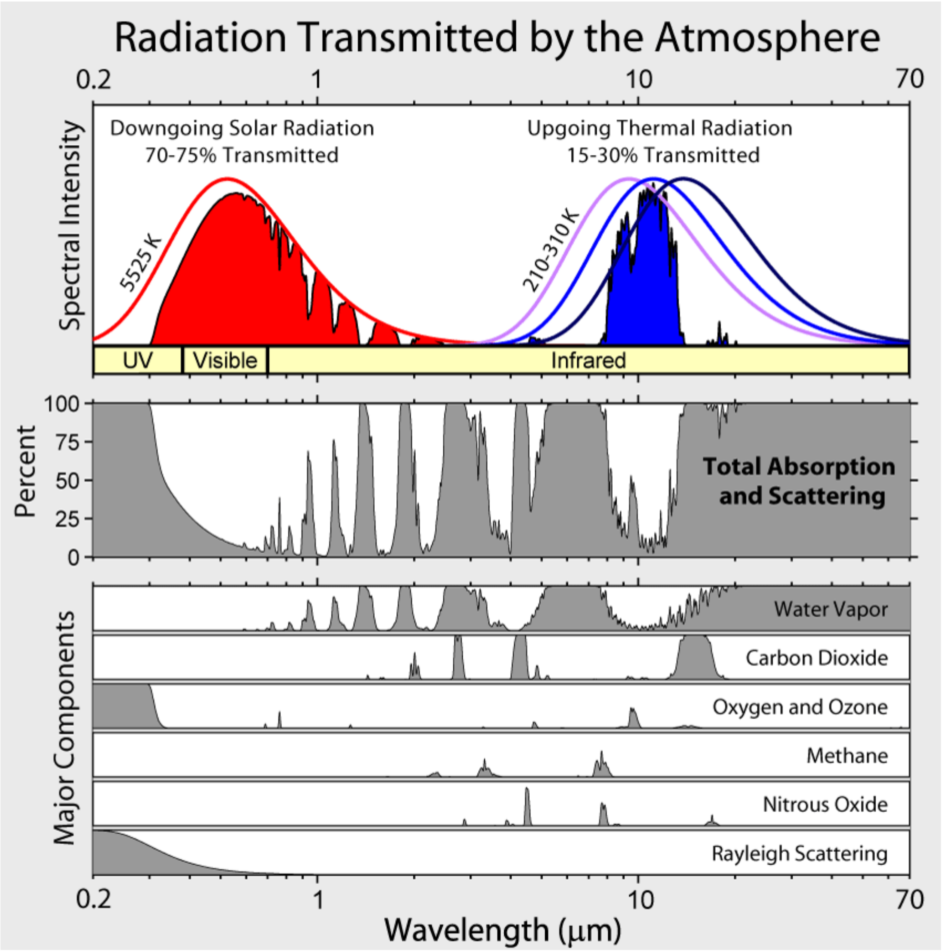
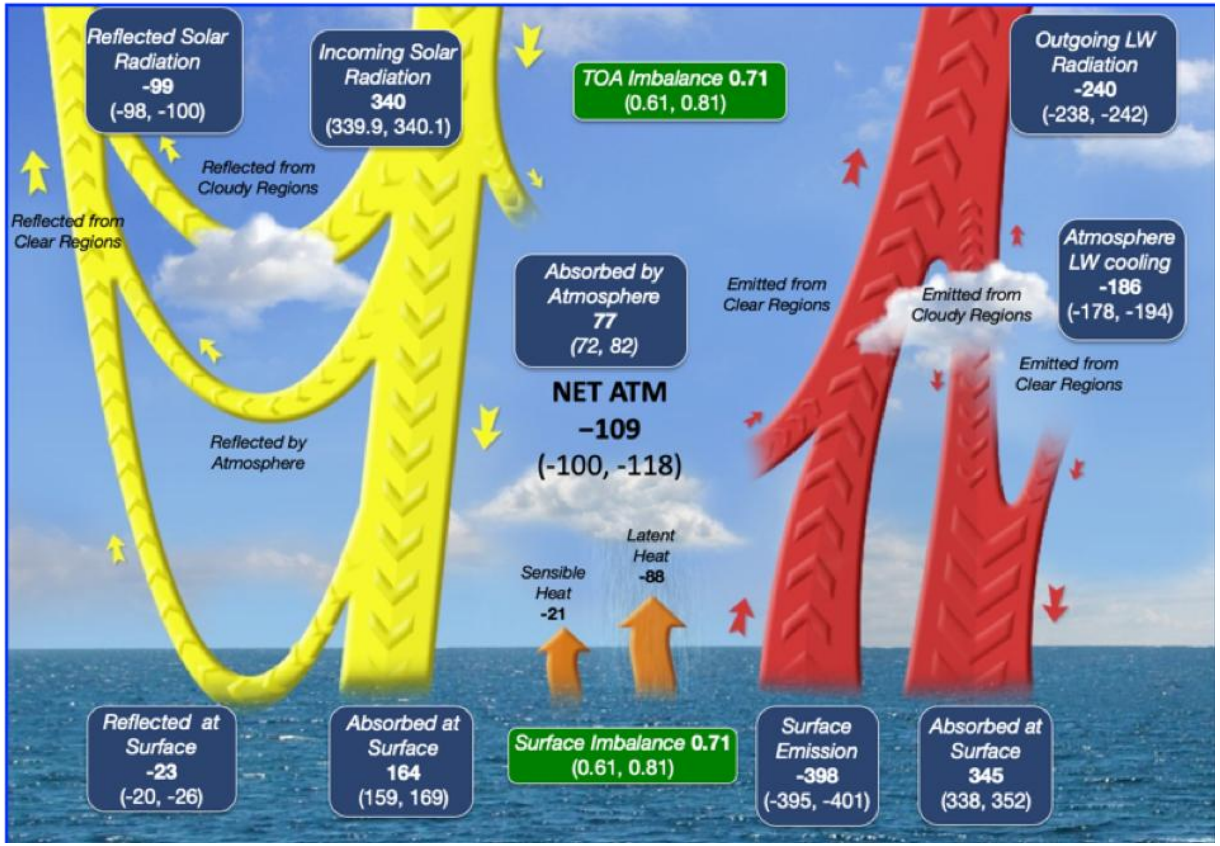
Take home messages from previous lecture

- Check out: https://ceres.larc.nasa.gov/science/
- What are atmospheric windows?
- What are key properties of greenhouse gases?
- The warming and cooling effects of clouds and aerosols.
- Unit optical depth as key parameter for temperature profile retrieval.
- Top of atmosphere radiation balance.
- Radiative forcing and the challenge of climate science.

Recap previous lecture



Atmospheric windows (shortwave, longwave)



Earth's radiation balance, net atmospheric heat loss, sensible and latent heat flux re-create the equilibrium

responseware.eu

env320

Overview on 2nd half of the course: Atmospheric Chemistry

- Atmospheric composition
  - Geochemical cycles, concept of lifetime
- Stratospheric chemistry
  - Ozone chemistry
- Tropospheric chemistry
  - Main oxidants and pollutants
- Aerosols
  - Microphysics and chemistry
- Clouds
  - Aerosol-cloud interactions

Atmospheric composition

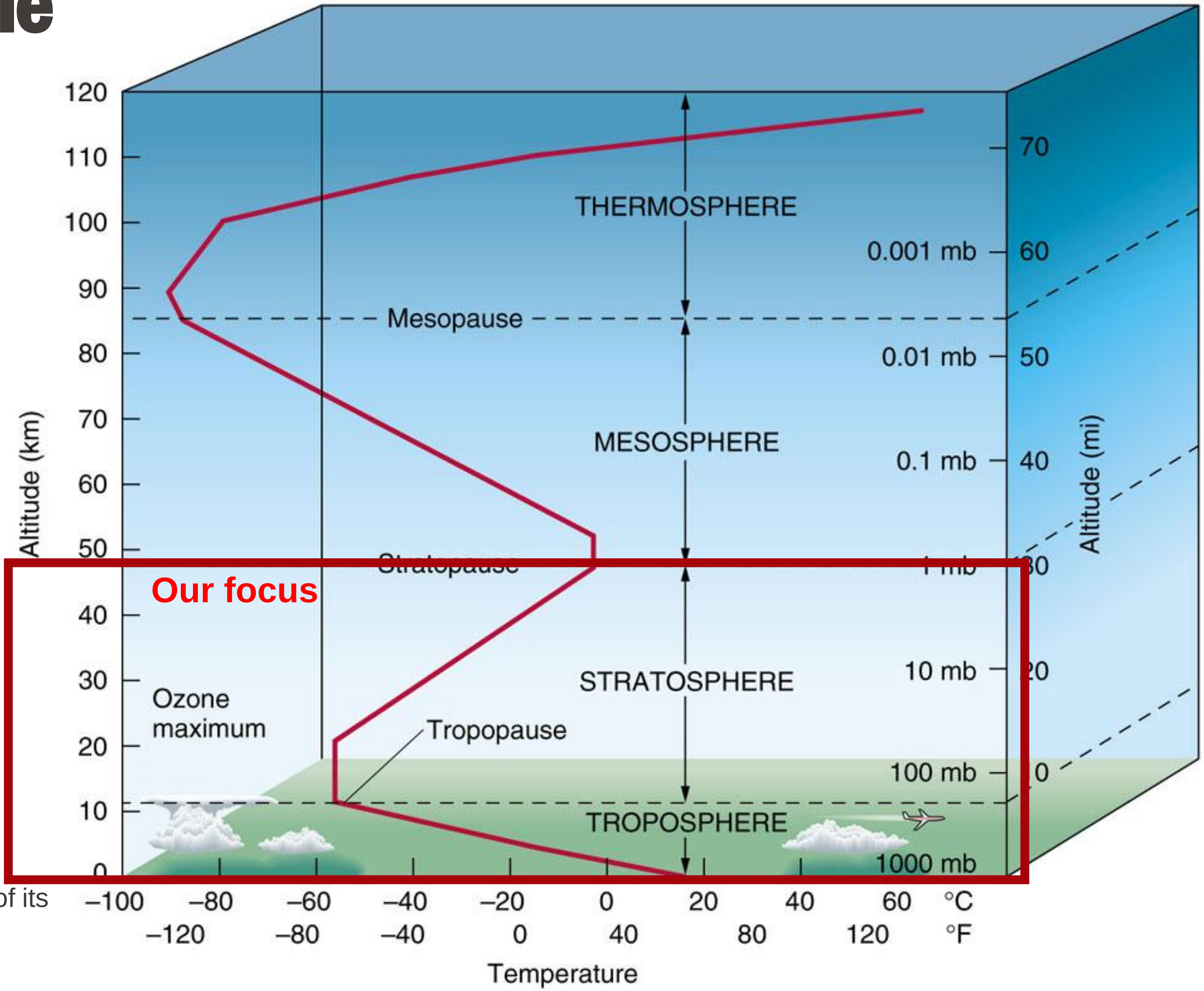
Vertical Profile

The vertical temperature profile provides basis for dividing the atmosphere into four layers:

- *Troposphere*: average lapse rate of -6.5 °C km^{-1}.
- *Stratosphere*: dry and ozone-rich; vertical mixing strongly inhibited.
- *Mesosphere*: temperature decreases to a minimum at top
- *Thermosphere*: increase in temperature due to absorption of solar radiation and photodissociation of nitrogen and oxygen molecules (radiation lecture)

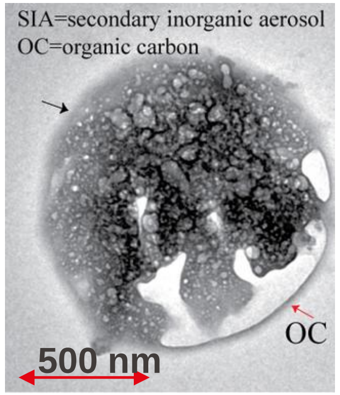
We care about the troposphere, because
- 85 % of atmospheric mass is in the troposphere,
- most emissions are at the surface.

We care about the stratosphere, because of its role in UV absorption.

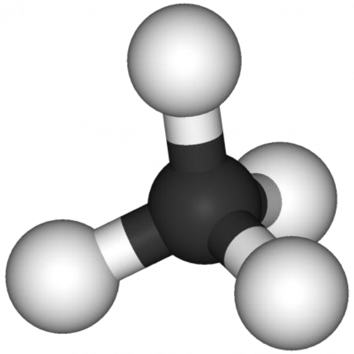


Atmospheric processes at a glance

Aerosols



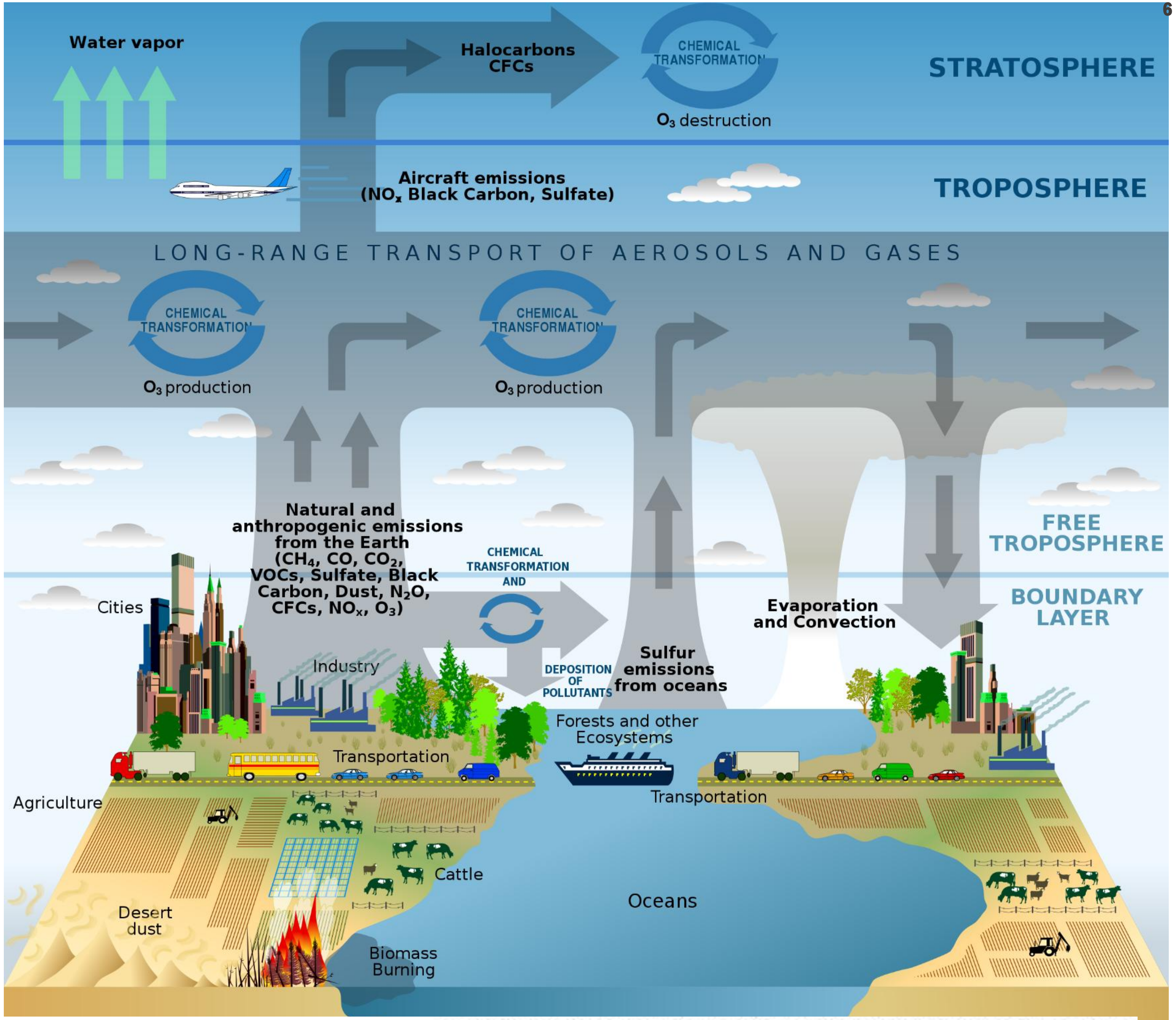
Gases



Why study these?

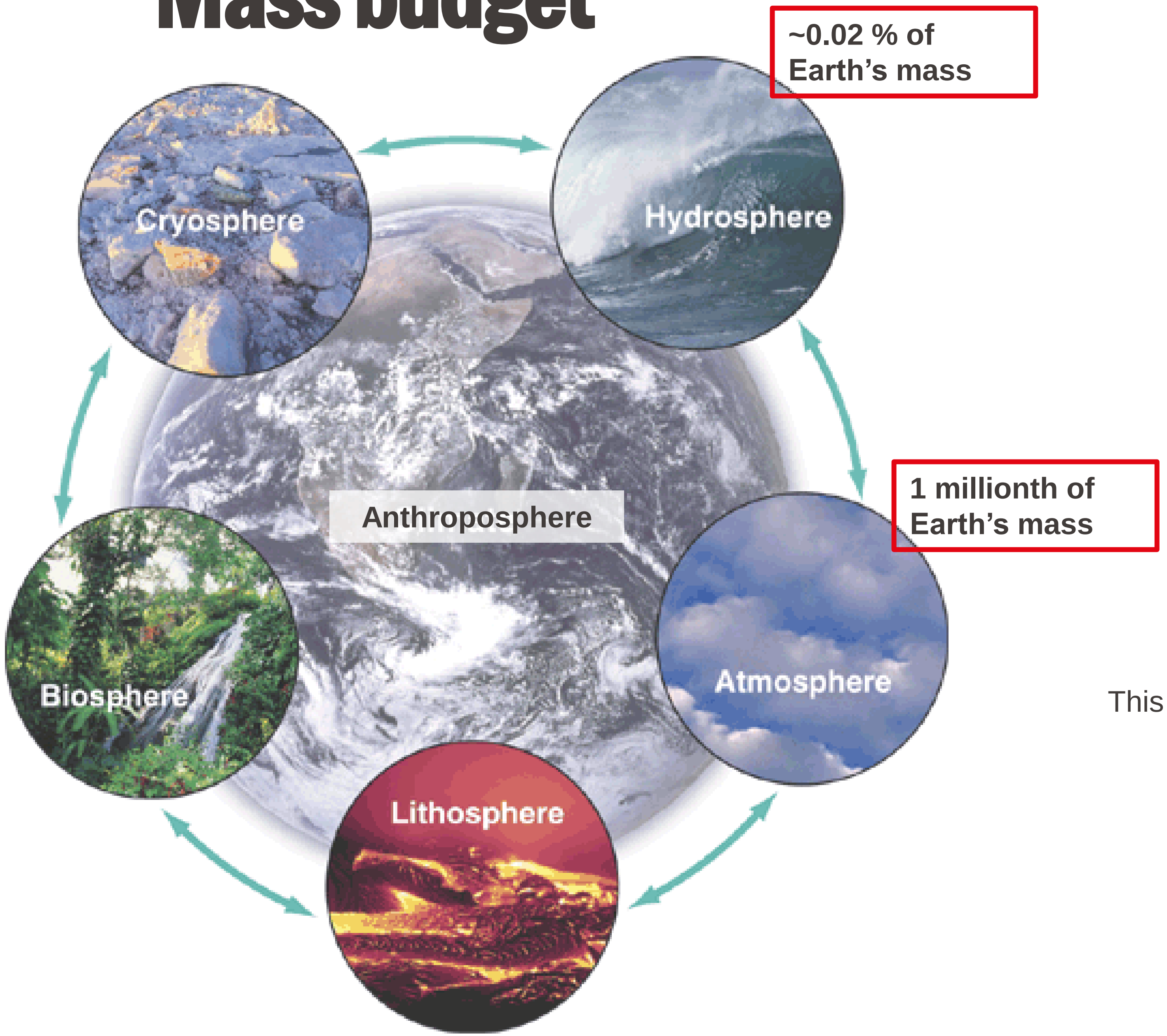
How do our anthropogenic activities influence atmospheric chemical composition and what are the implications?

