# Lecture 2 Sustainability

PHY 555 – Energy & Environment

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Picture from https://smallboxenergy.com

# Lecture 2 – Sustainability

I. **Sustainability – Introduction**

II. The Earth Climate – Greenhouse Effect and Global warming

III. Depletion of resources, peak oil & minerals

IV. Towards a green future ?

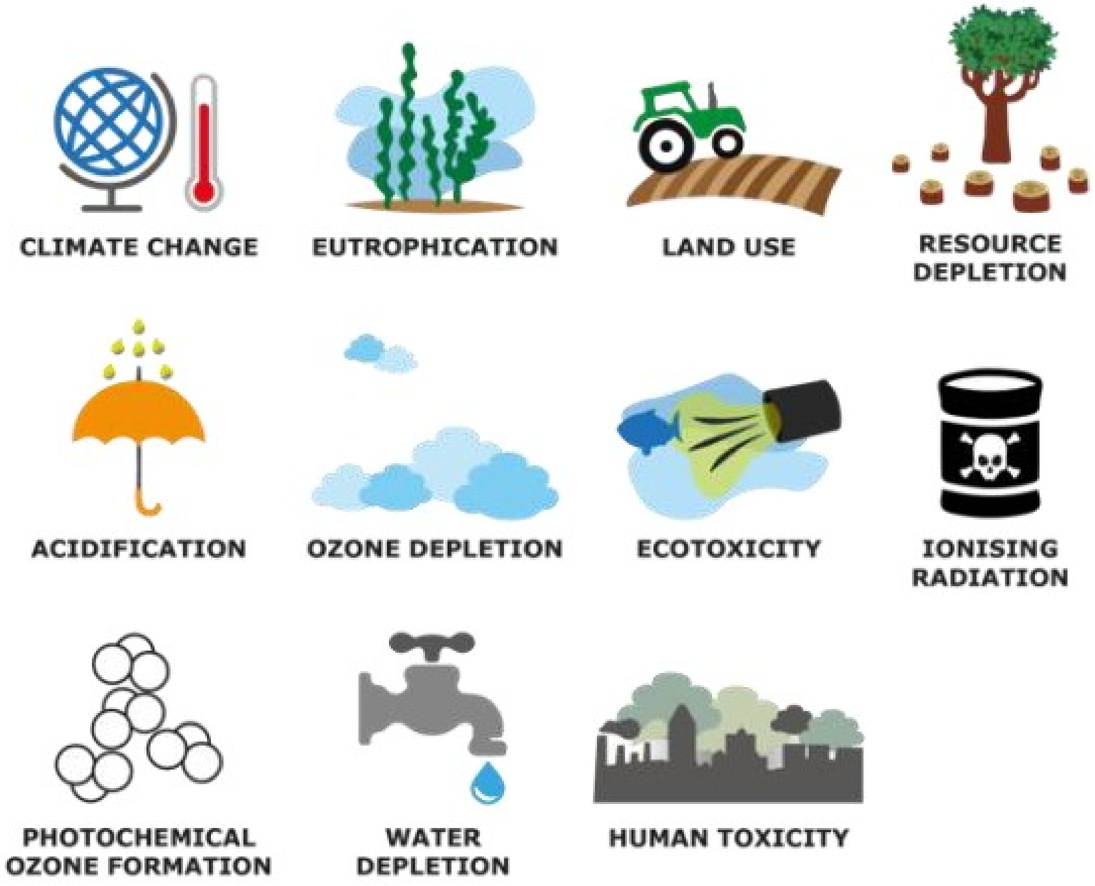
# Sustainability?

**Sustainability** is the capacity to endure in a relatively ongoing way across various domains of life. In the 21$^{st}$ century, it refers generally to the capacity for Earth's biosphere and human civilization to co-exist.

**Example Threats on Sustainability:**

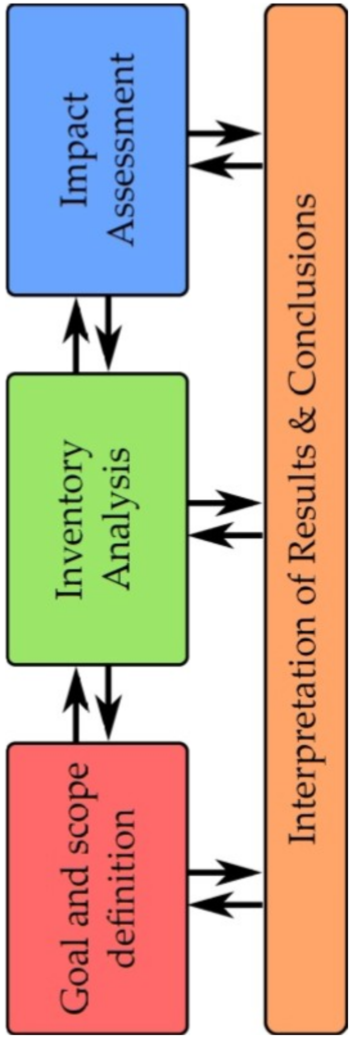
- Global Warming
- Resource exhaustion
    - Peak Oil
    - Minerals
    - Deforestation
    - Overfishing
    - ...
- Pollution

# Quantified Sustainability –Lifecycle analysis

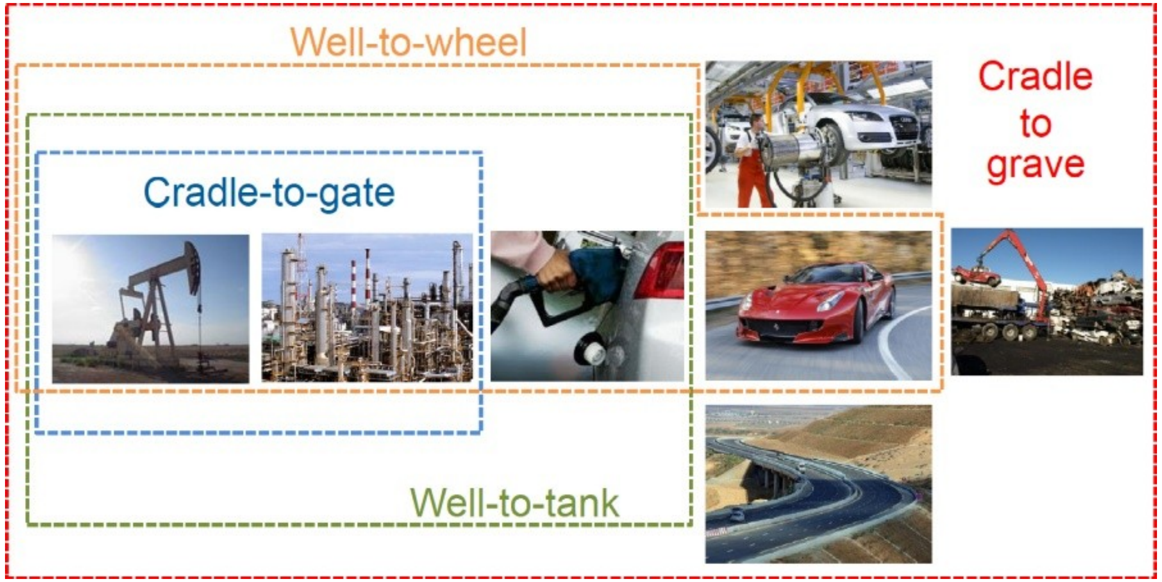

Life cycle assessment for the impact assessment of policies, Sala et al., JRC (European Commission), 2016

# LCA – Goal and scope definition



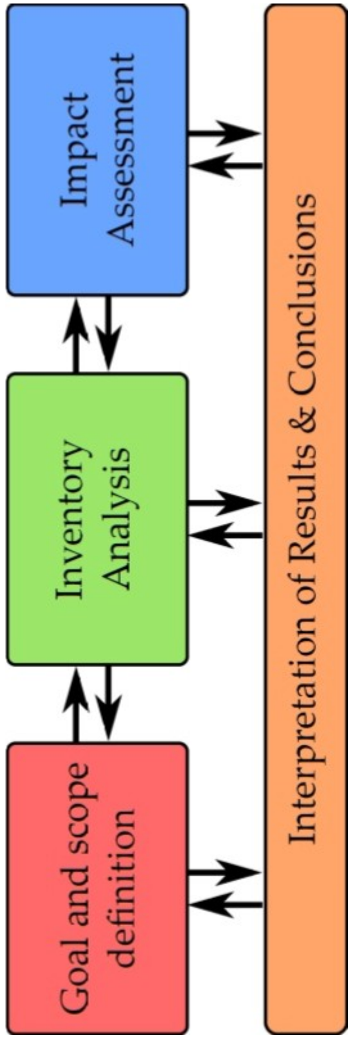

ISO 14040

- **Goal** = purpose (why is the study realized?), the intended audience (who is going to use it ?) and the intended application (typically, to decide among several options which one should be selected)
- **Scope** = the studied system (product, service...), the system boundaries and the functional unit




- **considered impacts** (global warming, energy content, acidification, human health...), the data requirements (accuracy, precision...) and should make working assumptions explicit.

# LCA – Inventory analysis

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*process vector*

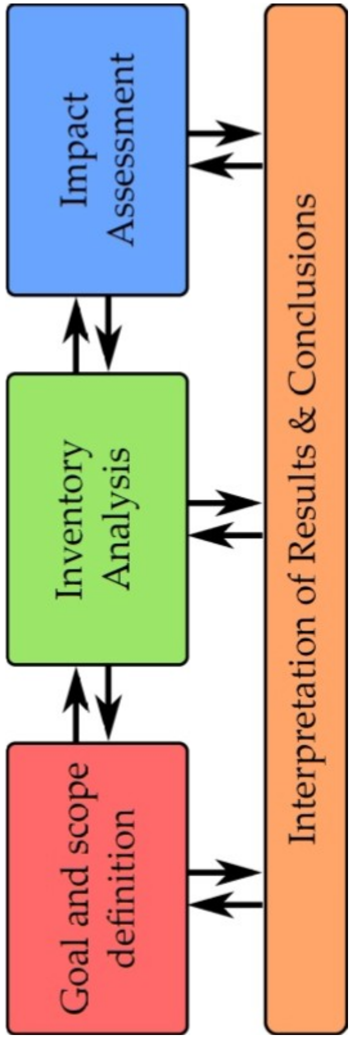
$$\mathbf{p} = \begin{pmatrix} \text{X kg of steel} \\ \text{Y kWh of electricity} \\ \text{Z L of oil} \\ \dots \end{pmatrix}$$

*emission matrix*

$$\underline{\text{E}} = \begin{pmatrix} \text{kgCO}_2 \text{ for 1 kg steel,} & \text{kgCO}_2 \text{ for 1 kWh elec,} & \text{kgCO}_2 \text{ for 1 L oil} & \dots \\ \text{kgCH}_4 \text{ for 1 kg steel,} & \text{kgCH}_4 \text{ for 1 kWh elec,} & \text{kgCH}_4 \text{ for 1 L oil} & \dots \\ \text{kgPO}_4^{3-} \text{ for 1 kg steel,} & \text{kgPO}_4^{3-} \text{ for 1 kWh elec,} & \text{kgPO}_4^{3-} \text{ for 1 L oil} & \dots \\ \dots & \dots & \dots & \dots \end{pmatrix}$$

- **Inventory** = Compilation of Input & Output for a product throughout its life cycle

# LCA – Impact assessment

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characterization matrix

$$\underline{Q} = \begin{pmatrix} \mathrm{kgCO_{2,eq}\ for\ 1\ kgCO_2}, & \mathrm{kgCO_{2,eq}\ for\ 1\ kgCH_4}, & \mathrm{kgCO_{2,eq}\ for\ 1\ kgPO_4^{3-}} & \dots \\ \mathrm{kgSO^-_{2,eq}\ for\ 1\ kgCO_2}, & \mathrm{kgSO^-_{2,eq}\ for\ 1\ kgCH_4}, & \mathrm{kgSO^-_{2,eq}\ for\ 1\ kgPO_4^{3-}} & \dots \\ \dots & \dots & \dots & \dots \end{pmatrix}$$

- **Impact Assessment** = classification of emissions according to impact categories (global warming, acidification, resource use, …)

  "weighting step"

$$\text{Impact for 1 functional unit} = \begin{pmatrix} N\,\mathrm{kgCO_{2,eq}}\ \text{(climate)} \\ M\,\mathrm{kgSO^-_{2,eq}}\ \text{(acidification)} \\ L\,\mathrm{kgPO^{3-}_{4,eq}}\ \text{(eutrophication)} \\ \dots \end{pmatrix}$$

$$= \underbrace{\underline{Q}}_{\text{Characterization matrix}} \times \underbrace{\underbrace{\underline{E}}_{\text{Emission matrix}} \times \underbrace{\mathbf{p}}_{\text{Process vector}}}_{\text{lifecycle inventory}}$$

# Lecture 2 – Sustainability

I. Sustainability – Introduction

**II. The Earth Climate – Greenhouse Effect and Global warming**

   I. Radiation – Thermal emission, absorption
   II. Radiative model of the earth
   III. Observational evidences of global warming

III. Depletion of resources, peak oil & minerals

IV. Towards a green future ?

# Black-body Radiation

- Bose-Einstein statistics for mass-less bosons (null chemical potential) at thermal equilibrium
- Spectral radiance (power per unit solid angle and area)

$$B(\nu,T)=\frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_B T}}-1}$$

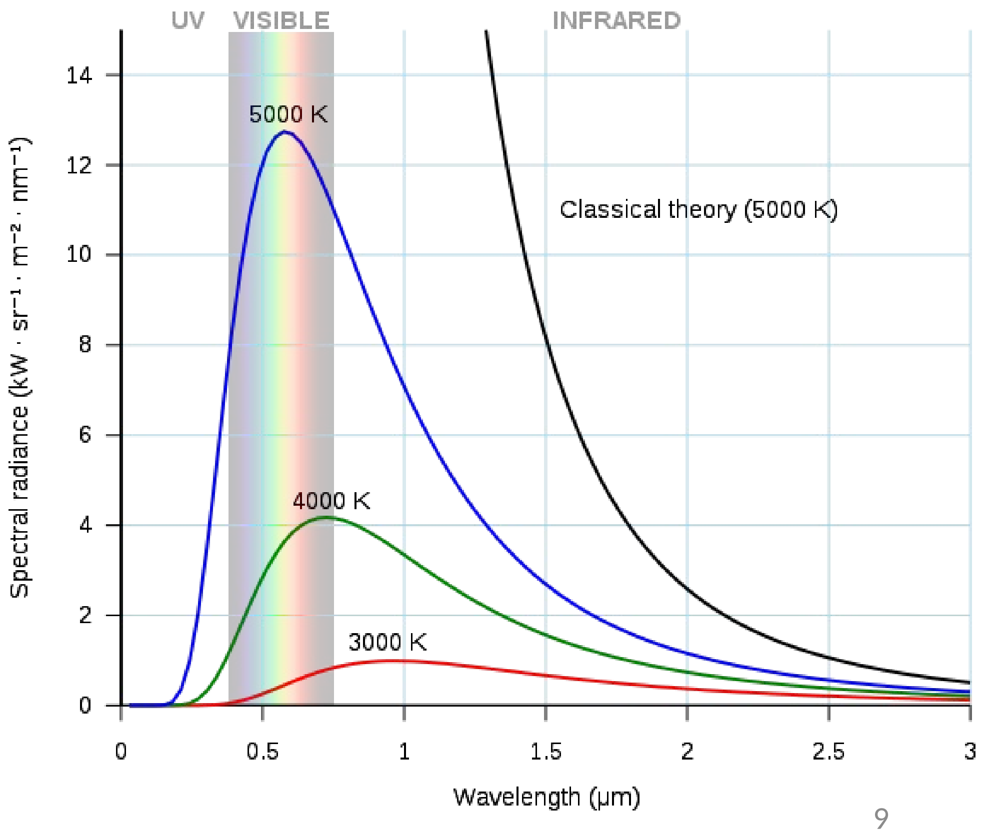
- Integrated Luminosity (Planck Law) per solid angle

$$L=\int B(\nu,T)\,\mathrm{d}\nu=\frac{2\pi^5}{15}\frac{k^4T^4}{c^2h^3}\frac{1}{\pi}=\sigma T^4\frac{1}{\pi}$$

with $\int \mathrm{d}x\frac{x^3}{e^x-1}=\frac{\pi^4}{15}$ $\qquad \frac{P}{S}=\int L\cos\theta\,\mathrm{d}\Omega=\sigma T^4$

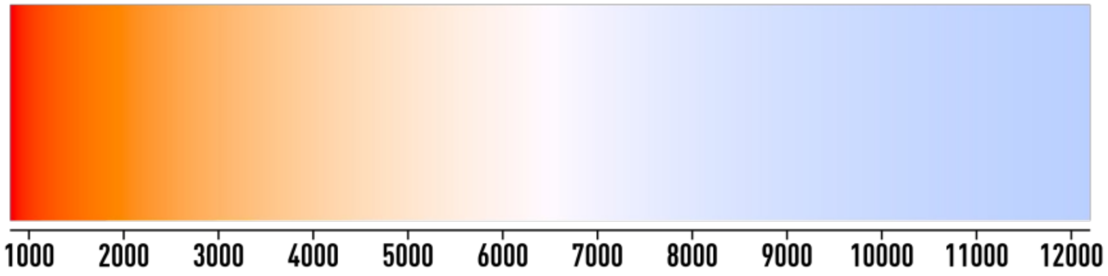
- Stefan–Boltzmann constant

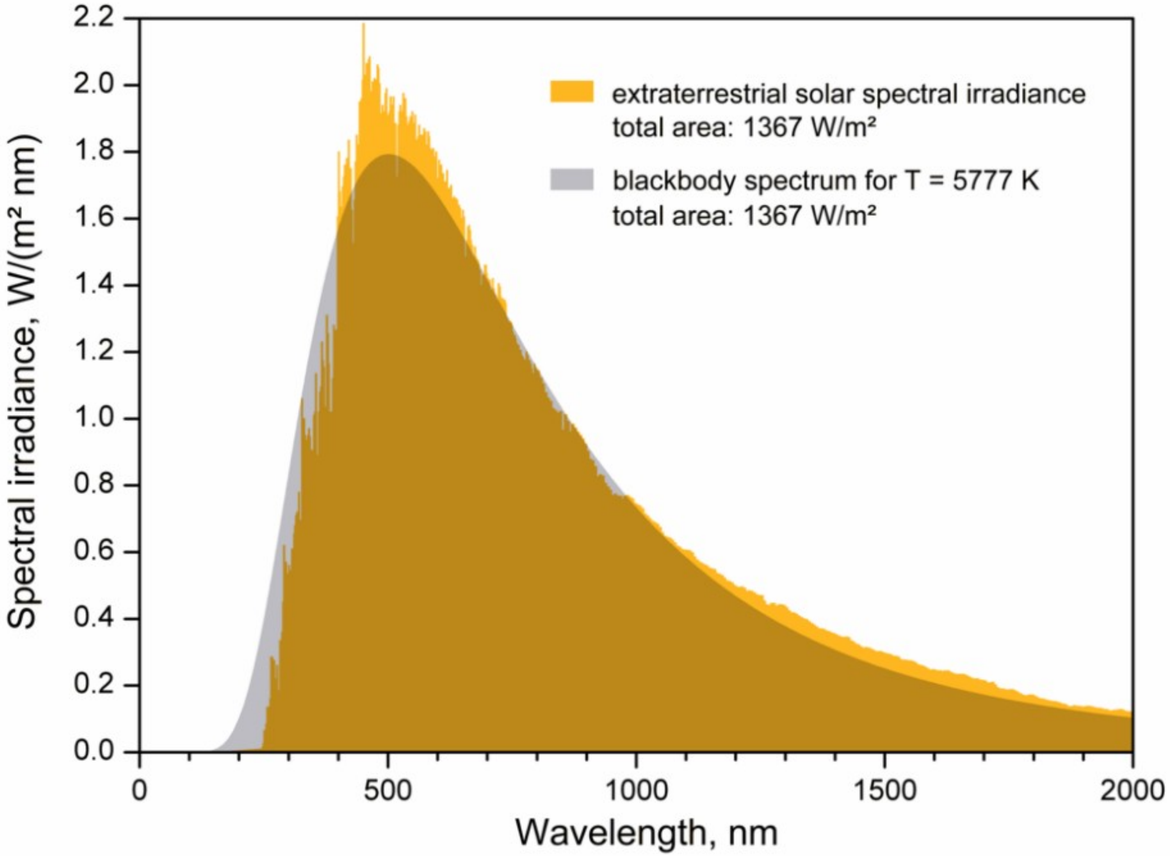
$$\sigma\equiv\frac{2\pi^5}{15}\frac{k^4}{c^2h^3}=5.670373\times10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$$



# Sun vs Blackbody

- The spectral radiance of the sun is very well approximated by a black-body spectrum at T = 5777K



# Solar irradiance?

- Total sun power

$$P_S = 4\pi R_S^2 \sigma T_S^4 \approx 3.8\times 10^{26}\,\mathrm{W}$$

- Incident normal power at distance d (solar constant)

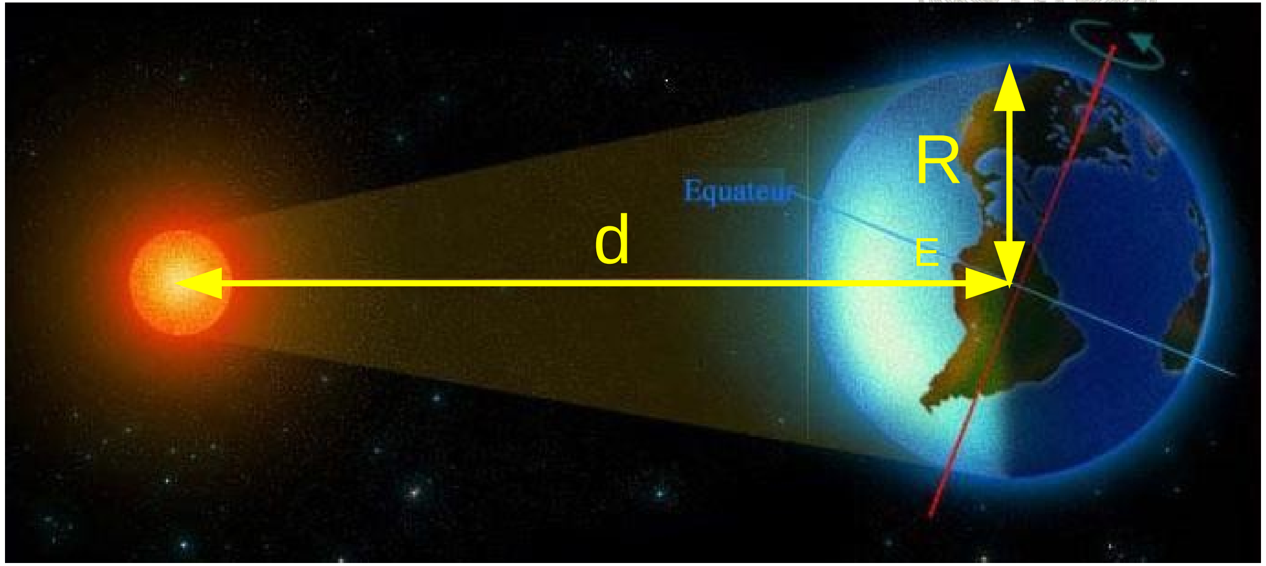
$$P_\perp = \frac{P_S}{4\pi d^2} = \sigma T_S^4 \frac{R_S^2}{d^2} \approx 1368\,\mathrm{W\,m^{-2}}$$

- Average power on Earth

$$P_{\mathrm{avg}} = \frac{1}{4} P_\perp \approx 342\,\mathrm{W\,m^{-2}}$$

- Total power received on Earth

$$P_{\mathrm{tot}} = 4\pi R_E^2 P_{\mathrm{avg}} \frac{1}{4} P_\perp \approx 2\times 10^{17}\,\mathrm{W} \approx \mathbf{1.5\times 10^{14}\,toe/year}$$




- Human primary energy consumption

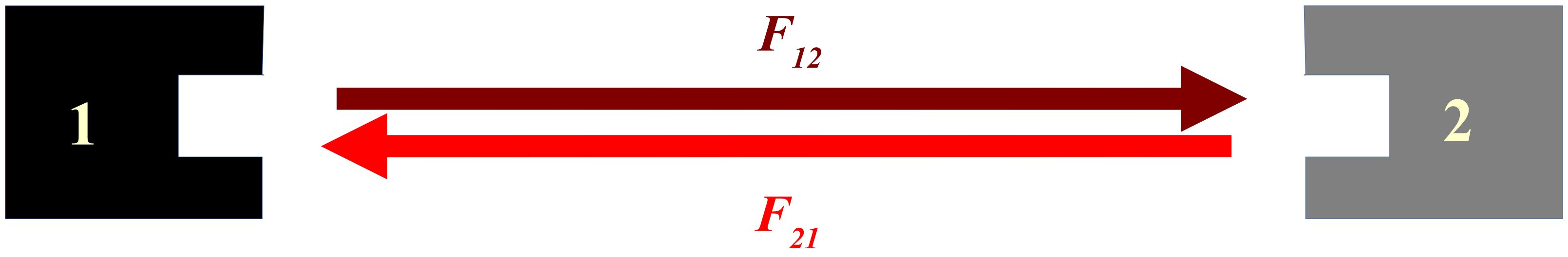
$$P_{\mathrm{primary}} \approx \mathbf{1.5\times 10^{10}\,toe/year}$$

$$\approx \frac{\mathbf{1}}{\mathbf{10\,000}}$$

# Kirchhoff's law

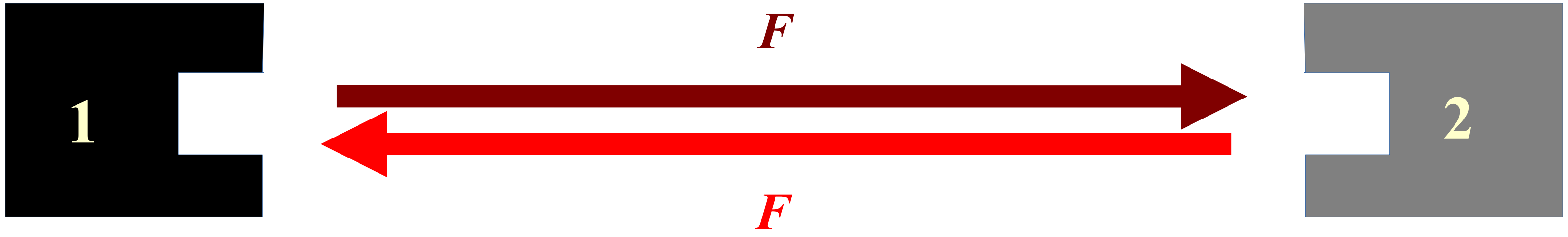
- radiative exchange between two grey body with the same area S
- emissivity: $I(\lambda)$ absorbency: $a(\lambda)$
- energy flow:

$$F_{12}(\lambda) = I_1(\lambda) S + \left(1 - a_1(\lambda)\right) F_{21}(\lambda)$$




$$F_{21}(\lambda) = I_2(\lambda) S + \left(1 - a_2(\lambda)\right) F_{12}(\lambda)$$

# Kirchhoff's law




- thermal balance: $T_1 = T_2 = T \quad \Rightarrow \quad \forall \lambda, \quad F_{12}(\lambda) = F_{21}(\lambda) \equiv F(\lambda)$

$$\begin{array}{l} F(\lambda) = I_2(\lambda) S + \left(1 - a_1(\lambda)\right) F(\lambda) \\ F(\lambda) = I_1(\lambda) S + \left(1 - a_2(\lambda)\right) F(\lambda) \end{array} \quad \Rightarrow \quad \begin{array}{l} a_1(\lambda) F(\lambda) = I_1(\lambda) S \\ a_2(\lambda) F(\lambda) = I_2(\lambda) S \end{array} \quad \Rightarrow \quad \frac{I_1(\lambda)}{a_1(\lambda)} = \frac{I_2(\lambda)}{a_2(\lambda)}$$

