PLANETARY CLIMATE TRENDS AND CAUSATION IIB

Agenda for Section (Sustainability @ “Anthropocene”)

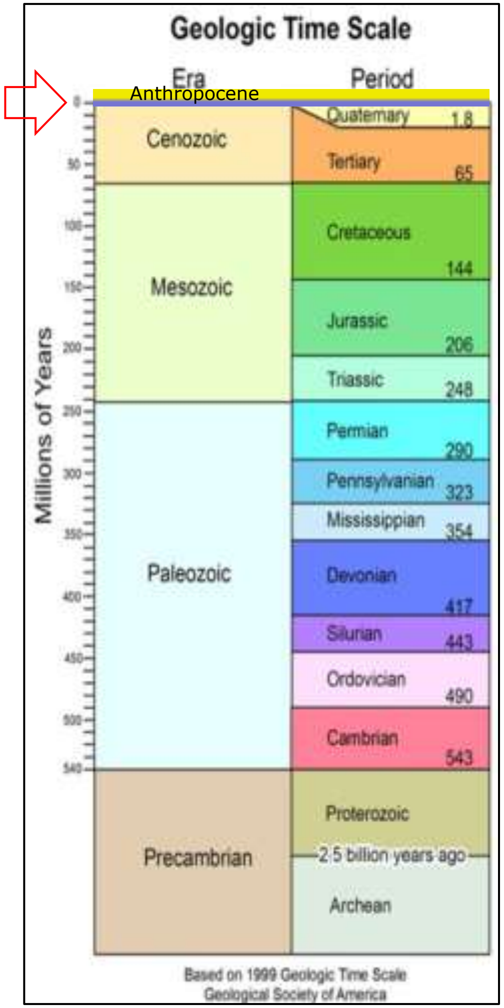
Grand picture Habitat and resource utilization

- Energy concept, human utilization of Energy
- Tools and fuels in human history

- Sustainability of Future Human Activity & Life on Earth
  Limit to growth, Club of Rome,
  Socio-economic/ecological network.

- Finite resources: arable land and water for food production, materials for fabrication & construction, fuels for machinery & transportation,
  Human eco-footprint, choices, and dilemmas,

- Energy utilization and environment,
  Energy consumption and human development
  External costs of energy consumption,
  Correlations energy use with planetary climate, greenhouse effect.



Solar Insolation on Earth

Solar Constant

$$Earth\ area\ A_E = 5.1\times 10^8\ km^2$$

$$exposed\ to\ Sun = disk\ of\ area\ A_{R_{SE}} = \pi R_E^2 = \frac{1}{4} A_E$$

Total Sol Power

$$S\cdot A_{R_{SE}} = \sigma \cdot T_S^4 \cdot \left(4\pi R_S^2\right)\cdot\left(\frac{A_{R_{SE}}}{4\pi R_{SE}^2}\right)$$

$$S = \sigma\cdot T_S^4\cdot\left(\frac{R_S^2}{R_{SE}^2}\right) \approx 1.370\, kW/m^2$$