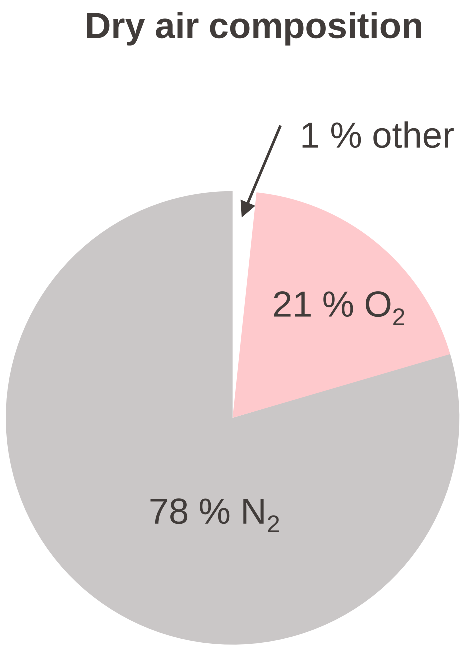
What is the «natural» or preindustrial state of the atmosphere, which we need to compare against to estimate the impacts?



U.S. Global Change Research Program (www.globalchange.gov) / NCU

Mass budget





This course is about trace compounds (1 % level)!

Adapted from DOI: 10.1126/science.1070629

Implications of emissions to the atmosphere

Air pollution		Climate Change
7 million premature deaths each year, life quality reduction, cardiovascular & respiratory diseases, mainly PM and ozone	**Health**	increasing allergens, malnutrition, mental health, heat, vector diseases (Malaria in Ticino)
relative global crop losses for soy 6-16%, wheat 7-12% and maize 3-5%, mainly ozone	**Food**	weather extremes (hail), drought, shifting vegetation zones, water resources
… and biodiversity – acid rain, eutrophication, and cell damage, mainly sulphur, nitrogen and ozone	**Eco-systems**	coral bleaching, invasive species, loss of wetlands, loss of Arctic tundra, fires…
shorter term and regional effects, direct interaction with solar radiation, interaction with clouds, overall cooling effect, largest uncertainty of anthropogenic climate forcing	↔	exacerbation of pollution (enhanced ozone production, fires), combined health effects
lives, work ability, food production, damage to historical monuments, ecosystems services, (economic damage from air pollution in Europe is close to USD 1.6 trillion)	**Economy**	climate refugees, work ability, adaptation measures, cost of food and water, …

Check out: https://ccacoalition.org/en

Implications of emissions to the atmosphere

Air pollution

Climate Change

Health

7 million premature deaths each year, life quality reduction, cardiovascular & respiratory diseases, mainly PM and ozone

increasing allergens, malnutrition, mental health, heat, vector diseases (Malaria in Ticino)

Food

relative global crop losses for soy 6-16%, wheat 7-12% and maize 3-5%, mainly ozone

weather extremes (hail), drought, shifting vegetation zones, water resources

… and biodiversity – acid rai
cell damage, mainly sulphur

e species, loss of wetlands,
es…

The atmosphere is highly non-linear:
Small amounts of trace compounds can have large effects.

shorter term and regional effects, direct interaction with solar radiation, interaction with clouds, overall cooling effect, largest uncertainty of anthropogenic climate forcing

↔

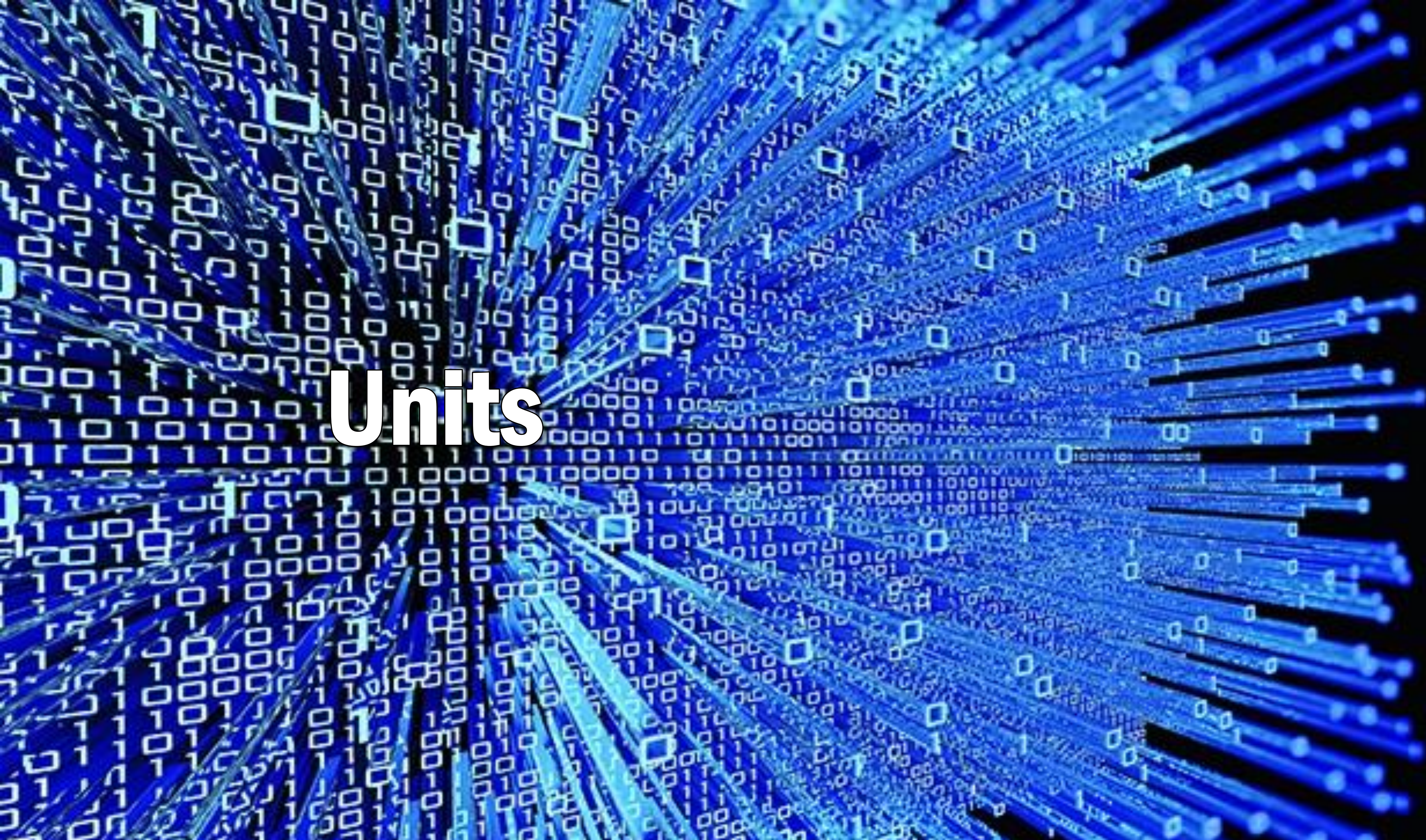
exacerbation of pollution (enhanced ozone production, fires), combined health effects

Economy

lives, work ability, food production, damage to historical monuments, ecosystems services, (economic damage from air pollution in Europe is close to USD 1.6 trillion)

climate refugees, work ability, adaptation measures, cost of food and water, …

Check out: https://ccacoalition.org/en

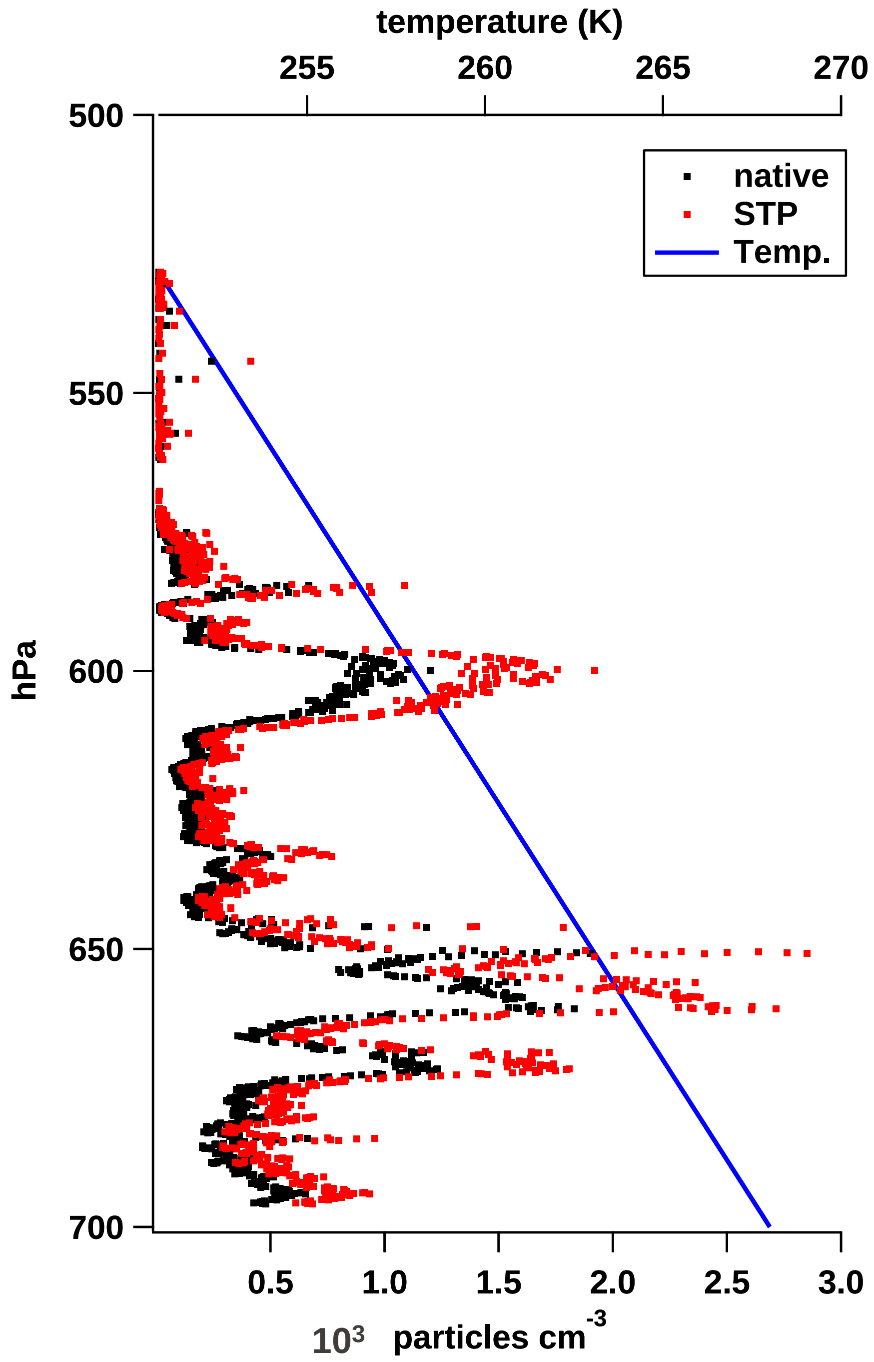


Units

Number concentrations

- Number concentration
  - Molecules per volume (molecules / cm^{-3})
  - Particles per volume (# / cm^{-3})

Caveat: the volume changes with pressure.
For comparability conversion to
standard temperature and pressure (STP).
T = 273.15 K
P = 1013.25 hPa



Mixing Ratios

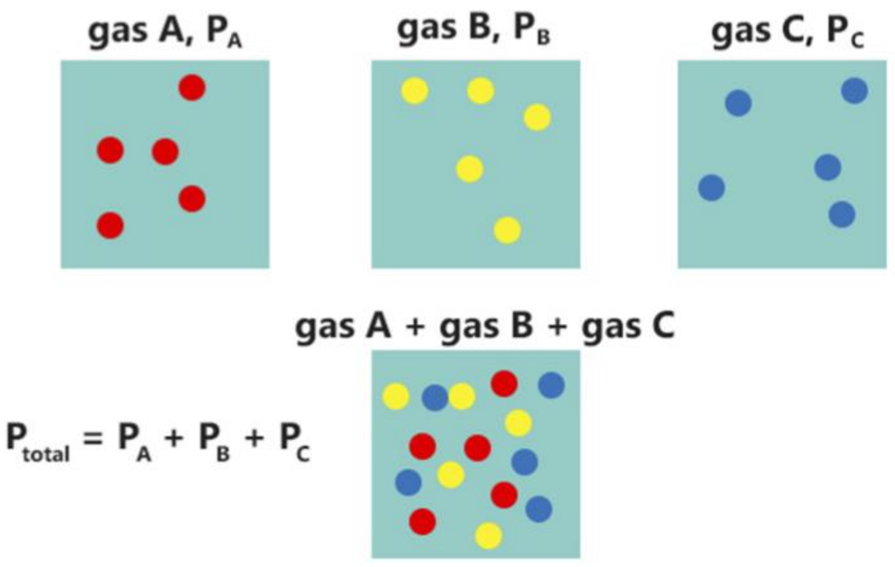
Mixing ratios provide a robust measure of atmospheric composition, because they remain constant with changing pressure.

- Partial pressure (ideal gas law)

$$PV = nRT$$

$$x_i = \frac{p_i}{p_{tot}} = \frac{n_i}{n_{tot}} = \frac{V_i}{V_{tot}}$$

x_i mole fraction of gas (species) i
n_i mole number of species i
p_i partial pressure of species i
V_i partial volume of species i



https://en.wikipedia.org/wiki/Partial_pressure#/media/File:Schematic_Depicting_Dalton's_Law.jpg

Partial pressure

- Partial pressure (ideal gas law)

$$PV = nRT$$

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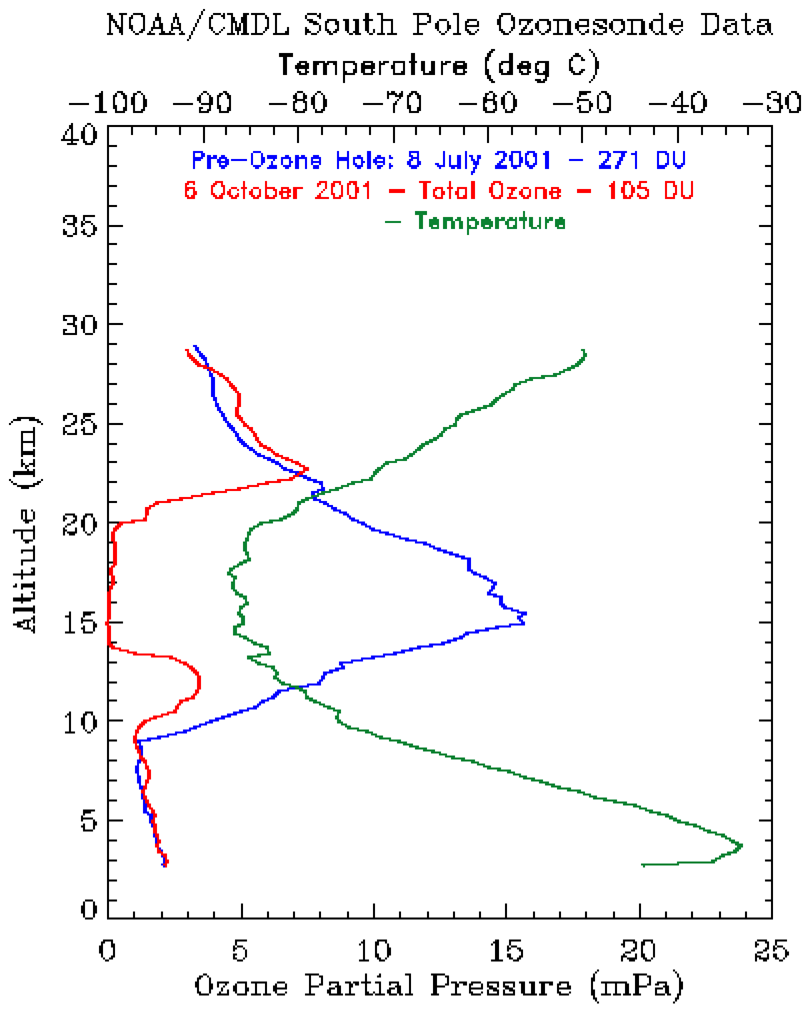


https://serc.carleton.edu/download/images/776/OzoneVertProfile.gif

Mixing ratios

- mixing ratios (dimensionless)
  - Molar mixing ratio r_i $$r_i = \frac{n_i}{n_{air}}$$
  - Volume mixing ratio $$VMR = \frac{V_i}{V_{air}}$$
  - Mass mixing ratio $$MMR = \frac{M_i}{M_{air}}$$

parts per million ppm (ppmv, ppmm)
parts per billion ppb
parts per trillion ppt

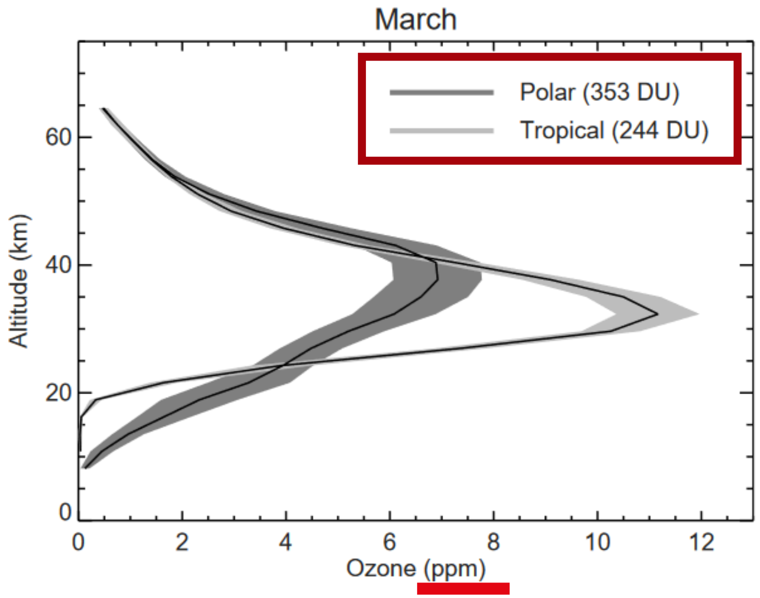


Figure 1.6: The vertical profile of ozone mixing ratio against altitude for polar (equivalent latitude 72.5°N) and tropical (equivalent latitude 2.5°N) conditions in March. The ozone data are from the climatology of Grooß and Russell (2005).

