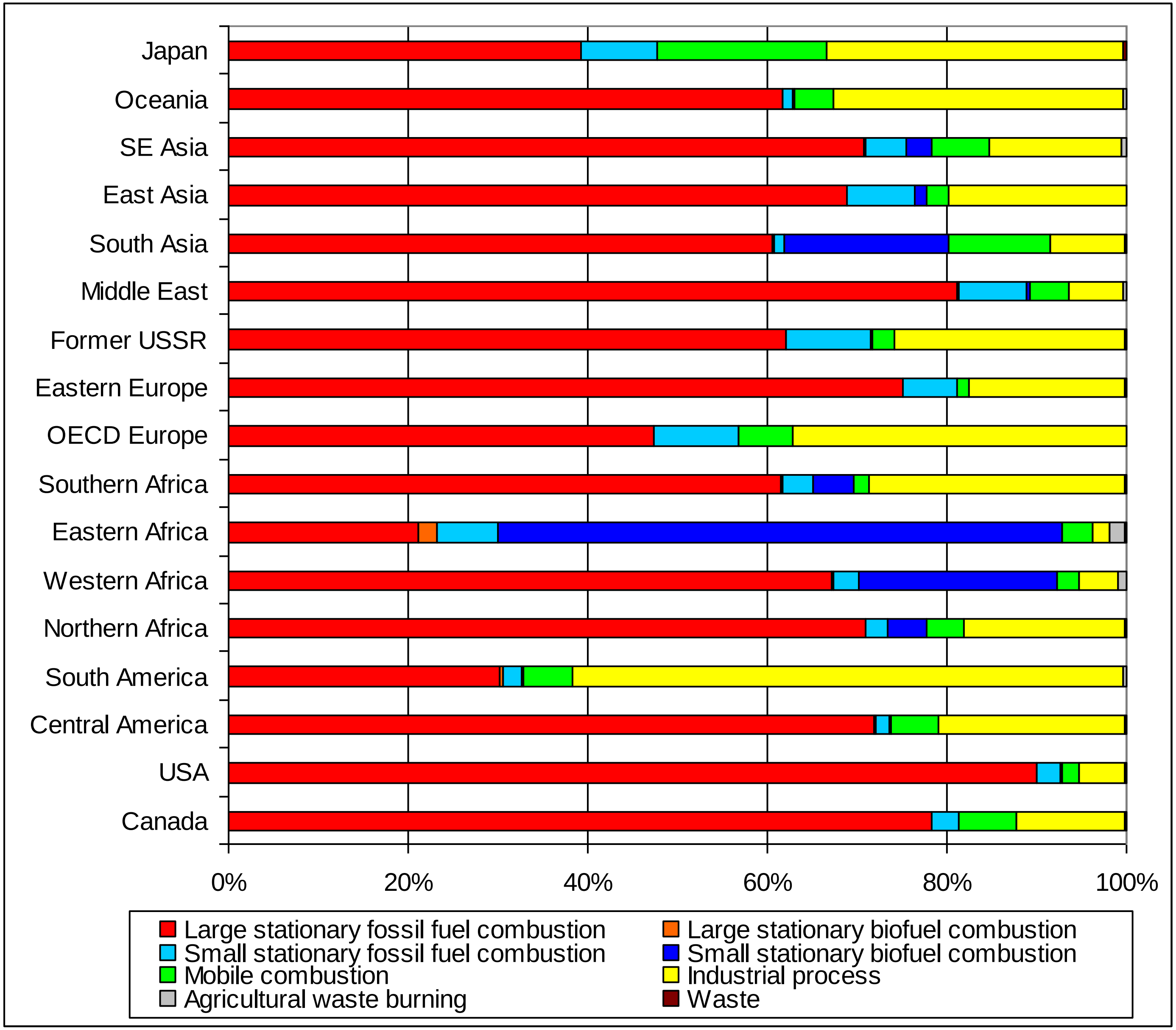
SO_2 emissions in 2000 (excluding international shipping and aviation)



