PLANETARY CLIMATE TRENDS AND CAUSATION

Agenda for Section (Sustainability @ “Anthropocene”)

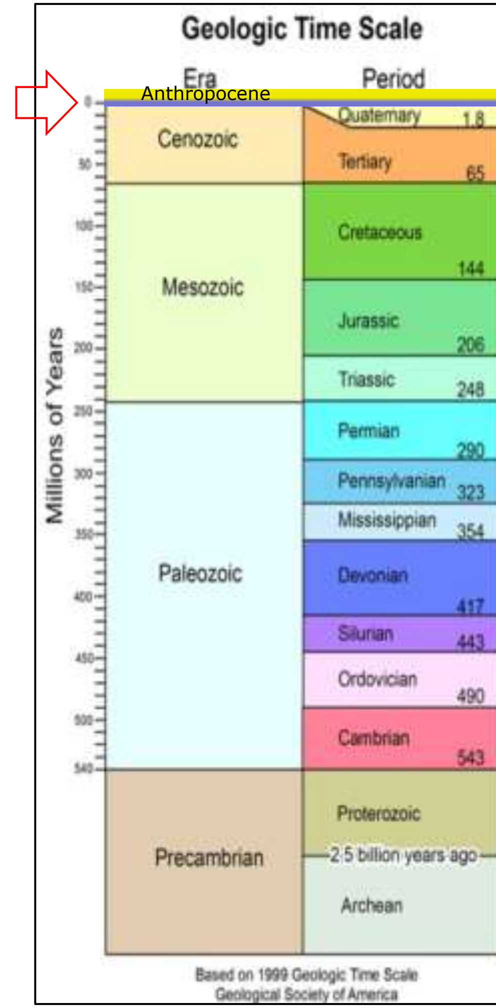
Grand picture Habitat and resource utilization

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

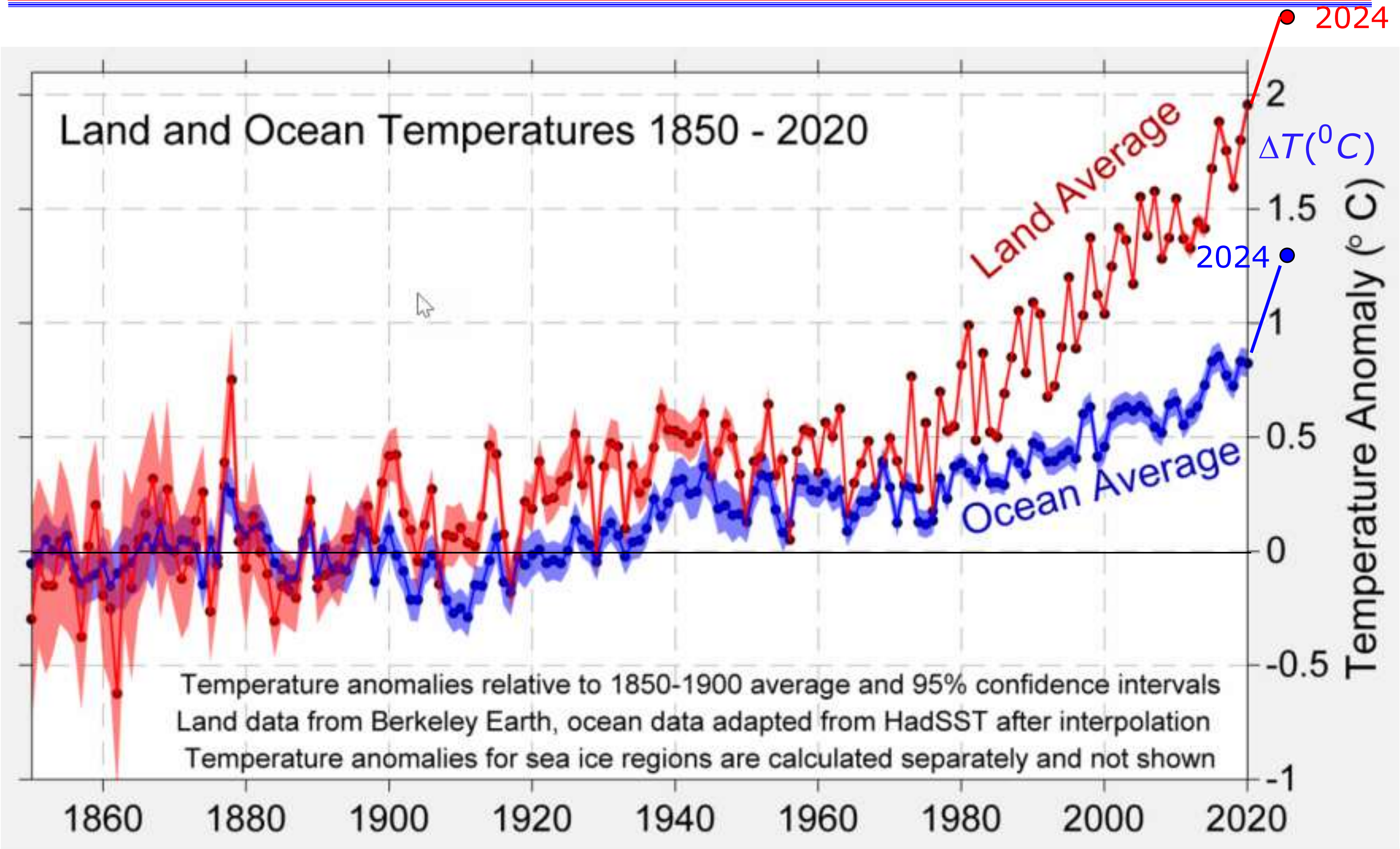
- Sustainability of Future Human Activity & Life on Earth
  Limit to growth, Club of Rome,
  Socio-economic/ecological network.