https://www.researchgate.net/publication/48693158_Tracer-tracer_Relations_as_a_Tool_for_Research_on_Polar_Ozone_Loss

Dobson units

- Amount of gas per vertical column, commonly used for ozone

- Definition: thickness (in 10 µm) of layer that a gas throughout the entire column would form at STP.
  - 250 DU: 250 * 10 µm = 2.5 mm
  - 1 DU = 2.687×10^{20} (molecules m^{-2})
  - Ozone hole: < 220 DU

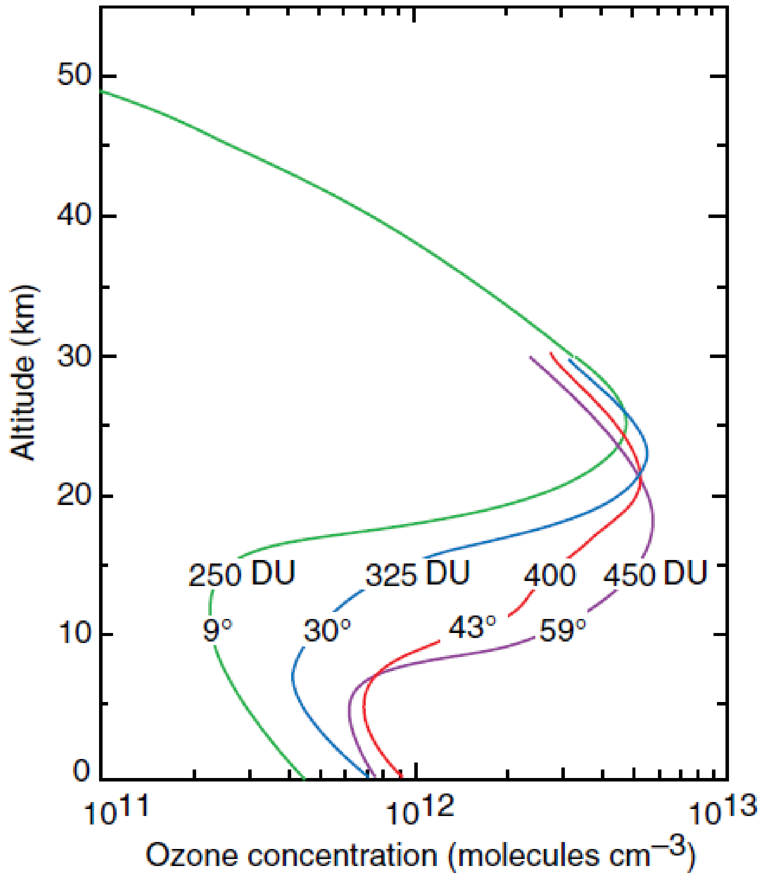


Fig. 5.16 Mean vertical distributions of ozone concentrations based on measurements at different latitudes (given in degrees). Note the increase in the total ozone column abundance (given in DU) with increasing latitude. [Adapted from G. Brasseur and S. Solomon, *Aeronomy of the Middle Atmosphere*, D. Reidel Pub. Co., 1984, Fig. 5.7, p. 215. Copyright 1984 D. Reidel Pub. Co., with kind permission of Springer Science and Business Media.]

Common air quality units

- Particulate matter (PM)
  - $\leq$ 10 µm: PM_{10}
  - $\leq$ 2.5 µm: $PM_{2.5}$
- Swiss standard
  - $PM_{2.5}$: 10 µg m^{-3} (annual mean), 25 µg m^{-3} (daily mean)
  - PM_{10} : 20 µg m^{-3} (annual mean), 50 µg m^{-3} (daily mean)

- Ozone

CH:

- < 100 µg m^{-3} (98 % of ½ -h averages in one month)
- 120 µg m^{-3} hourly average, only to be surpassed once per year

USA

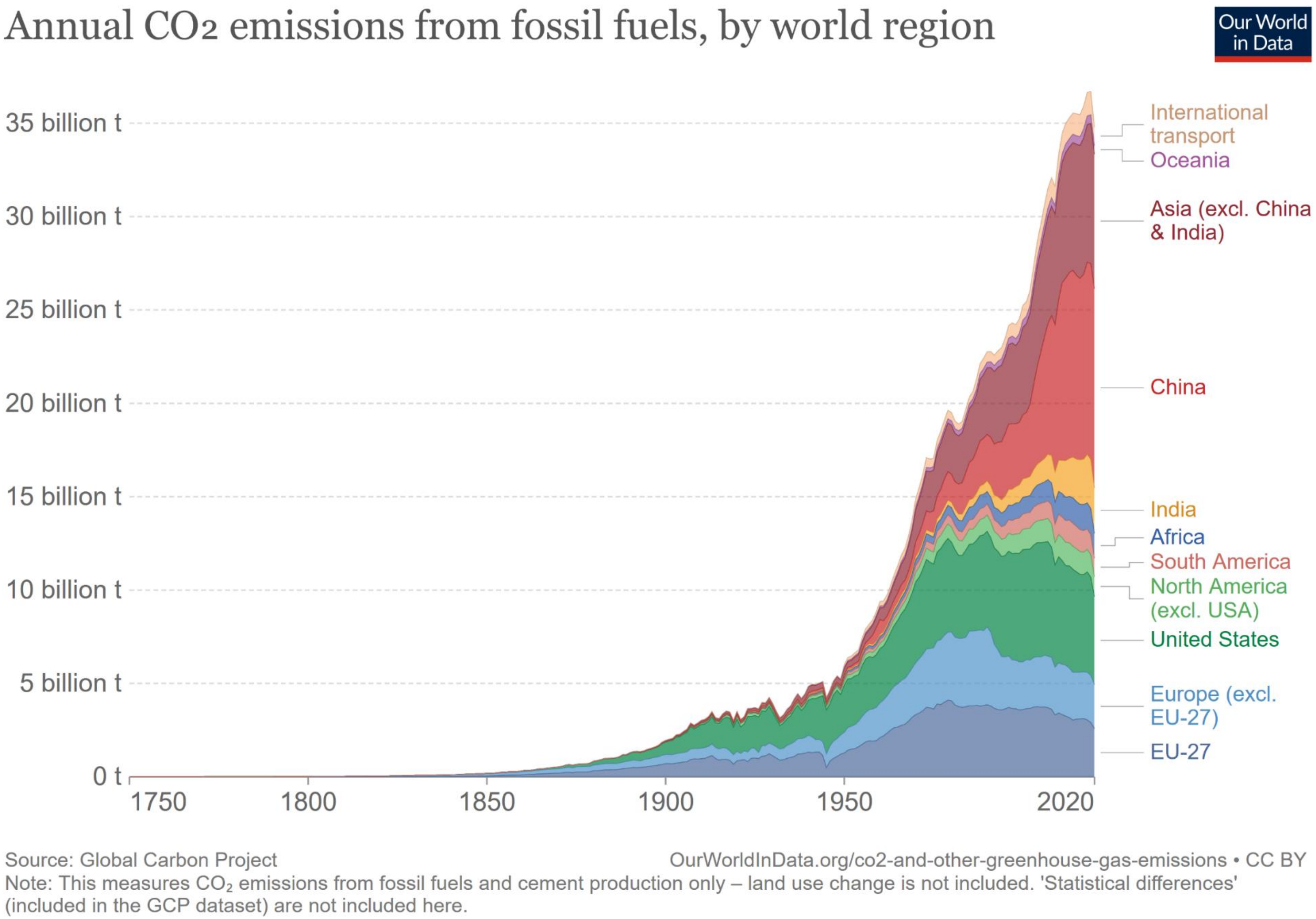
- 0.070 ppm (8-hour average)

Emission Rates

- Emission Rates
  - Tg / year
    or similar units

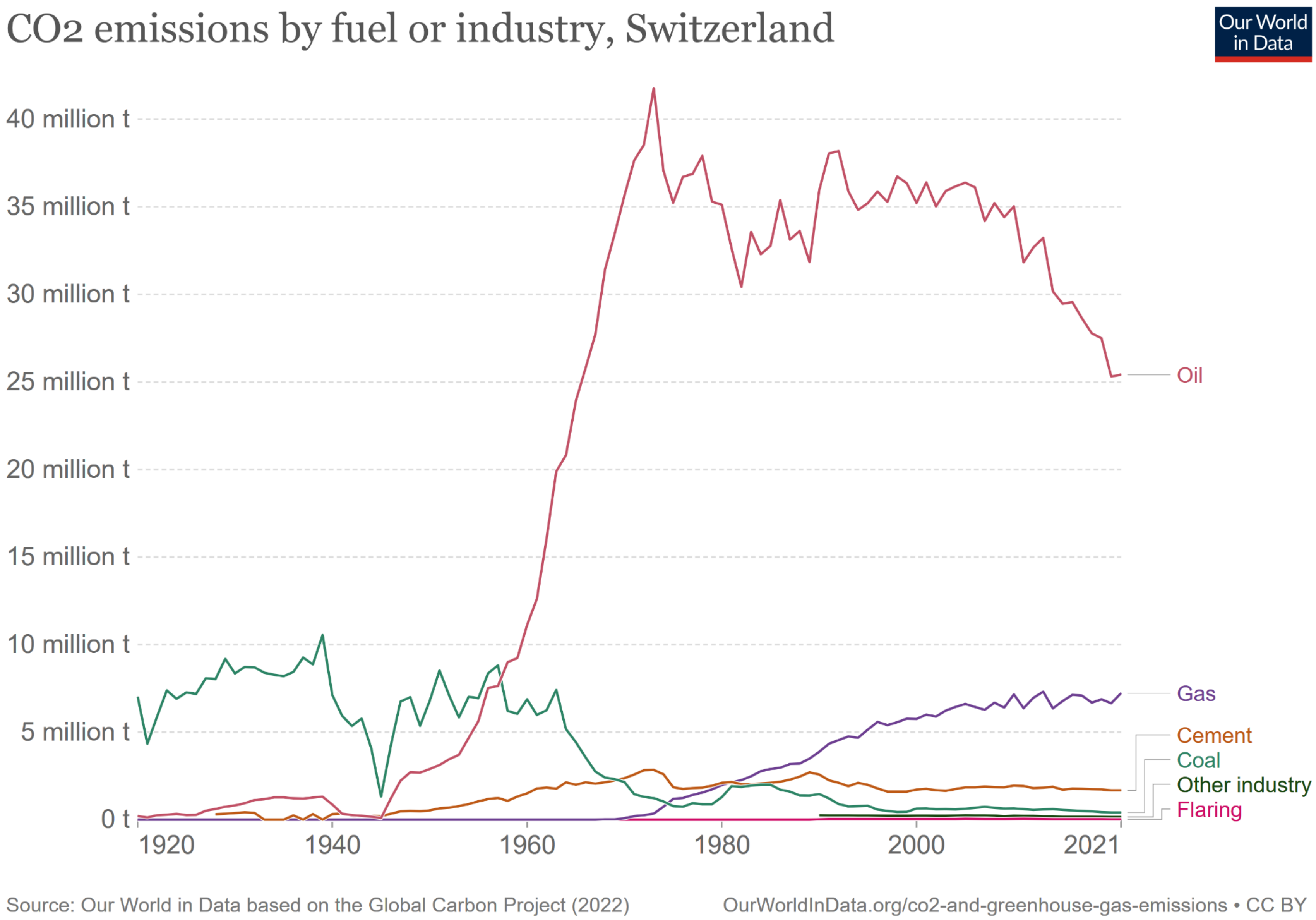
1 billion t / year
10^9 t / year
1 t = 10^6 g
$10^6 * 10^9$ g / year = 10^3 Tg/y