$$Time\ averaged\ over\ spinning\ earth\ A_E = 4\,A_{R_{SE}}$$

$$S_{effective} = S/4 = 0.343\, kW/m^2$$

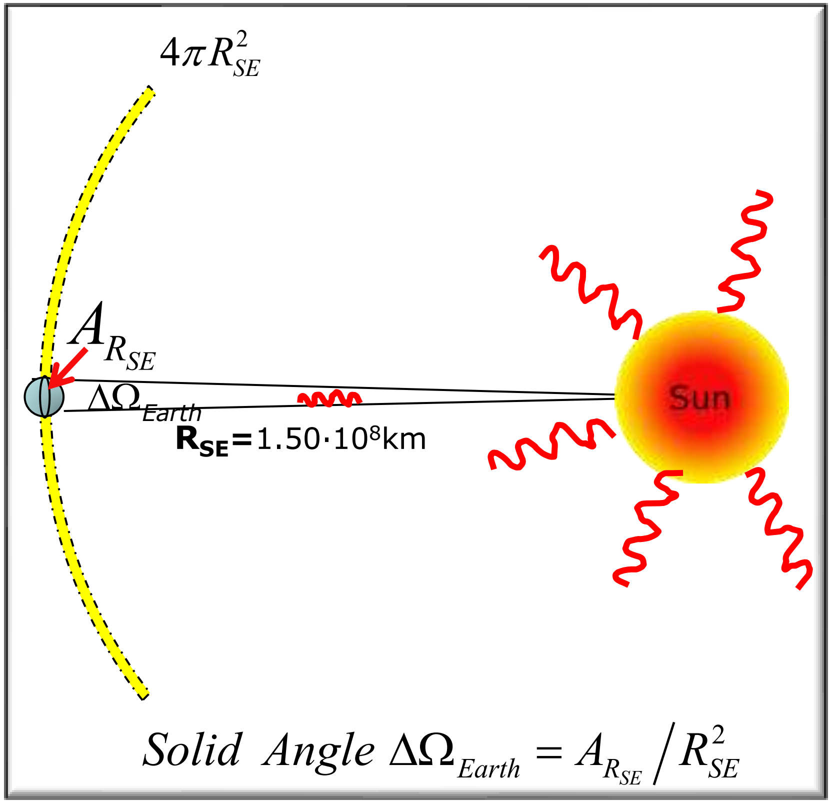
$$Albedo\ \alpha = reflectivity,\ \alpha_E \approx 0.3\ \ (expt.)$$

$$\rightarrow mean\ power\ absorbed\ by\ Earth's\ surface$$

$$S'_{eff} = (1-\alpha)\cdot S/4 = 0.240\, kW/m^2$$

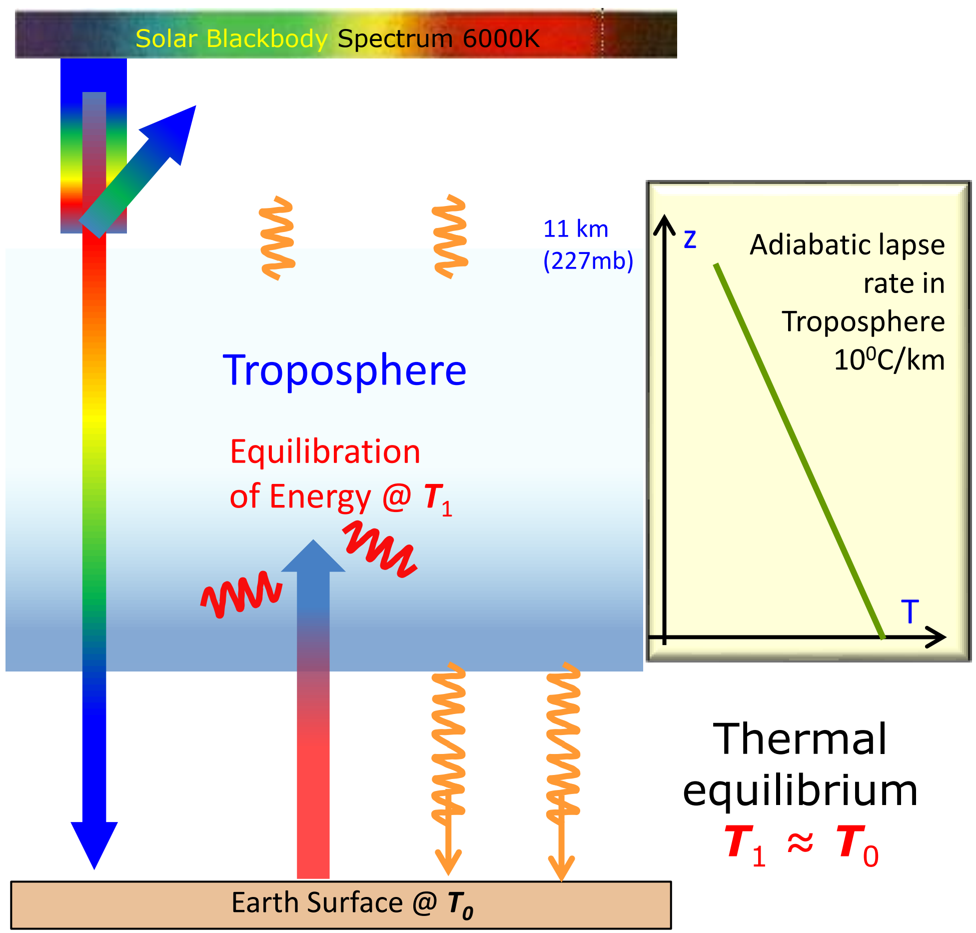
$$T_E^{theo} = 255\,K\ (= -18^0 C)\quad T_E^{actual} = 288K(+15^0 C)$$