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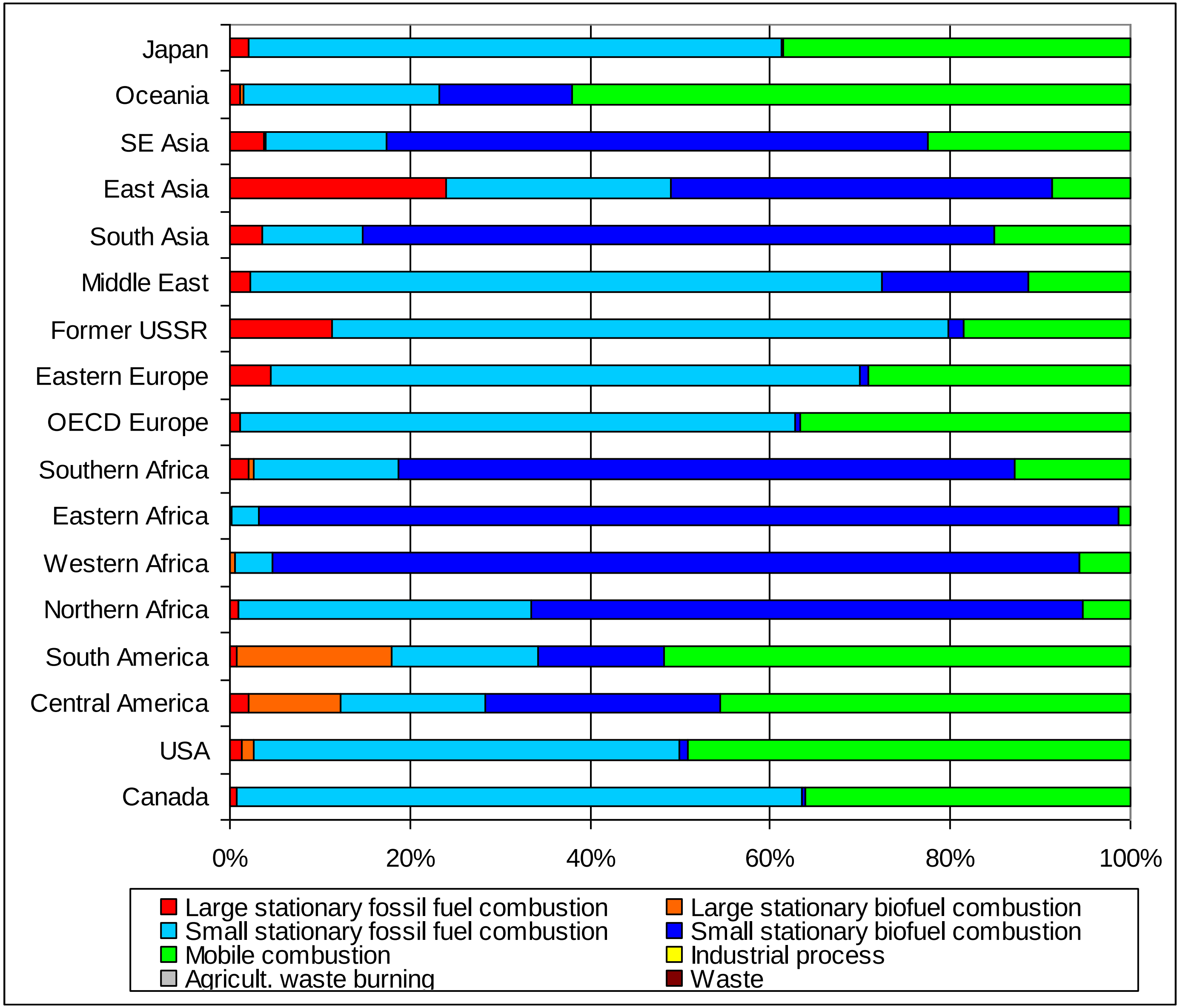