Mega: 10^6
Giga (G): 10^9
Tera (T): 10^{12}
Peta (P): 10^{15}



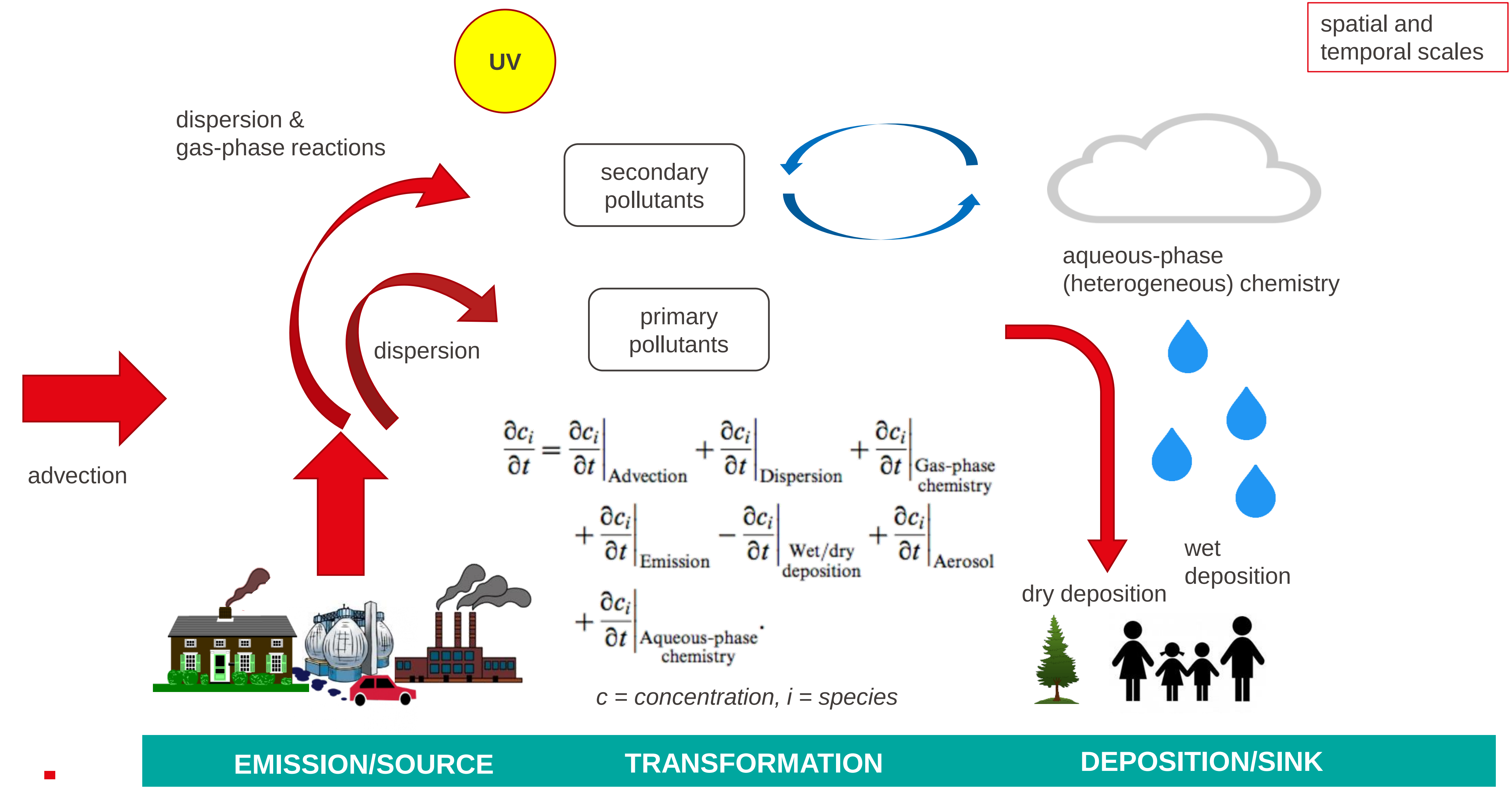
Swiss emissions

Europe total 5 billion tons
Switzerland total: ~0.05 billion tons



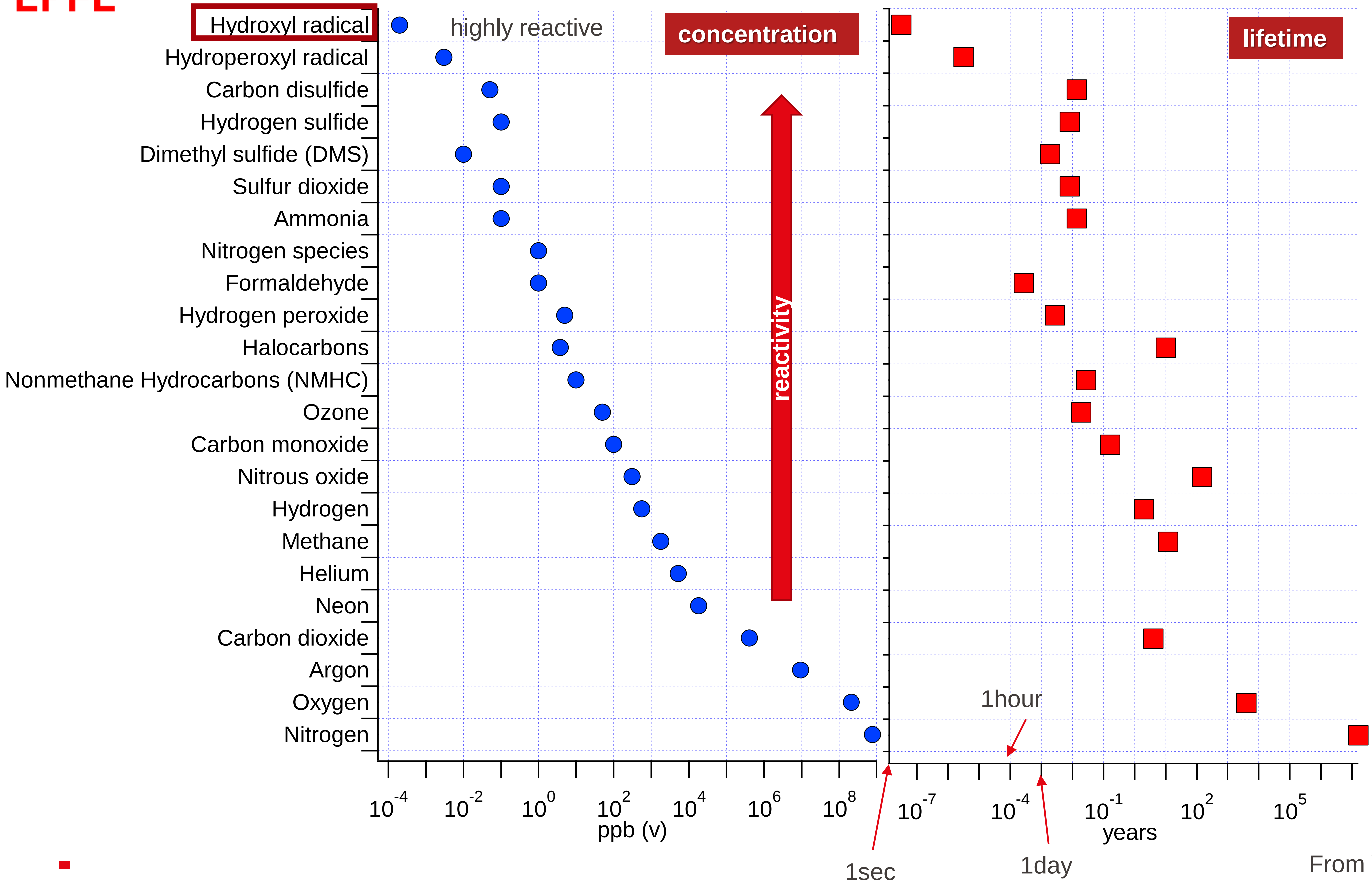
Main compounds and oxidants

The atmosphere is a chemical reactor



$$\frac{\partial c_i}{\partial t} = \left.\frac{\partial c_i}{\partial t}\right|_{\text{Advection}} + \left.\frac{\partial c_i}{\partial t}\right|_{\text{Dispersion}} + \left.\frac{\partial c_i}{\partial t}\right|_{\substack{\text{Gas-phase}\\\text{chemistry}}} + \left.\frac{\partial c_i}{\partial t}\right|_{\text{Emission}} - \left.\frac{\partial c_i}{\partial t}\right|_{\substack{\text{Wet/dry}\\\text{deposition}}} + \left.\frac{\partial c_i}{\partial t}\right|_{\text{Aerosol}} + \left.\frac{\partial c_i}{\partial t}\right|_{\substack{\text{Aqueous-phase}\\\text{chemistry}}}.$$

c = concentration, i = species



Very large ranges of mixing ratios and lifetimes.

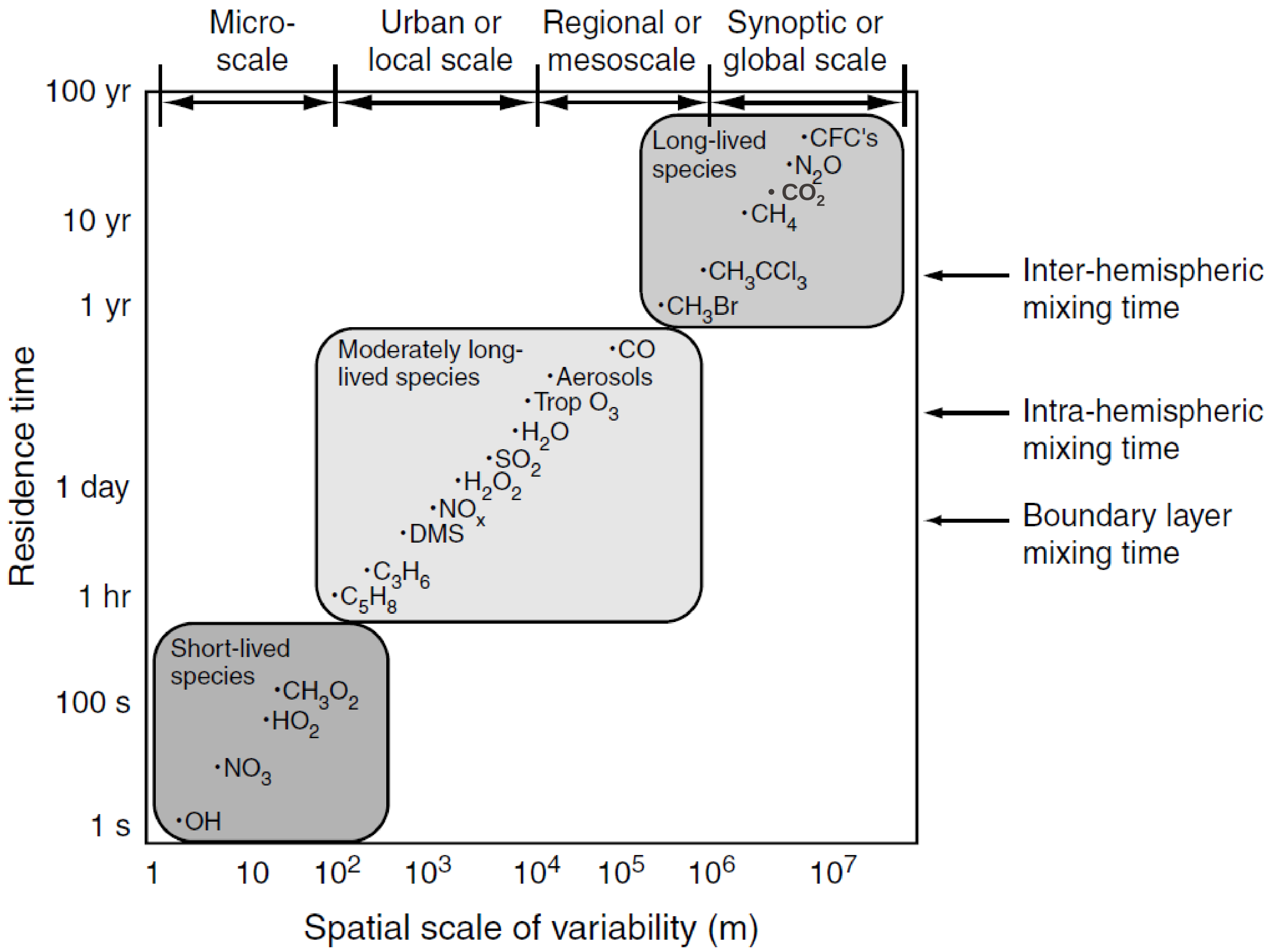
Greenhouse gases have typically longer lifetimes than air pollutants.

Some atmospheric oxidants have extremely short lifetimes (seconds).

Concentrations are driven by emission and deposition processes as well as chemical transformation.

From Wallace and Hobbs (2006)

Lifetime and dispersion



Greenhouse gases are mostly globally dispersed.

Air pollutants play a role on a local and regional scale.

The chemical transformations play a large role for the lifetime and spatial dispersion.

Fig. 5.1 Wallace and Hobbs (2006)

Atmospheric lifetime

Mass balance for species X in the (well-mixed) box:

$$\frac{dm}{dt} = F_{in} - F_{out} + E + P - L - D$$

m = mass of species

The lifetime or residence time in the box:

$$\tau = \frac{m}{F_{out} + L + D}$$

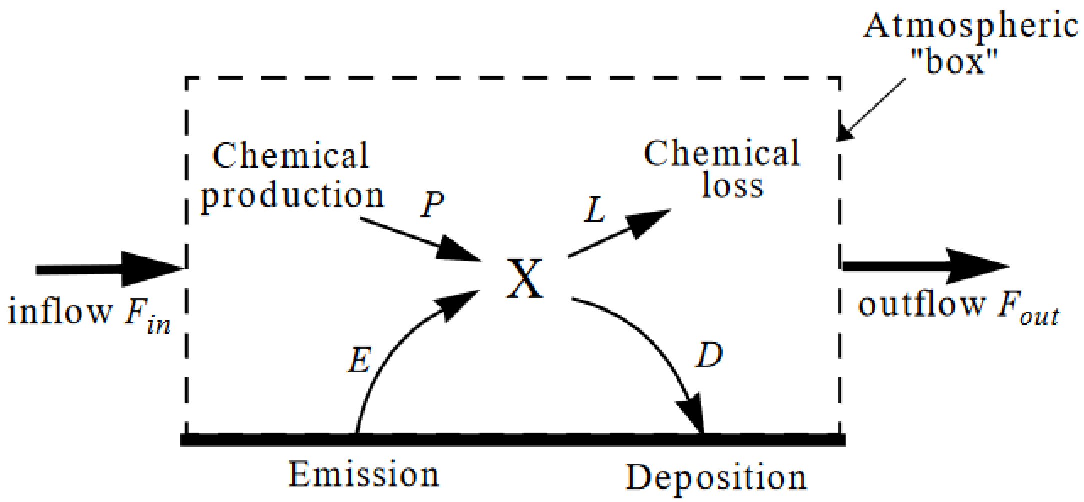


Figure 3-1 One-box model for an atmospheric species X

"Introduction to Atmospheric Chemistry" by Daniel J. Jacob Princeton University Press, 1999

EPFL

Atmospheric lifetime

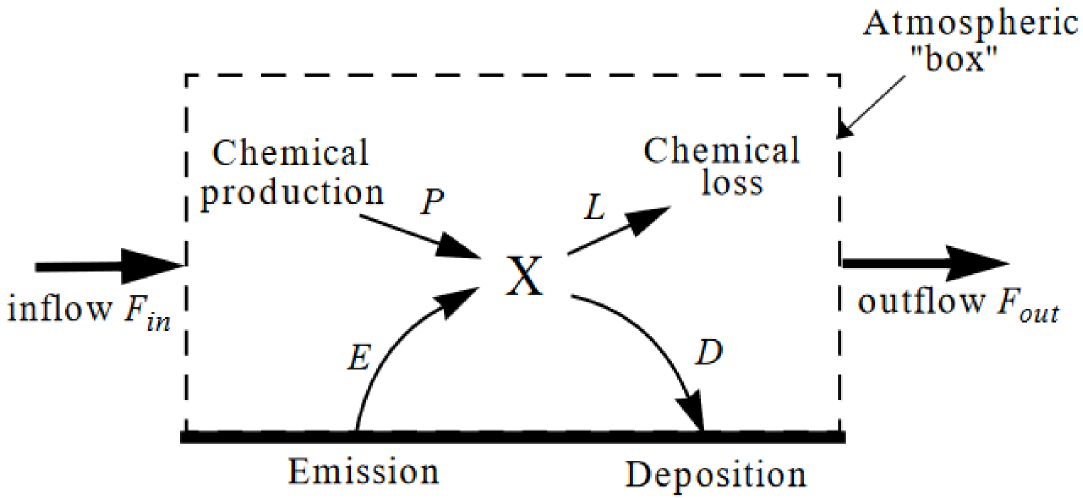


Figure 3-1 One-box model for an atmospheric species X

Mass balance for species X in the (well-mixed) box:

$$\frac{dm}{dt} = F_{\text{in}} - F_{\text{out}} + E + P - L - D$$

m = mass of species

The lifetime or residence time in the box:

$$\tau = \frac{m}{F_{\text{out}} + L + D}$$

We are often interested in determining the relative importance of different sinks contributing to the overall removal of a species:

$$f_{\text{out}} = \frac{F_{\text{out}}}{F_{\text{out}} + L + D}$$

Lifetime with respect to various sinks:

$$\tau_{\text{out}} = \frac{m}{F_{\text{out}}} \quad \text{(export)}$$

$$\tau_c = \frac{m}{L} \quad \text{(chemical loss)}$$

$$\tau_d = \frac{m}{D} \quad \text{(deposition)}$$

which can be combined using a harmonic sum:

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{out}}} + \frac{1}{\tau_c} + \frac{1}{\tau_d}$$

Consider a first-order chemical loss for X with rate $L = k_c m$.

$$\tau_c = \frac{m}{L} = \frac{1}{k_c}$$

We can generalize the notion of chemical rate constants to define rate constants for each loss mechanism:

$$k_{\text{out}} = \frac{1}{\tau_{\text{out}}}$$

$$k_c = \frac{1}{\tau_c}$$

$$k_d = \frac{1}{\tau_d}$$

and an overall loss rate constant can be obtained by an arithmetic sum:

$$F_{\text{out}} + L + D = (k_{\text{out}} + k_c + k_d)\, m = km$$

"Introduction to Atmospheric Chemistry" by Daniel J. Jacob Princeton University Press, 1999

- Courtesy of S. Takahama

Example dry deposition

Example of a first order loss process: dry deposition

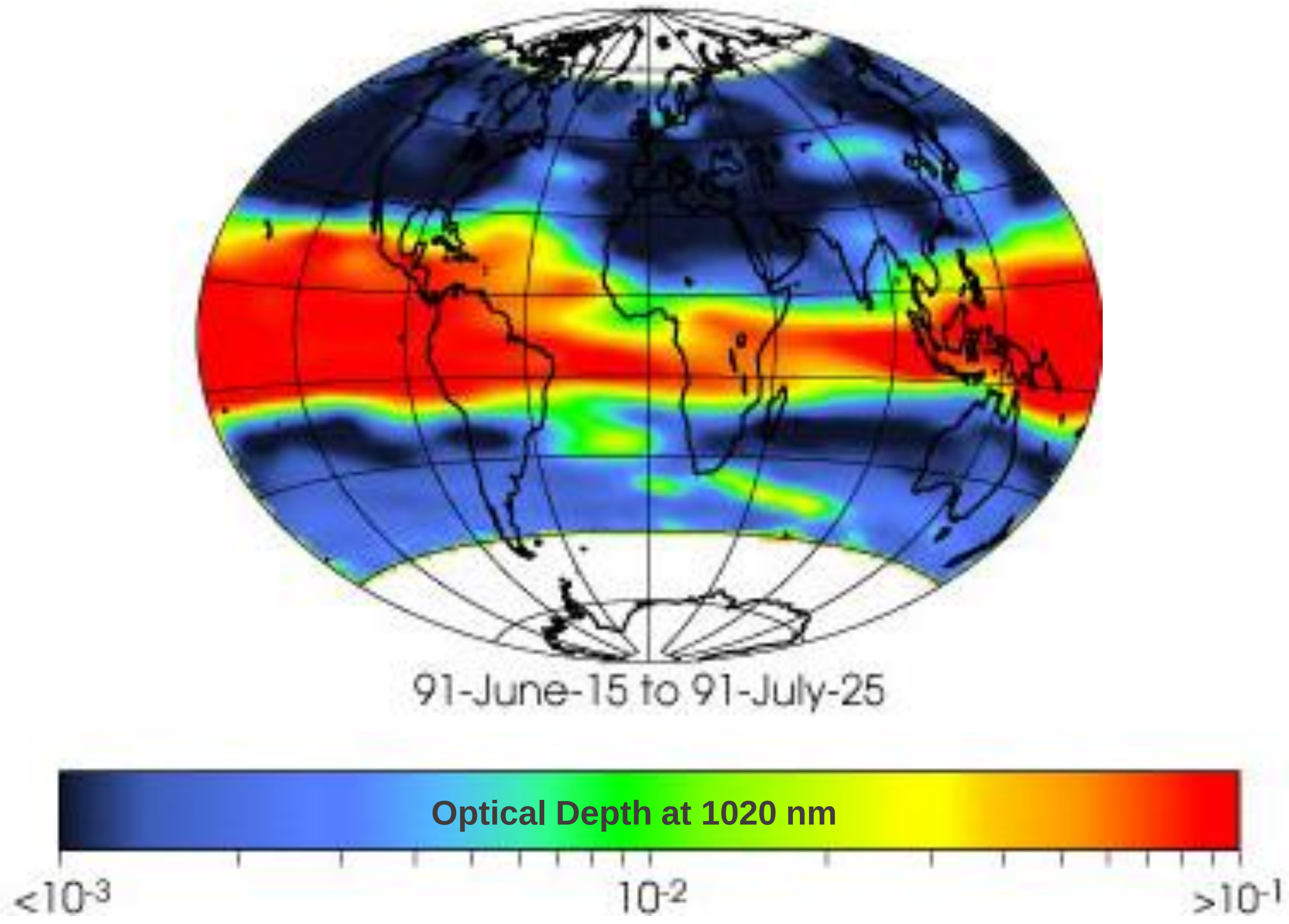
$$D = -\left[\frac{dm}{dt}\right]_d = \frac{v_d}{H} m$$

D Depositional loss rate (kg/s)
H is a representative lengthscale (e.g., boundary layer height (m))
v_d deposition velocity (m/s)
m is mass of a substance (kg)

Characteristic time: $$\tau_d = \frac{m}{D} = \frac{H}{v_d}$$

Mt. Pinatubo eruption

15 June 1991



- https://earthobservatory.nasa.gov/images/1510/global-effects-of-mount-pinatubo

https://sites.google.com/site/naturaldisasteroutbreak/

How long did it take until the Pinatubo layer was dissolved?

- Assume the layer was 2 km thick
- Assume a sensible particle diameter

Characteristic time: $$\tau_d = \frac{m}{D} = \frac{H}{v_d}$$

1

TABLE 3.1 Effect of Pressure on Terminal Settling Velocity of Standard Density Spheres at 293 K [20°C].

Particle Diameter (μm)	V_{TS} at the Indicated Pressure (m/s)		
	$P = 0.1$ atm	$P = 1.0$ atm	$P = 10$ atm
0.001	6.9×10^{-8}	6.9×10^{-9}	6.9×10^{-10}
0.01	6.9×10^{-7}	7.0×10^{-8}	8.7×10^{-9}
0.1	7.0×10^{-6}	8.8×10^{-7}	3.5×10^{-7}
1	8.8×10^{-5}	3.5×10^{-5}	3.1×10^{-5}
10	0.0035	0.0031	0.0029
100	0.29	0.25	0.17

Atmospheric lifetime

Now we can use the loss term to calculate lifetime.
Lifetimes are defined by the e-folding or half-lifetimes.