(More sophisticated models for Earth energy balance are available)



Effect of solar irradiation on Earth surface is non-cumulative, non-linear, possibly unstable.
System of several negative and positive feed-back effects.
Possible: Thermal equilibrium ?

Near-Surface Energy Equilibration



In actual calculations, atmosphere divided into layers, consider also clouds, dust, etc. Albedos of clouds, ocean, ice can be taken from measurement.

Greenhouse Effect

Absorption of solar radiation by the atmosphere is not lost into space.

Relaxation into IR thermal kinetic spectrum of atmospheric particles. Most of the energy content is radiated back to Earth surface.

In equilibrium *influx* = *outflux*

1) Earth surface + atmosphere receive P=S(1-a)/4.

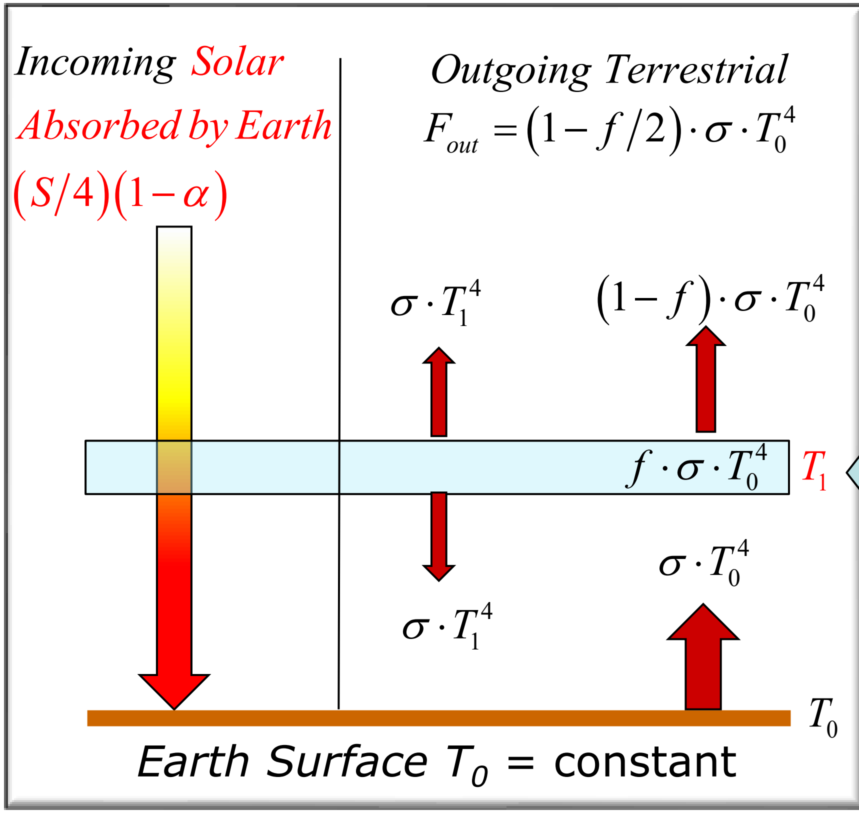
IR radiation from surface is absorbed by atmosphere, heating it up.

2) Atmosphere radiates power ***P***=S(1-a)/4 at very low ***T*** back into space and at higher ***T*** toward surface, heating the surface in addition to direct insolation.