- This implies the existence of a universal emission law, i.e. the Black Body spectrum
- If body 1 is black body $\left(I_1 = B_\lambda \text{ and } a_1 = 1\right)$, then $I_2(\lambda) = \epsilon_2 \times B_\lambda \quad , \quad \epsilon_2 = a_2$

« *Thermal Emissivity* »

# Kirchhoff's law

*For a body of any arbitrary material emitting and absorbing thermal electromagnetic radiation at every wavelength in thermodynamic equilibrium, the ratio of its emissive power to its dimensionless coefficient of absorption is equal to a universal function only of radiative wavelength and temperature. That universal function describes the perfect black-body emissive power.*

or more simply

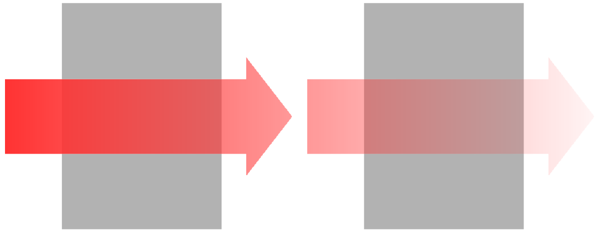
*For an arbitrary body emitting and absorbing thermal radiation in thermodynamic equilibrium, the emissivity is equal to the absorptivity.*

# Absorption of radiation

- Classical expression for a semi-transparent homogeneous medium (Bouguer-Lambert law)

$$I(z) = I_0 \exp(-\alpha z)$$

- Transparencies are combined in a multiplicative way

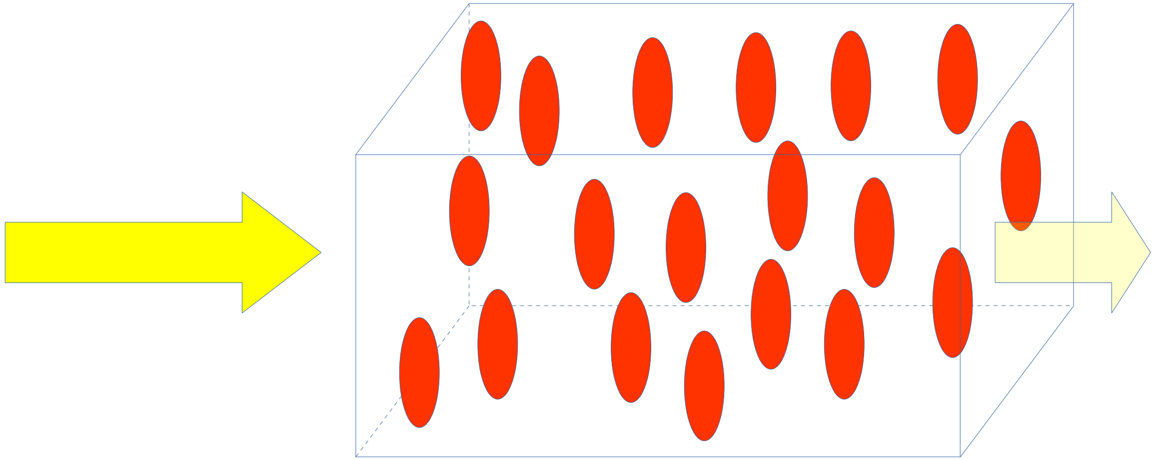


$$I_2 = t_2 \times I_1 = \underbrace{t_2 \times t_1}_{\equiv t} \times I_0$$

- “Optical Density” (OD) is the $\log_{10}$ of the transmittance, optical densities add up

# Absorption of radiation

- Microscopic approach

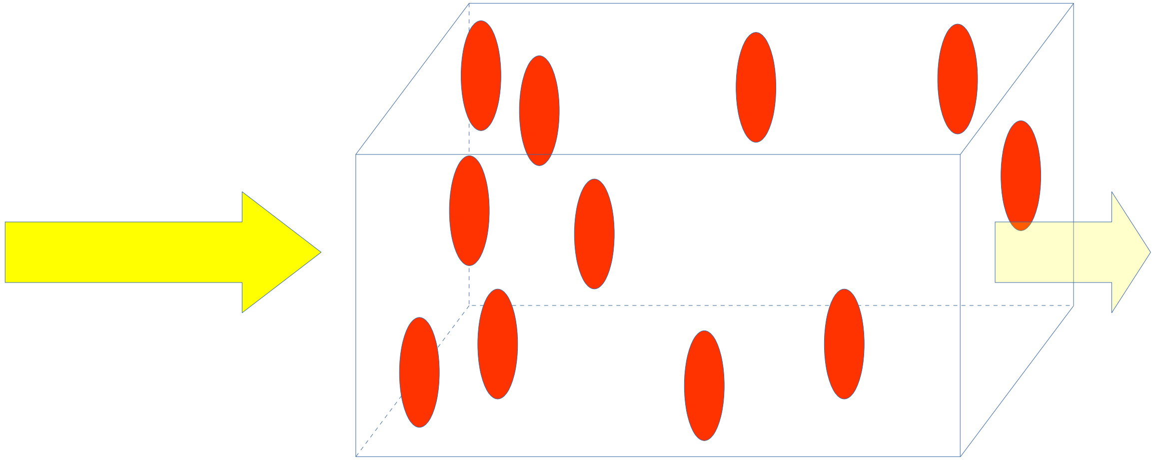


Absorbing centers, density n(z)

$$\mathrm{d}I = -\sigma \times \underset{[\mathrm{m}^{-3}]}{n(z)} \times I(z)\,\underset{[\mathrm{m}]}{\mathrm{d}z}$$

- **σ** is homogeneous to a surface : « cross section »
  - Each absorbing center acts as an opaque disk of section **σ**
  - In quantum mechanics, **σ** is the integrated interaction probability over the surface

# Absorption of radiation – Varying density



$$\mathrm{d}I = -\sigma \times n(z) \times I(z)\,\mathrm{d}z$$

$$\frac{\mathrm{d}I}{I} = -\sigma \times n(z)\,\mathrm{d}z$$

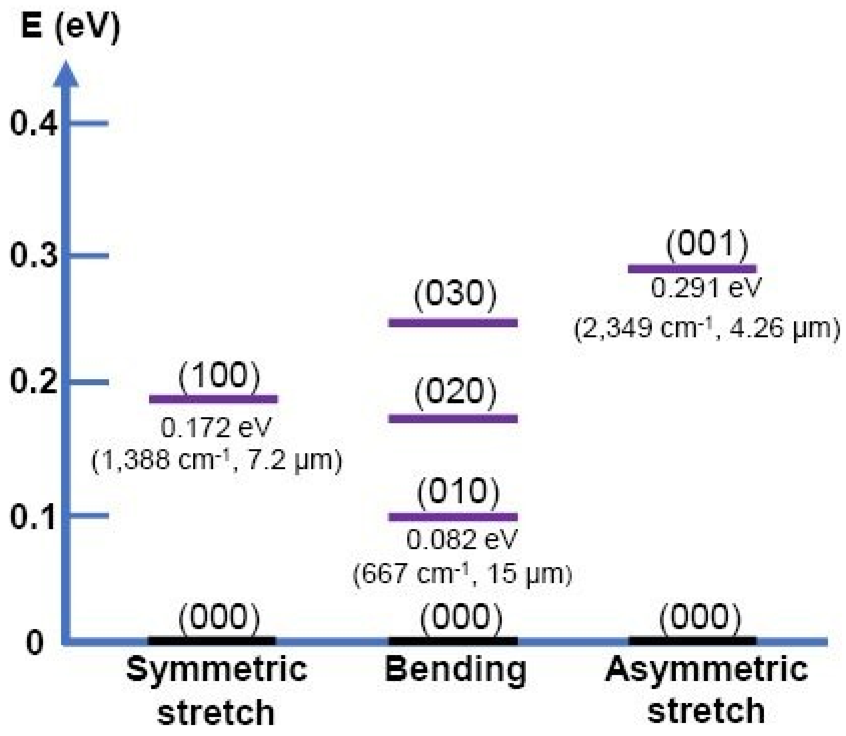
$$I(z) = I_0 \exp\left(-\underbrace{\int_0^z \sigma \times n(z')\,\mathrm{d}z'}_{\equiv \tau(z)}\right)$$

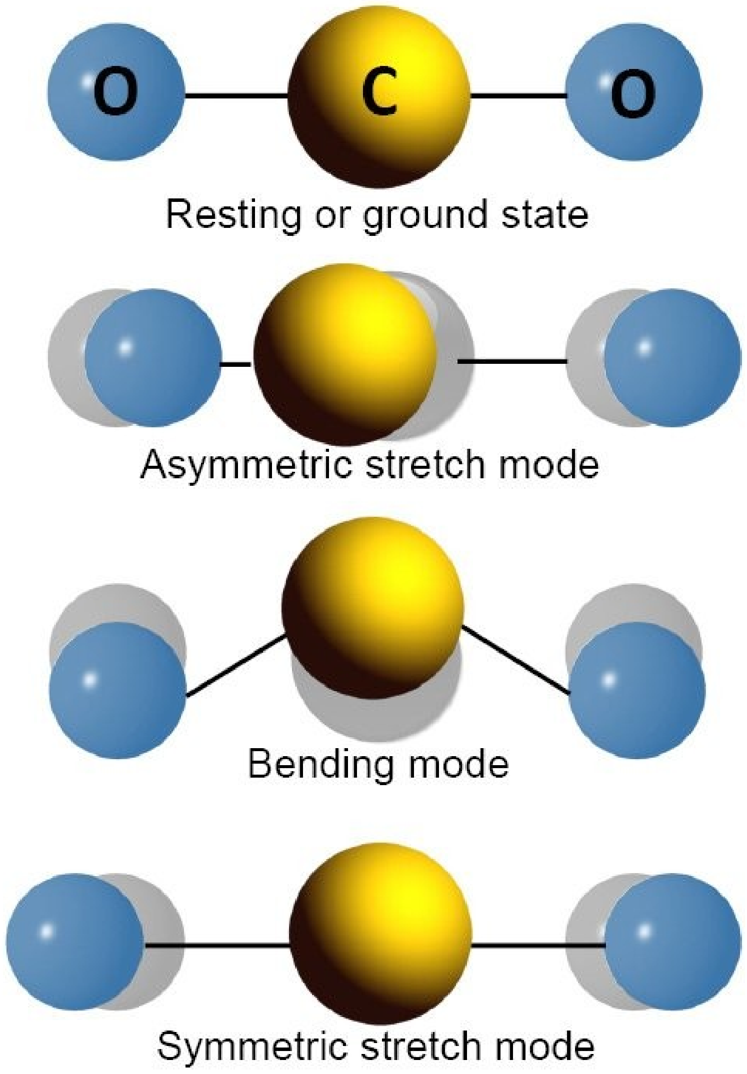
- **τ** is unit-less and is called : « optical depth »
- For a mixture of gases, optical depths of each component add up

$$I(z) = I_0 \exp(-\tau(z)), \quad \tau(z) = \int_0^z \sum_i \sigma_i \times n_i(z')\,\mathrm{d}z' = \sum_i \int_0^z \sigma_i \times n_i(z')\,\mathrm{d}z' = \sum_i \tau_i(z)$$

# $CO_2$

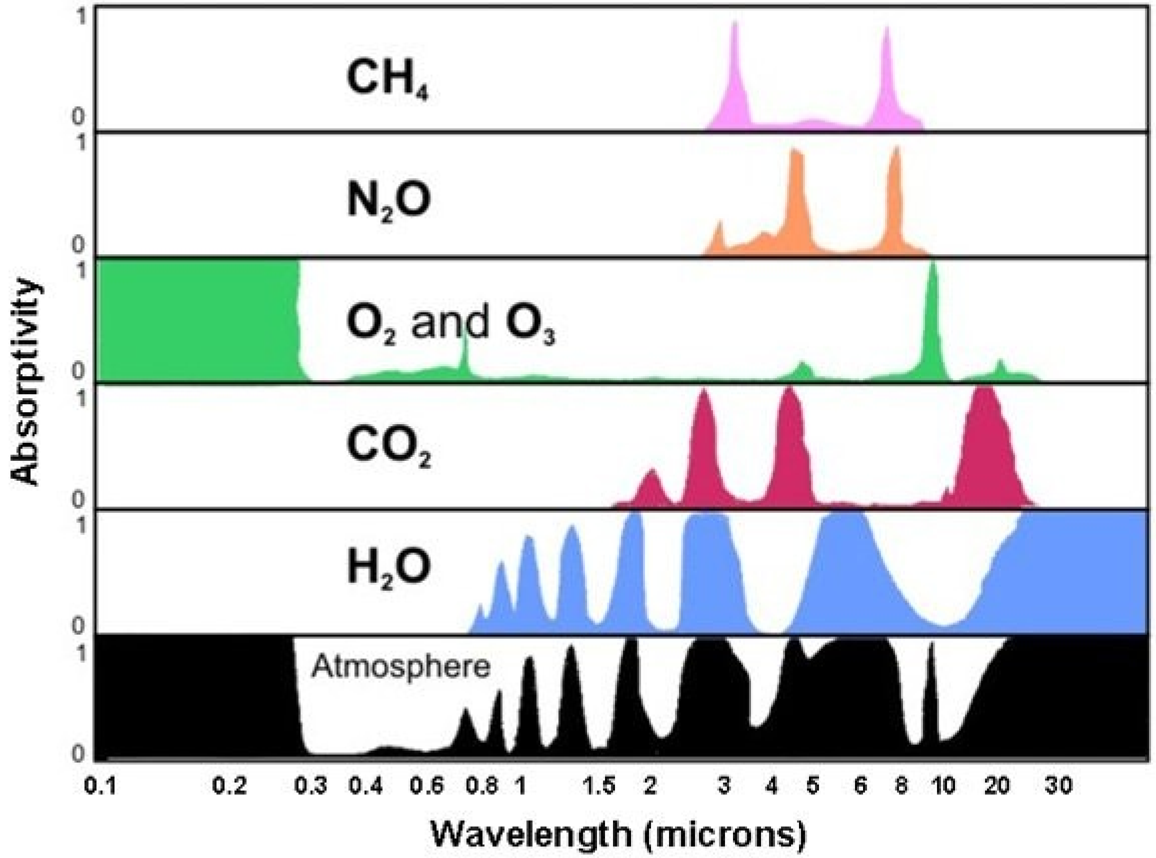
- $CO_2$ is a linear molecule with various vibration modes
- Vibrational energy levels correspond to IR radiations
- $CO_2$ molecules can absorb IR radiation and relax through collisional losses



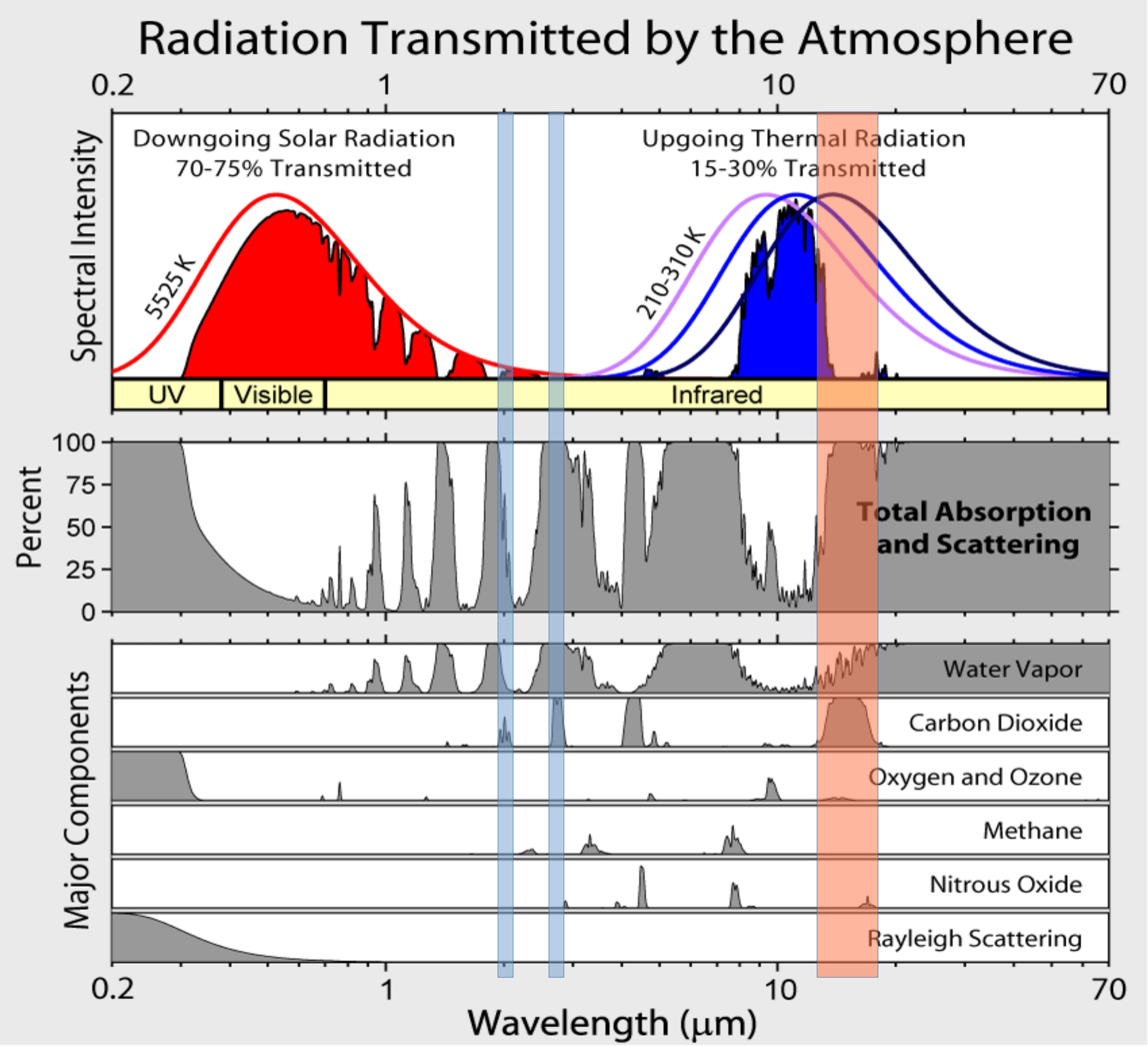
# Absorption spectra of various gases

- All tri-atomic molecules have vibration modes corresponding to IR absorption levels



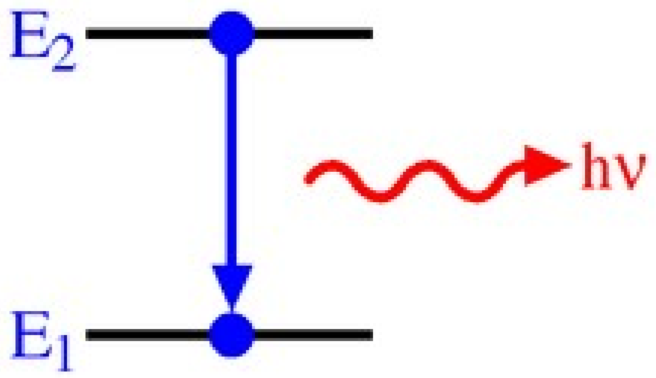
# Effect of $CO_2$

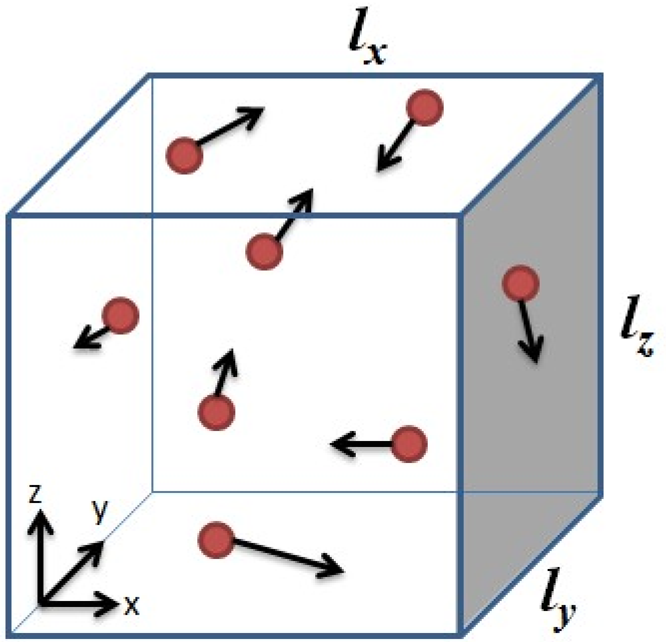
- $CO_2$ absorbs a tiny fraction of the incoming solar radiation
- $CO_2$ absorbs a significant (~35%) fraction of out-going IR radiation
- Water vapour is the dominant greenhouse gas (absorbs ~50% of outgoing IR)



# Molecular de-excitation

- Excited $CO_2$ molecule can relax by
  - Spontaneous emission ⇒ IR emission
  - Collisions ⇒ coupling between vibrational modes and velocities ⇒ Heat
- Which mode is dominant?



# Molecular de-excitation

- Spontaneous emission rate

$$\frac{\partial N(t)}{\partial t} = -A_{21} N(t)$$

- Einstein Coefficient $A_{21}$ depends on transition dipole moment (Fermi Golden rule)

$$A_{21} = \frac{4 \alpha \nu^3 n \left| \langle 1 | \mathbf{r} | 2 \rangle \right|^2}{3 c^2}$$

- Spectroscopic databases, $CO_2$ line @ 667 cm-1

$$A_{21} \approx 1.542\, \mathrm{s}^{-1} \quad \Rightarrow \tau = 1/A_{21} \approx \mathbf{0.45\, s}$$

- Air density $\rho = 1.2\, \mathrm{kg/m^3}$
- Molar mass $M = 29\, \mathrm{g/mol}$
- Numerical density

$$n = \frac{N_A \times \rho}{M} = 2.5 \times 10^{25}\, \mathrm{m^{-3}}$$

- Intermolecular distance

$$d = n^{-1/3} = 3.4\, \mathrm{nm}$$

- Molecular velocity

$$v = \sqrt{3 \frac{k_B T}{m}} = \sqrt{3 \frac{k_B T N_A}{M}} \approx 500\, \mathrm{m/s}$$

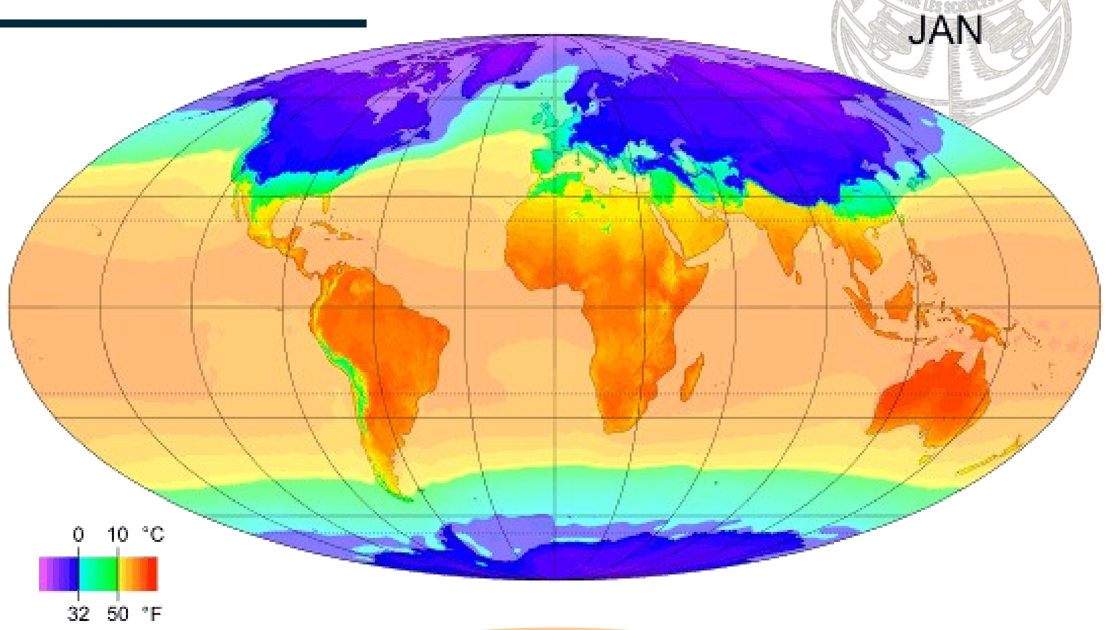
- Inter-collision time

$$\tau \approx d/v \approx \mathbf{7 \times 10^{-12}\, s}$$

⇒ The atmosphere is thermalized quickly

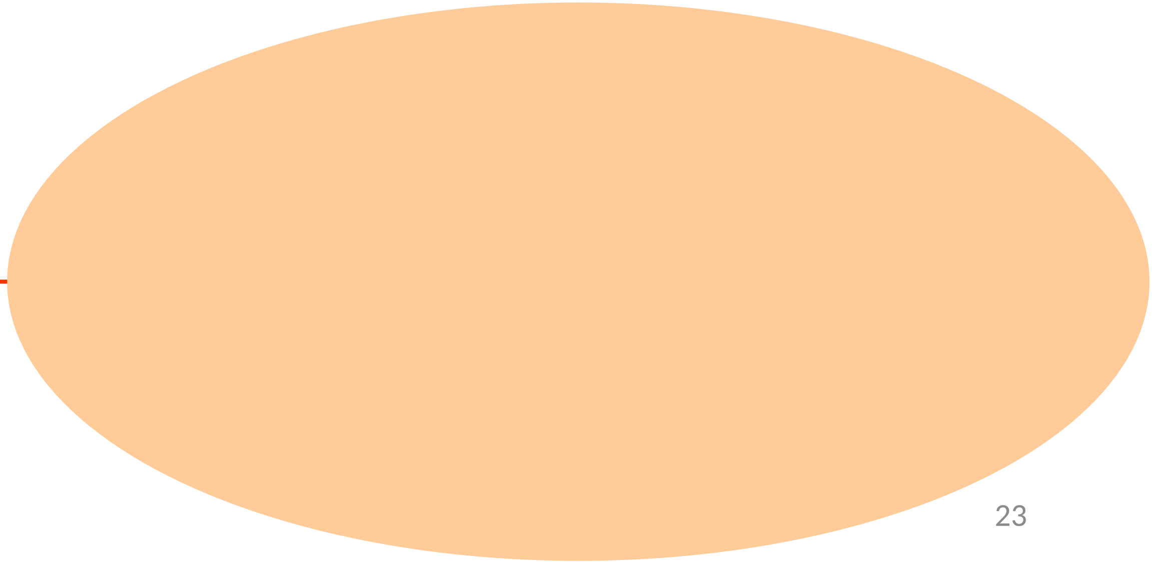
# Average temperature?