Consider a first order reaction for X:

$$\frac{d[X]}{dt} = -k[X]_0$$

The solution is:

$$[X] = [X]_0 e^{-kt}$$

$[X]_0$ ... initial concentration

The e-folding lifetime (τ_e) is the time at which:

$$\frac{[X]}{[X]_0} = e^{-1} = e^{-k\tau_e}$$

The characteristic lifetime, e-folding lifetime is hence:

$$\tau_e = \frac{1}{k}$$

More common

The half-lifetime can be defined as:

$$\frac{[X]}{[X]_0} = \frac{1}{2} = e^{-k\tau_{(1/2)}}$$

Then

$$\tau_{(1/2)} = \frac{\ln(2)}{k}$$

Global Carbon Cycle

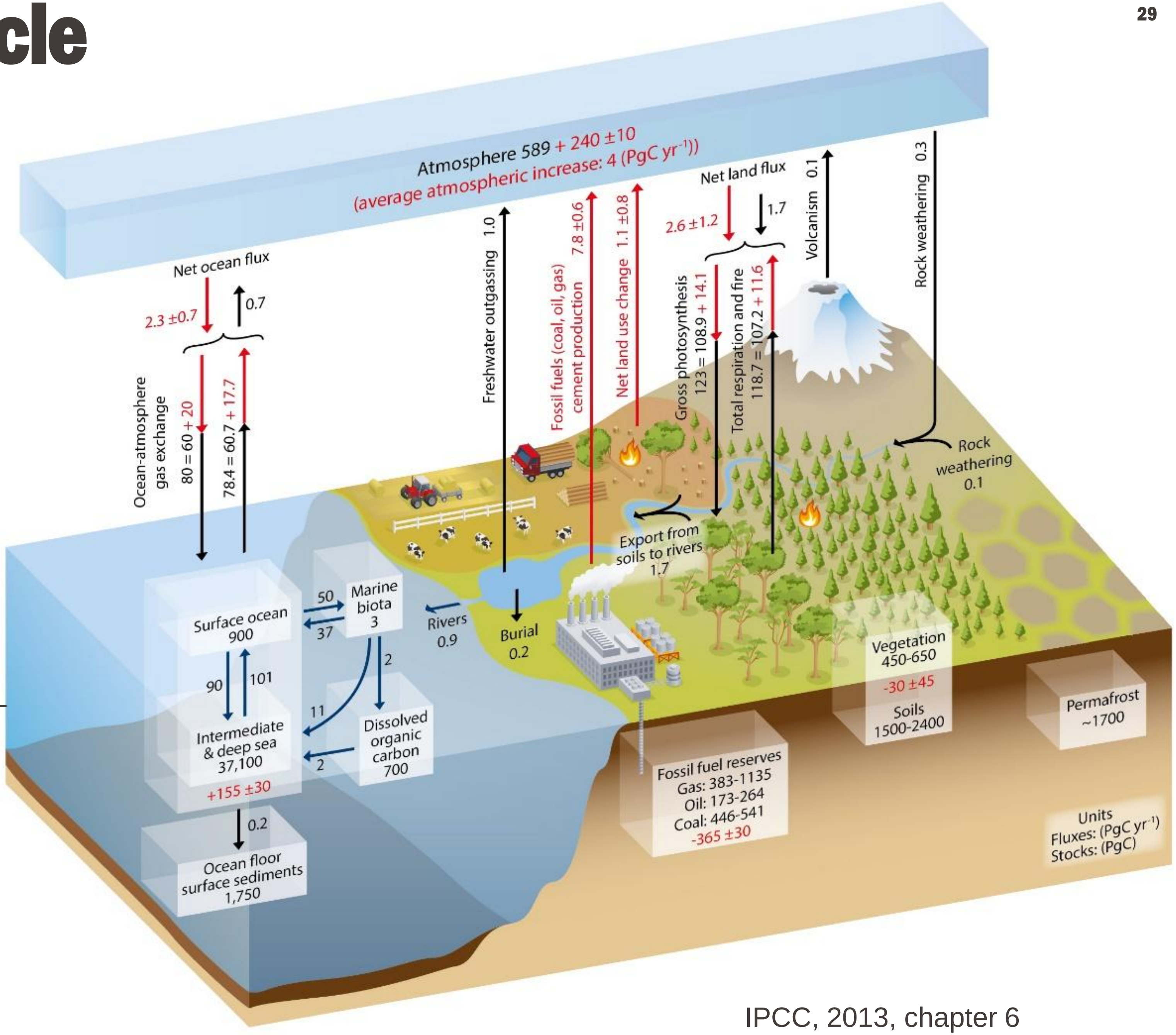
Units: PgC (1 PgC = 10^{15} gC), PgC yr^{-1}

Black: reservoir or fluxes prior to 1750 (pre-industrial), reservoir also called «carbon stock»
Red: «anthropogenic» fluxes 2000-2009

Two domains:
«Fast»: carbon in the atmosphere, the ocean, surface ocean sediments and on land in vegetation, soils and freshwaters
Slow: carbon stores in rocks and sediments

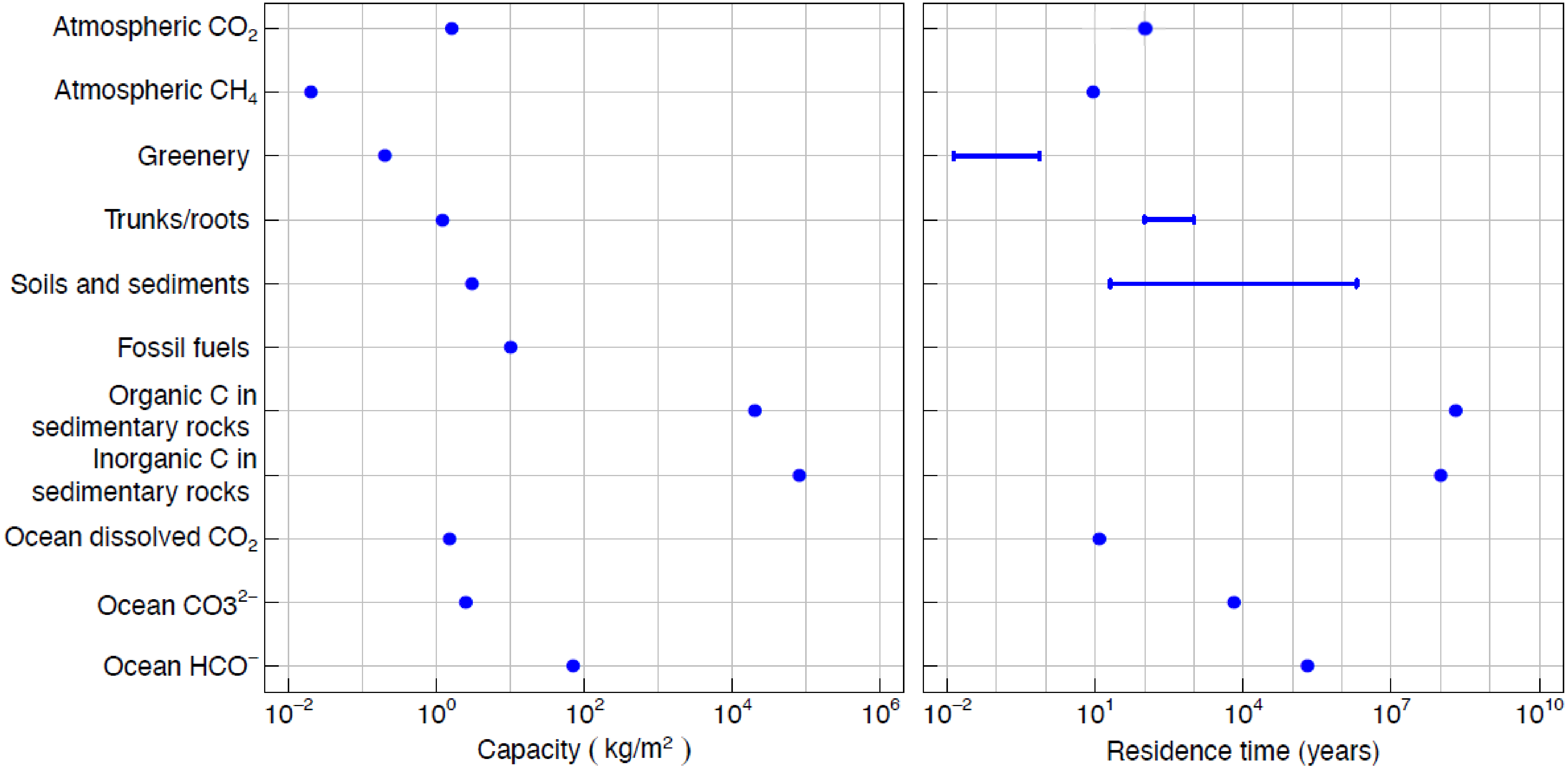
They exchange via volcanic eruptions and chemical weathering of rock.

Location	% C	Type of carbon
Lithosphere	99.985	fossil, sediments, organic carbon, marine sediments
Hydrosphere	0.0076	carbonate ions, dissolved CO2, biocarbonate ions
Pedosphere	0.0031	soil organisms, plant remains
Cryosphere	0.0018	frozen mosses
Atmosphere	0.0015	gaseous carbon
Biosphere	0.0012	living plants and animals



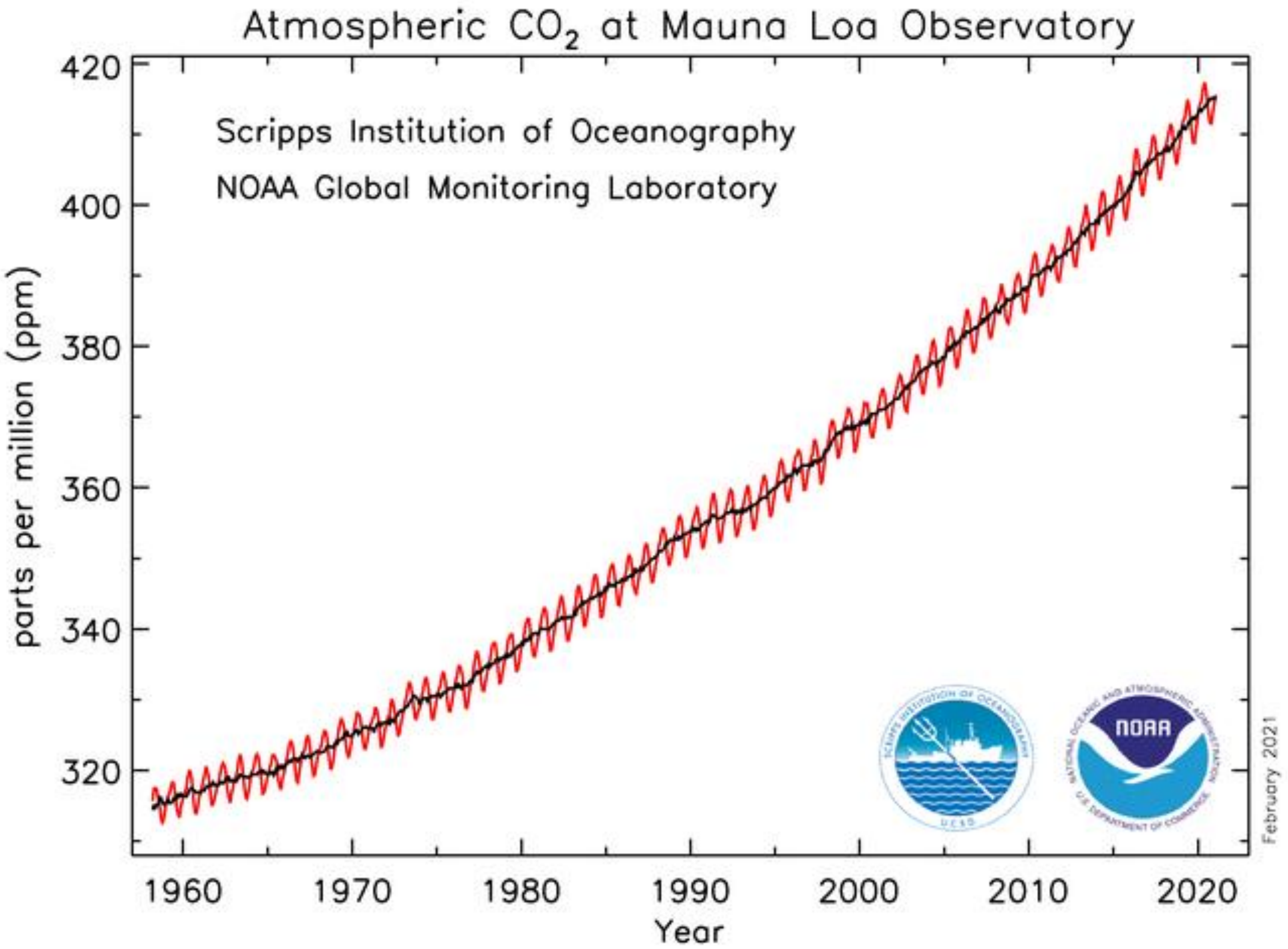
IPCC, 2013, chapter 6

Carbon reservoirs



Wallace and Hobbs (2006), p. 41

CO_2 Concentration Trends



Keeling curve

Daily observations at Mauna Loa (Hawaii) since 1958.

One of the most important scientific records of the 20th century.

https://www.esrl.noaa.gov/gmd/ccgg/trends/

Explore on your own

CAIT Climate Data Explorer

▾ CAIT Homepage

- Historical Emissions
- Equity Explorer
- Emission Projections
- Pre-2020 Pledges Map
- Paris Contributions Map
- Business Emissions and Targets
- Google Public Data Explorer

Google Public Data Explorer*

Dive deeper into the CAIT Historical Emissions data with the Google Public Data Explorer. Use it to compare country-level and region-level emissions by gases, sectors, per capita information, GDP and other socio-economic indicators and create your own visualizations and animations.

Go to Google Public Data Explorer »

Business Emissions and Targets*

CAIT Business offers the most trusted, decision-relevant data on how companies are contributing and responding to climate change. Full transparency empowers public and private sector leaders, civil society, NGOs and the media to take action to manage companies' climate impacts.

Start Business Emissions and Targets »

Global Forest Watch Climate*

GFW Climate is mapping platform that increases transparency about the climate impacts of tropical deforestation and gives access to comprehensible data on carbon emissions. It provides a benchmark for measuring countries' emissions and tracking progress toward meeting emissions-reduction goals.

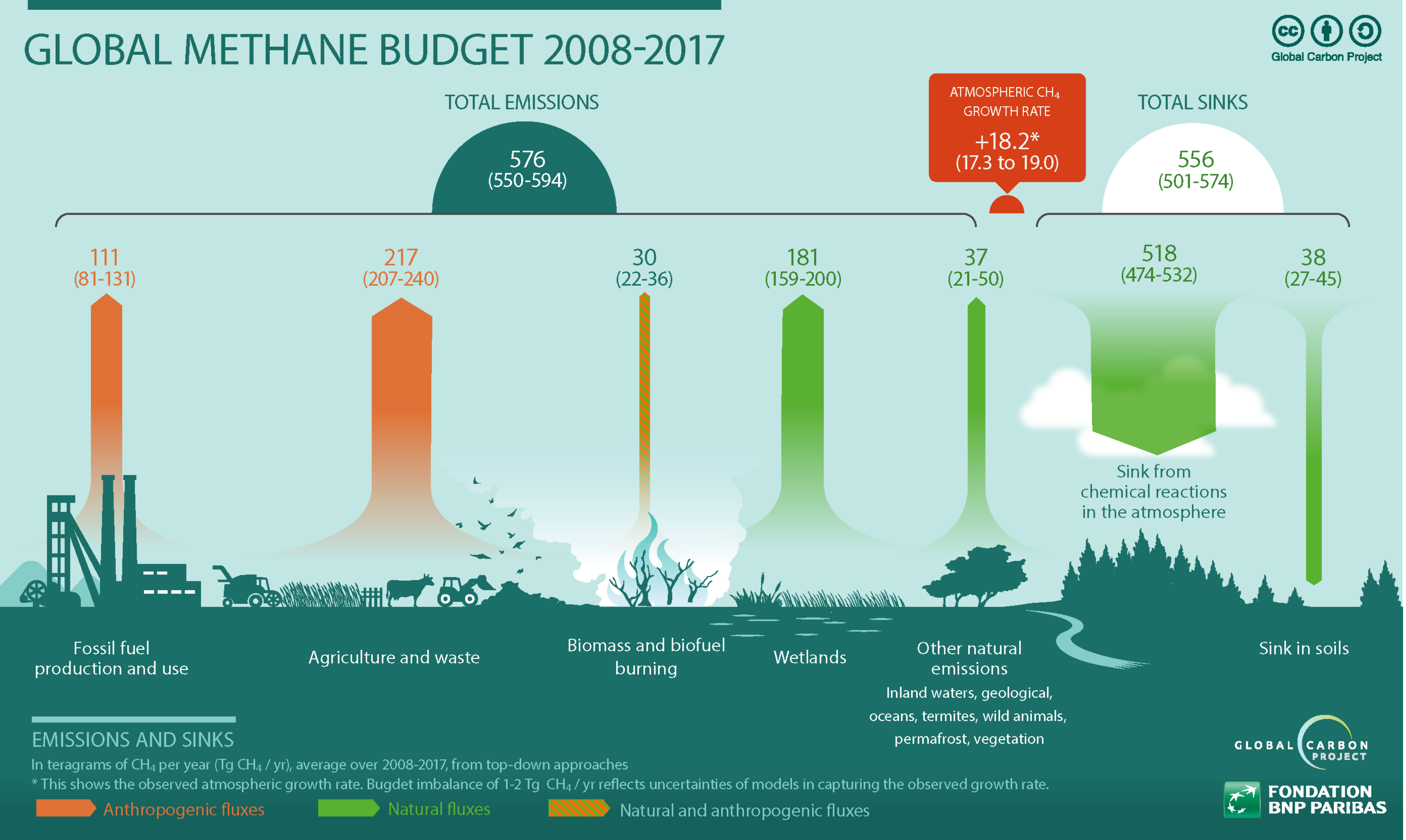
Start GFW Climate »

* These CAIT Tool will no longer be updated. Please refer to Climate Watch for latest data.