Solve numerically consistently in iteration. → T_E = 283 K (+10^0C)

See, e.g., F. P. J. Valero et al., J. GEOPHYS. RES., 105, 4743 (2000)

Simple Greenhouse Model



Approximations: Atmosphere is transparent to incoming solar radiation. Earth surface absorbs part (1 - α) of it. Emits absorbed energy as thermal radiation at T_0. Part *f* of that is absorbed by atmosphere, heating it to T_1. part (1 - *f*) is transmitted to space.

Slab Energy Content @T_1 after equilibration

$$f\cdot\sigma\cdot T_0^4 = 2\cdot\sigma\cdot T_1^4 \rightarrow T_1 = (f/2)^{1/4}\cdot T_0$$

Stationary state equilibrium requires

$$Absorbed = Radiated\ Energy\ (Power\ F)$$

$$(S/4)(1-\alpha) = (1-f)\cdot\sigma\cdot T_0^4 + (f/2)\cdot\sigma\cdot T_0^4$$

$$F_{out} = (1-f/2)\cdot\sigma\cdot T_0^4 \rightarrow \Delta F_{retained} = (f/2)\cdot\sigma\cdot T_0^4$$

$$\rightarrow T_0 = \left[\frac{F_{in}}{F_{out}}\right]^{1/4} = \left[\frac{(S/4)(1-\alpha)}{\sigma\cdot(1-f/2)}\right]^{1/4}$$

$$Observed: T_0 = 288\,K \rightarrow f = 0.77$$

$$\rightarrow T_1 = 2^{-1/4}T_0 = 241\,K\ \ corresponds\ to\ z = 7\,km$$

Improve model by accounting for altitude dependent, continuous absorption *f*(z).

Radiative Forcing Produces Linear Correlation T_0-$\rho(CO_2)$

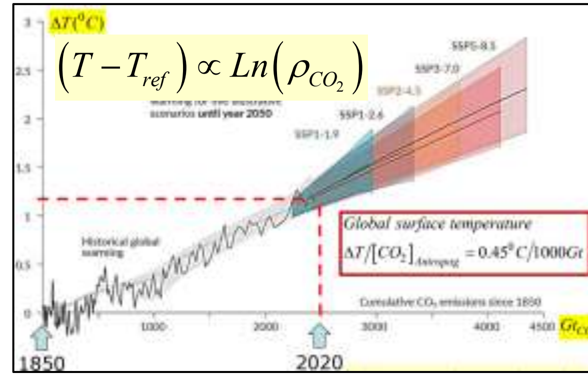
Atmospheric Perturbation (adding GHG) produces change in heat absorption →

Model $f \rightarrow f+\Delta f$ *with* $\Delta f/f \ll 1$

$$\Delta f \Leftrightarrow \Delta \rho_{CO_2}$$

→ *"Forcing"* $= \Delta F$ = *hypoth.* change in *power* flux *onto surface to explain* ΔT_0 (*reflects surface* T_0).

Check with simple GH model **if**: $\Delta T_0 \approx \lambda \cdot \Delta f\left(\Delta\rho_{CO_2}\right)$



Given T_0, *perturbation* Δf *changes the emitted power flux by*

$$\Delta F := \Delta F_{out} = \left[1-\left(f+\Delta f\right)/2\right]\cdot\sigma\cdot T_0^4 - \left[1-f/2\right]\cdot\sigma\cdot T_0^4 = \frac{\Delta f}{2}\cdot\sigma\cdot T_0^4 \quad \rightarrow \underline{\Delta F \propto \Delta f}$$

$$\textit{Equilibration of the same absorbed solar flux with GH}: T_0 \rightarrow T_0' = T_0 + \Delta T_0$$