- Temperature varies with position and time
- How to define an "*average temperature*"




Same Radiative Balance

$$\langle T_{\text{moy}} \rangle = \frac{\int_{\text{year}} \mathrm{d}t \iint_{S} T(\vec{r},t)\,\mathrm{d}S}{1\,\text{year} \times S} \, ?$$



# Average temperature?

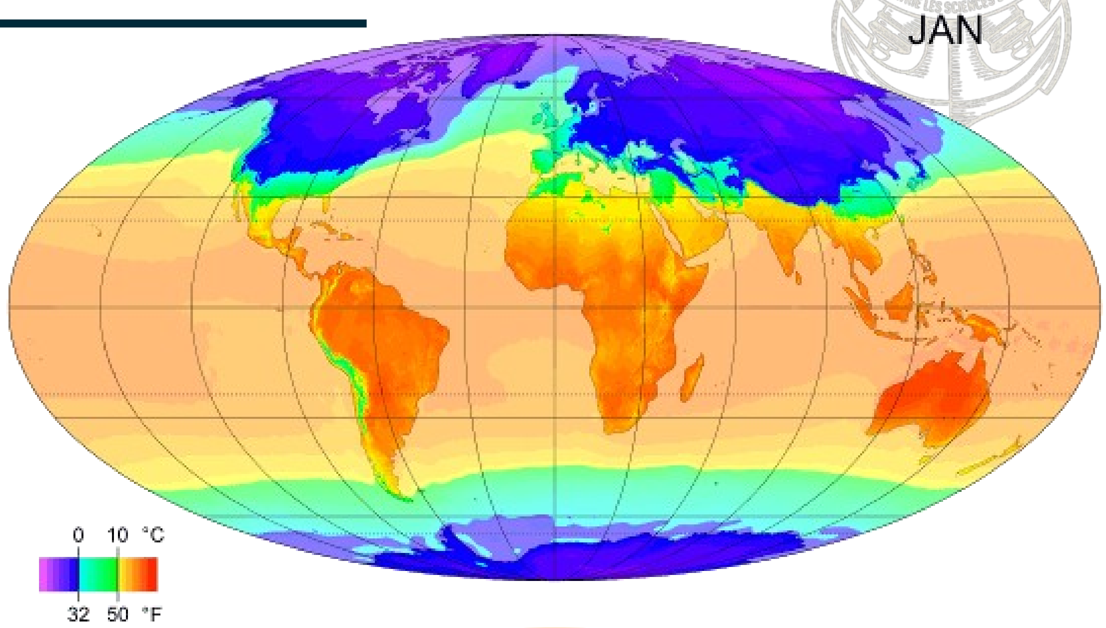
- How to define an "*average temperature*"

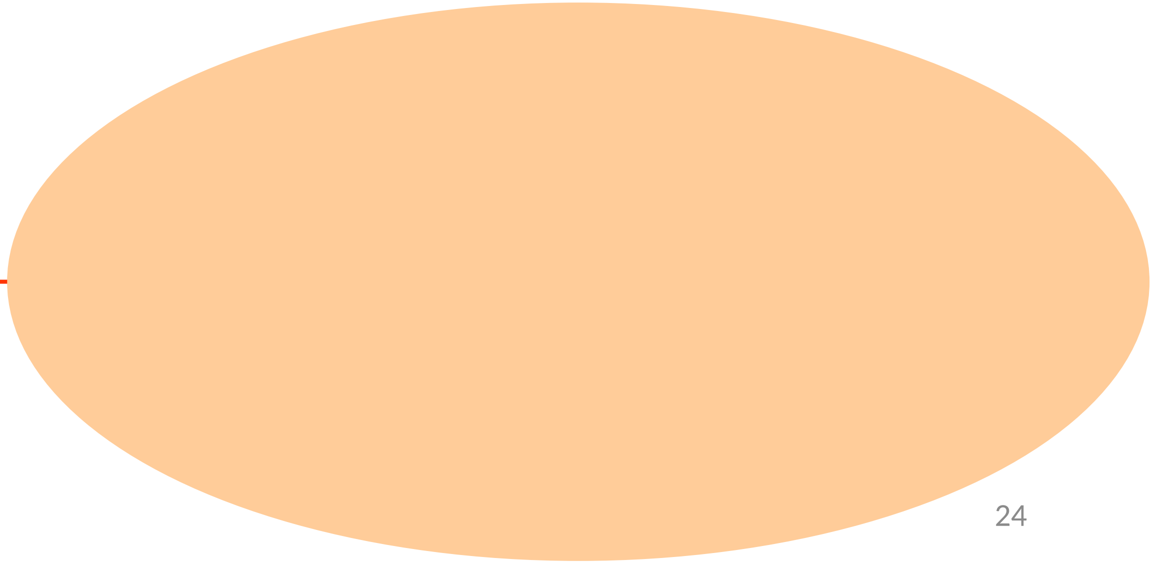
$$\langle T_{moy} \rangle = \frac{\int_{year} \mathrm{d}t \iint_S T(\vec{r},t)\,\mathrm{d}S}{1\,\text{year} \times S} \; ?$$

Same Radiative Balance

$$\langle T_{moy} \rangle = \left[ \frac{\int_{year} \mathrm{d}t \iint_S T^4(\vec{r},t)\,\mathrm{d}S}{1\,\text{year} \times S} \right]^{1/4}$$

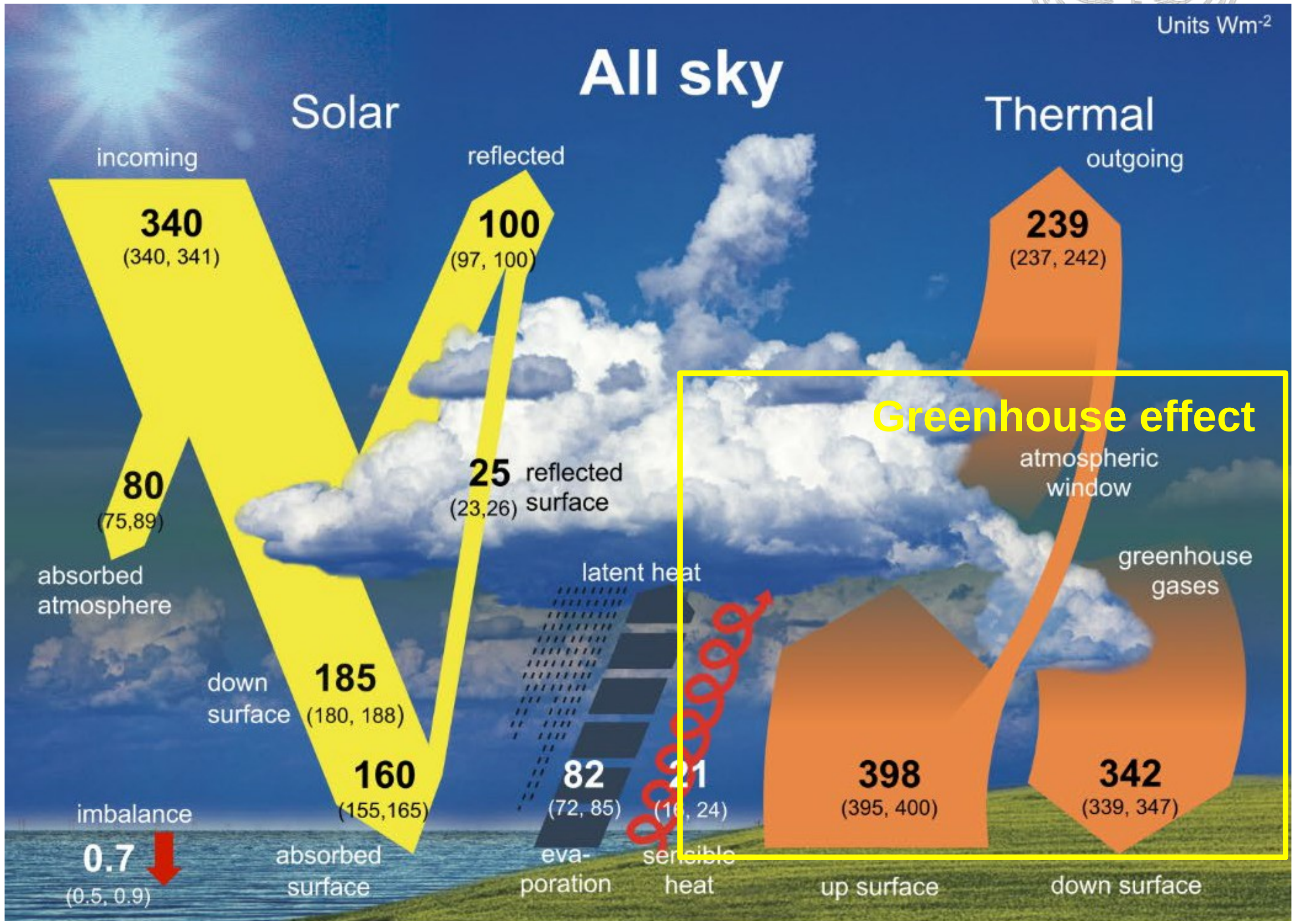
$$\iiint_{time \times S} \sigma T^4 \,\mathrm{d}S\,\mathrm{d}t = \text{time} \times S \times \sigma \langle T_{moy} \rangle^4$$



# Radiative Balance of the Earth

- Simple radiative model
- Optical
  - Overall Albedo ~30%
  - Atmospheric Absorption ~23%
  - Remaining ~47% absorbed by ground
- IR is emitted by ground and atmosphere
- Atmospheric Average Temperature?



# Earth temperature – simple radiative models

- Transparent atmosphere
  (No IR absorption ⇒ no IR emission)

$$T_T = T_S \sqrt[4]{\frac{(1-A)}{4}\left(\frac{R_S}{d}\right)^2} \approx -18\,°\mathrm{C}$$

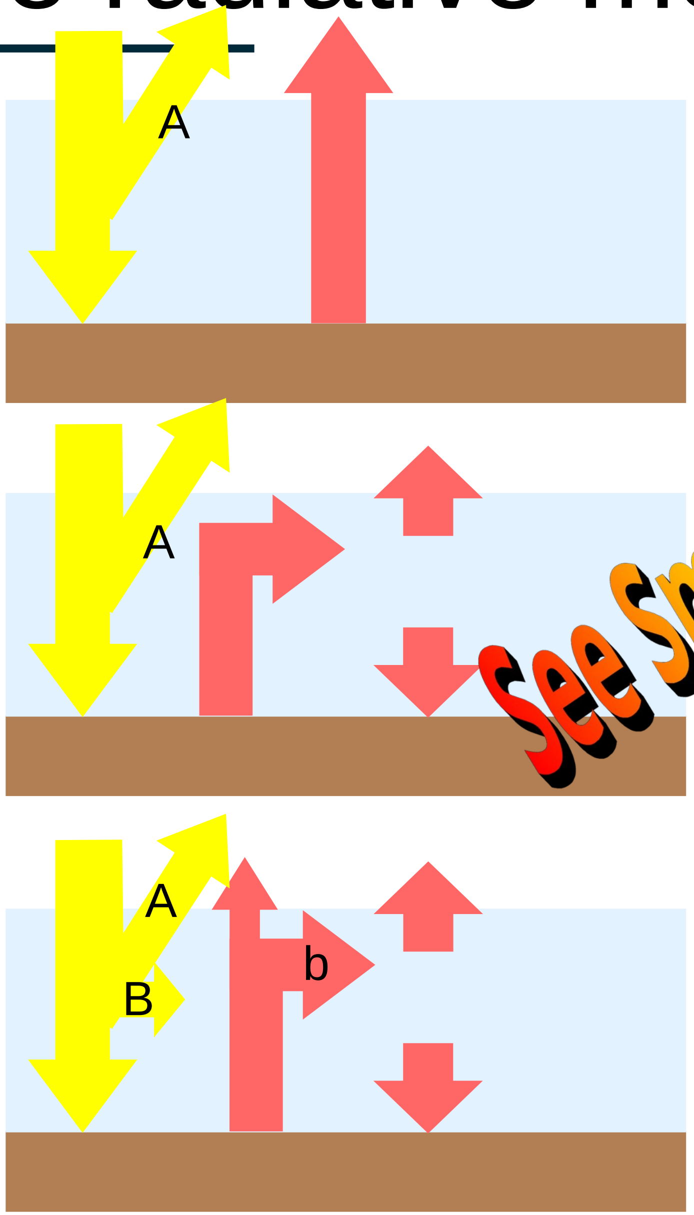
- Greenhouse effect is beneficial for life!
- Completely opaque atmosphere

$$T_T = T_S \sqrt[4]{\frac{(1-A)}{2}\left(\frac{R_S}{d}\right)^2} \approx +30\,°\mathrm{C}$$

- Partially transparent atmosphere

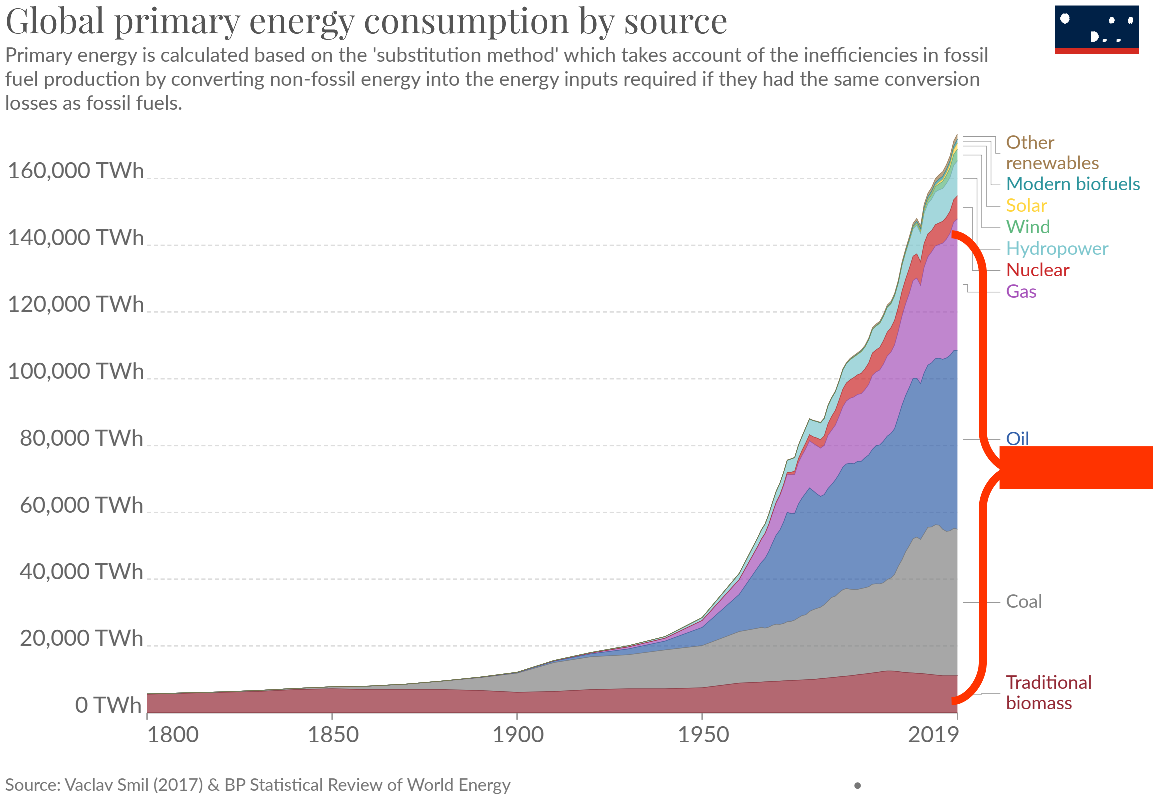
$$T_T = T_S \sqrt[4]{\frac{(1-A-B/2)}{4-2b}\left(\frac{R_S}{d}\right)^2} \approx +12\,°\mathrm{C}$$

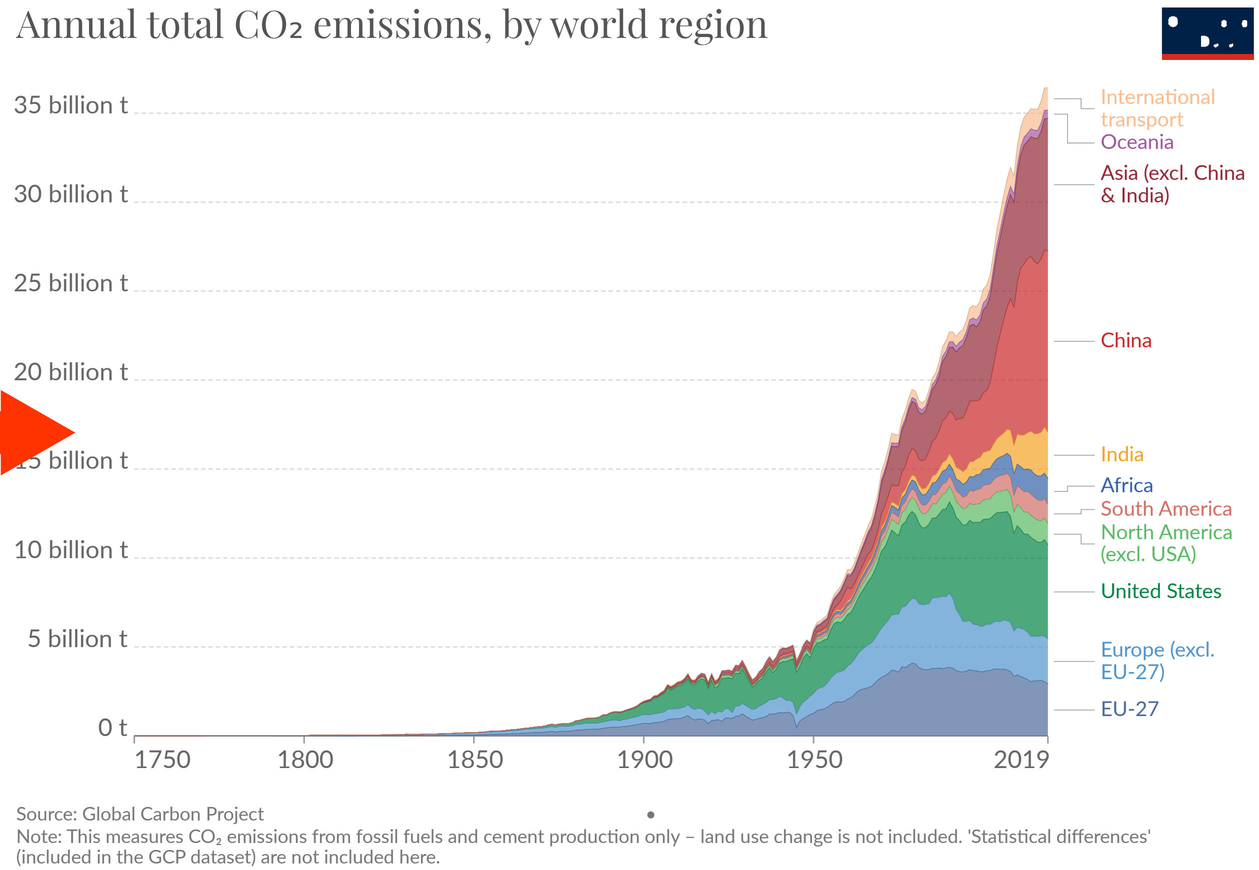
$(A=0.3,\ B=0.2,\ b=0.91)$



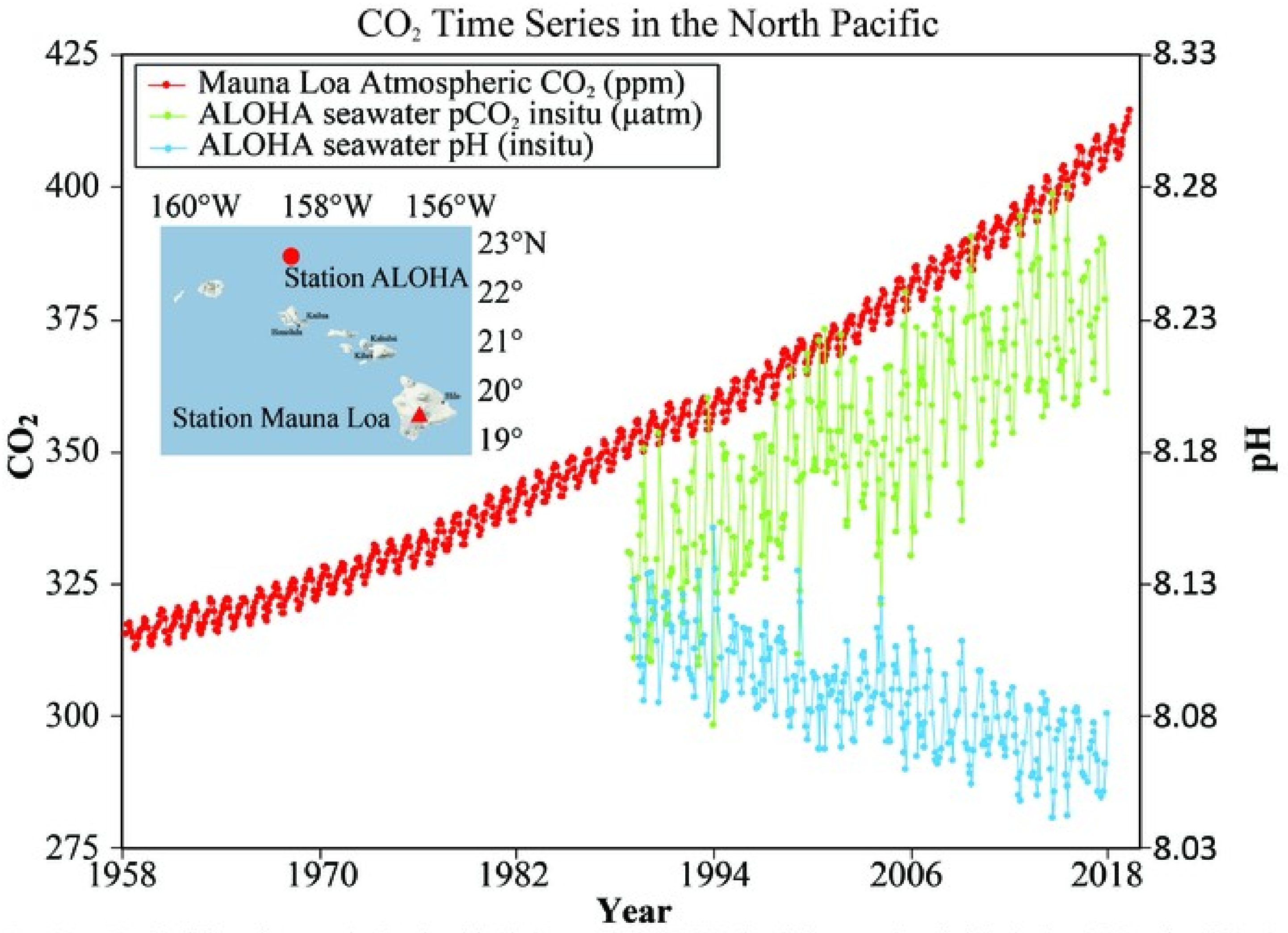

See Small Classes

# Worldwide $CO_2$ emissions



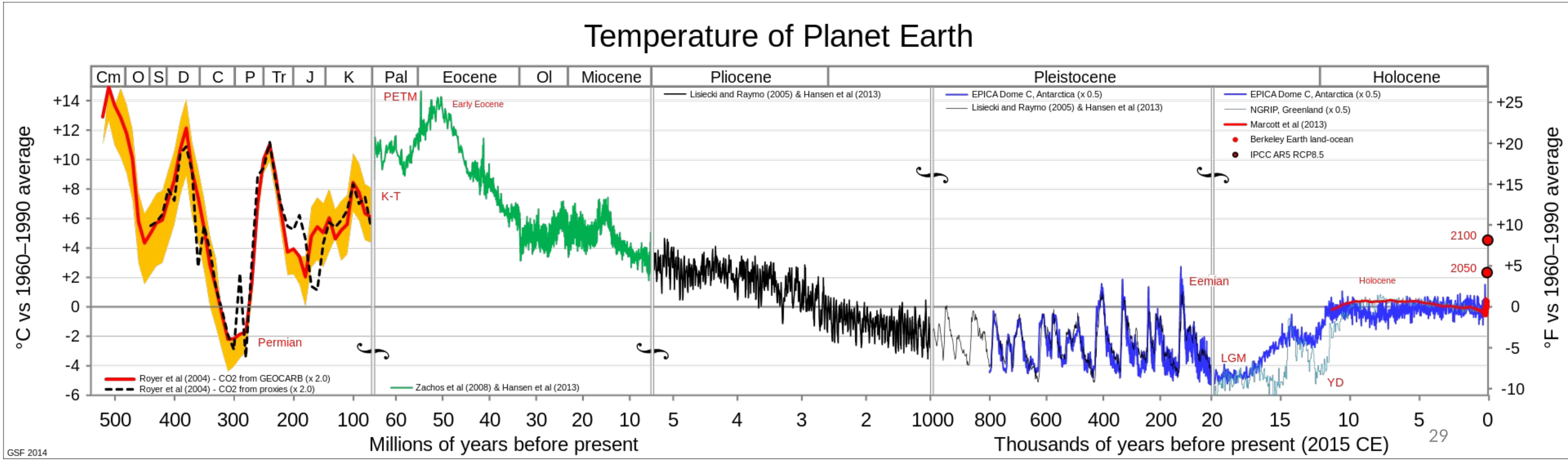



# Atmospheric $CO_2$



# Paleo-climatology

- Reconstruction of past temperature using several proxies
  - $^{18}O/^{16}O$ ratio in trapped bubbles of air, Pollen in ice layers, Growth rings of trees, Sedimentary content, Volcanic ashes, corals growth, …
  - Variation dues to solar luminosity, atmosphere, glaciation cycles, ...