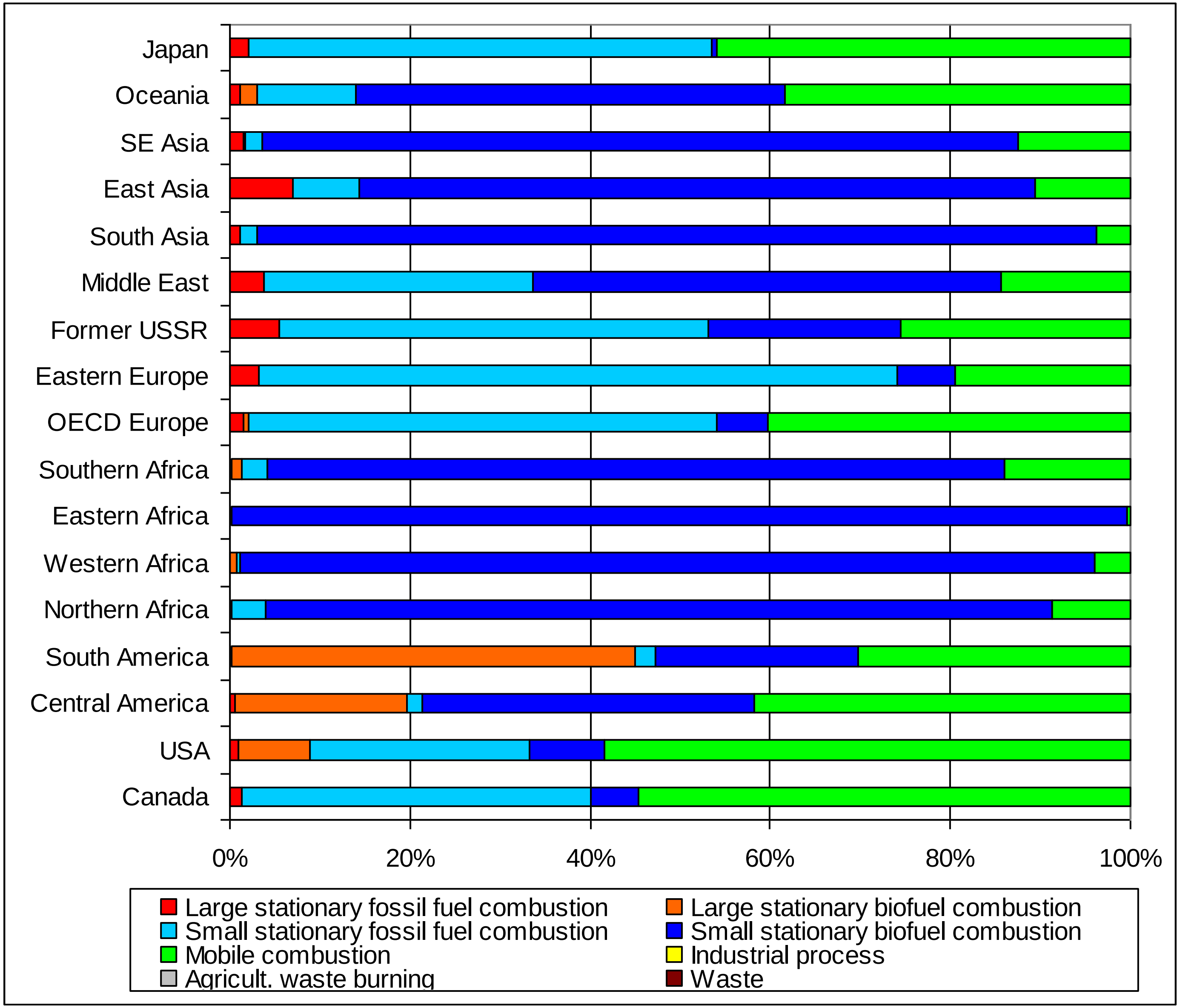
BC emissions in 1996 (excluding international shipping and aviation)