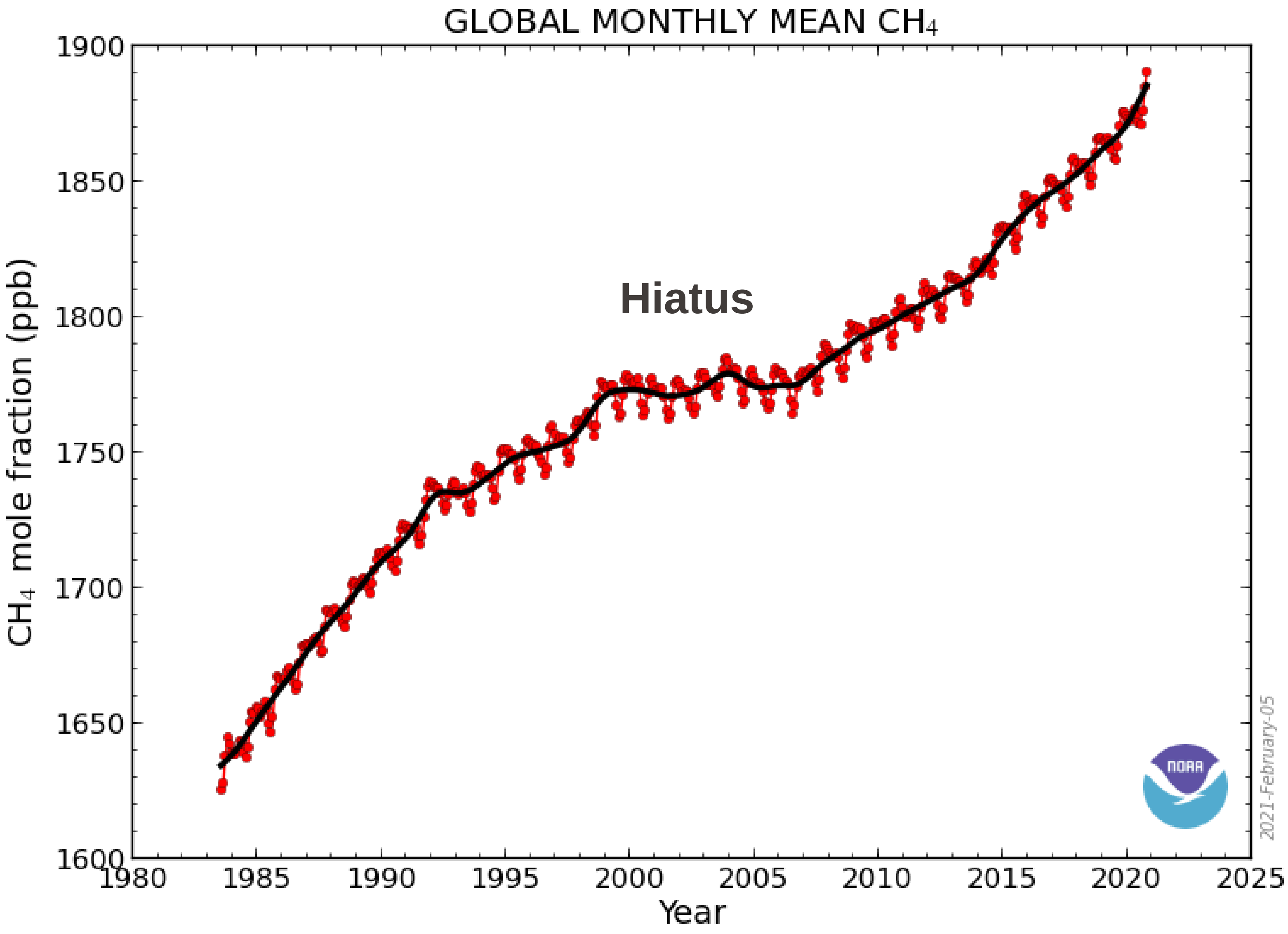
Watch out for the differences:

- Carbon vs CO_2 emissions
- Greenhouase gas vs CO_2 emission
- CO_2 vs CO_2 equivalent

http://cait.wri.org/


GLOBAL METHANE BUDGET 2008-2017
Global Carbon Project
TOTAL EMISSIONS
576
(550-594)
ATMOSPHERIC CH_4 GROWTH RATE
+18.2*
(17.3 to 19.0)
TOTAL SINKS
556
(501-574)
111
(81-131)
217
(207-240)
30
(22-36)
181
(159-200)
37
(21-50)
518
(474-532)
38
(27-45)
Sink from chemical reactions in the atmosphere
Fossil fuel production and use
Agriculture and waste
Biomass and biofuel burning
Wetlands
Other natural emissions
Inland waters, geological, oceans, termites, wild animals, permafrost, vegetation
Sink in soils
EMISSIONS AND SINKS
In teragrams of CH_4 per year (Tg CH_4 / yr), average over 2008-2017, from top-down approaches
* This shows the observed atmospheric growth rate. Bugdet imbalance of 1-2 Tg CH_4 / yr reflects uncertainties of models in capturing the observed growth rate.
Anthropogenic fluxes
Natural fluxes
Natural and anthropogenic fluxes
GLOBAL CARBON PROJECT
FONDATION BNP PARIBAS

CH_4 concentration trends



Is there something «strange» in the curve?

Stagnation not yet resolved:
- More anthropogenic emissions in that period.
- Main sink process with OH saw little change.

CO

TABLE 2.15 Estimates of Global Tropospheric CO Budget [in Tg(CO) yr^{-1}] and Values Adopted by IPCC (2001)

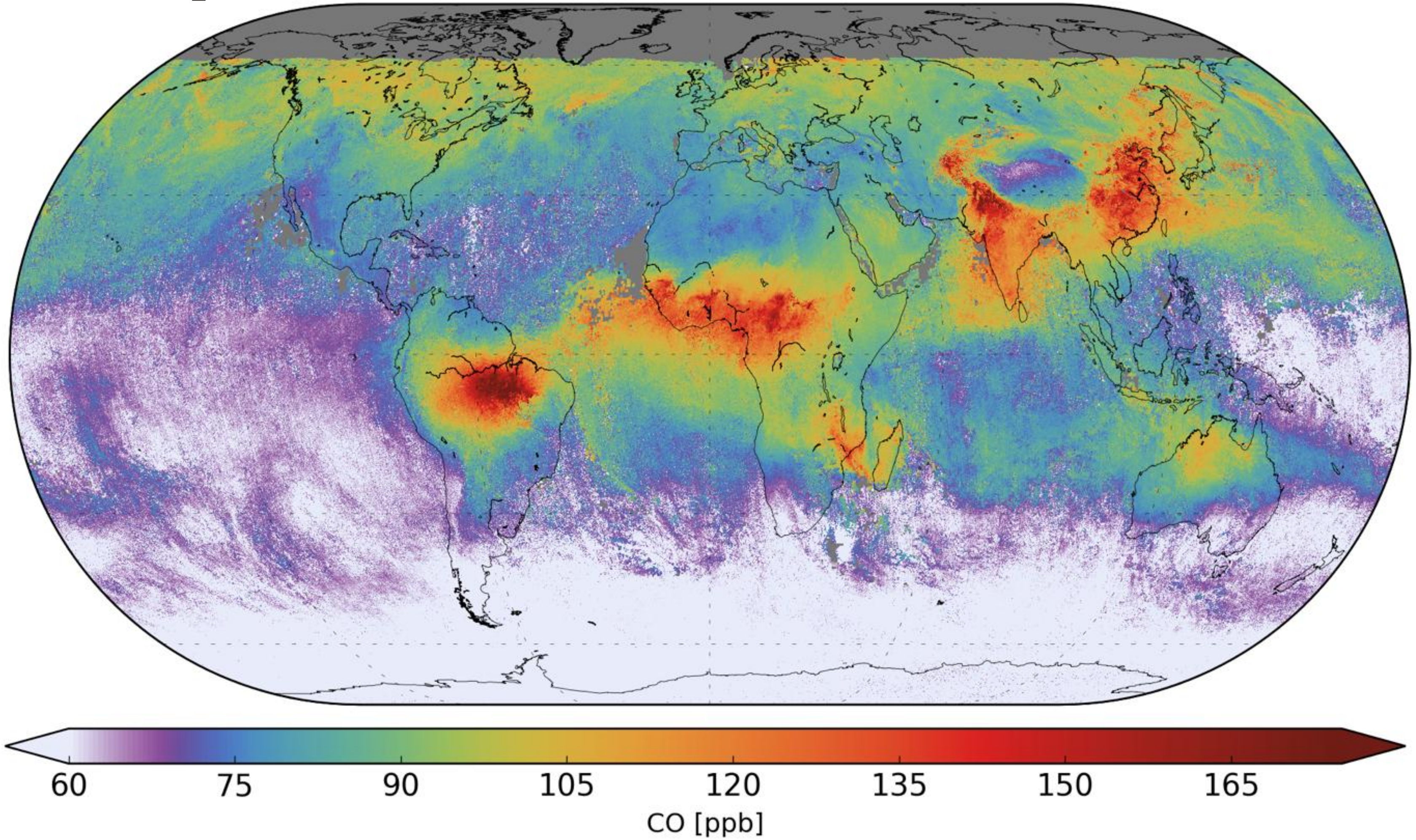
anthropogenic contribution

	Hauglustaine et al. (1998)	Bergamaschi et al. (2000)	WMO (1998)	IPCC (2001)
Sources				
Oxidation of CH_4		795		800
Oxidation of isoprene		268		270
Oxidation of terpenes		136		~0
Oxidation of industrial NMHC		203		110
Oxidation of biomass NMHC		—		30
Oxidation of acetone		—		20
Subtotal in situ oxidation	881	1402		1230
Vegetation		—	100	150
Oceans		49	50	50
Biomass burning		768	500	700
Fossil and domestic fuel		641	500	650
Subtotal direct emissions	1219	1458	1150	1550
Total sources	2100	2860		2780
Sinks				
Surface deposition	190			
OH reaction	1920			

- Seinfeld and Pandis, 2016

CO seen from satellite (TROPOMI)

$CO + OH \rightarrow CO_2 + H$
Lifetime of ~2 months

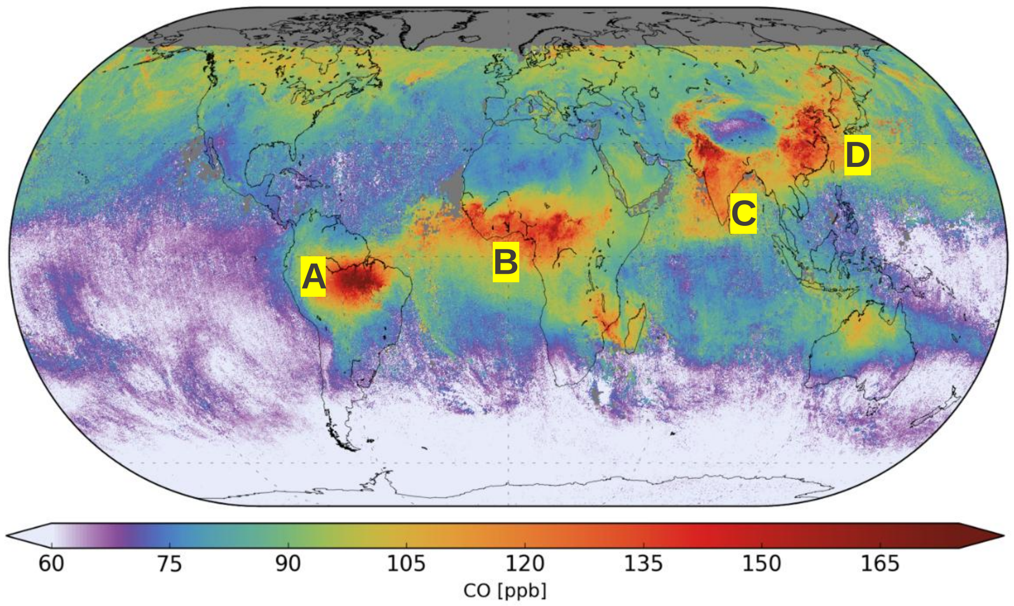


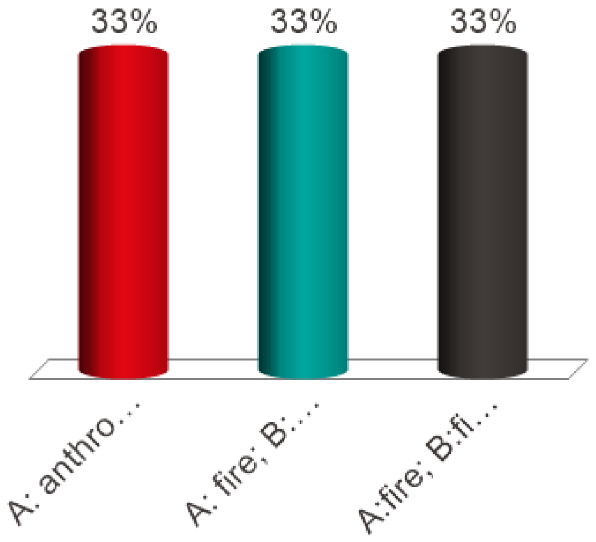
(Borsdorff et al., GRL, 2018), Nov. 13-19, 2017

http://www.tropomi.eu/data-products/carbon-monoxide
Measured at 2.3µm, total column, sensitive to boundary layer

What are the high emissions?

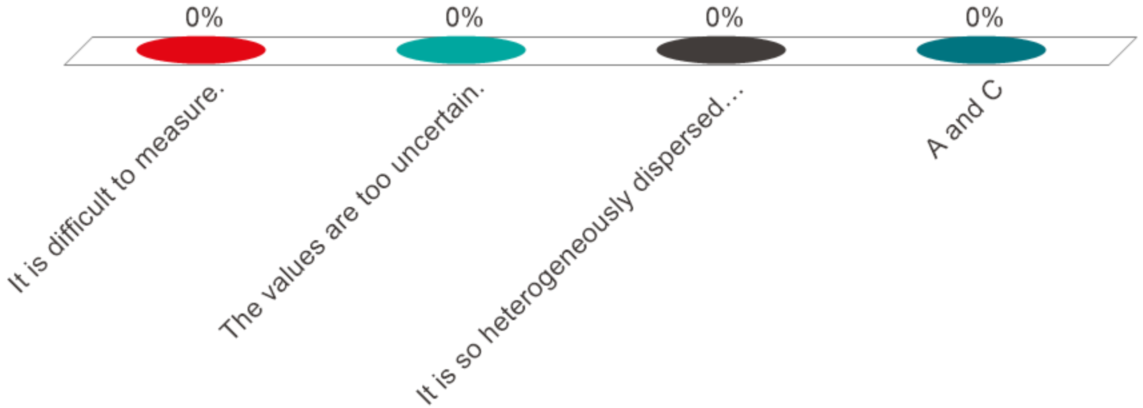
A. A: anthropogenic, B: fire, C: fire, D: anthropogenic
B. A: fire; B: fire; C: volcano; D: fire
C. A:fire; B:fire; C: anthropogenic; D: anthropogenic





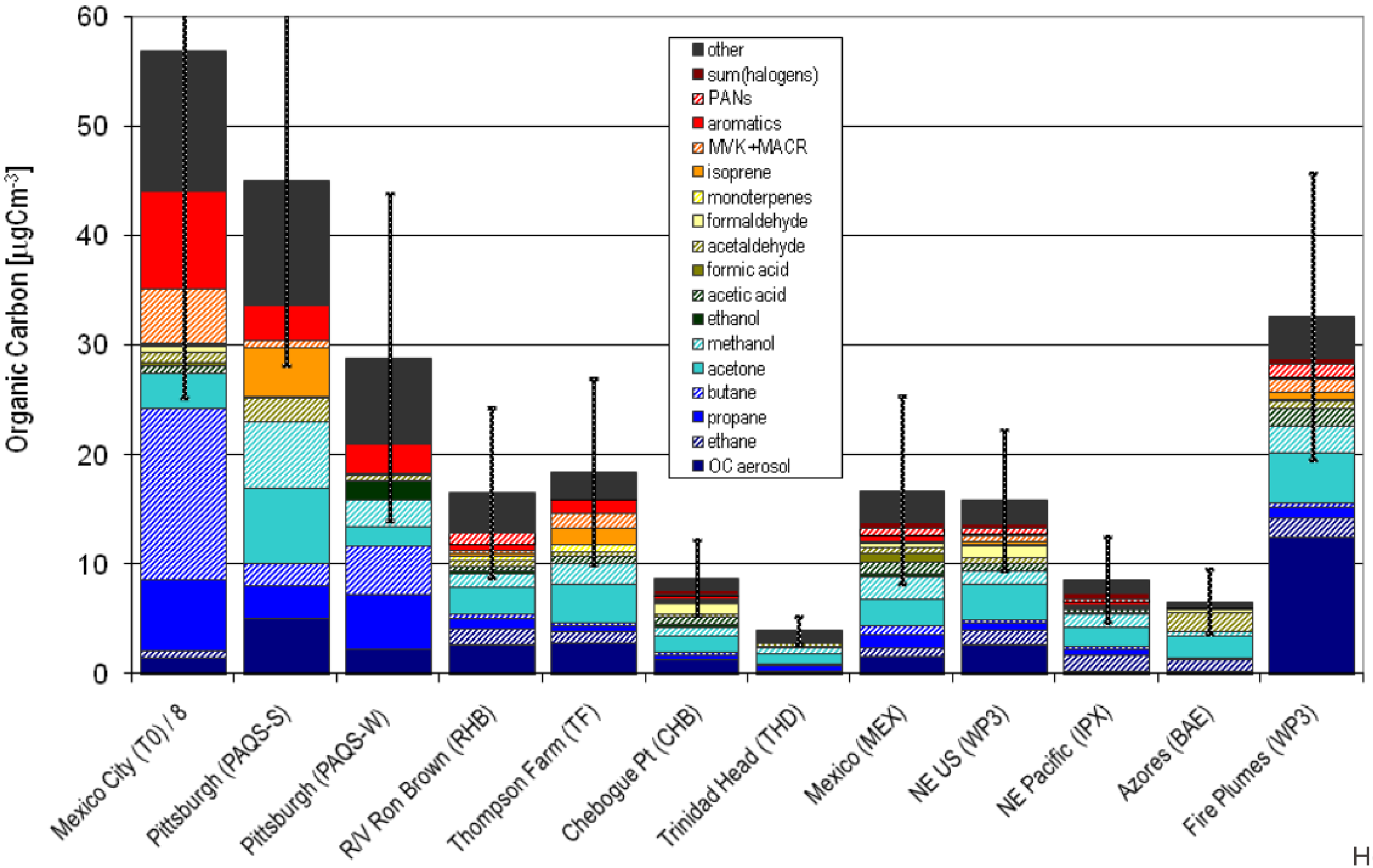
Why do you not find global concentration trends for CO?