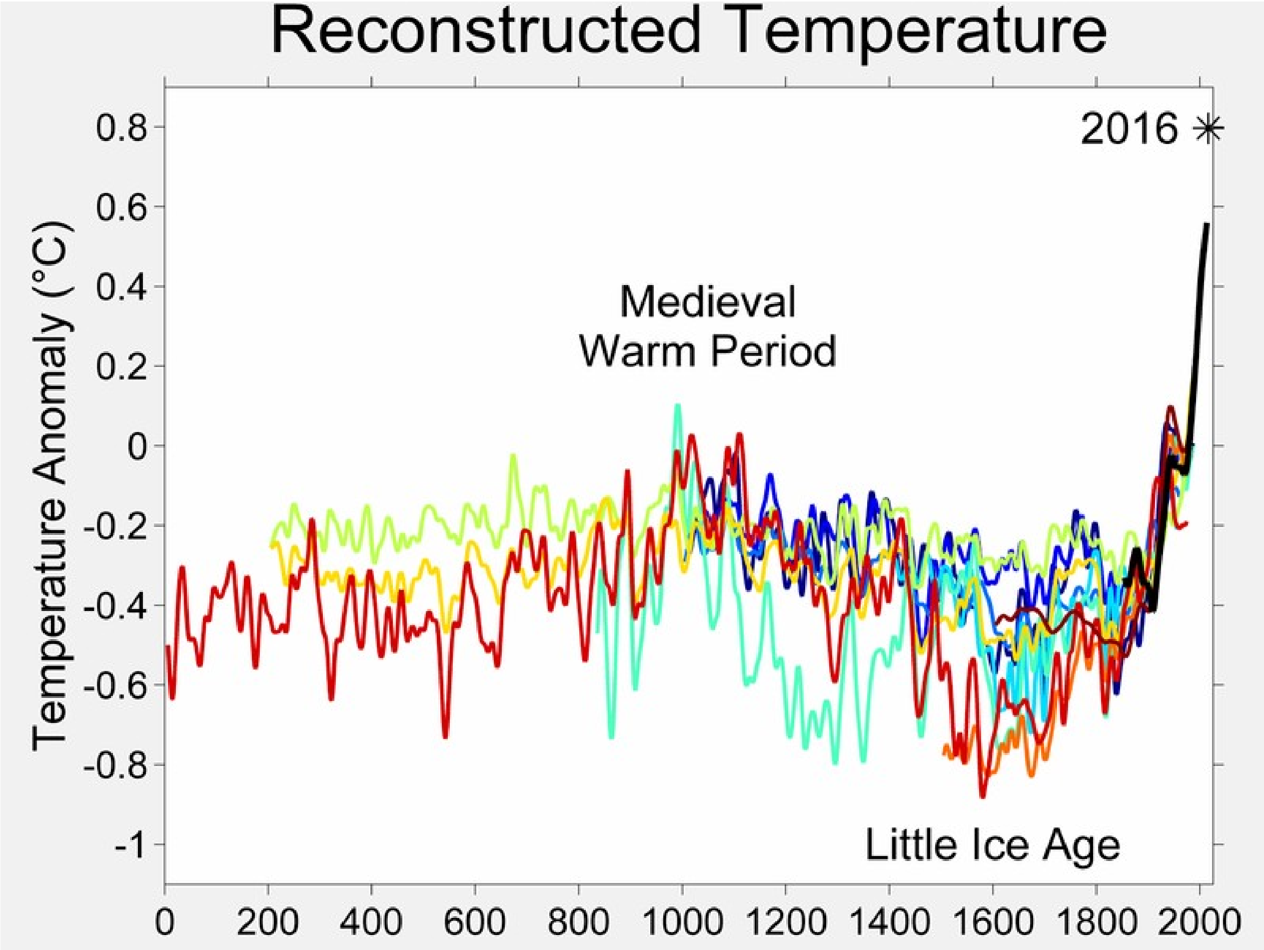


# Paleo-climatology

- Data over the last 2000 years indicate a warm medieval period and a little ice age (XVII$^{th}$ century), due to increased volcanic activity

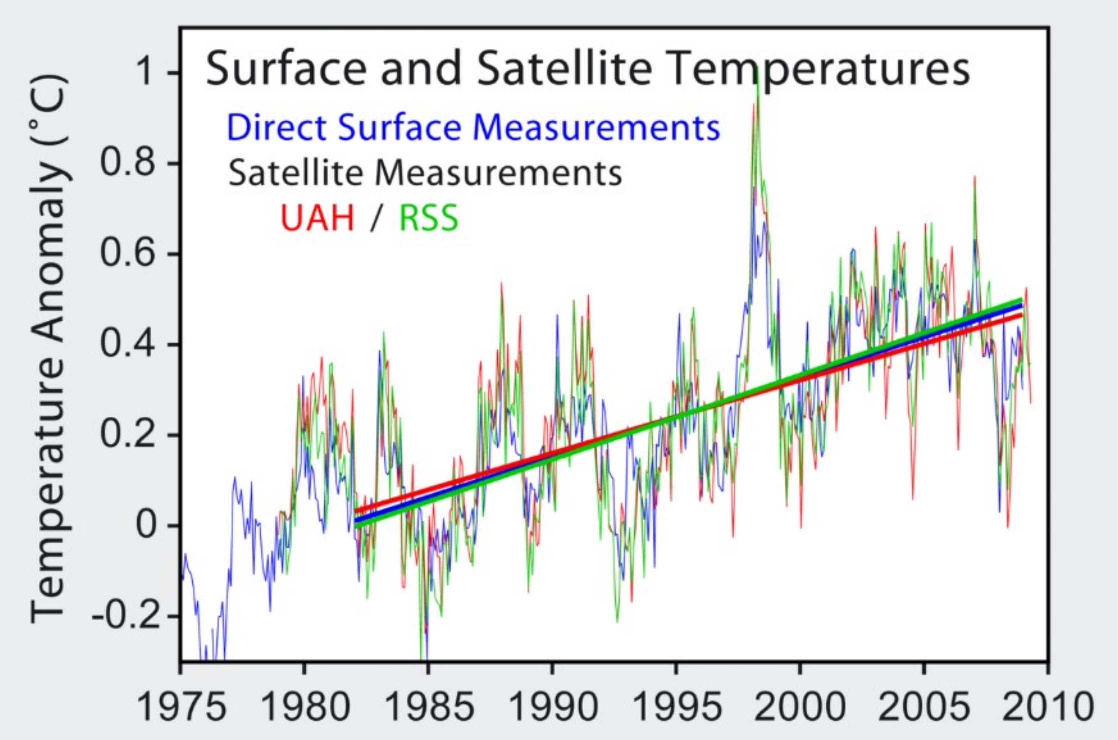
The Frozen Thames, 1677

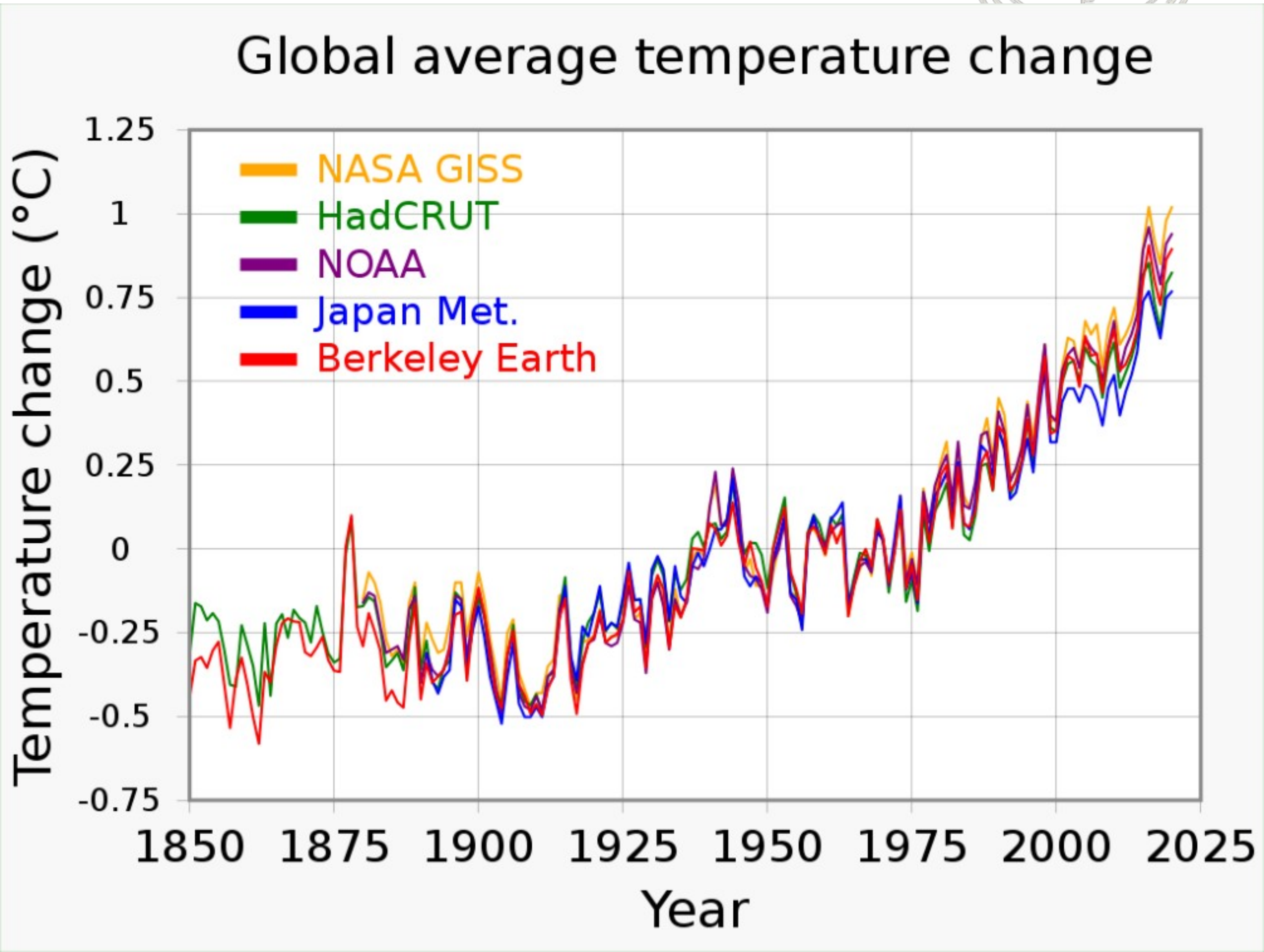
Solar Cycles



# Observational Evidences of Global Warming

- Direct temperature measurement (meteorological stations)
- Since ~ 1980 satellite measurements

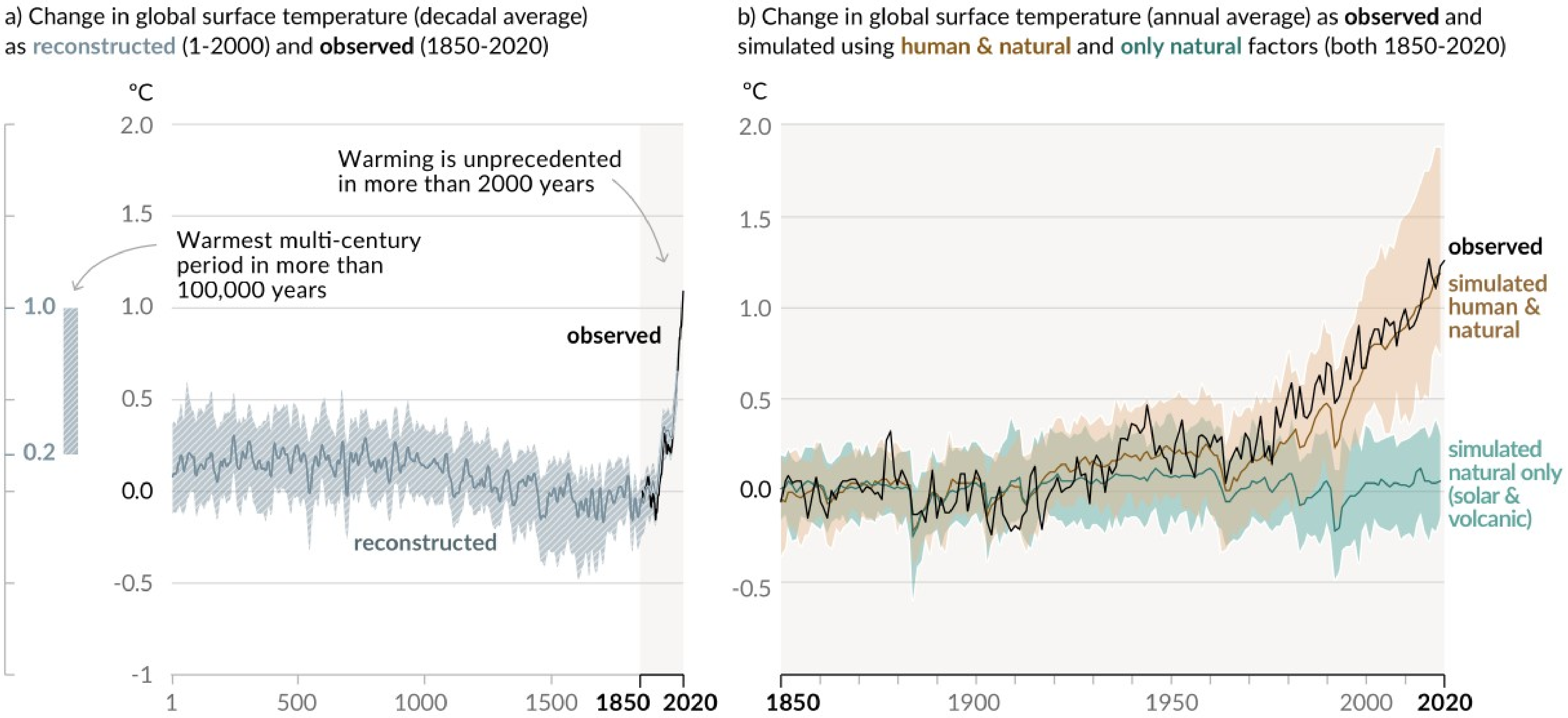


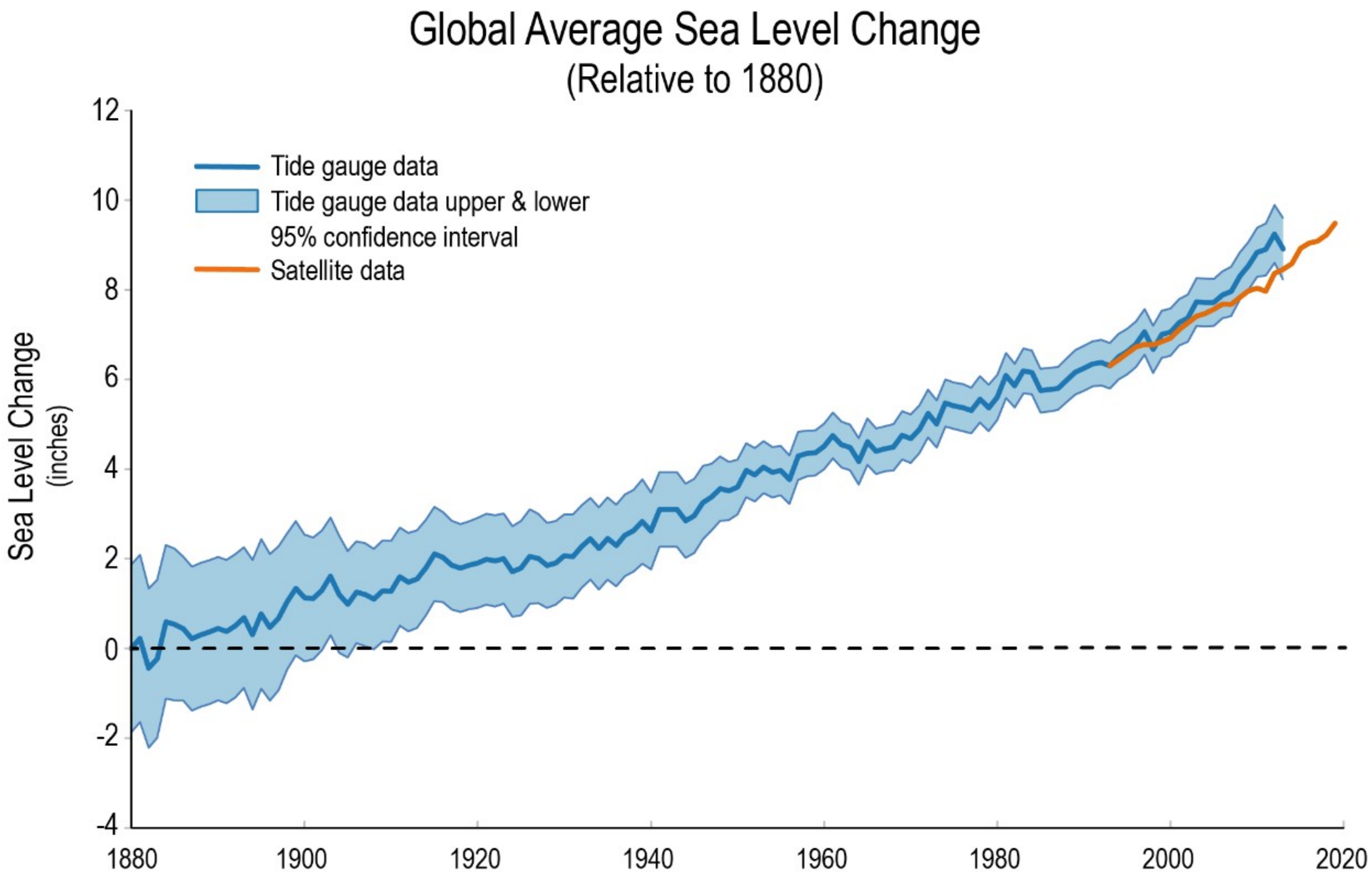

Global average temperature data-sets from NASA, NOAA, Berkeley Earth, and meteorological offices of the U.K. and Japan,

# Global Surface temperature

- Changes in global surface temperature relative to 1850-1900 (IPCC, 2021)

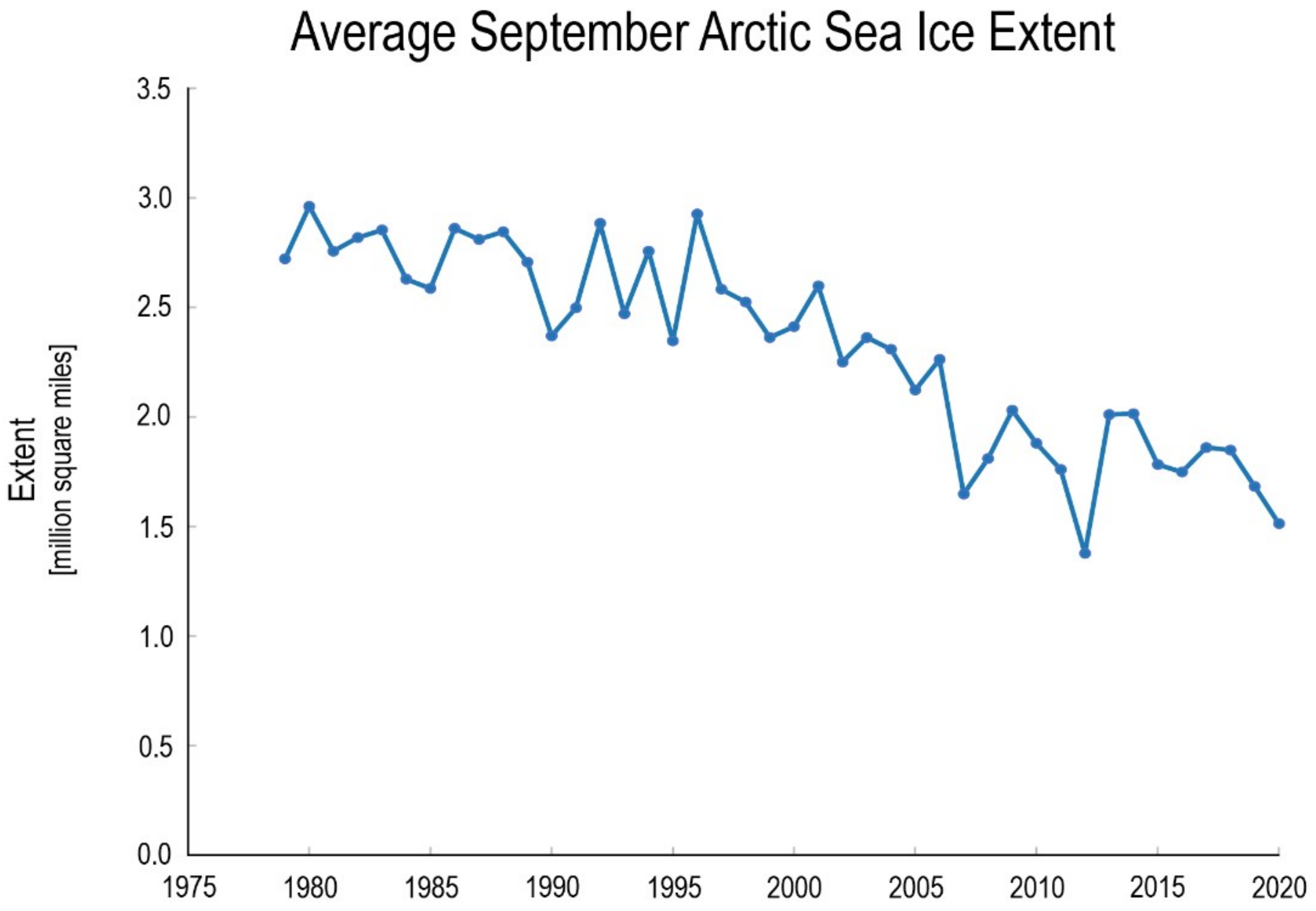


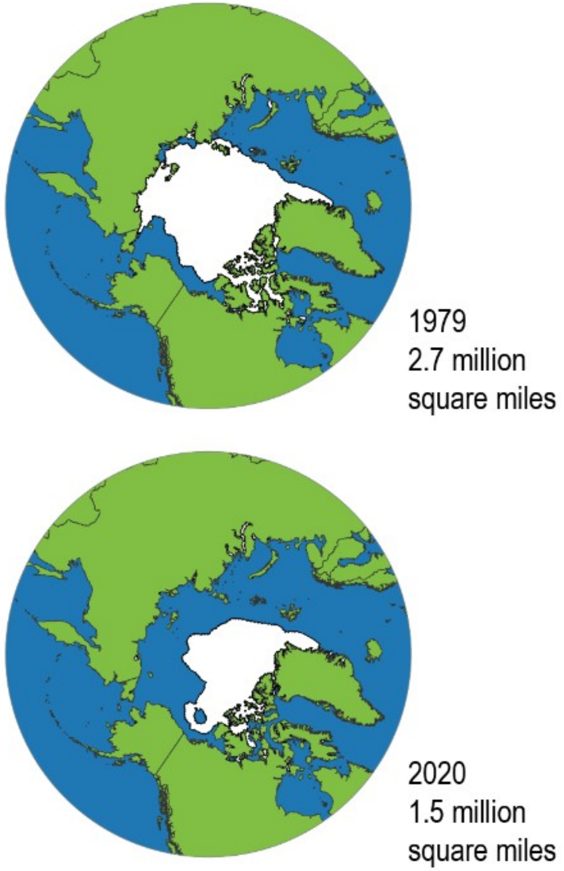
# Sea-level




U.S. Global Change Research Program

# Arctic Sea Ice Extent

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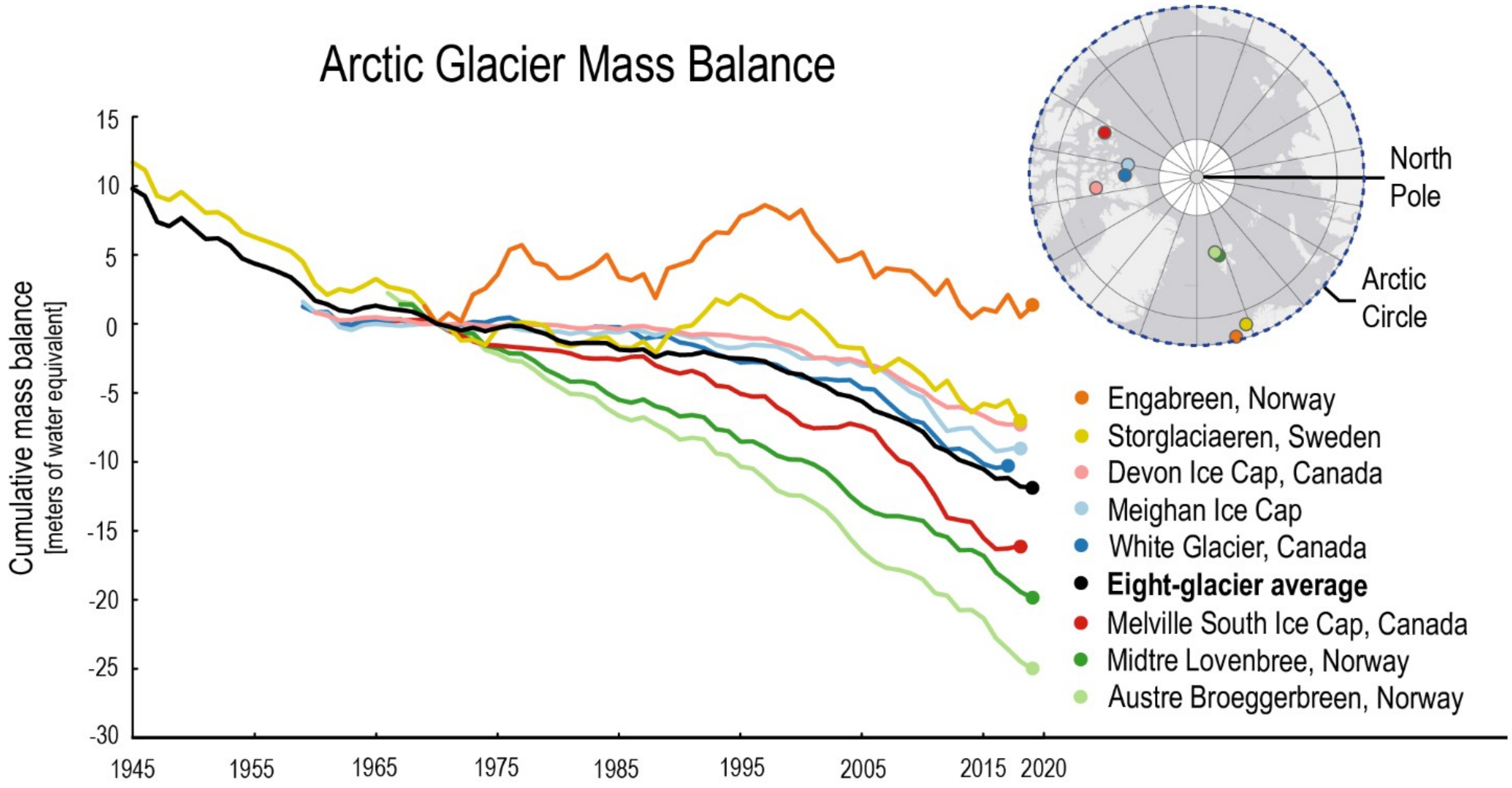
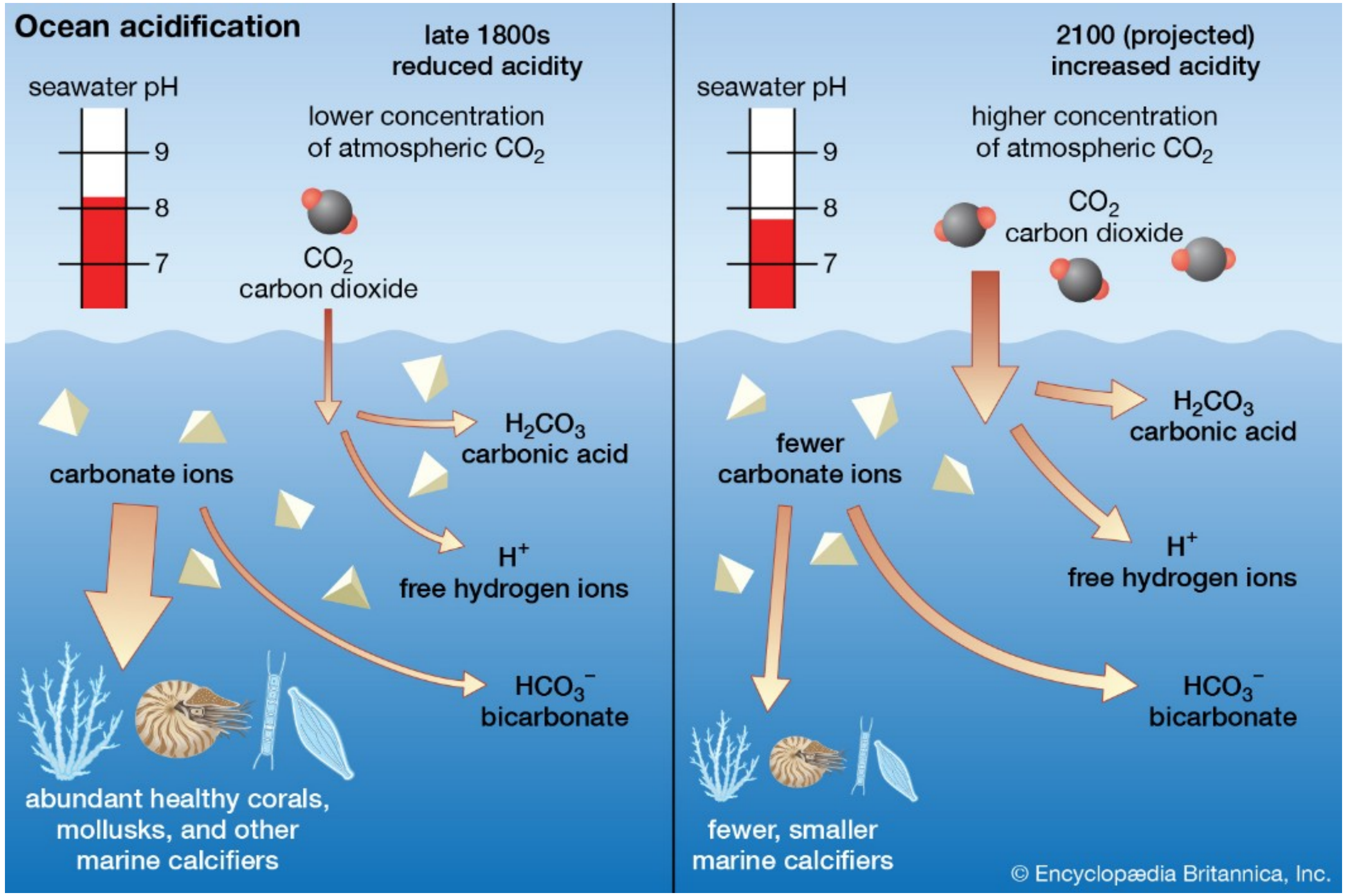
# Glacier Mass Balance