OC emissions in 1996 (excluding international shipping and aviation)



Emissions from selected countries from EDGAR calculations (CO, NMVOC, NOx, SO2 1990, 1995, 2000)

“your emissions are wrong !”

YES, WE KNOW !

General problems in emission inventory calculations

(i) Not practical possible to monitor each individual emission source:
Emission factor approach is adopted: **Emission = activity x emission factor**

(ii) We know that emission inventories are inaccurate representations of emission that has actually occurred:

$$E_{real} = E_{inventory} + \bigcup_{i=1}^{N} \varepsilon_i$$

Examples of errors ε_i:

aggregation error	Calculation of emissions on other spatial, temporal scale and for emissions sources that are different from scale on which emissions occur in reality
extrapolation error	Due to lack of measurements of emission rates or activity data, non-specific data are extrapolated
Measurement error	Errors in measurement lead to inaccurate values of emission factors of activity data

(iii) Often, we do not know the extent to which emission inventories are inaccurate

- detailed review of existing inventories not performed yet
- several inventories are non-transparent about method and data
- lack of different independent inventories
- lack of measurement data and model studies to confront inventories with

Uncertainties: qualification/quantification

Table 1.14 Indication of uncertainty estimate for ozone and aerosol precursors. Source: Olivier et al., 1999b.

Main source	Sub-category	Activity data	Emission factors CO	NO_x	SO_2	NMVOC	Global total and regional emissions CO	NO_x	SO_2	NMVOC
Fossil fuel use	Fossil fuel combustion									
	Fossil fuel production		-	-	-		-	-	-	
Biofuel	Biofuel combustion									
Industry/ solvent use	Iron & steel production									
	Non-ferro production									
	Chemicals production									
	Cement production		-	-	-	-	-		-	-
	Solvent use		-	-	-		-	-	-	
	Miscellaneous									
Landuse/ waste treatment	Agriculture		-	-	-	-	-	-	-	-
	Animals (excreta; ruminants)		-	-	-	-	-	-	-	-
	Biomass burning									
	Landfills		-	-	-	-	-	-	-	-
	Agricultural waste burning									
	Uncontrolled waste burning		-	-	-		-	-	-	
Natural sources	Natural soils		-		-	-	-		-	-
	Grasslands		-	-	-	-	-	-	-	-
	Natural vegetation			-	-			-	-	
	Oceans/wetlands			-	-	-		-	-	-
	Lightning		-		-	-	-		-	-
			CO	NO_x	SO_2	NMVOC	CO	NO_x	SO_2	NMVOC
All sources		-	-	-	-	-	M	M	M	L

Notes: Expert judgement of uncertainty ranges, which were assigned with the following classification in terms of order of magnitude of the uncertainty in mind: S = small (10%); M = medium (50%); L = large (100%); V = very large (>100%).
"-" Indicates that the compound is not applicable for this source or that emissions are negligible.