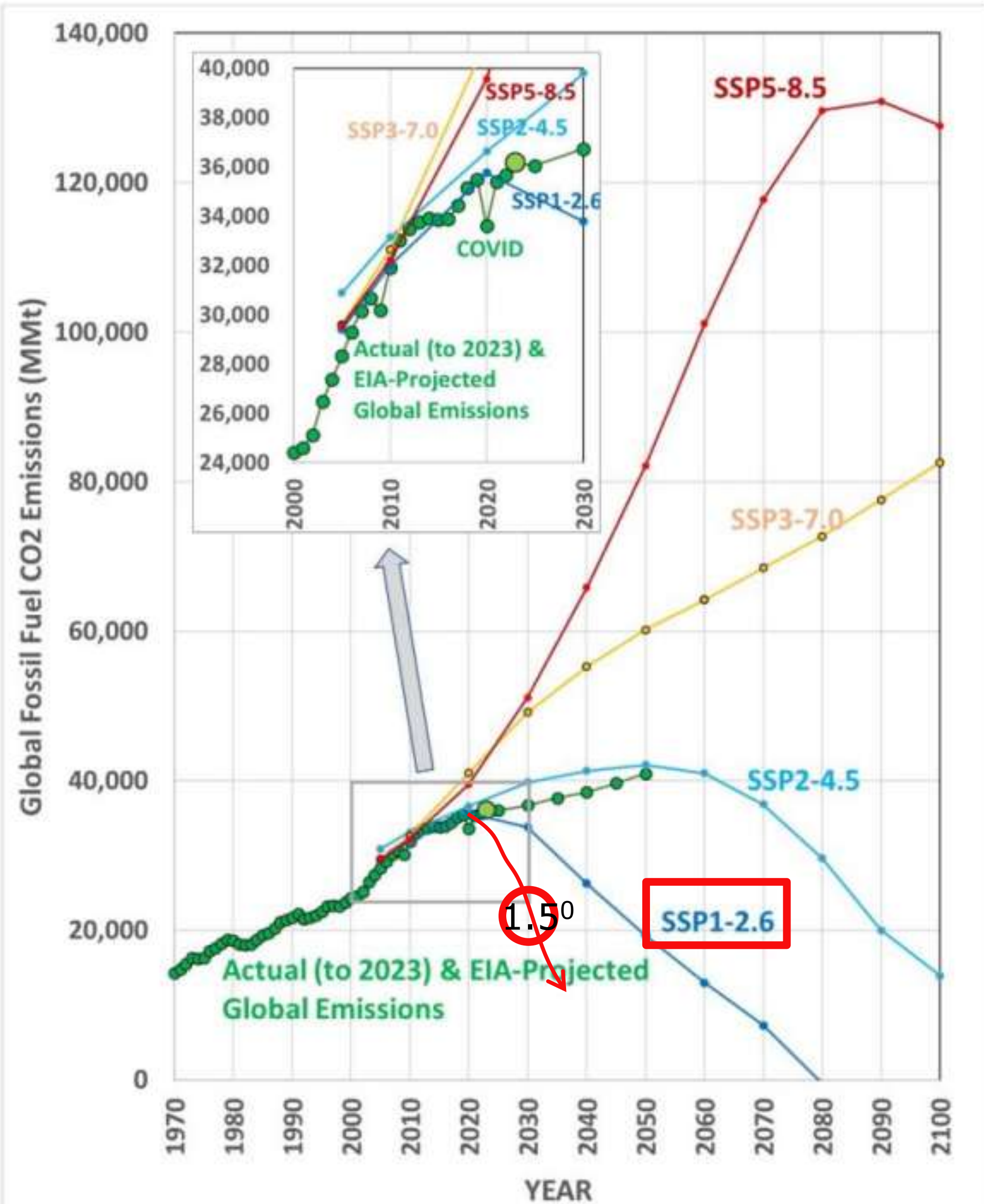
$$F = (S/4)(1-\alpha) \stackrel{!}{=} (1-f/2)\cdot\sigma\cdot T_0^4 = \left[1-\left(f+\Delta f\right)/2\right]\cdot\sigma\cdot\left[T_0+\Delta T_0\right]^4$$

$$\left[T_0+\Delta T_0\right]^4 \approx T_0^4\cdot\left[1+\Delta T_0/T_0\right]^4 \approx T_0^4 + 4T_0^4\left(\Delta T_0/T_0\right) \qquad \textit{for } \Delta T_0/T_0 \ll 1$$

$$\rightarrow \Delta T_0 \approx \frac{T_0}{8\left(1-f/2\right)}\cdot\Delta f = \frac{1}{4\left(1-f/2\right)\sigma T_0^3}\cdot\Delta F =: \lambda\cdot\Delta F \qquad \Rightarrow \Delta T_0 \propto \Delta f \propto Ln\left(\frac{\rho_{CO_2}}{\rho_{ref}}\right)$$