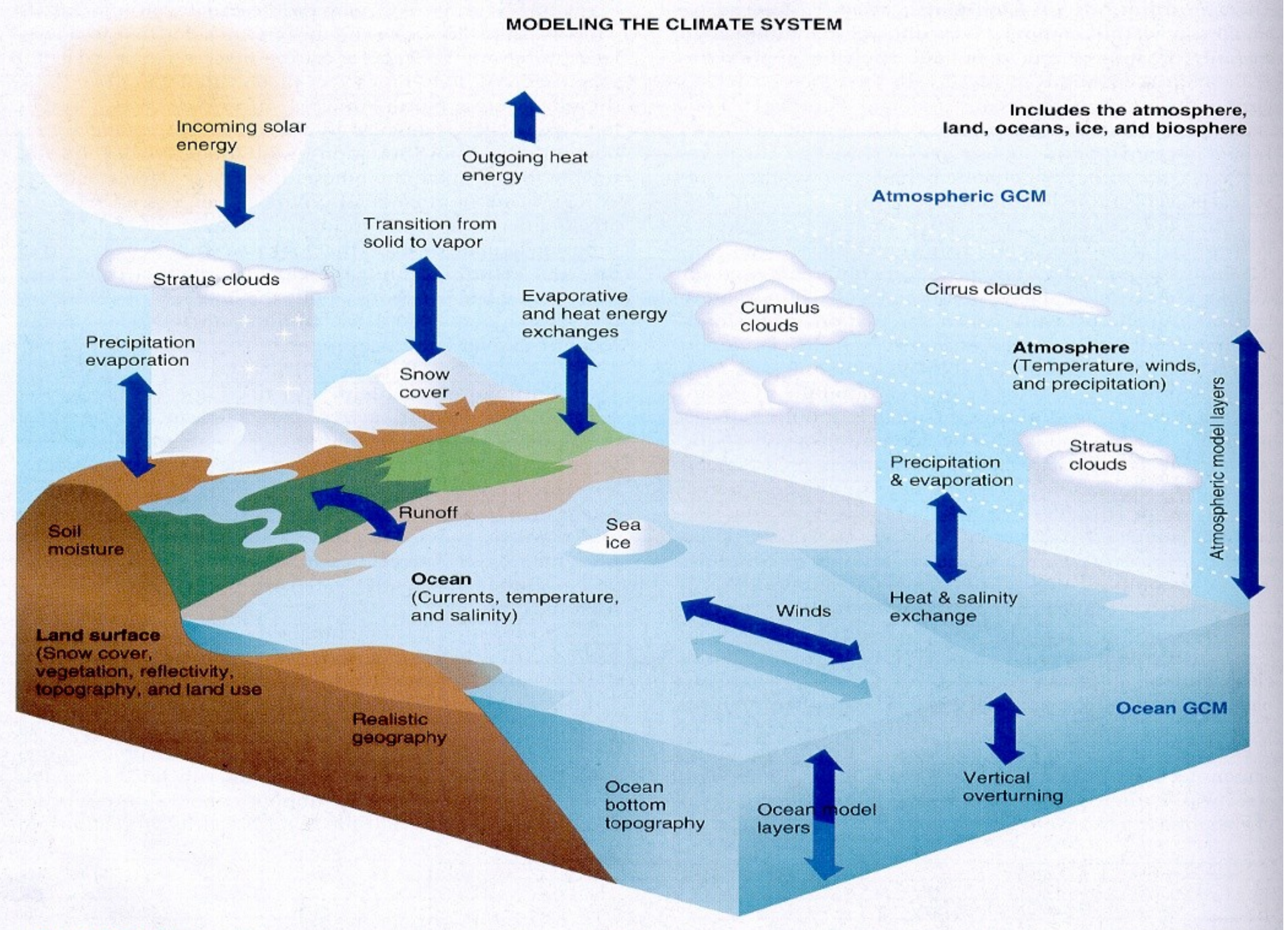
# Ocean Acidification




Healthy fire coral in Bermuda on left, bleached on right.
XL Catlin Seaview Survey/Underwater Earth

# Predicting the future – Climate models

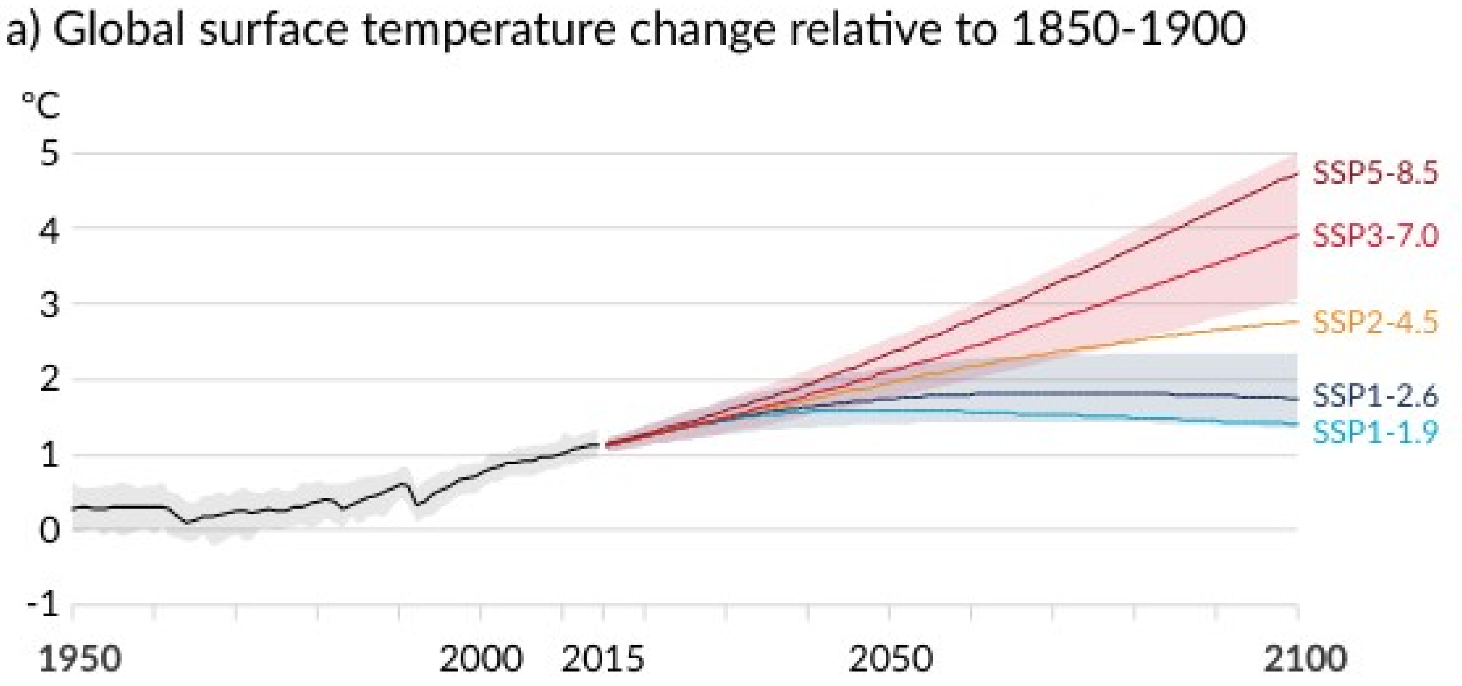
- Climate models involve
  - Radiation Budget
  - Dynamic Coupling (atmosphere – ocean, surface – atmosphere, …)
  - Inertia (oceans)
  - Feedback & loops (clouds, …)
- Heavy grid computing, resolution limited by computing power
  - Different characteristic times
  - Very different from weather forecast




▲ FIGURE 21–14 ***Modeling the climate system.*** The coupled general circulation models used in the U.S. climate change assessment employed physical and mathematical parameters involving all of the processes illustrated here. The models were used to simulate changes in these parameters over the Earth for all the seasons and for periods of decades. (*Source*: U.S. Global Change Research Program, U.S. National Assessment, 2000.)

# Future

- Climate Prediction for 2100 highly uncertain
- Temperature increase in the range 0.5 to 5 °C
- Depends heavily on the GHG emission scenario, but also on climate models
  - SSP5-8.5: doubling of $CO_2$ emissions by 2050
  - SSP3-7.0: doubling of $CO_2$ emissions by 2100
  - SSP2-4.5 stable emissions
  - SSP1-2.6, SSP1-1.9 zero emission in 2050 followed by (varying) negative

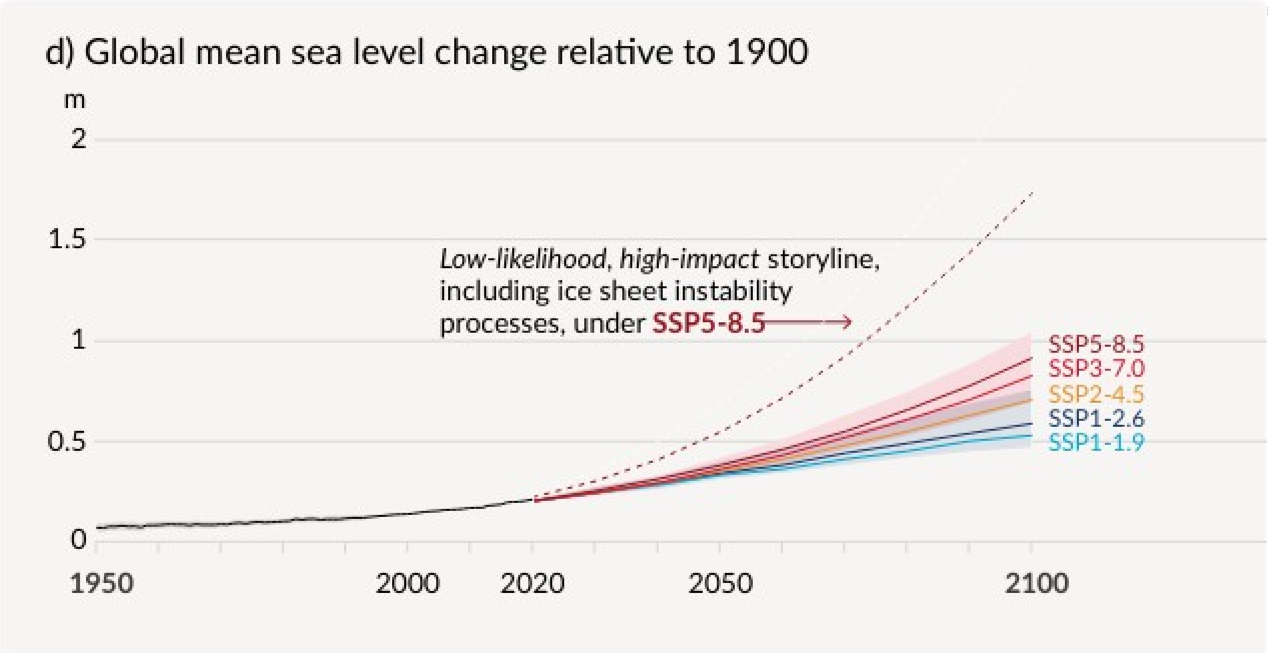



IPCC, 2021

# Projected Sea Level Rise

- Depend on the GHG emission scenario

- Can reach ~1 m next centuries, several meters on the long term




IPCC, 2021

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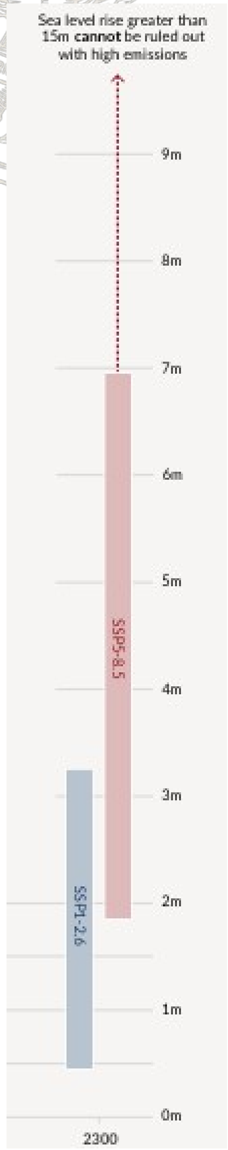
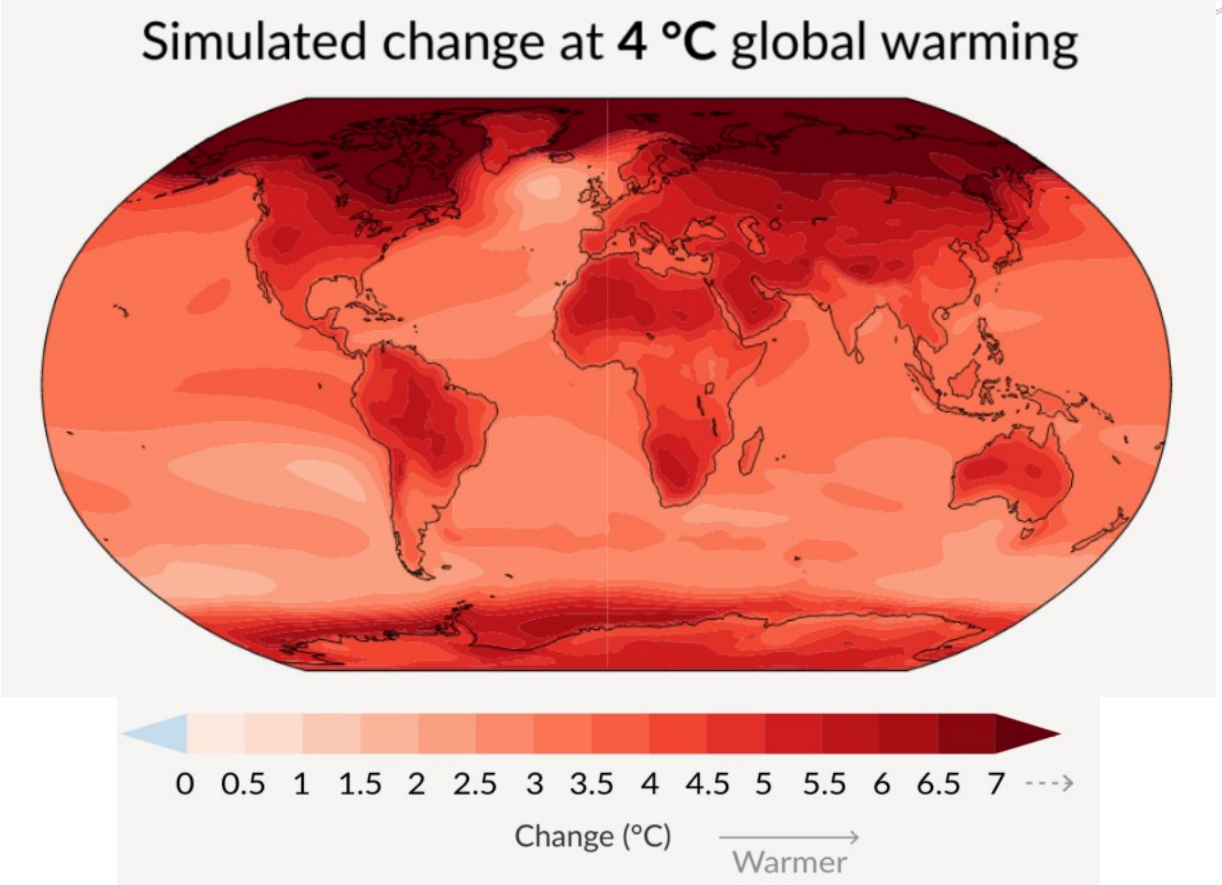


# Regional disparities

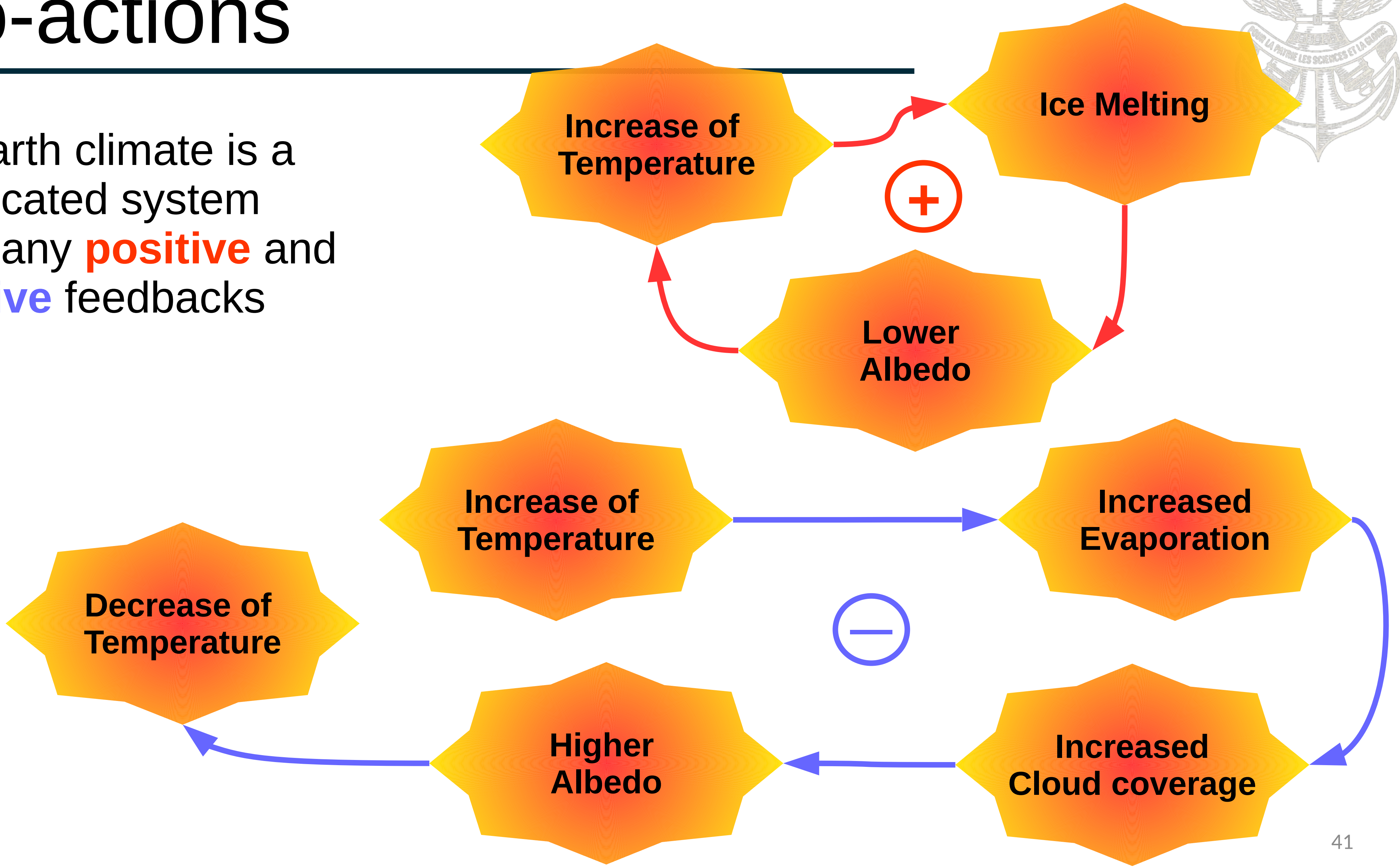
- Global warming will have very different intensity depending on locate
- Warming more intense on land than on sea
- A +4°C global increase can translate on > +7° on the polar regions




IPCC, 2021

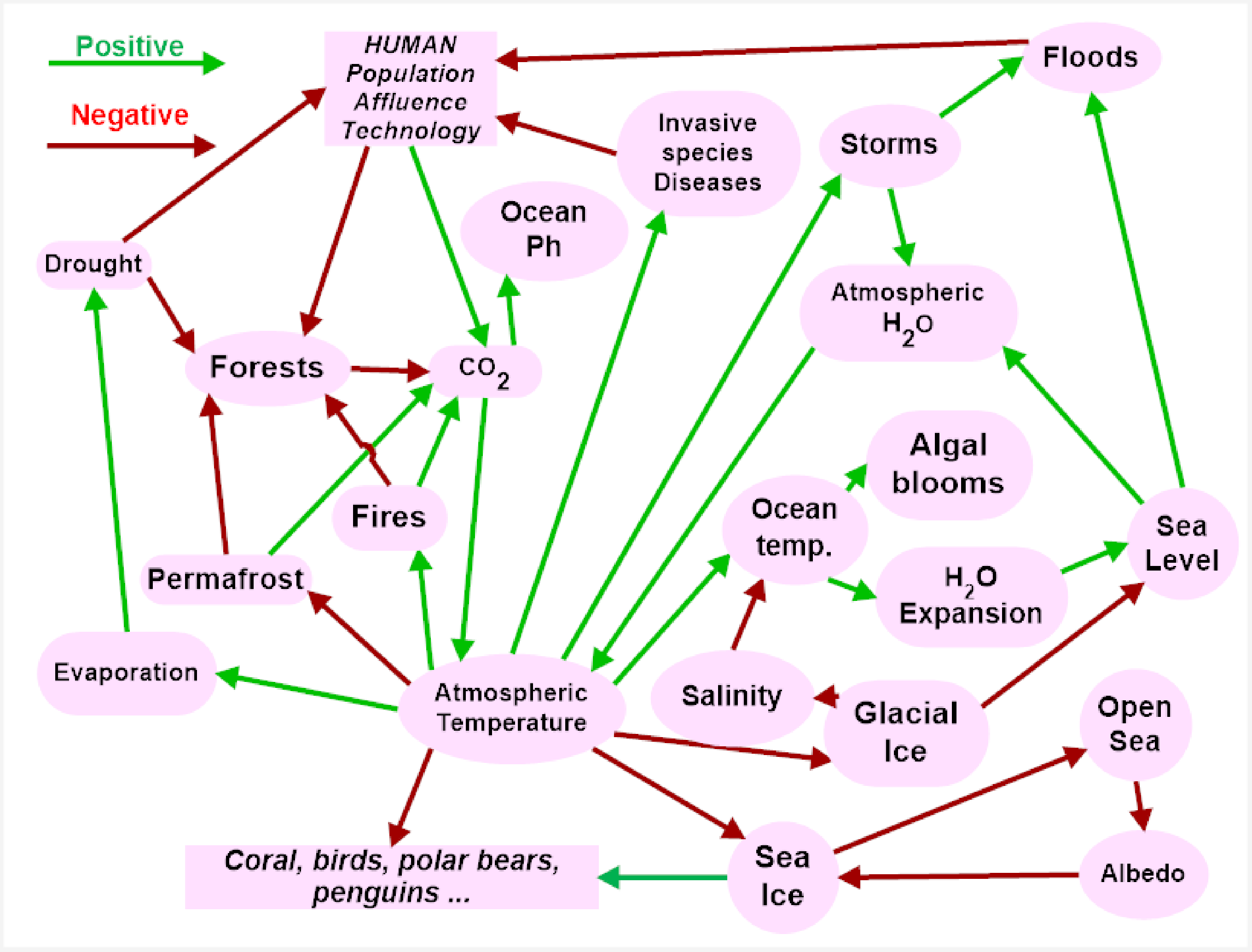
# Retro-actions

- The earth climate is a complicated system with many **positive** and **negative** feedbacks



# Retro-actions

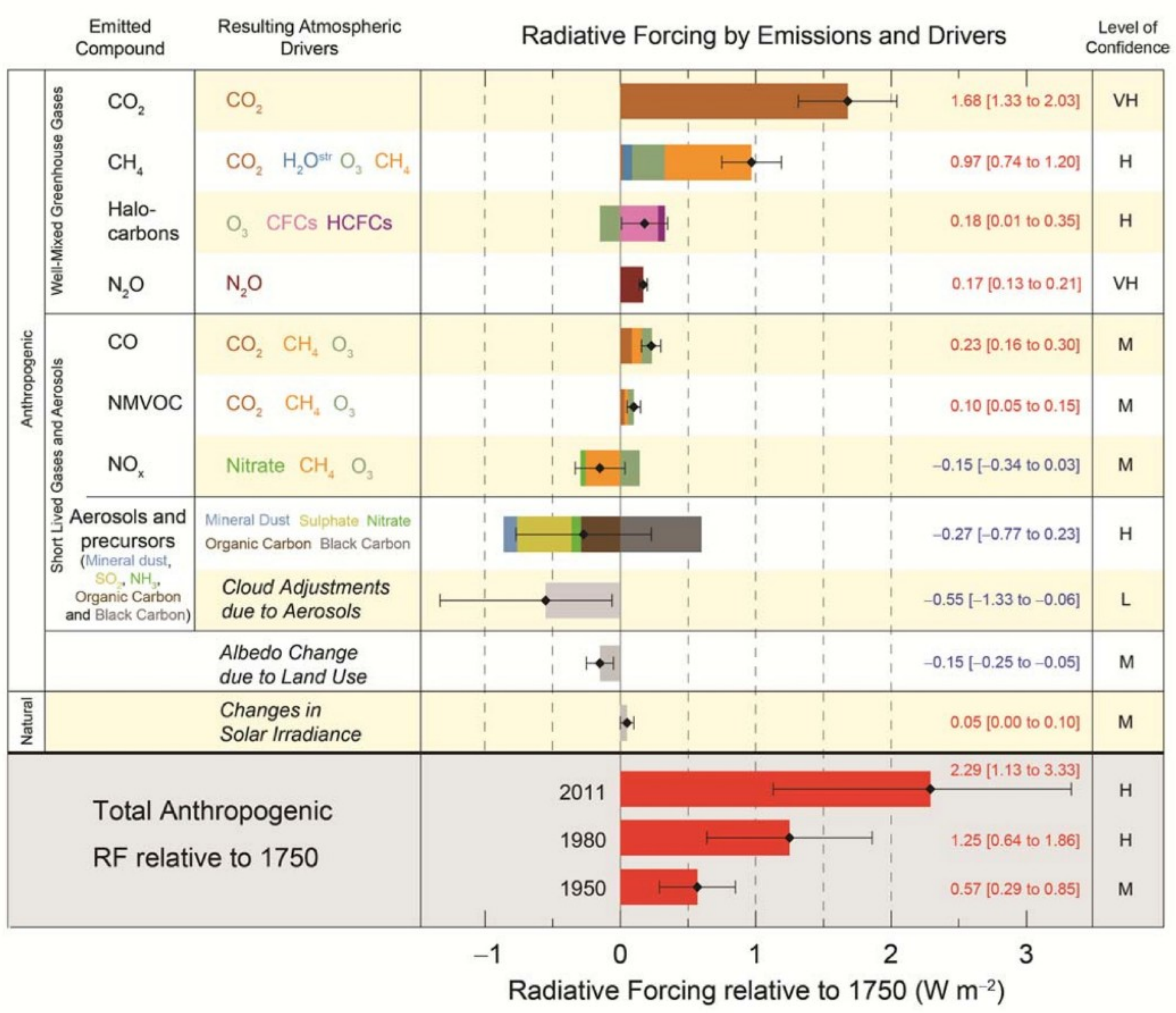
- Complete system analysis mandatory




Feedback loops from the book Al Gore (2006). An inconvenient truth.