A. It is difficult to measure.
B. The values are too uncertain.
C. It is so heterogeneously dispersed that a global average does not make much sense.
D. A and C



VOCs

Volatile organic compounds



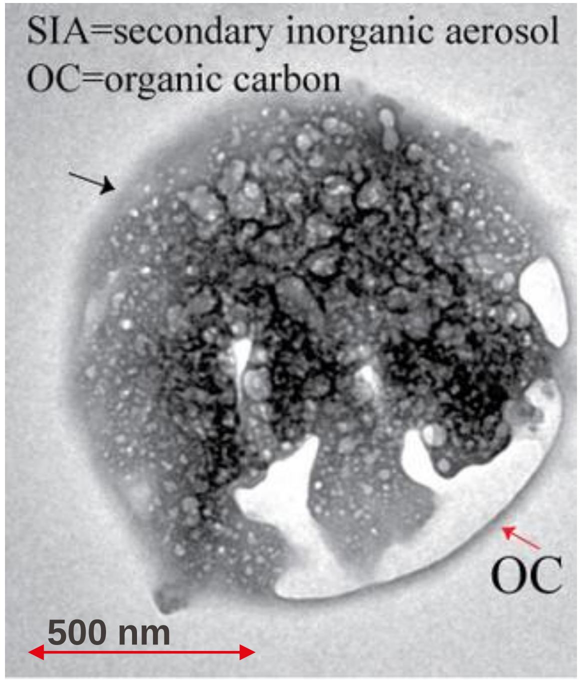
Also called NMHC (non-methane hydrocarbons)

TOC is total organic carbon

Form organic aerosol particles

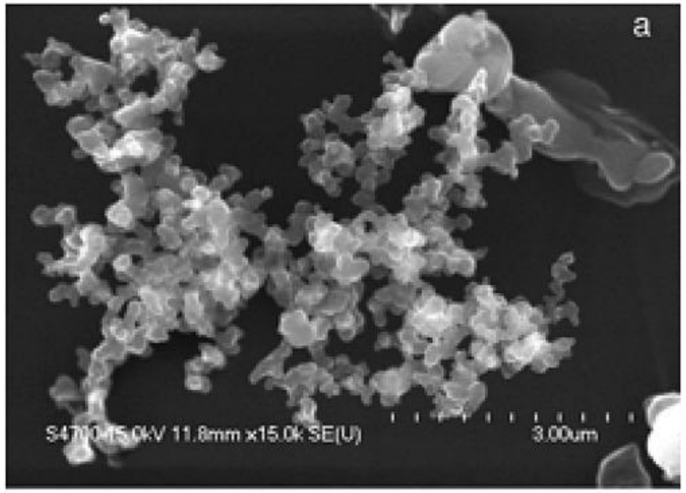
Heald et al., 2008, ACP
https://doi.org/10.5194/acp-8-2007-2008

Carbon in the atmosphere is not only contained in gases but also particles



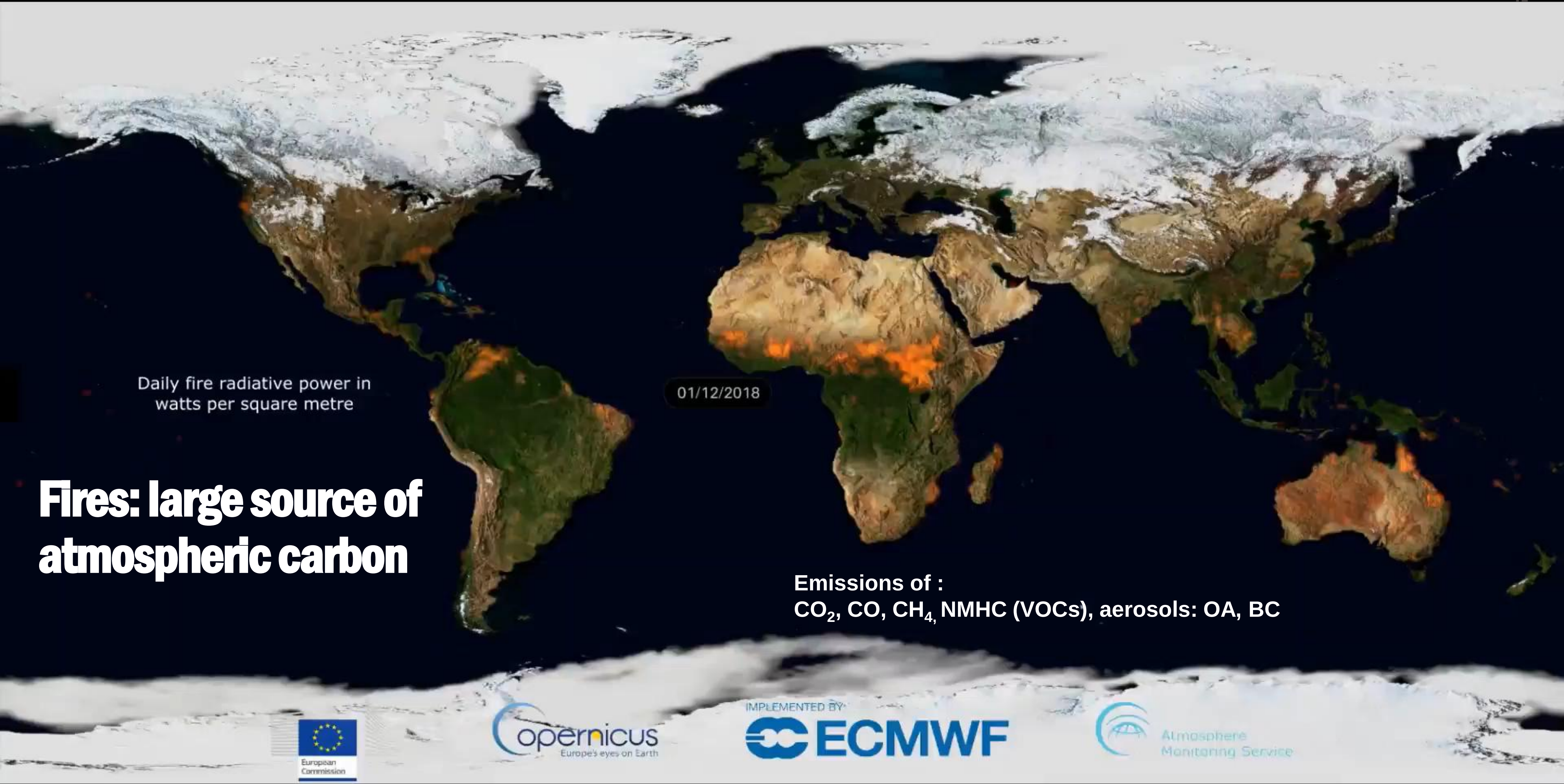
DOI:10.5194/acp-15-13365-2015

Black carbon aggregates



Sources are combustion processes (fossil and biogenic) https://atmosphere.copernicus.eu/media/494

Fires: large source of atmospheric carbon



Emissions of :
CO_2, CO, CH_4, NMHC (VOCs), aerosols: OA, BC

The global carbon cycle includes…

A. Only CO_2.

B. CO_2 and CH_4.

C. Only gases that contain C.

D. Gases and particles that contain C.

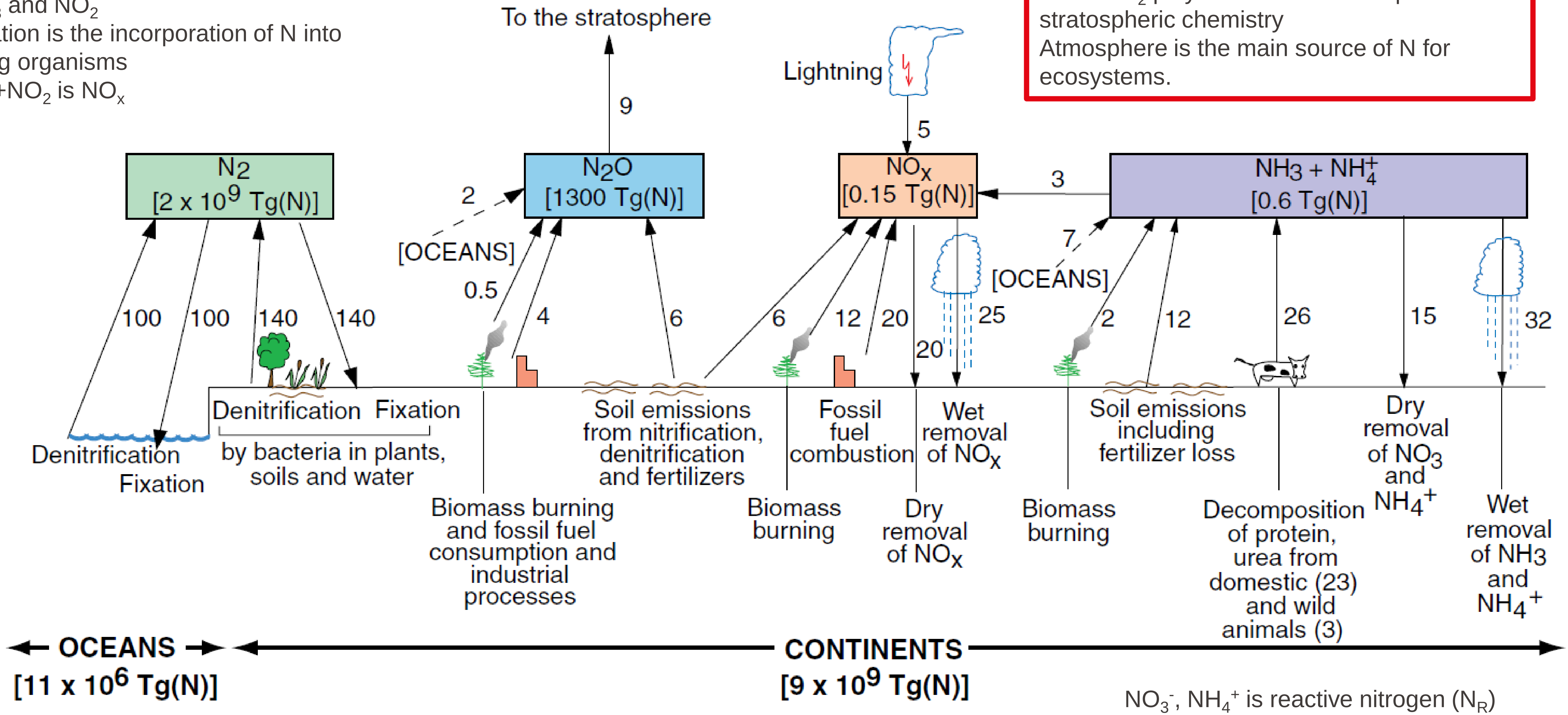
E. Aerosol organic carbon is not part of the carbon cycle.

F. NMHCs.

Nitrogen Cycle

N_2 makes up > 99.99 % of atmospheric N
N_2O makes up > 99 % of the remaining N
NH_3 is of crucial importance, only basic gas (neutralization of aerosols)
NO + NO_2 play a critical role in tropos- and stratospheric chemistry
Atmosphere is the main source of N for ecosystems.

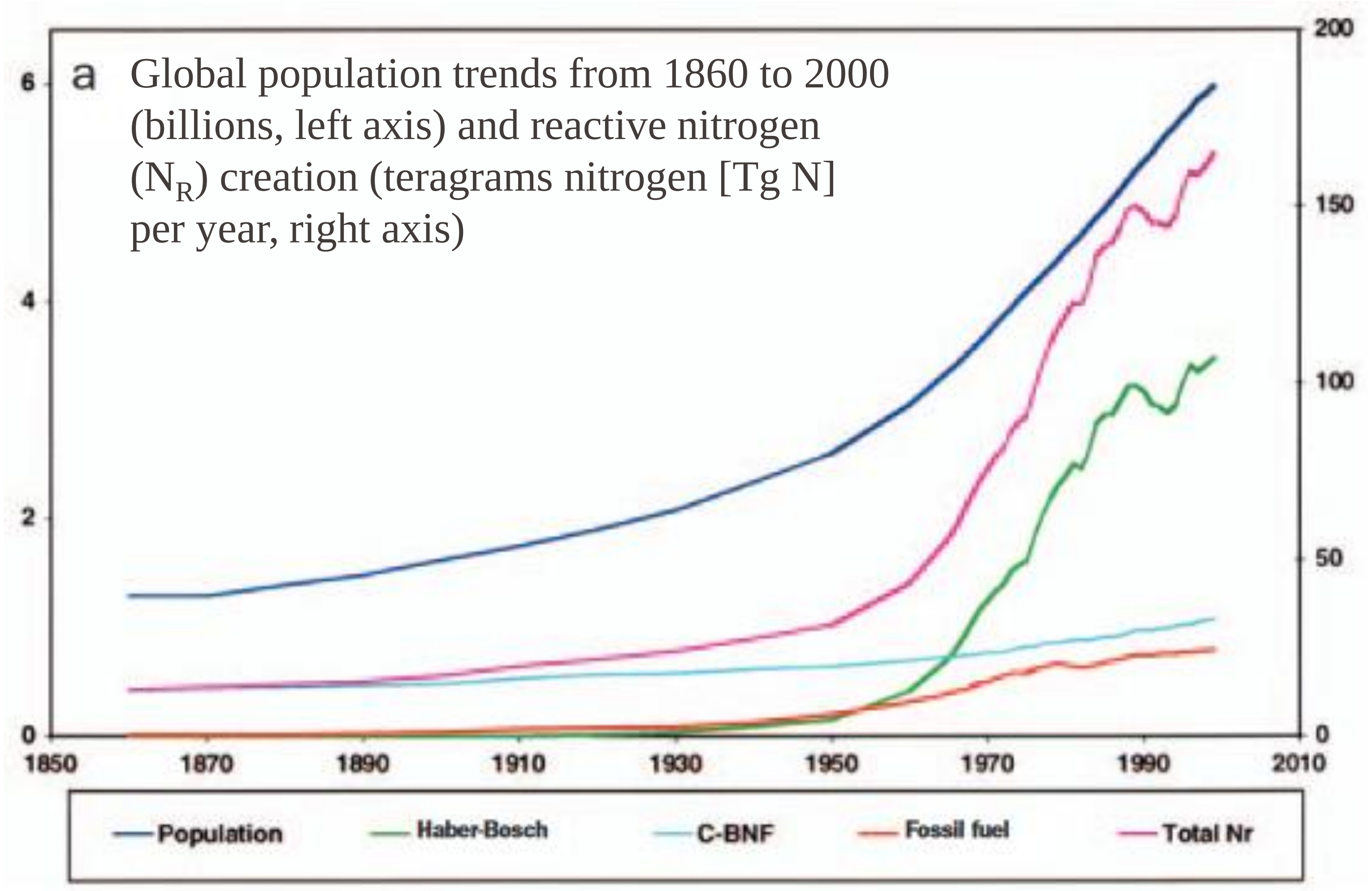
Denitrification produces N_2 and N_2O from NO_3 and NO_2
Fixation is the incorporation of N into living organisms
NO+NO_2 is NO_x



NO_3^-, NH_4^+ is reactive nitrogen (N_R)

- Figure 5.14, Wallace and Hobbs, 2006

Nitrogen from Agriculture



Haber-Bosch process:

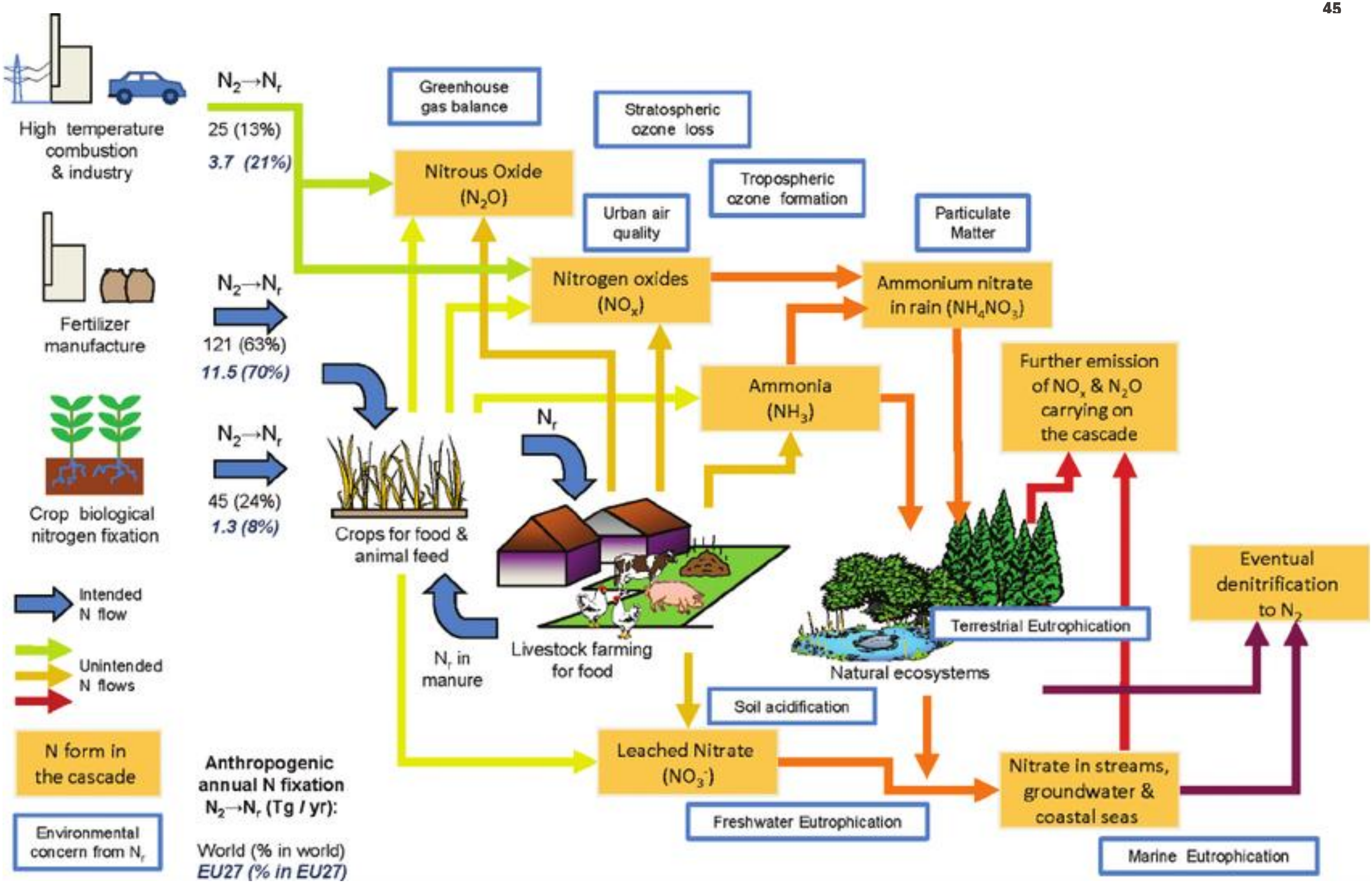
$N_2 + 3H_2 \rightarrow 2NH_3$
Ammonia as fertilizer (Nobel prize in 1918 and 1931)