Increasing GHG concentration → increases absorption of surface radiation → increases surface temperature T_0 → *Beer-Lambert Absorption Law*

Global GHG (CO_2-equ.) Emissions: Outlook



IPCC CO_2 Radiative Forcing

$$\Delta F_{CO_2} \approx 5.35 \cdot Ln\left(\frac{[CO_2]_{atm}}{278ppm}\right)\frac{W}{m^2}$$ IPCC fit

Different scenarios SSPn-x simulated by IPCC collaboration.

Current annual emissions

$39Gt_{CO2}/a \triangleq 2.7W/m^2$

2015 Paris Agreement:

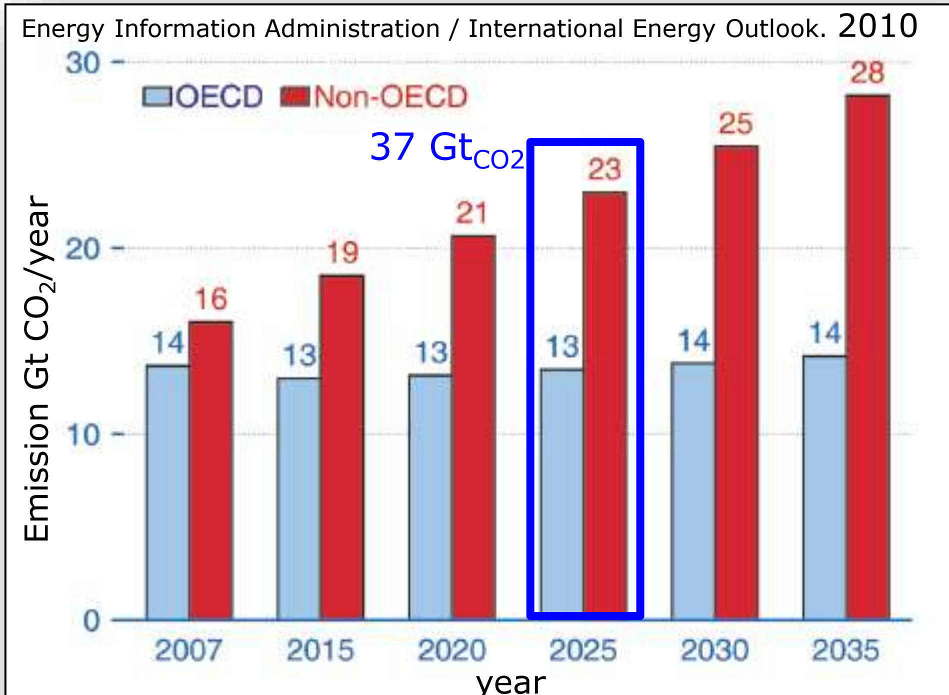
Reduce GHG emission to for $\Delta T < 2^0C$, report efforts, provide funding.

2018 IPCC-Special Report

1.5^0C : For $\Delta T < 1.5^0C$ reduce GHG down to 45% of 2010 by 2030 and achieve net-zero by 2050.