# Retro-actions & forcing

- Consensus towards global temperature increase
- Largest uncertainty arising from the retro-action of clouds
- Expressed as "Radiative Forcing": difference between average received power and average emitted power (imbalance)



# Lecture 2 – Sustainability

I. Sustainability – Introduction

II. The Earth Climate – Greenhouse Effect and Global warming

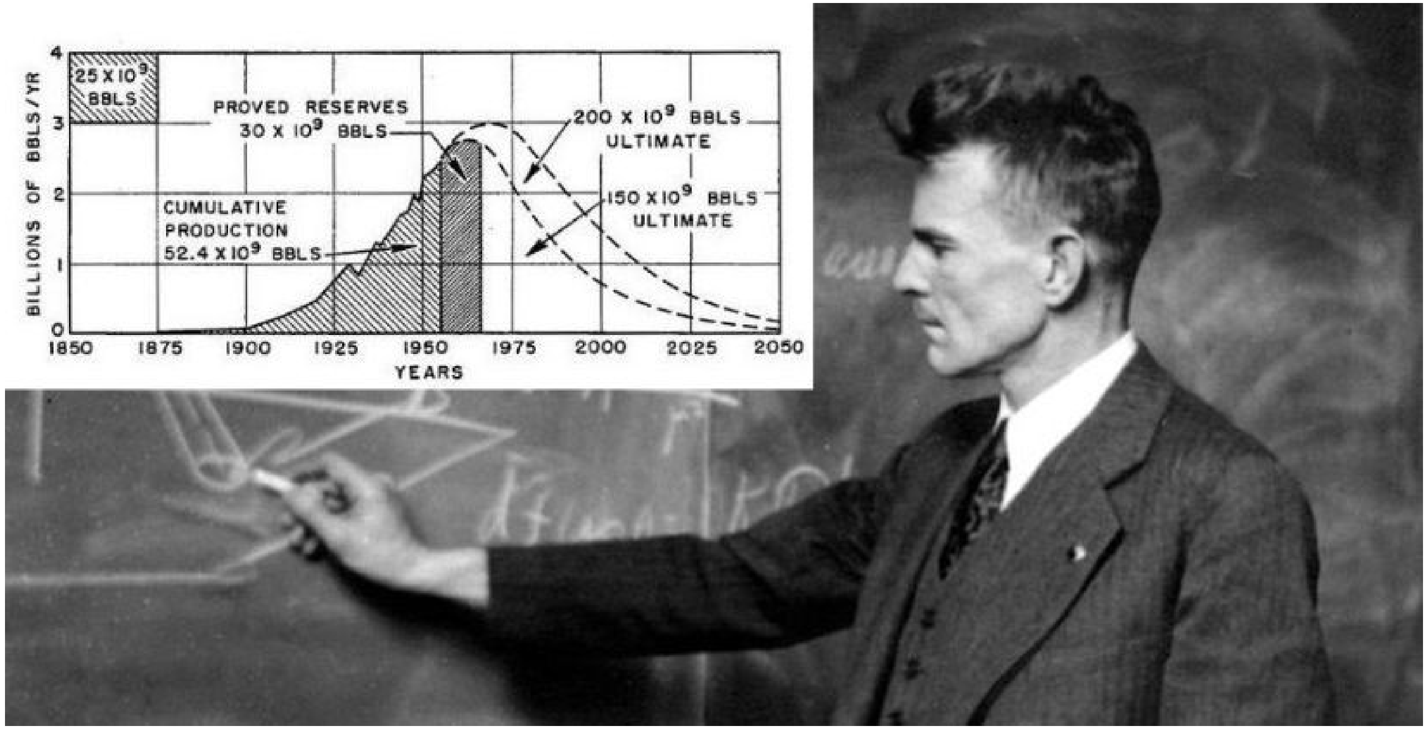
**III. Depletion of natural resources**

- **I. peak oil**
- II. minerals

IV. Towards a green future ?

# Peak Oil

- Mr. King Hubbert (Shell Company), 1956:
  Whenever a new **non-renewable** resource is made available, its extraction is first exponential with time



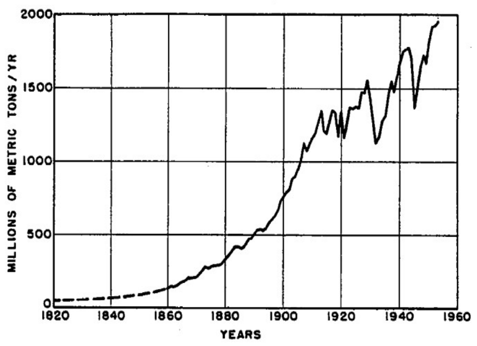




Figure 1 – World production of coal.

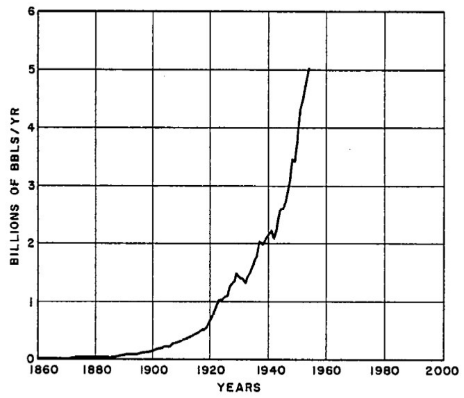



Figure 2 – World production of crude oil.

# Exponential growth – Driven by demand

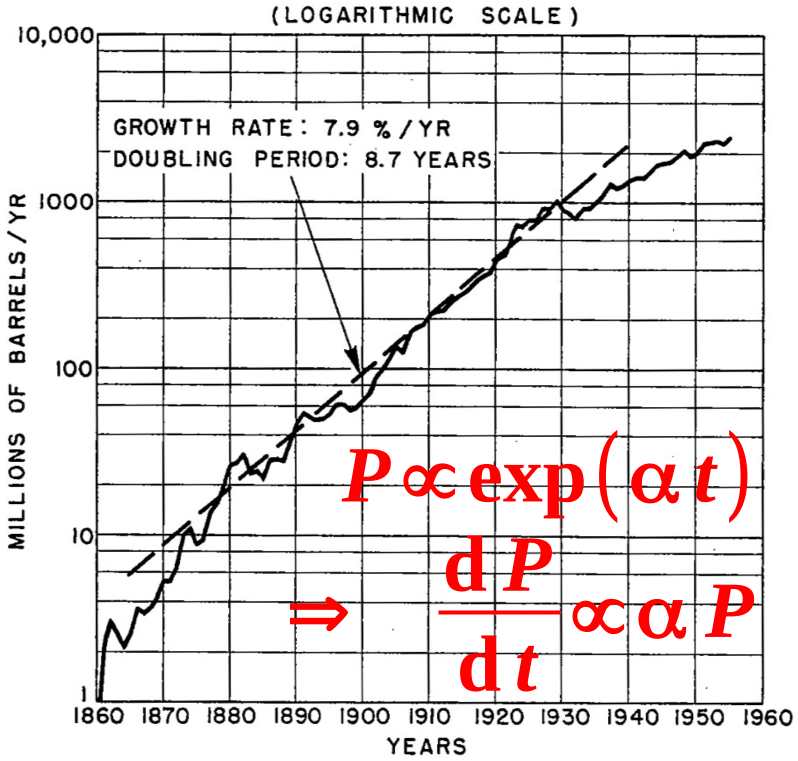



Figure 10 – Crude-oil production in the United States plotted on semilogarithmic scale.

$$P \propto \exp(\alpha t)$$

$$\Rightarrow \quad \frac{dP}{dt} \propto \alpha P$$

$$\Rightarrow \quad \frac{dQ}{dt} \propto \alpha Q$$

A more informative representation of the rate of growth of the production can be obtained by plotting the logarithm of the production rate versus time on semilogarithmic graph paper.

The significance of this is that during the initial stages all of these rates of production tend to increase exponentially with time. Coal production in the United States from 1850 to 1910 increased at a rate of 6.6 percent per year, with the production doubling every 10.5 years. Crude-oil production from 1880 until 1930 increased at the rate of 7.9 percent per year, with the output doubling every 8.7 years.

Q: Total amount extracted

# Slow down of production?

- The resource being available in finite quantity $Q_\infty$, the production rate must decrease as the extracted quantity approaches $Q_\infty$. The resource becomes more and more difficult to extract (deeper, less concentrated, …)
- This leads to a "bell-like" shape with finite, known area
- Assumption: the production rate is proportional to the remaining quantity

$$P(t) \propto Q_\infty - Q(t) = Q_\infty - \int_0^t P(t')\,\mathrm{d}t'$$

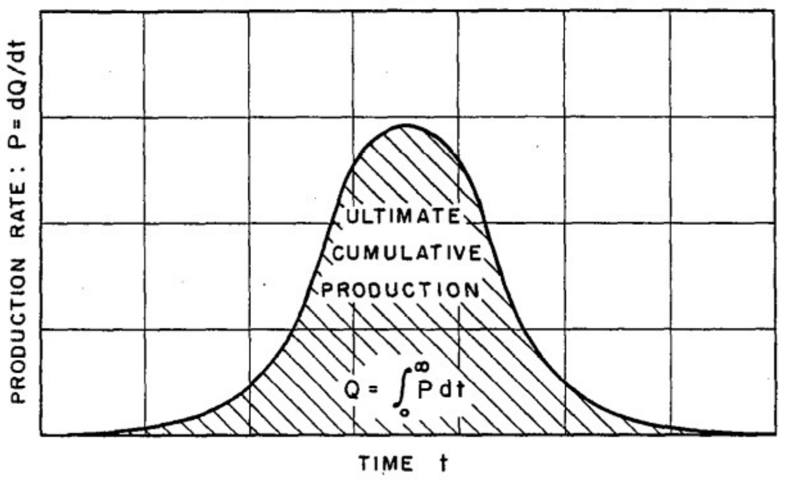



Figure II – Mathematical relations involved in the complete cycle of production of any exhaustible resource.

# Hubbert Peak Model – The Math

- P(t) production at time t
- Q(t) cumulative production
- $Q_\infty$ total resource quantity

$$P(t) = \frac{dQ}{dt} = \alpha \underbrace{Q(t)}_{\text{Already produced}} \times \underbrace{(Q_\infty - Q(t))}_{\text{Remaining resource}}$$

- Resolution

$$\frac{dQ}{Q(t)\times(Q_\infty - Q(t))} = \alpha\, dt$$

$$\log\left(\frac{Q(t)}{Q_\infty - Q(t)}\right) = \alpha Q_\infty t + C_{ste}$$

$$\frac{Q(t)}{Q_\infty - Q(t)} = \beta \exp(\alpha Q_\infty t)$$

$$Q(t) = \frac{Q_\infty}{1 + C\exp(-t/\tau)}$$

- Boundary conditions: $t_0$ is reference point $Q(t_0) \equiv Q_0$

$$Q(t) = \frac{Q_0 Q_\infty}{Q_0 + (Q_\infty - Q_0)\exp(-(t - t_0)/\tau)}$$

# Hubbert Peak Model – The Math

Q(t) cumulative production:

$$Q(t) = \frac{Q_0 Q_\infty}{Q_0 + (Q_\infty - Q_0)\exp(-(t - t_0)/\tau)}$$

Can be expressed more simply as:

$$Q(t) = \frac{Q_\infty}{1 + \exp(-(t - t_m)/\tau)}$$

With time of maximum of production:

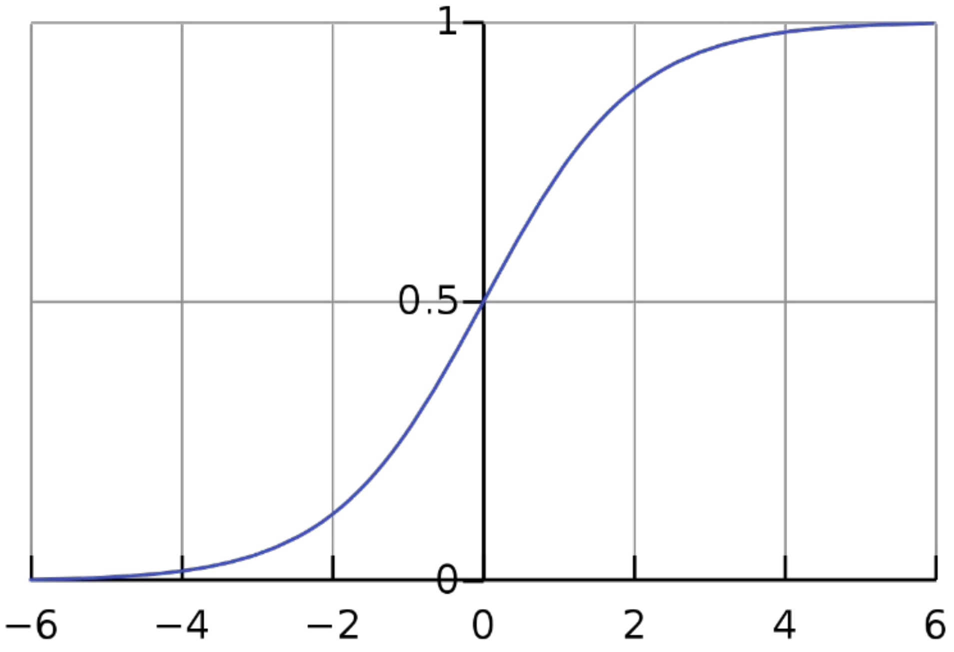
$$t_m = t_0 + \tau \log\left(\frac{Q_\infty - Q_0}{Q_0}\right)$$

# Hubbert Peak Model – Cumulative

- Solution uniquely determined by total resource inventory and consumption growth rate

$$Q(t) = \frac{Q_\infty}{1 + \exp\left(-(t - t_m)/\tau\right)}$$

- Cumulative production follows a logistic (aka Verhulst) function
- Initially developed for a population growth model: population tend to grow exponentially, until individuals have to fight for limited resources


$$f(x) = \frac{1}{1 + \exp(-x)}$$

# Hubbert Peak Model – Instantaneous

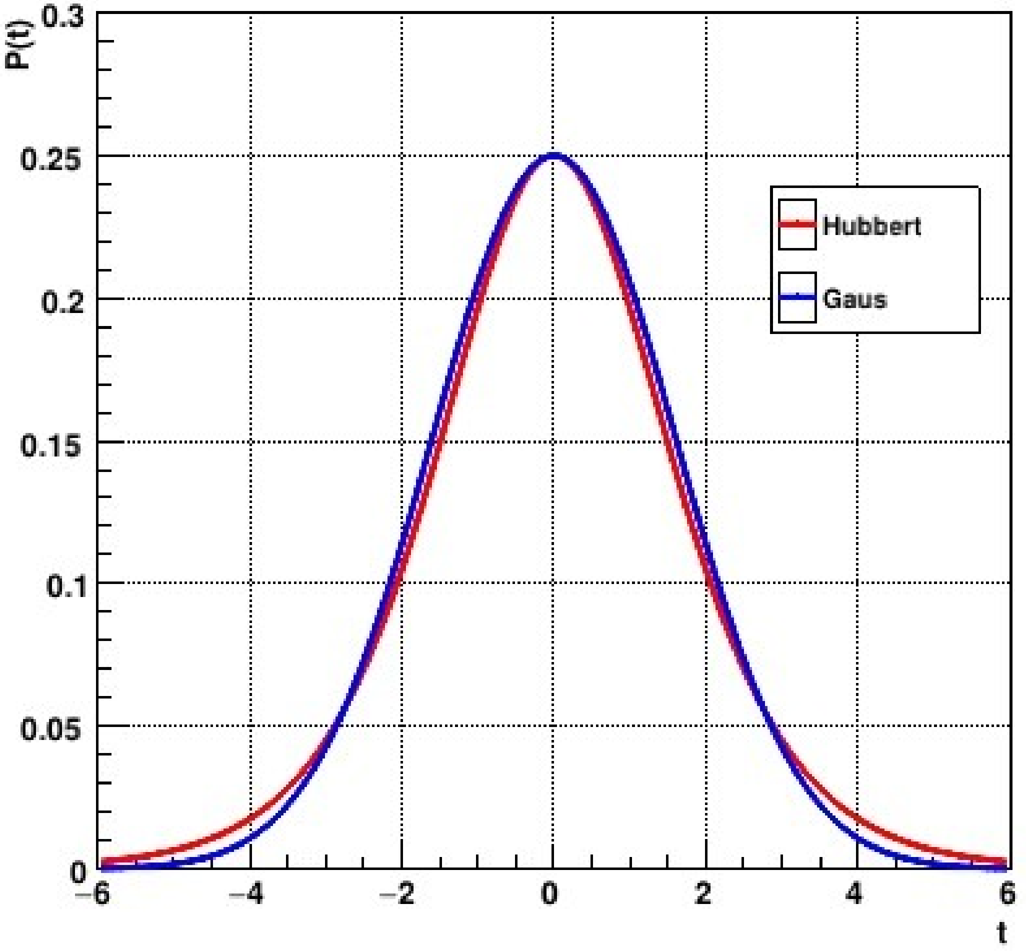
- Production rate follows the "Hubbert function", approaching 0 more slowly than a Gaussian function

$$P(t)=\frac{\mathrm{d}Q}{\mathrm{d}t}=\frac{Q_\infty}{\tau}\times\frac{\exp\left(-(t-t_m)/\tau\right)}{\left(1+\exp\left(-(t-t_m)/\tau\right)\right)^2}$$

- Symmetrical curve, maximum production rate at

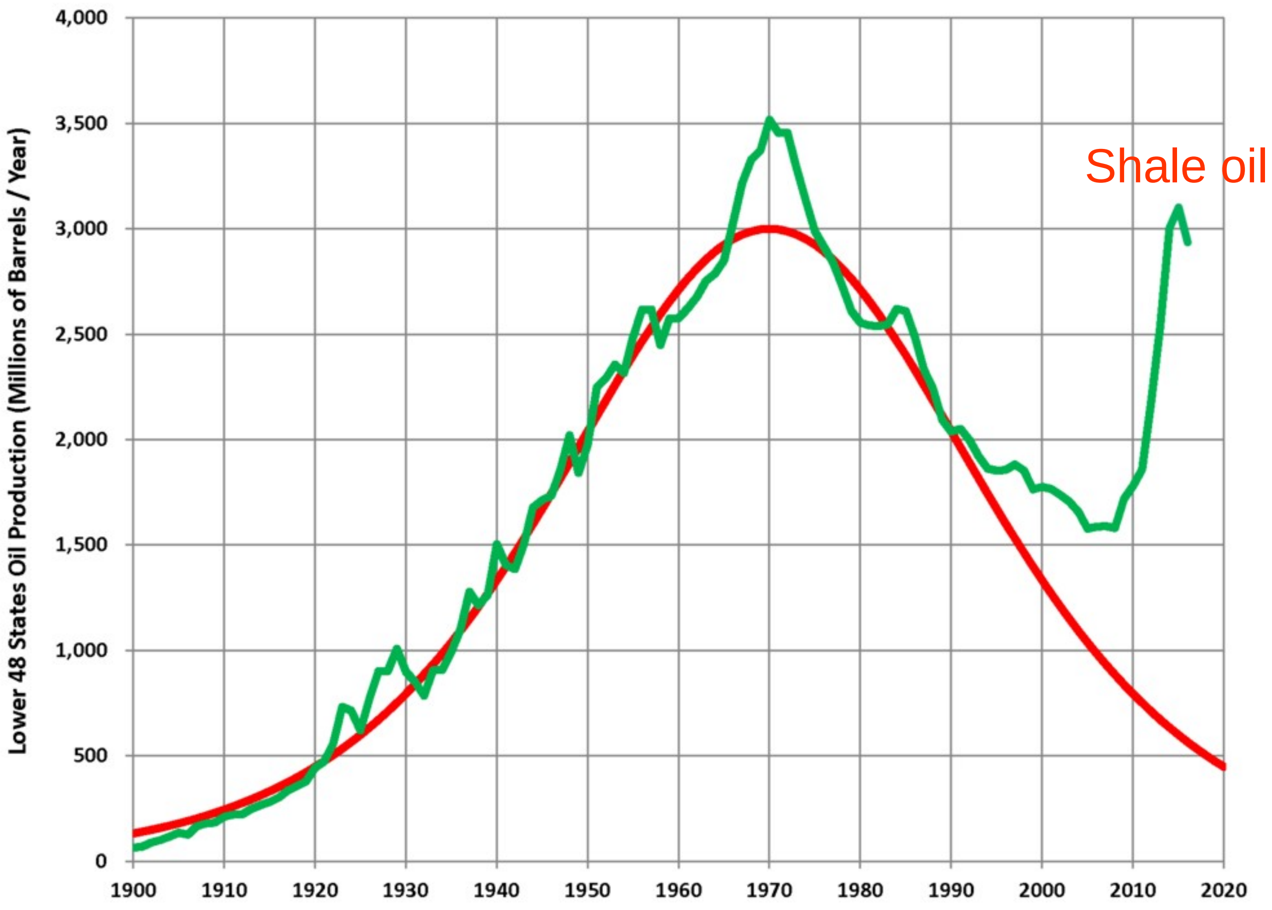
$$t_m=t_0+\tau\log\left(\frac{Q_\infty-Q_0}{Q_0}\right)$$

$$Q(t_m)=\frac{Q_\infty}{2}$$



# Hubbert Peak vs Data

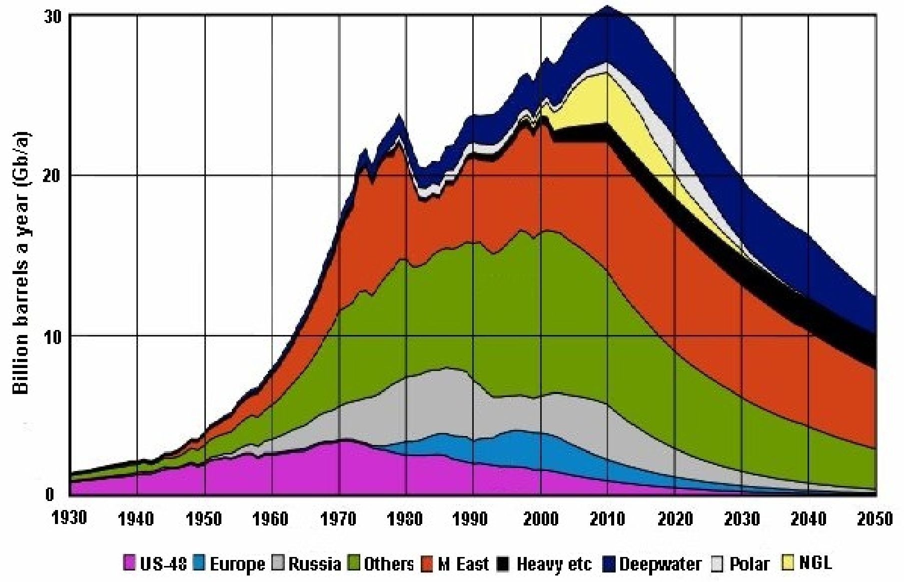
- Hubbert model properly predicted the peak of the U.S. conventional oil production in 1970
- Production rise after 2010 from a different resource (shale oil)

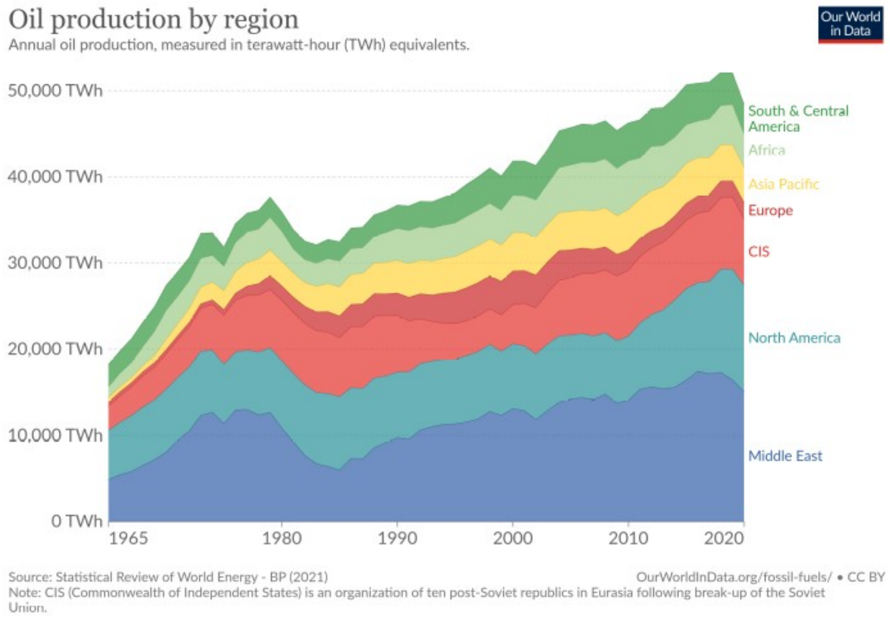



Hubbert's upper-bound prediction for US crude oil production (1956) in red, and actual lower-48 states production through to 2014 in green. Wikipedia

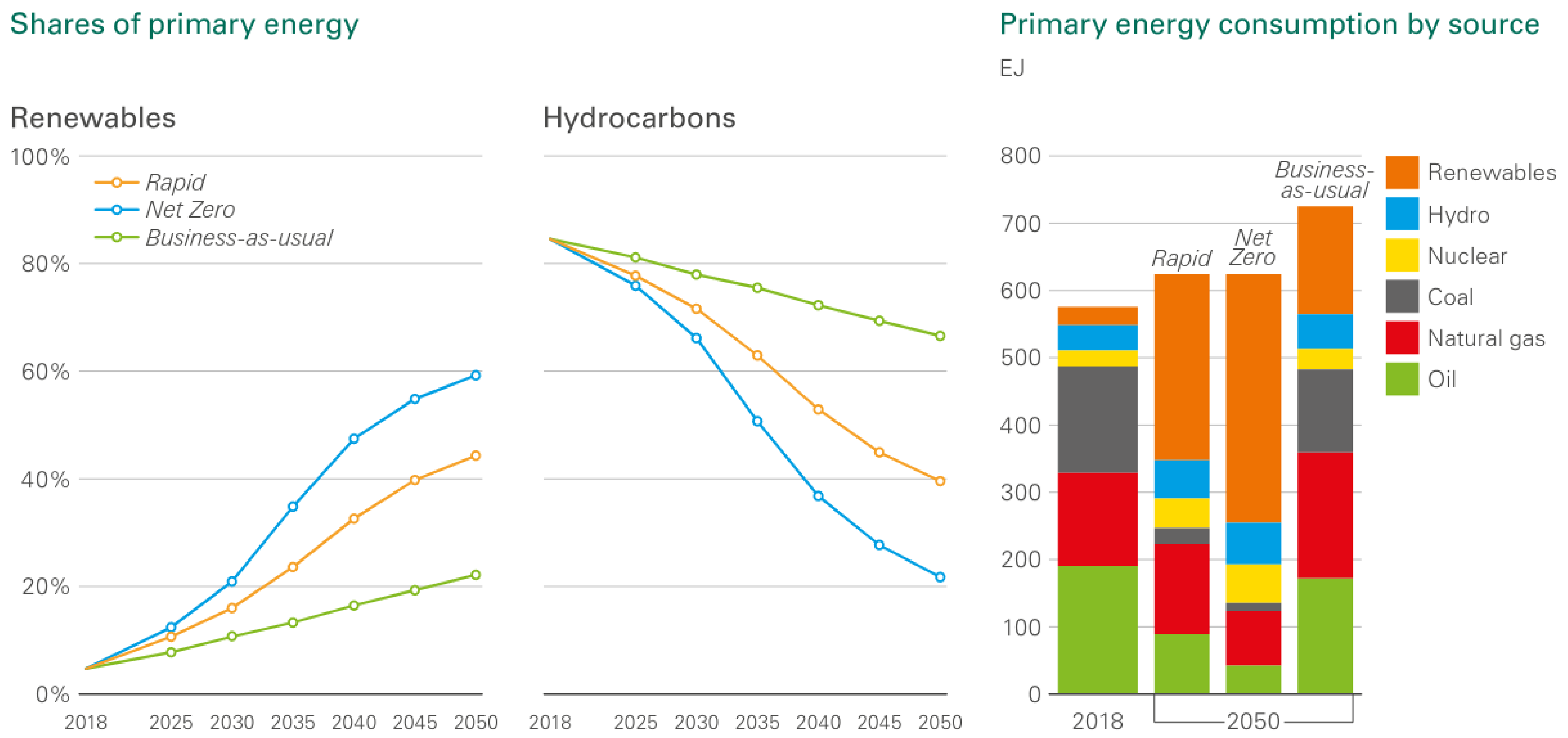
# Worldwide production

- Production from different regions are shifted in time
- Overall production can be modelled by a sum of Hubbert functions (quite trivial)
- 2004 forecast predicted global peak oil in ~2010
- Production still rose due to non-conventional resources
- BP claims peak oil was reached in 2020 (BP's Energy Outlook 2020)
- Total claims demand will peak in 2030