- 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.



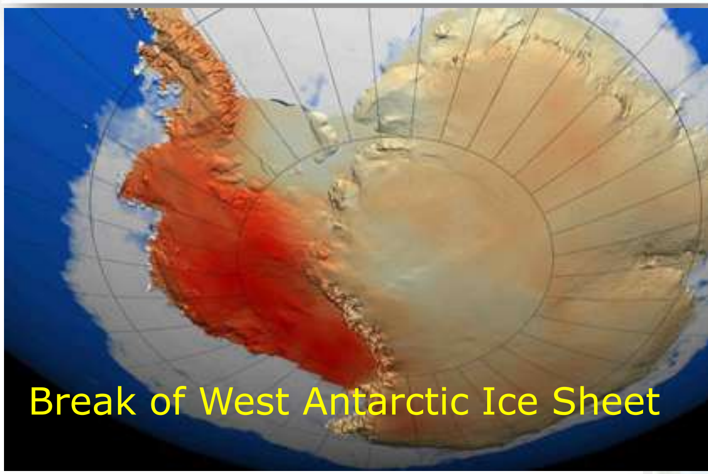
Mean Land and Ocean Temperature Trends



http://berkeleyearth.org/global-temperature-report-for-2020/

Evidence for Current Large-Scale Changes

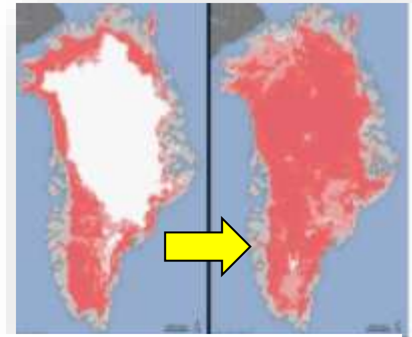
Melting Sea Ice in Arctic Ocean
(Economist)



Break of West Antarctic Ice Sheet

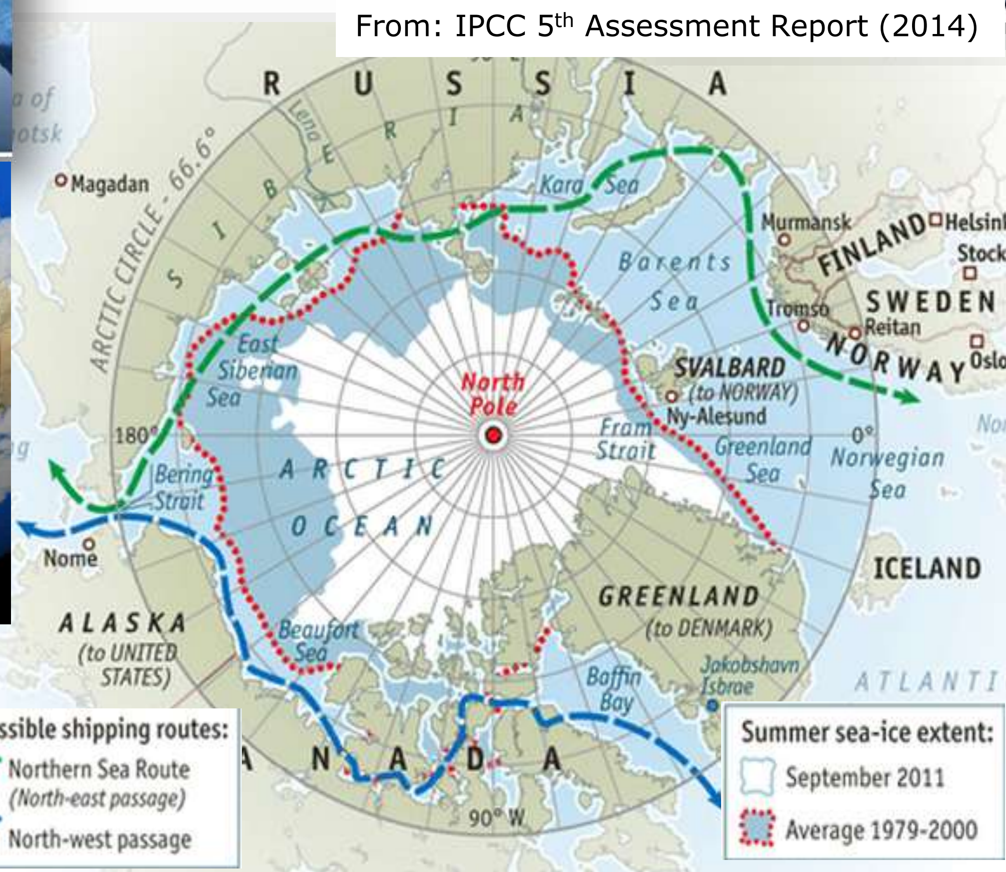
Q1: Anecdotal or systematic?
Q2: Natural or man-made?
→ Economic Implications
(negative and positive)

Greenland ice surface layer melts within 4 days:
July 8–July 12, 2011
NASA/NOAA satellite image.