Figure adapted from DOE-CRCC 2025

Projections for CO_2 Emissions

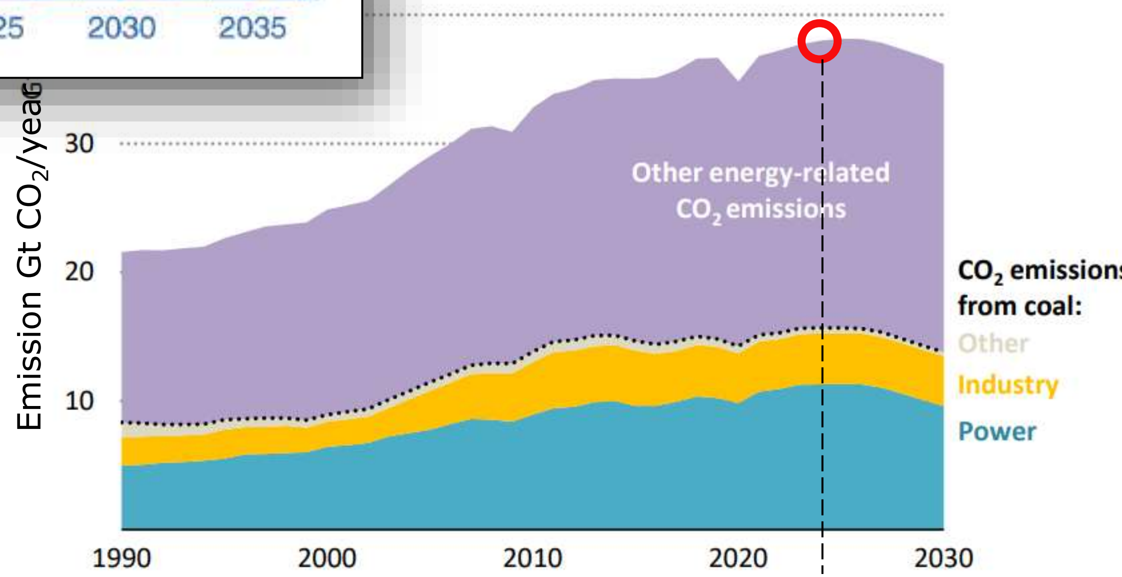


World energy-related CO_2 emission projections (in $GtCO_2$), by OECD (Organization for Economic Cooperation and Development) and non-OECD countries over the period 2007-2035.

Non-OECD countries include developing, newly industrialized, Eastern European plus former Soviet countries. http://www.oecd.org/countrieslist/.

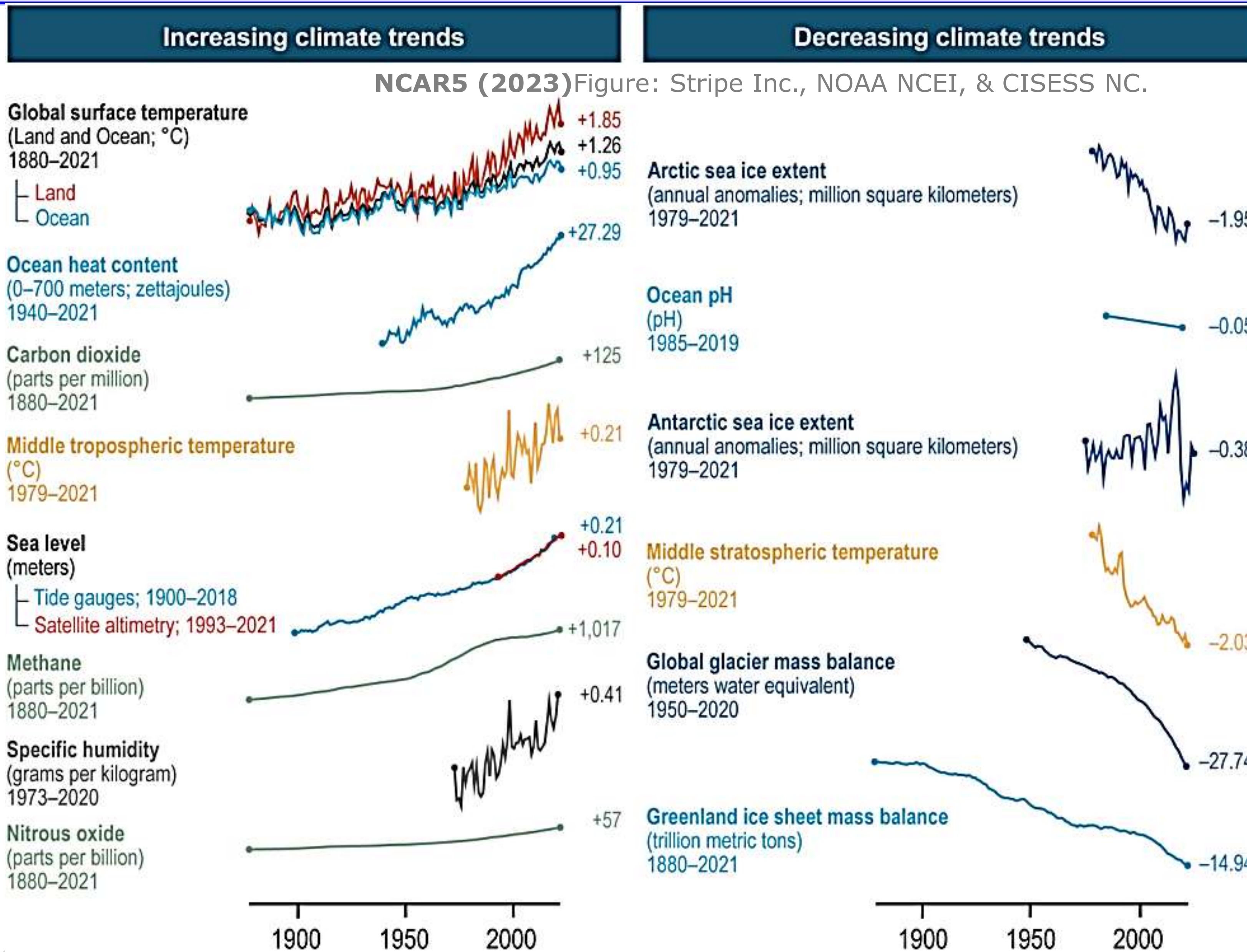
US (5% world population) produce 20% of global CO_2 emissions.