# Evolution Scenario




BP's Energy Outlook 2020

# Lecture 2 – Sustainability

I. Sustainability – Introduction

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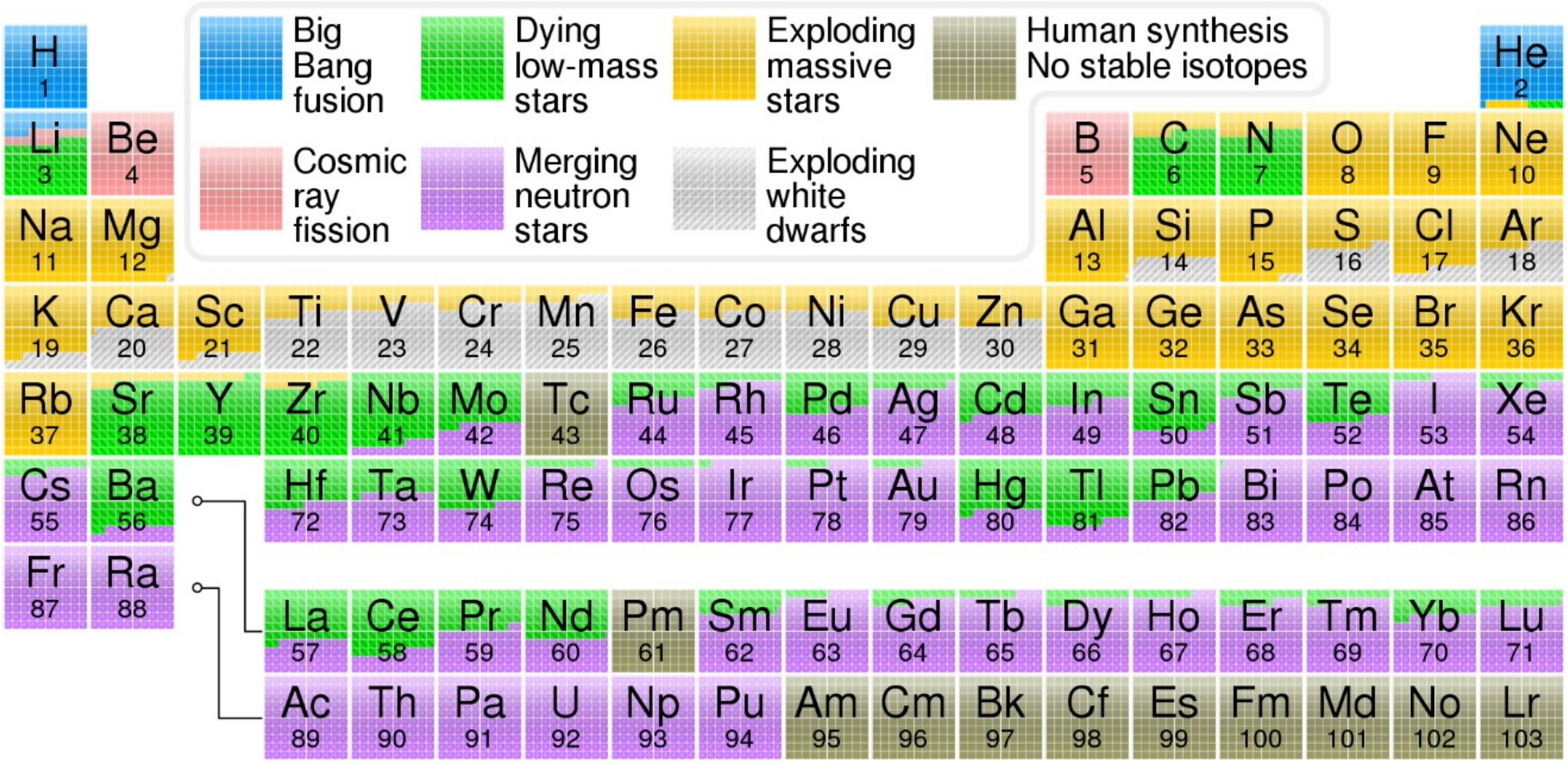
**III. Depletion of natural resources**

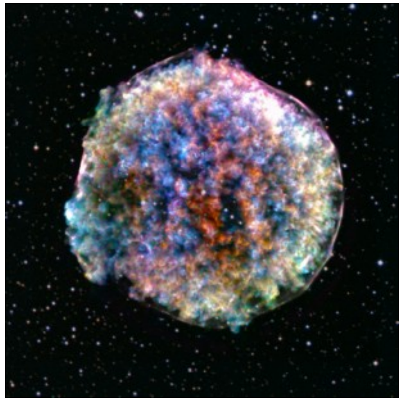
   I. peak oil
   **II. minerals**

IV. Towards a green future ?

# Where are the elements formed ?

- Light elements produced in low-mass, long-lived stars
- Most intermediate elements (O ⇒ Rb) produced in exploding, massive stars
- Heaviest elements (rare earth minerals) produced in merging neutron stars



# Explosive Nucleosynthesis

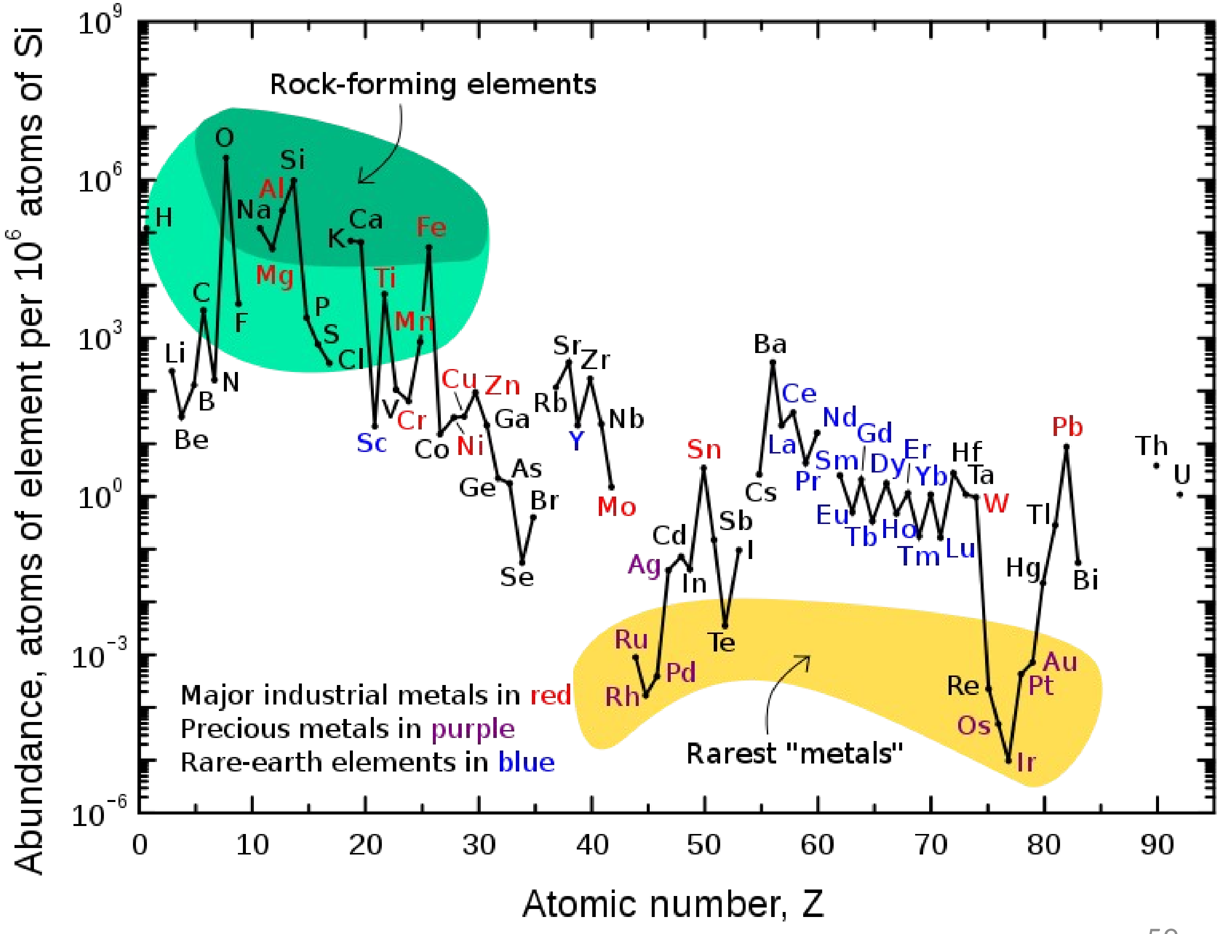
- Star : equilibrium between pressure (nuclear fusion) & gravity
- Supernova:
  - Star runs out of fuel
  - Core-collapse (~1 s)
  - Falling matter bounces back
  - Massive explosion ($10^{16}$ Hiroshima)
  - Outer-shell ejected
  - Explosive nucleo-synthesis, collision of nuclei, …
    → Z ~ 37 (Rb)

# Kilonova

- Neutron star merger
- Massive explosion
- Release of huge neutron flux
- Formation of heavy element by neutron capture followed by $\beta^-$ decay (R process) up to Z~94 (Pu)

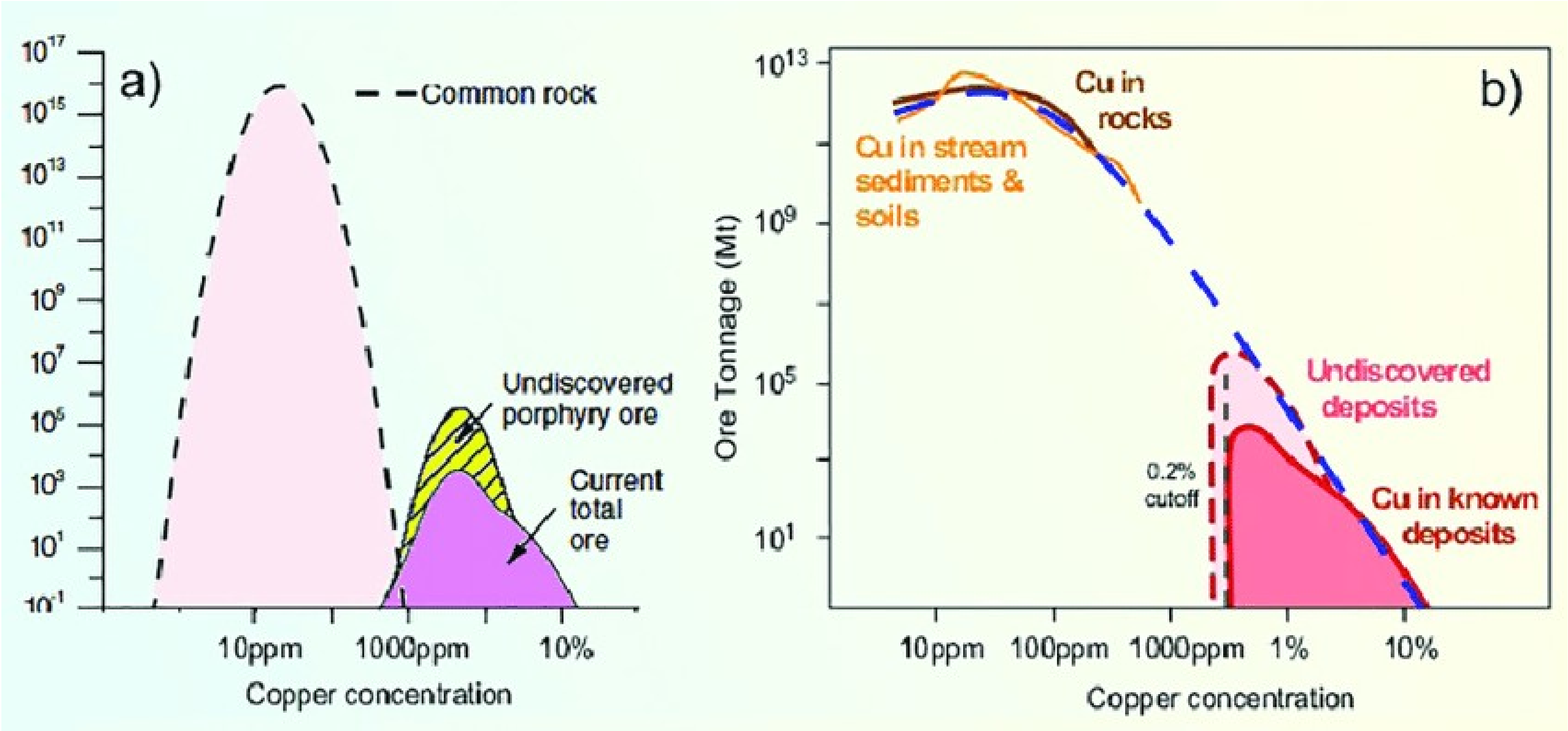
# Overall resources

- « rare earth » elements represent ~ $10^{-9}$ of the earth crust composition (1 mg/ton)
- Some metals rather abundant (Fe, Al)



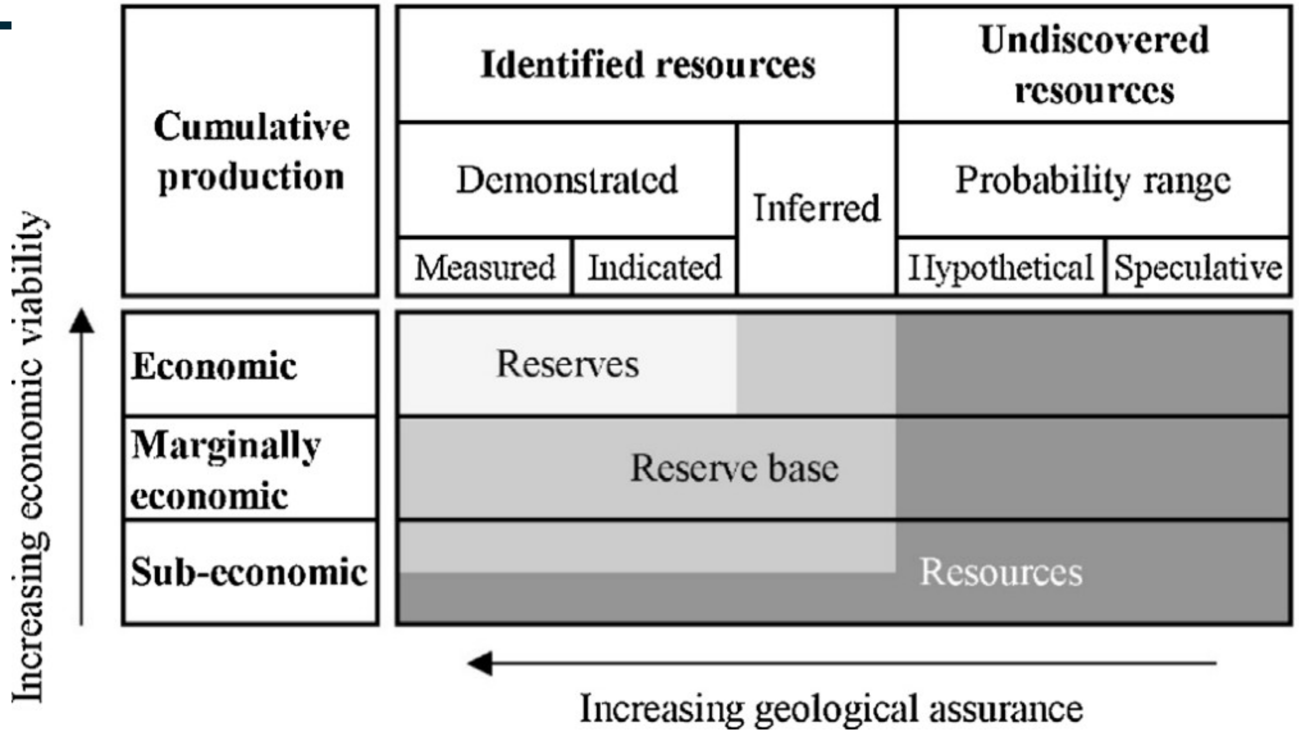
# Accessible resources

- Represent a tiny fraction of the total inventory, e.g. copper
- The vast majority of minerals are spread on low concentration rocks



# Reserves?

- The final accessible resources are **unknown**
  - **Identified Resources:** location, grade, quality and quantity known (**measured**), estimated from low density sampling (**indicated**), or inferred
  - **Undiscovered resources:** postulated resources based on similarity to known mineral bodies

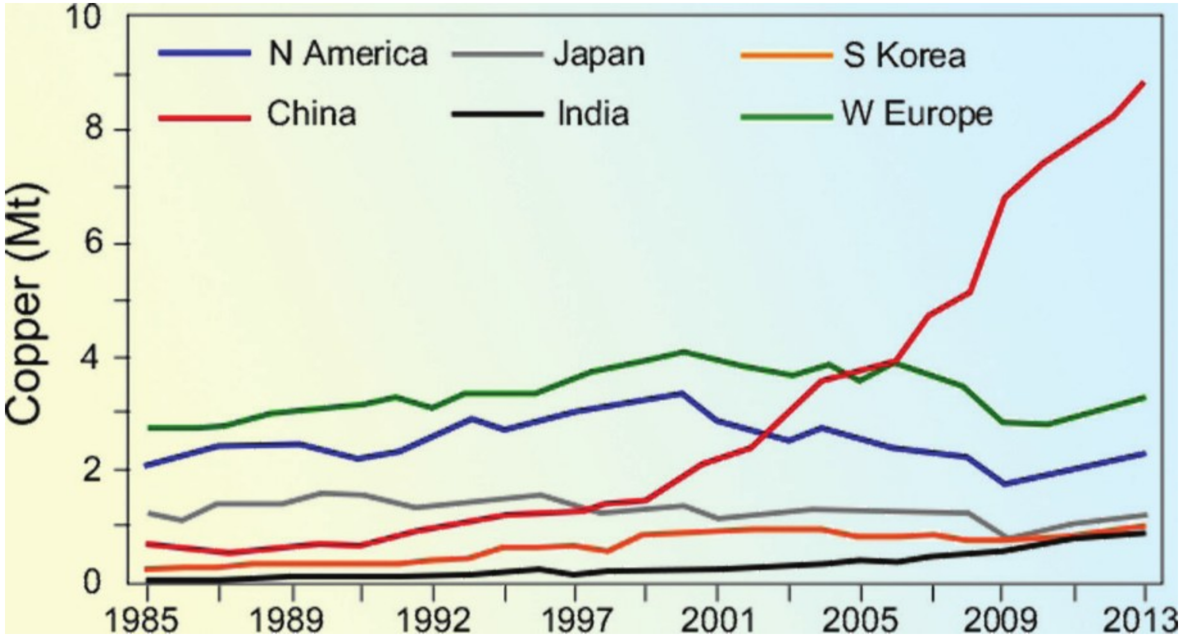



  - **Reserve base**: resources that meat minimum physical & chemical criteria related to current mining & production practices
- As geological survey & mining practices improves, undiscovered resources become identified, and some **resources** turn into **reserves**

# Mistakes are easy...

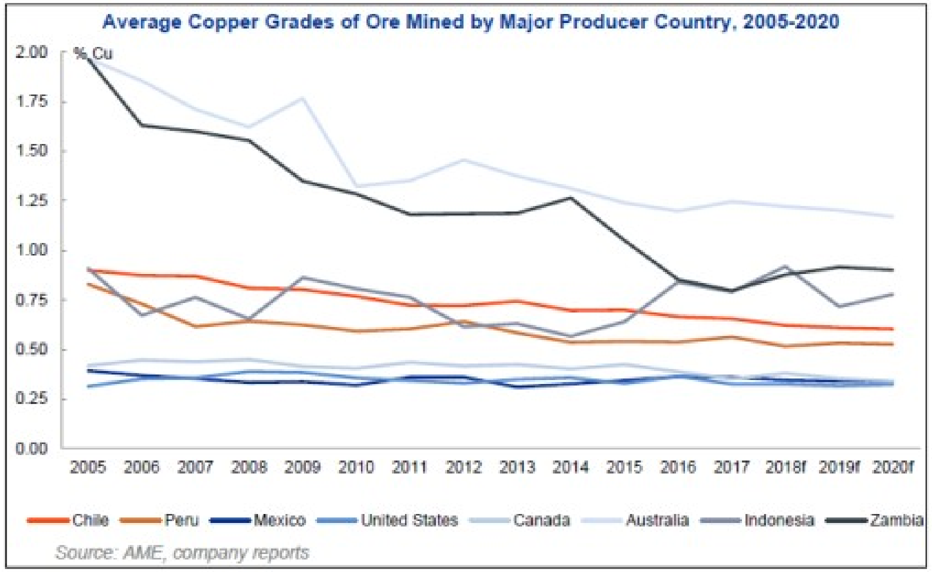
- 1924, Ira Joralemon (American Mining Engineer) *Copper and electricity to vanish in twenty years?*:

  « [T]he age of electricity and of copper will be short. At the intense rate of production that must come, the copper supply of the world will last hardly a score of years. [...] Our civilization based on electrical power will dwindle and die. »
- Production continuously growing
- 80 % of the mined copper is still in used, recycled many times



# Evolution of reserves

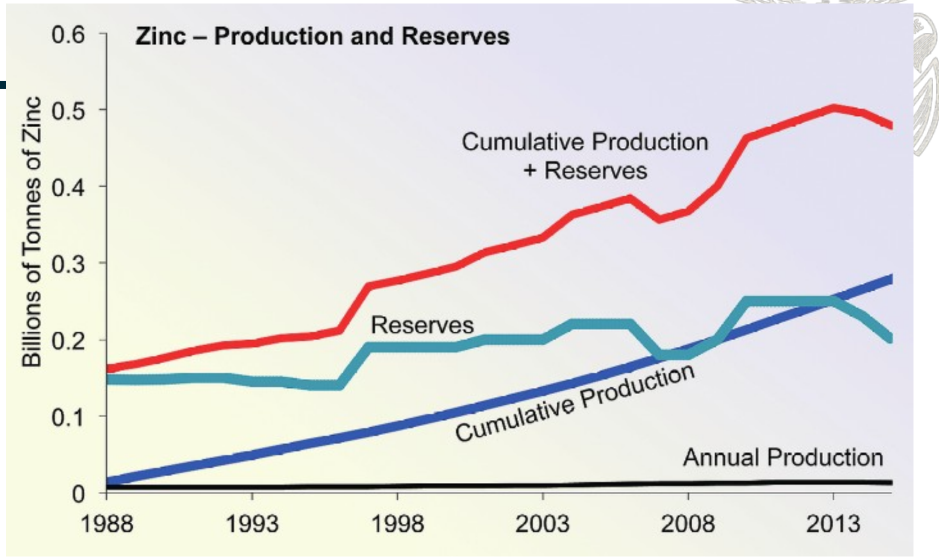
- Although the production is quickly increasing, the amount of reserves is still in the growing phase for most mineral (improved knowledge of ultimate resources).
- Concentration of mineral decreasing in most mines

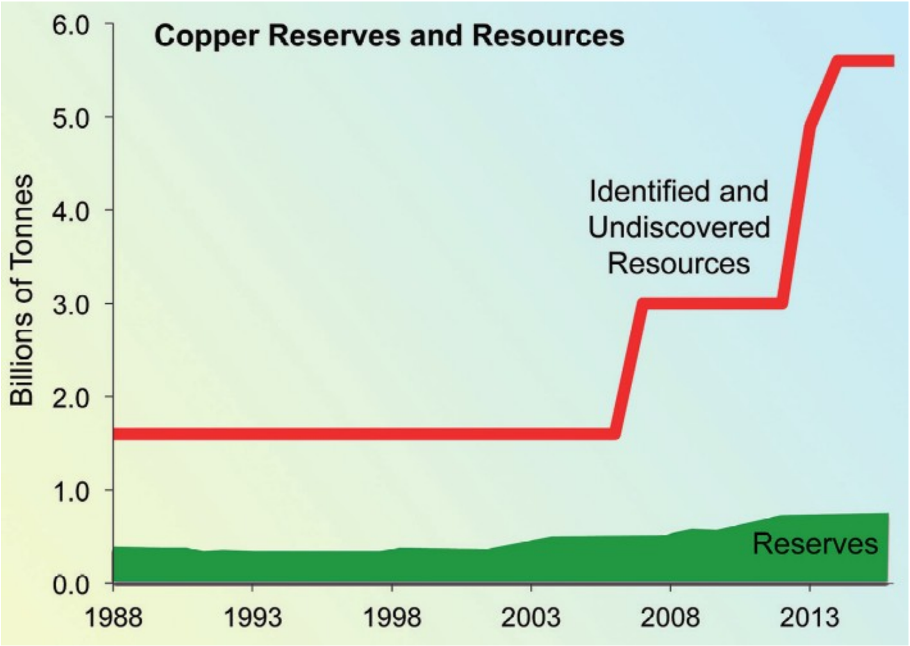



*Average mined copper grades (2017):*
- *World 0.59%*
- *Canada 0.35%*
- *US 0.33%*

*Examples of Canadian copper mines (P&P reserves):*
- *Copper Mountain 0.24% Cu, 0.11g/t Au*
- *Highland Valley 0.31% Cu*
- *Red Chris 0.36% Cu, 0.27g/t Au*

*Source: AME, company websites*



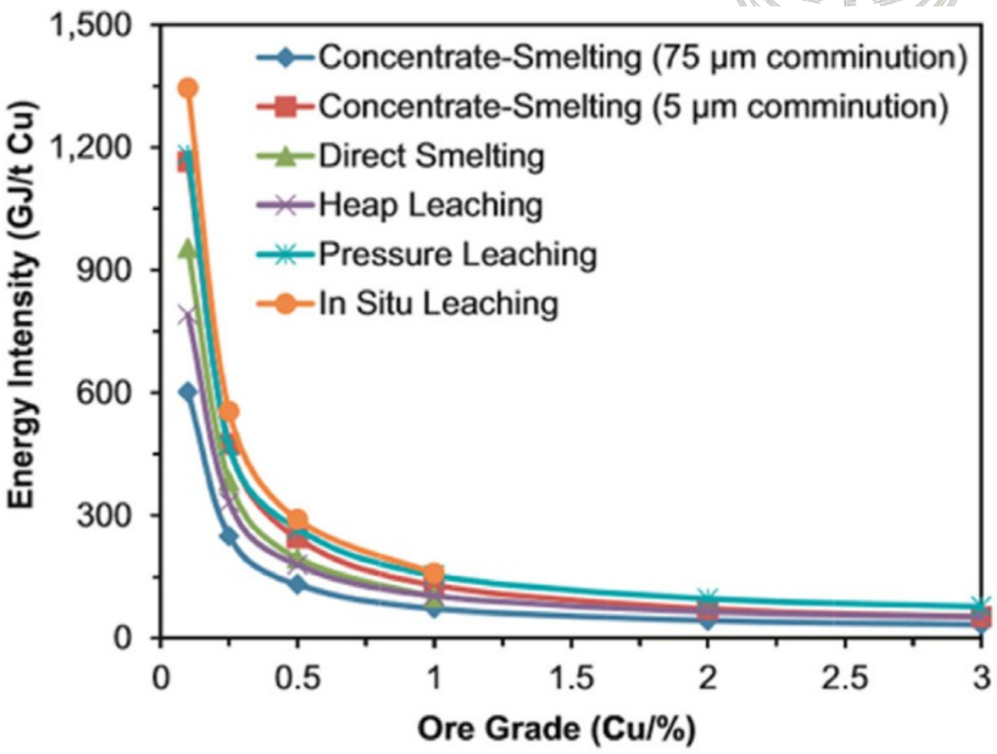

Future Global Mineral, N. T. Arndt Resources, 2017

# Extraction

- Mixture has a larger entropy than pure bodies.
- Separation of constituent implies a local entropy decrease, compensated by a global energy increase
- Extraction cost increases for lower concentration

$$W_{1\,\mathrm{mol}} \geq -RT\left(\log x + \frac{1-x}{x}\log(1-x)\right) \approx -RT(\log x - 1)$$