Courtesy: Jos Olivier

Example: limitations of large scale inventories

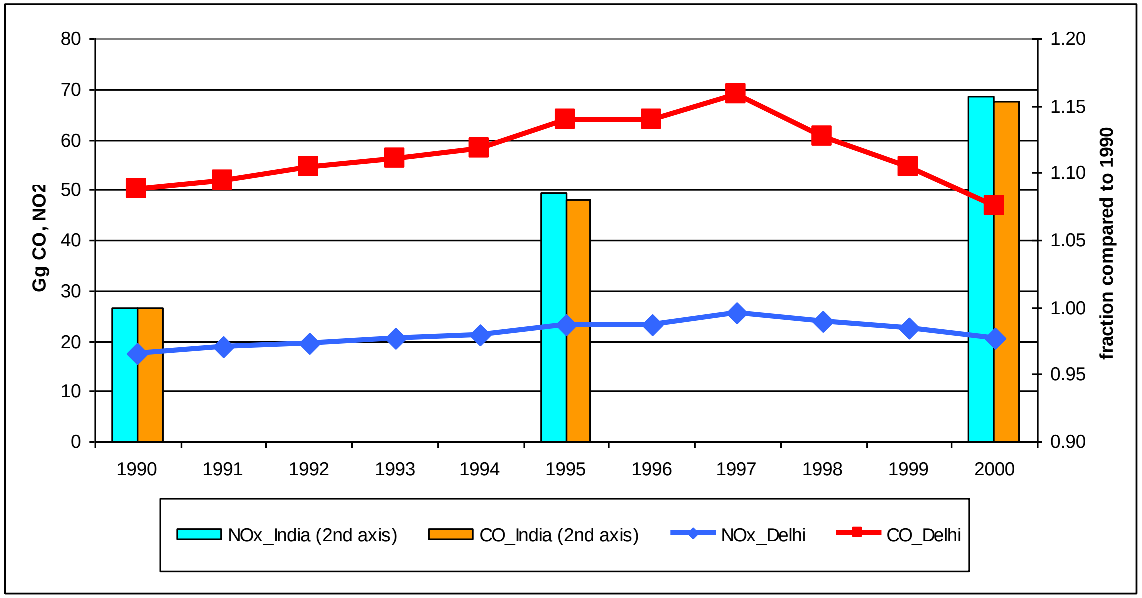


Figure 2. Emissions of CO and NO_2 from the domestic sector in Delhi as calculated for the city domain (in Gg, lines) and the trend in emissions from the domestic sector (as fraction of 1990 emissions) calculated on the national level in EDGAR. References. Gurjar et al. (2004); Olivier et al., (2001), Van Aardenne et al. (2005).

Example: emissions from international shipping

Mobile sources: international shipping (1)

$$Fuelconsumption_{tyr^{-1}} = FC = \sum_{i=1}^{132} FC_i = \sum_{i=1}^{132} P_i * F_{MCR,i} * \tau_i * SFOC$$

$$TE_{NOx} = \sum_{i=1}^{132} FC_i * EI_{NOx,i}$$

n	Number of sub-groups = 132
P_i	Accumulated installed engine power for each subgroup
$F_{MCR,i}$	Engine load factor based on duty cycle profile
$\tau_{i[hrs/yr]}$	Average engine running hours for each sub-group
$SFOC_{g/kWh}$	Power-based specific fuel oil consumption
$EI_{g/kWh}$	Power-based emission factor for each pollutant (NO_x, SO_X, CO_2, HC, PM)

Mobile sources: international shipping (2)

Ship type	All vessels	Cargo vessels					Non-cargo vessels	Auxiliary engines (gensets)	Military vessels [1]
		All cargo ships	Tanker [2]	Container ships	Bulk and combined carriers	General cargo vessels	**Passenger & fishing ships, tugboats, others**		
Number of ships	**90,363**	**43,967**	11,156	2759	6457	23,595	**45,096**	**-**	**1300**
P_{MCR} (MW)	**343,384**	**218,733**	54,514	46,461	46,297	71,461	**67,051**	**40,000**	**17,600**
F_{MCR} (%)			75	72	80	70	**65-75**	**60**	**80**
Time τ [3] (hrs/yr)			6500	6600	5400	6500	**4000-5500**	**3000**	**2500**
SFOC [4] (g/kWh)	**212**	**210**	191-229	194-222	192-202	200-230	**207-240**	**230-240**	**250-280**
FC [5] (Mt)	**279.7**	**207.8**	56.8	42.7	39.4	68.9	**46.2**	**16.3**	**9.4**
EI_{NOx} (g/kWh) (kg/t fuel)	**16.2** **76.4**	**-** **85.9**	9.3-16.8 50-90	11.9-18.8 64-101	10.9-16.8 58-90	10.9-15.8 58-85	**7.9-10.9** **42-58**	**8.9** **48**	**8-15** **42-80**
TE_{NOx} (Mt NO_2)	**21.38**	**17.85**	4.44	4.67	3.78	4.96	**2.39**	**0.8**	**0.34**

Mobile sources: international shipping (3)