New data centers for AI are expected to add estimated 0.1Gt$_{CO2}$ by 2028



Climate Change Across Multiple Variables ()

NCAR5 (2023) Figure: Stripe Inc., NOAA NCEI, & CISESS NC.



National Climate Assessment and Development Advisory Committee

Summary Findings (2017/23, edited). **Projections → 2100**, Different polit. scenarios:

1) Global climate is changing, apparent in a wide range of observations. The climate change of the past 150 years is due largely to human activities (burning of fossil fuels).

2) Extreme weather and climate events have increased in recent decades; evidence is mounting for human activities as dominant cause (More recently "high confidence"_).

3) Human-induced part of climate change will accelerate significantly if emissions of heat-trapping gases continue to increase.

4) Impacts of climate change, evident in many sectors, become increasingly challenging.

5) Threats to human health and well-being from extreme weather events, wildfire, dangerous air quality, diseases transmitted by insects, food, and water, and threats to mental health.

6) Infrastructure is adversely affected by climate change: sea level rise, storm surge, heavy downpours, extreme heat.

7) Lower reliability of water supplies, affecting ecosystems and livelihoods in many regions: US Southwest, Great Plains, Southeast, Caribbean and Pacific islands, including the state of Hawaii.

8) Adverse impacts to crops and livestock over the next 100 years, increasing disruptions from extreme heat, drought, and heavy downpours.

9) Natural ecosystems directly affected, changes in biodiversity and location of species.

10) Life in the oceans is changing as ocean waters become warmer and less alkaline.

11) Necessary planning for adaptation (address and prepare for impacts) and mitigation (reduce emissions) is increasing, but progress with implementation is limited.

→12) Large-scale human migration will result, significant challenges to contain/dilemmas.

Literature

F.W. Taylor, *Elementary Climate Physics,* Oxford University Press, Oxford, New York, 2005.

K. McGuffie and A. Henderson-Sellers, *A Climate Modelling Primer*, Wiley, Hoboken, 2005

National Academy of Sciences Report on Climate Change (2010) http://nas-sites.org/americasclimatechoices/files/2012/06/19014_cvtx_R1.pdf

Reports of Working Groups of the Intergovernmental Panel on Climate Change

Climate Change 2007: The Physical Science Basis
http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm

Climate Change 2007: Mitigation of Climate Change and Synthesis Report
http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4_wg3_full_report.pdf
http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf

National Climate Assessment and Development Advisory Committee, Draft Report 2013, http://ncadac.globalchange.gov/download/NCAJan11-2013-publicreviewdraft-fulldraft.pdf