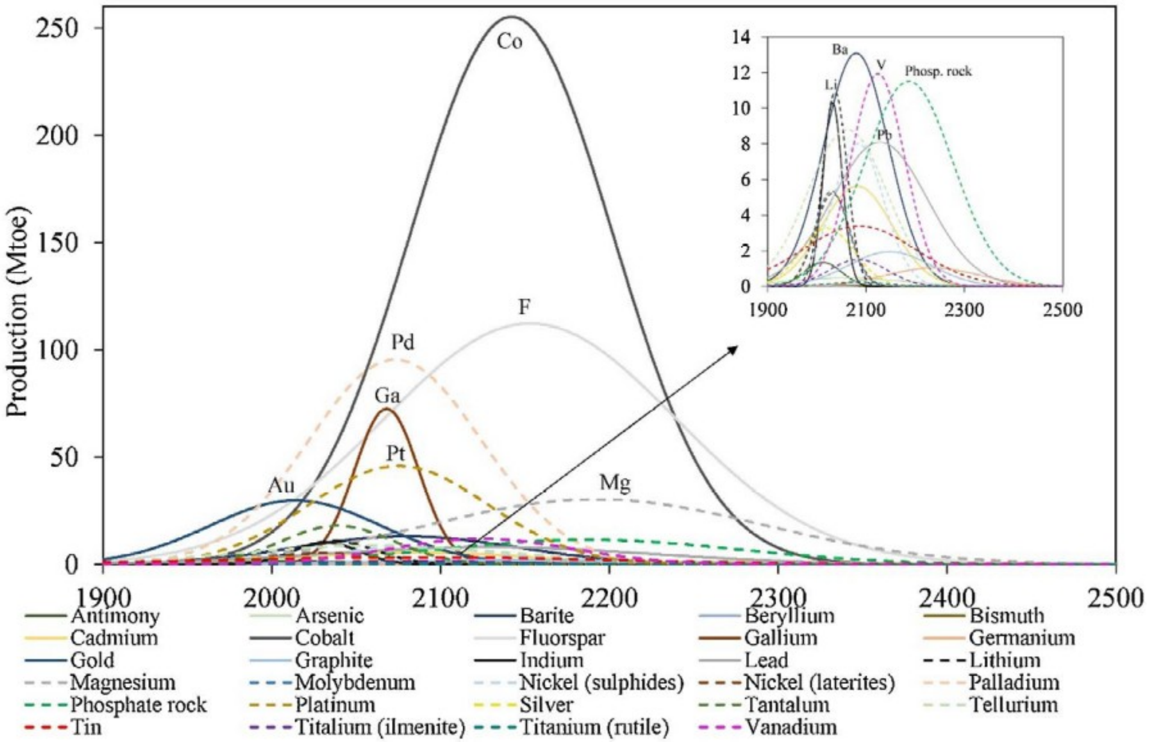
See PC3

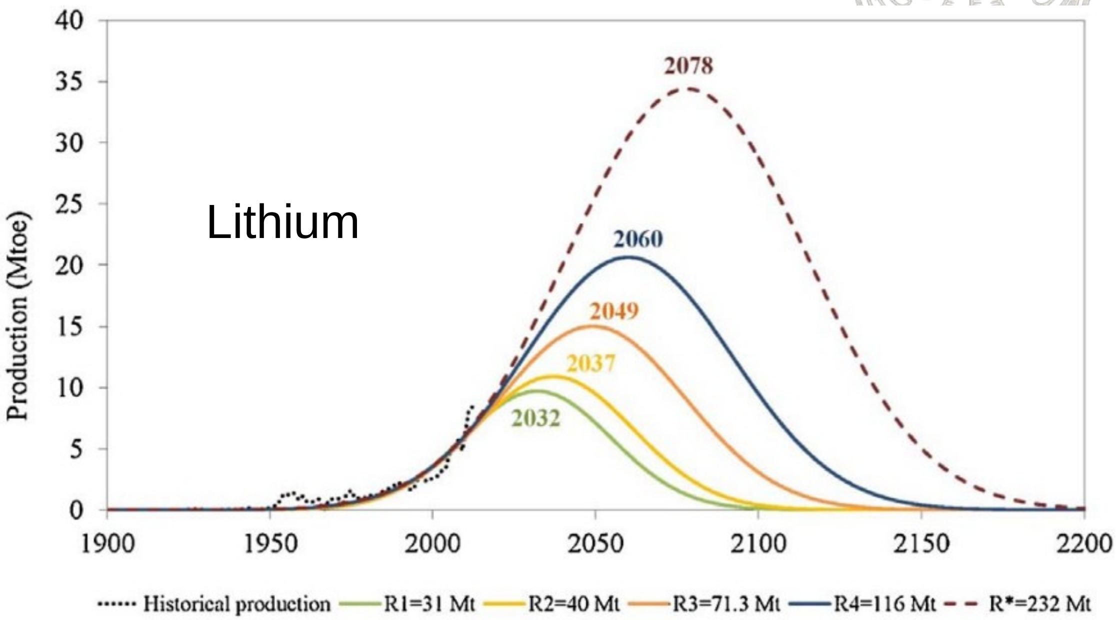



The amount of energy required to produce copper by different processing pathways (Norgate and Jahanshahi, 2010). Data are from 2010.

# Prediction of future production

- Estimation of future production and sustainability depends a lot on ultimate resources




- Mineral “shortage” in a few years to ~ 100 yrs depending on metal, using current resource knowledge

Resources, Conservation & Recycling 125 (2017) 208–217

# Selected minerals

Resources, Conservation & Recycling 125 (2017) 208–217

- Peak approaching for many minerals
- Other authors claim we will have enough material for 1000’s of years
  e.g. Lluis Fontboté, 2017
- Other options might become soon accessible
  - Extraction from sea water (desalination)
  - Poly-metallic nodules covering the bottom of the oceans

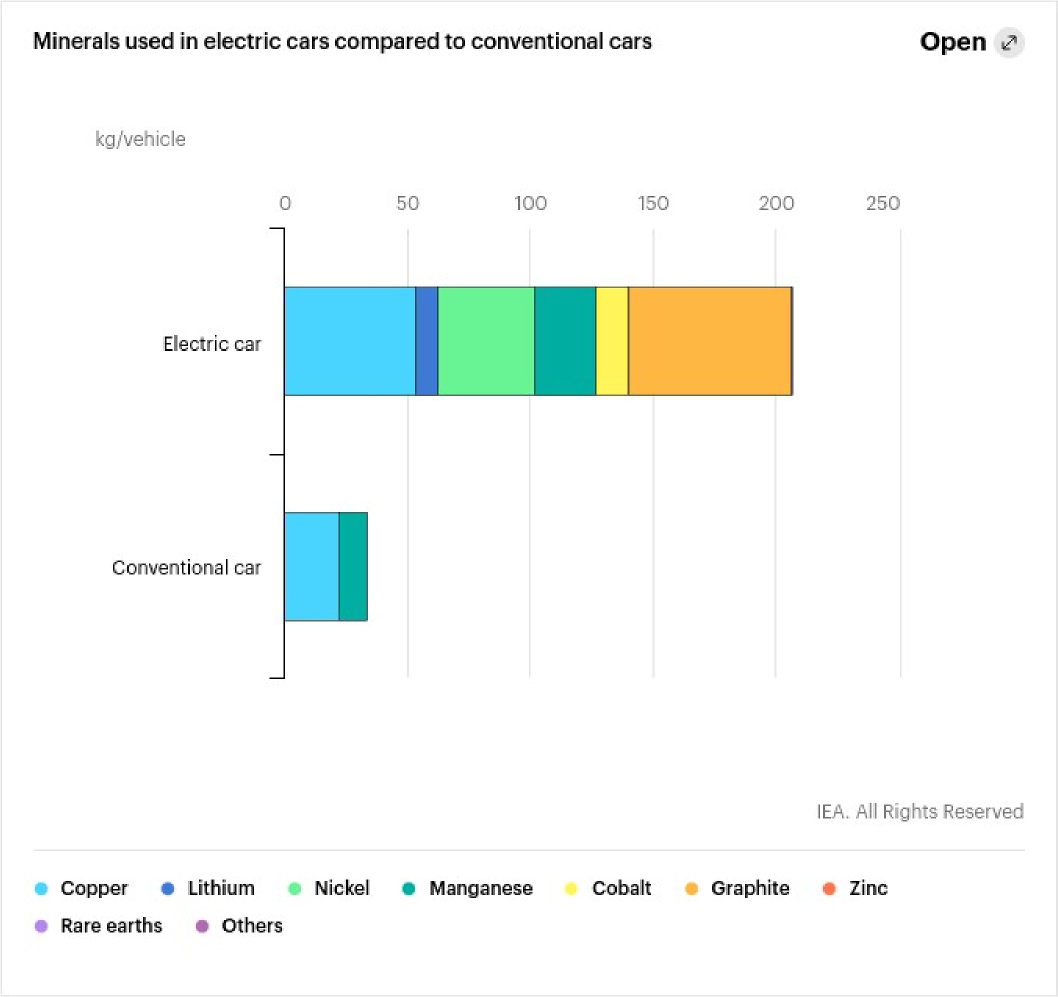
| Commodity | Peak | Commodity | Peak | Rare Earth Elements | |
|---|---|---|---|---|---|
| Aluminium | 2084 | Lead | 2128 | Cerium | 2092 |
| Antimony | 2012 | Lithium | 2037 | Dysprosium | 2219 |
| Arsenic | 2059 | Magnesium | 2192 | Erbium | 2279 |
| Barite | 2080 | Manganese | 2030 | Europium | 2121 |
| Beryllium | 2247 | Molybdenum | 2030 | Gadolinium | 2162 |
| Bismuth | 2040 | Nickel | 2033 | Lanthanum | 2110 |
| Cadmium | 2082 | Palladium | 2073 | Neodymium | 2105 |
| Chromium | 2107 | Phosphate | 2187 | Praseodymium | 2101 |
| Cobalt | 2142 | Platinum | 2075 | Samarium | 2139 |
| Copper | 2072 | Silver | 2022 | Scandium | 2126 |
| Fluorspar | 2153 | Tantalum | 2039 | Terbium | 2171 |
| Gallium | 2068 | Tellurium | 2062 | Ytterbium | 2297 |
| Germanium | 2236 | Tin | 2086 | | |
| Gold | 2014 | Titanium | 2084 | | |
| Graphite | 2148 | Vanadium | 2124 | | |
| Indium | 2032 | Zinc | 2061 | | |
| Iron | 2091 | | | | |

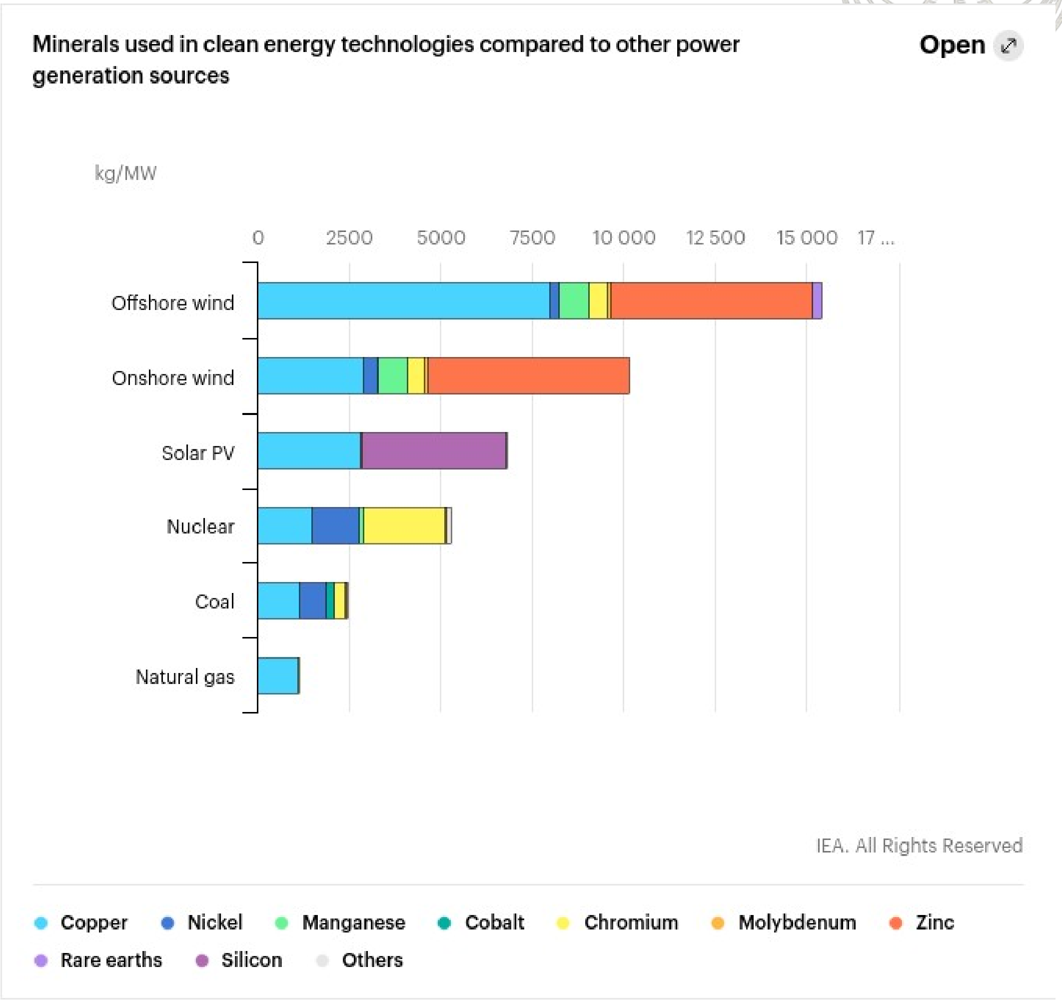
# Minerals for Energy

- Minerals are critical for a clean energy transition
- IEA, May 2021

  *"Today, the data shows a looming mismatch between the world's strengthened climate ambitions and the availability of critical minerals that are essential to realising those ambitions."*

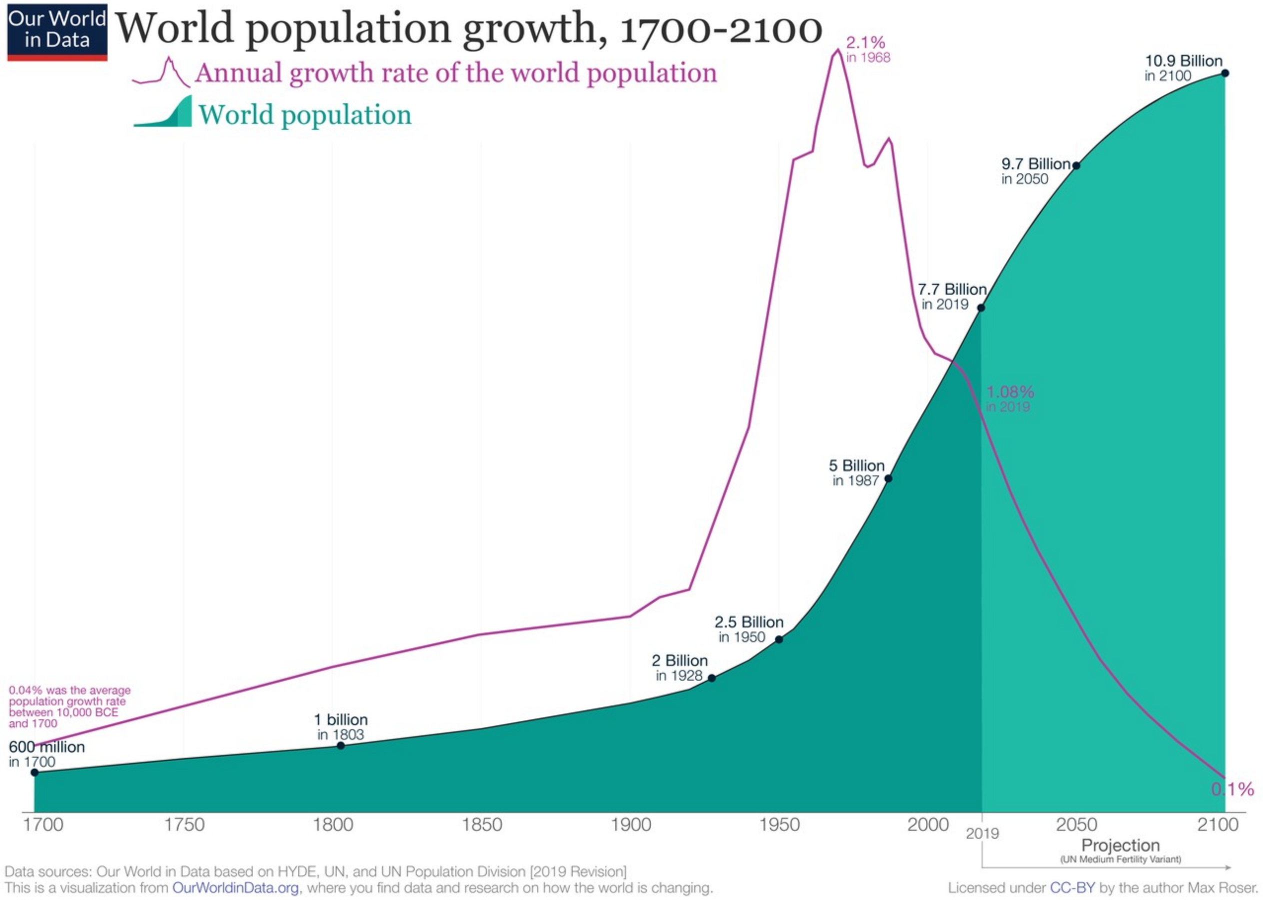
# Minerals for Energy – Examples



# A many-fold crisis

- During the 21st Century, human kind will have to face
  - Energetic Crisis: end of cheap energy
  - Shortage of mineral
  - Global warming
  - Collapse of bio-diversity
  - Peak of population
- What future?



# Reasons for fear

- Current development model is unsustainable on the long term and leads to rapid exhaust of resources & environmental treats
- Despite this evidence, the world remains massively fuelled by fossil energies that might be rapidly exhausted. Their massive use leads to global warming with associated consequences.
- Mineral shortage is also possible at the same time-scale and might derail the energy transition
- Public policies, despite numerous warning, are not reacting fast and seriously enough (involving "pragmatism")

# Reasons for hope

- A very small share of the input solar energy can fuel humanity
- Population are getting aware of the challenge and (partially) changing their habits. Overall population increase is finaly slowing down
- Tools (LCA) are development and use to quantify the sustainability, and help in decision making
- Some past, coordinated international actions were successful (e.g. Ozone layer)
- The total inventory of critical material might make a clean energy transition possible
- On the long term, cheap & massive energy might become available (Fusion, ...)

# Last words (for today)

- Human kind experienced a tremendous increase in level-of-live, mainly driven by fossil fuel
- This model is coming to an end
- Green energy transition and world sustainability appears possible, although not trivial.
- Humankind has to react now
- Valerie Masson Delmotte: “Each fraction of a degree counts, every year counts, every action counts”

# Backup

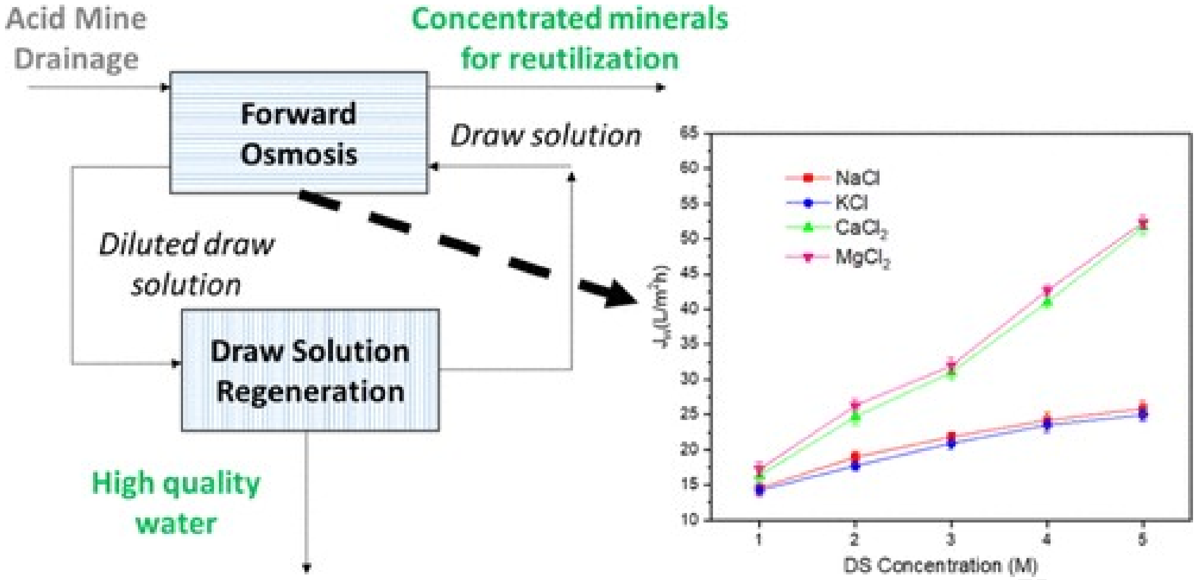
# Missing elements

- Average temperature of the Earth (with/without atmosphere)
- $CO_2$ Emission statistics (by source, sector, …)
- Future sources of minerals (nodules, space)
- Carbon intensity of economies
- Previous Successes (Ozon layer, ...)

# Other sources of minerals

- Polyletalic modules
  - Made of ickel, cobalt, copper, titanium and rare earth elements sorb
  - estimate of ~ 500 billions tons available

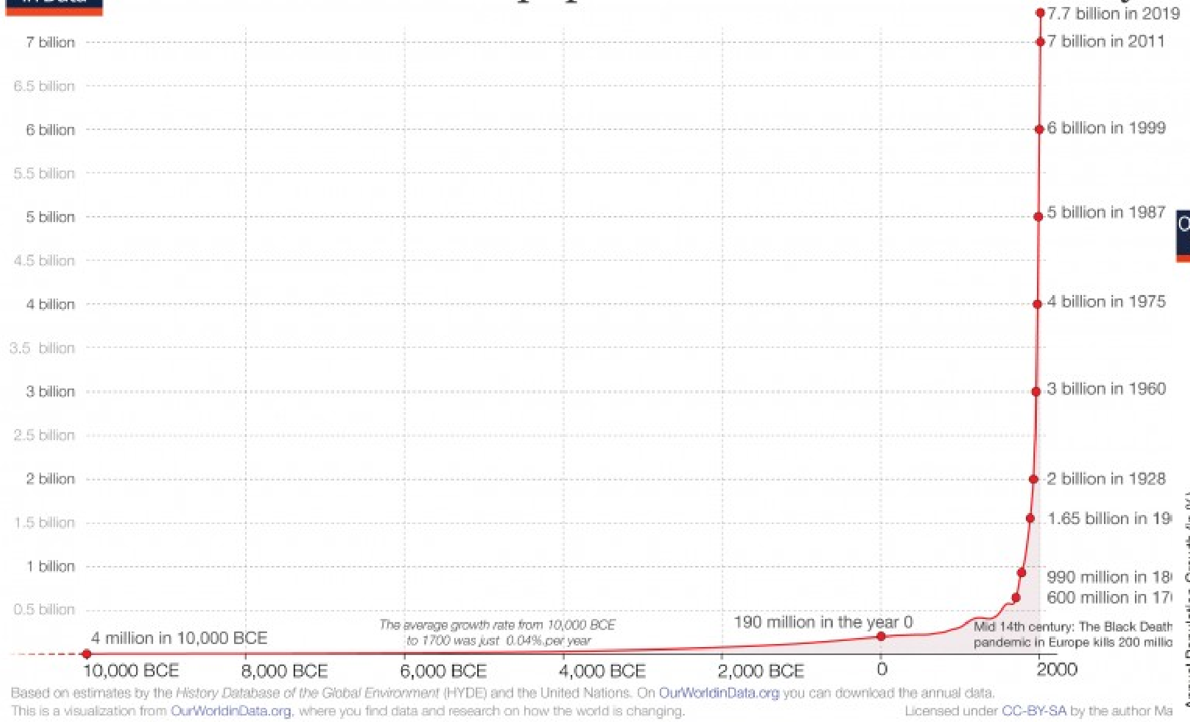
- By product of sea-water desalinisation
- 1 m³ of sea water contains
  - 19 g of Chloride
  - 11 g of Sodium
  - 1.2 g of Magnesium
  - 103 mg of Lithium
  - …
  - 3.8 µg of Uranium



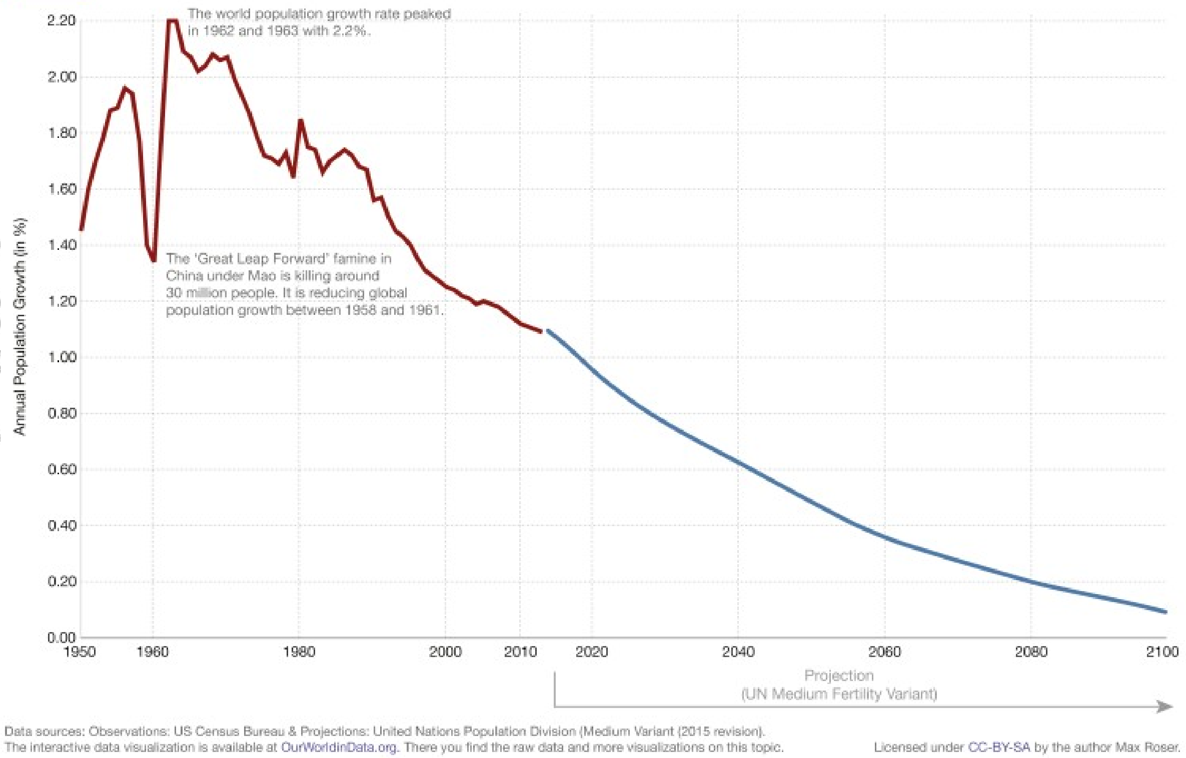
# IPCC Conclusion

- The conditions necessary to constrain global warming to 1.5°C will require cooperation / political will / financing. Overall, we face three major risks:
  1. Climate risk.
  2. The risk of delaying, placing the burden on future generations and relying on the development of carbon capture technologies.
  3. Financial risk, as the sustainability of a number of sectors relies on the implementation of a planned, rapid and voluntary transition.
- In short, every half degree counts. Each year counts. All of our individual and collective choices count. And whatever happens, the finance sector will have an important role to play.

## Our World in Data – The size of the world population over the last 12.000 years




## Our World in Data – Annual world population growth rate (1950-2100)



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# Copper Surges Above $9,000 as Shortfall Concern Spurs Rally

Bloomberg News

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(Bloomberg) -- Copper rose above $9,000 a metric ton for the first time in nine years, taking another step closer to an all-time high set in 2011 as investors bet that supply tightness will increase as the world recovers from the pandemic.

Copper is surging amid a broad rally in commodities from iron ore to nickel, while oil has gained more than 20% this year. The bellw industrial metal has doubled since a nadir in March, boosted by rapidly tightening physical markets, prospects for rebounding econo growth and the expectation that a years-long era of low inflation in key economies may be ending.

# Copper Prices