Galloway et al., 2003, BioScience «The Nitrogen Cascade»   C-BNF cultivation-induced biological nitrogen fixation)

Nitrogen Cascade

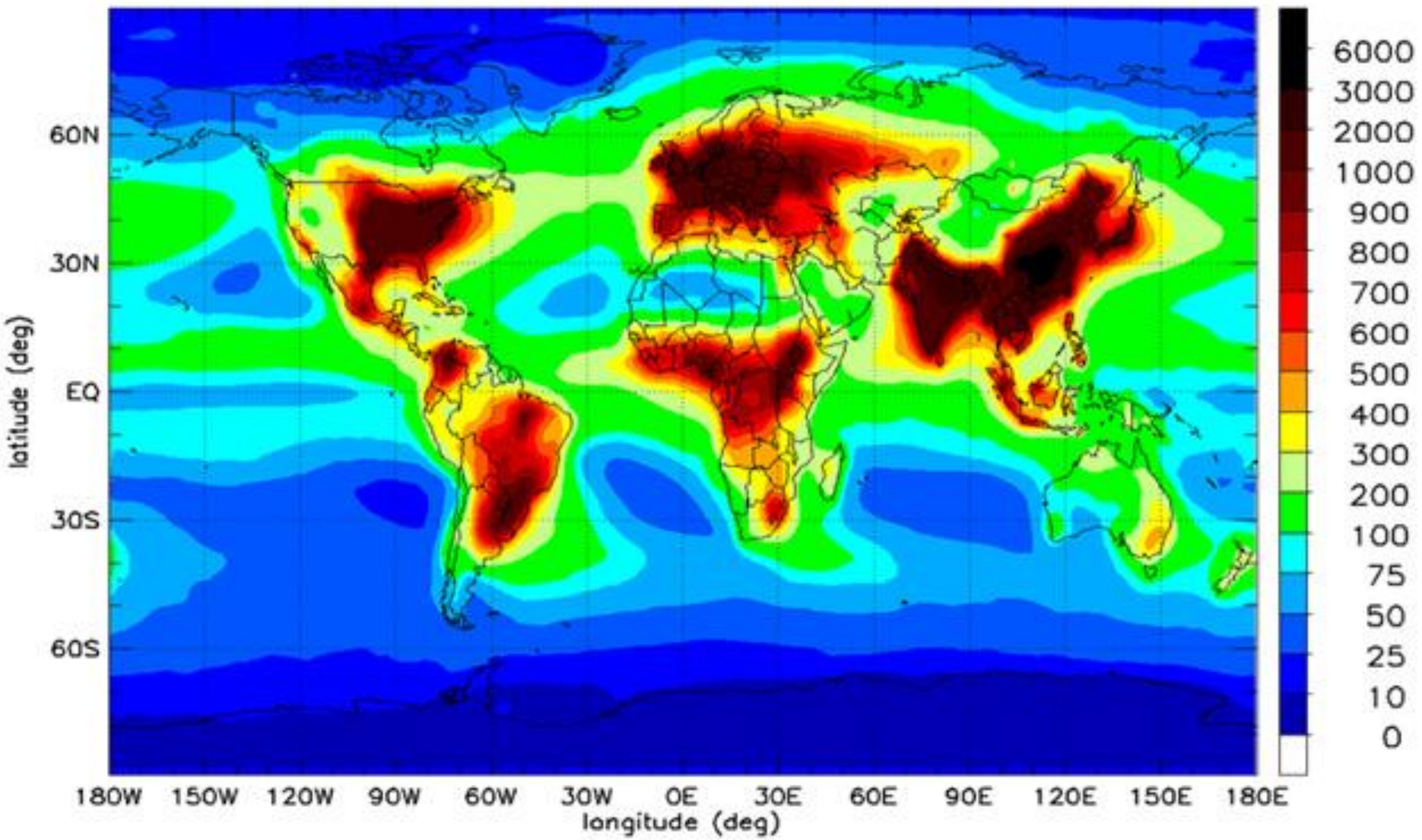
- N_R is released to the environments
- Effects are magnified the longer N_R stays in the environment, because the same atom of N_R can cause effects in the atmosphere, terrestrial ecosystems and in freshwater/marine systems

Integrated measures in agriculture to reduce ammonia emissions



Galloway et al., 2003; https://doi.org/10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2

Global nitrogen deposition



Estimated N deposition from global total N (NOy and NHx) emissions, totaling 105 Tg N y^{-1}. The unit scale is kg N ha^{-1} y^{-1}, modified from the original units (mg m^{-2} y^{-1})

Galloway et al., 2008, Science, https://science.sciencemag.org/content/320/5878/889

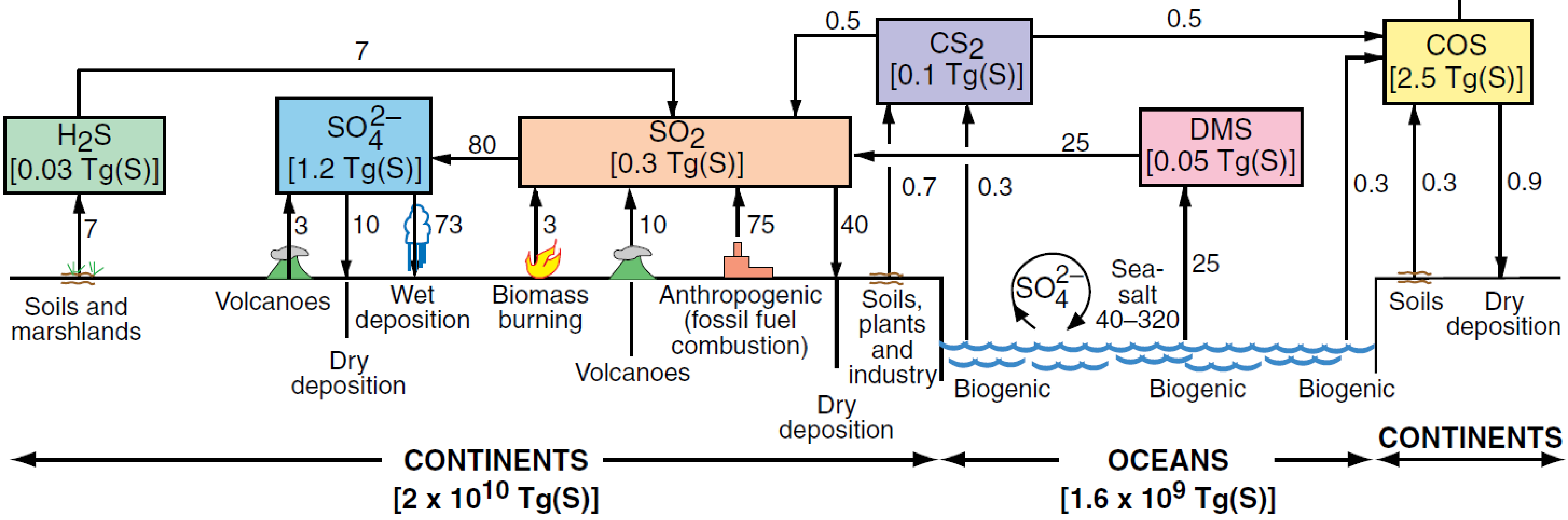
The main air pollutants containing nitrogen are

A. N_2O
B. NO_x
C. Nitrate aerosols
D. N_2
E. Ammonium
F. A and D
G. A, B, C, E
H. B, C, E

Sulfur cycle

Main natural sources are reduced S (COS, DMS, CS_2, H_2S)
COS has a long lifetime.
Anthropogenic emissions of S dominate, mainly as SO_2.

Species	Average lifetime
H_2S	2 days
OCS	7 years
CS_2	1 week
CH_3SCH_3	0.5 day
SO_2	2 days
SO_4^{2-}	5 days

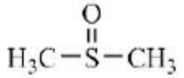
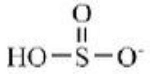
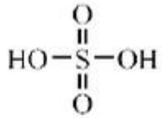
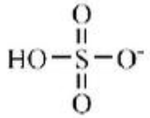
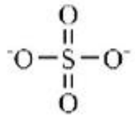
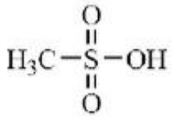


COS… carbonyl sulfide
DMS… Dimethyl sulfide
CS_2 … carbon disulfide
H_2S…hydrogen sulfide

- Figure 5.15, Wallace and Hobbs, 2006

Oxidation state

TABLE 2.1 Atmospheric Sulfur Compounds

Oxidation State	Compound: Name	Compound: Formula	Chemical Structure	Usual Atmospheric State
−2	Hydrogen sulfide	H_2S	$H-S-H$	Gas
	Dimethyl sulfide (DMS)	CH_3SCH_3	$H_3C-S-CH_3$	Gas
	Carbon disulfide	CS_2	$S=C=S$	Gas
	Carbonyl sulfide	OCS	$O=C=S$	Gas
	Methyl mercaptan	CH_3SH	H_3C-S-H	Gas
−1	Dimethyl disulfide	CH_3SSCH_3	$H_3C-S-S-CH_3$	Gas
0	Dimethyl sulfoxide	CH_3SOCH_3		Gas
4	Sulfur dioxide	SO_2	$O=S=O$	Gas
	Bisulfite ion	HSO_3^-		Aqueous
6	Sulfuric acid	H_2SO_4		Gas/aqueous/aerosol
	Bisulfate ion	HSO_4^-		Aqueous/aerosol
	Sulfate ion	SO_4^{2-}		Aqueous/aerosol
	Methane sulfonic acid (MSA)	CH_3SO_3H		Gas/aqueous Also as aerosol

- Seinfeld and Pandis, 2016

Global emissions

TABLE 2.2 Global Sulfur Emissions Estimates [Tg(S) yr^{-1}]

Source	H_2S	DMS	CS_2	OCS[a]	SO_2[b]	Sulfate	Total[c]
Fossil fuel combustion + industry		Total reduced S: 2.2			56.3	2.2	71–77 (mid-1980s) (68/6)
Biomass burning	<0.01?	—	<0.01?	0.075	1.3	0.1	2.2–3.0 (1.4/1.1)
Oceans	<0.3	15–25	0.08	0.08	—	40–320	15–25 (8.4/11.6)[d]
Wetlands	0.006–1.1	0.003–0.68	0.0003–0.06	—	—	—	0.01–2 (0.8/0.2)
Plants + soils	0.17–0.53	0.05–0.16	0.02–0.05	—	—	2–4	0.25–0.78 (0.3/0.2)[e]
Volcanoes	0.5–1.5	—	—	0.01	6.6	2–4	9.3–11.8 (7.6/3.0)
Anthropogenic (total)							73–80
Natural (total, without seasalt and soil dust)							25–40
Total							98–120

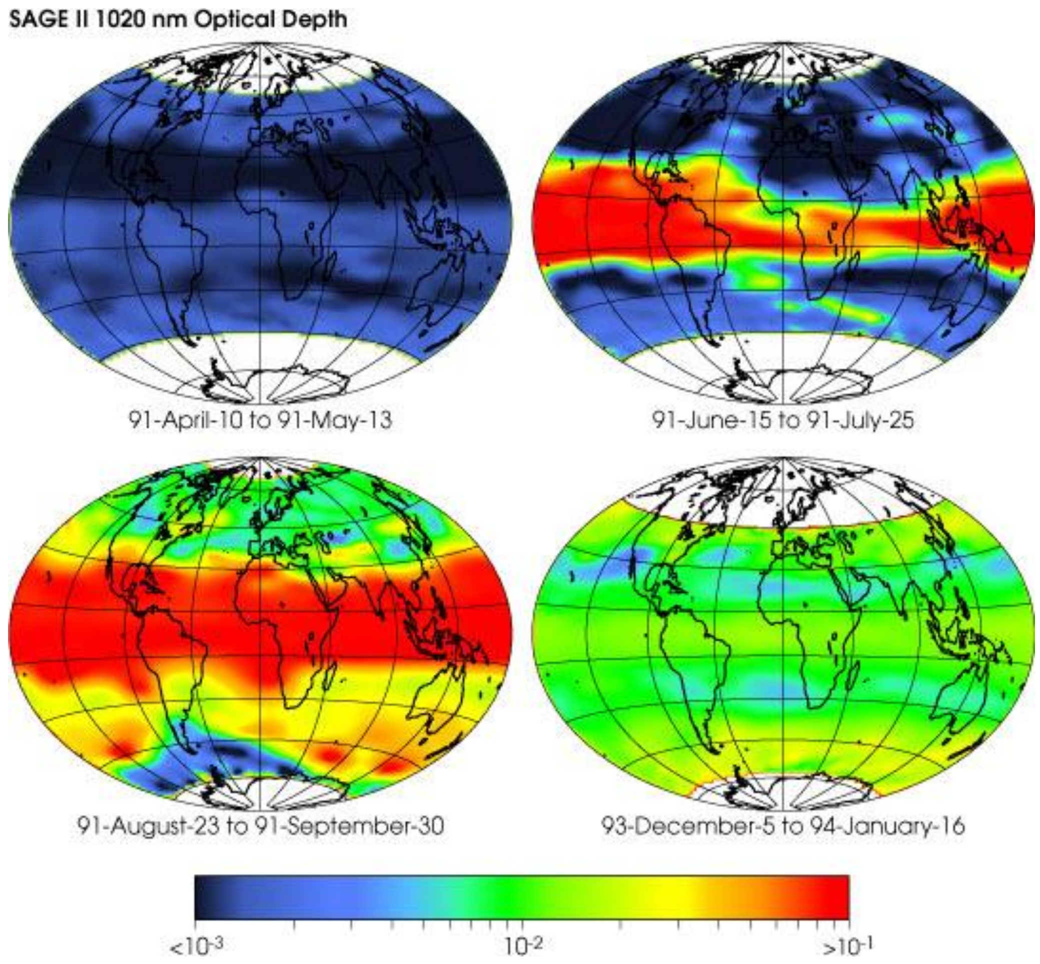
[a] Andreae and Crutzen (1997).
[b] Lee et al. (2011).
[c] Numbers in parentheses are fluxes from Northern Hemisphere/Southern Hemisphere.
[d] Excluding seasalt contributions.
[e] Excluding soil dust contributions.

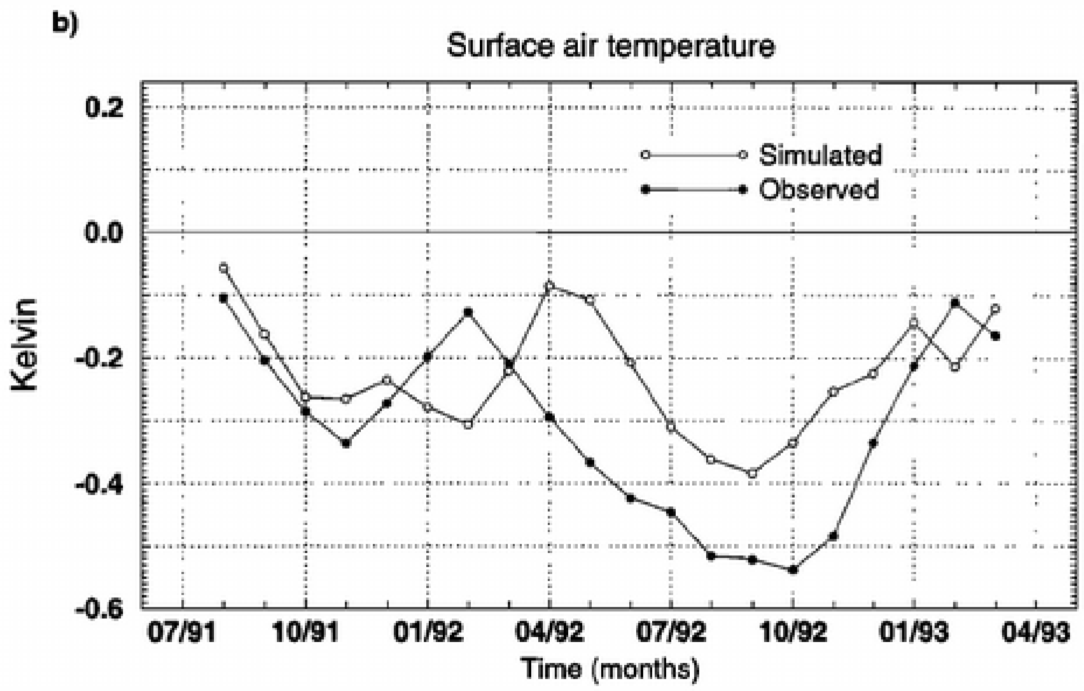
Source: Berresheim et al. (1995).

Seinfeld and Pandis, 2016

Mt. Pinatubo eruption

15 June 1991





https://earthobservatory.nasa.gov/images/1510/global-effects-of-mount-pinatubo

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/1999JD900213, Kirchner et al., 1999, JGR

Why does SO_2 survive longer in the stratosphere?

A. There is less OH.
B. There is less UV radiation.
C. There are no clouds.

Take home messages

- We talk about 1% of a millionths of Earth's mass, i.e. 1% of the atmospheric mass.
- We care about atmospheric composition because it affects air quality, ecosystems and climate change.
- The atmosphere is a chemical reactor: emission, advection, production, decomposition, deposition.
- Atmospheric constituents have a lifetime. Greenhouse gases are generally long-lived, while air pollutants are shorter-lived.
- Air pollutants and greenhouse gases play a role in global climate forcing.