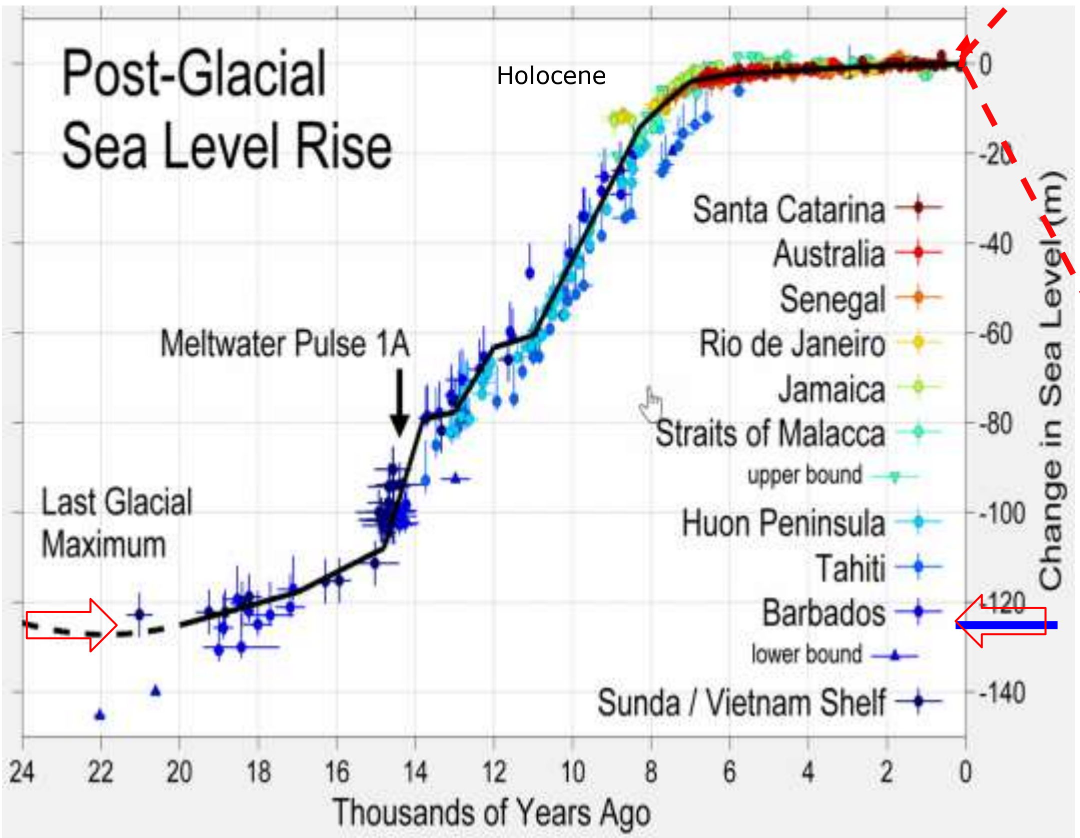


Positive (amplifying) Feedback Loops

From: IPCC 5th Assessment Report (2014)

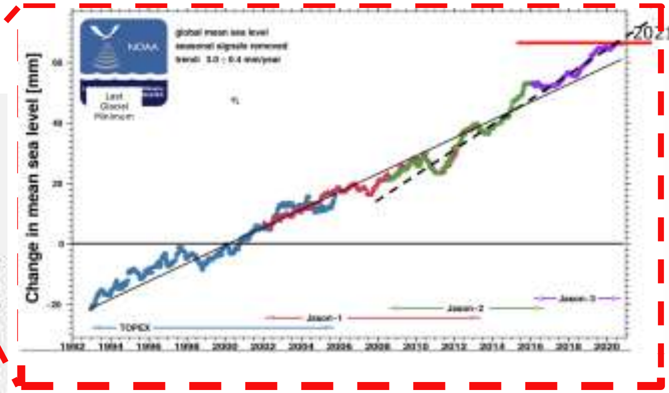


Ancient and Modern Sea Level Trends



Adapted: https://commons.wikimedia.org/wiki/File:Post-Glacial_Sea_Level.png

Sea levels since last glacial minimum. Rise $\Delta H=+125$ m until 6,000 BCE, then constant. (uncertainty $\Delta H=\pm 10$m)



1850→2021: $\Delta H=+67$ mm

Mean rate:

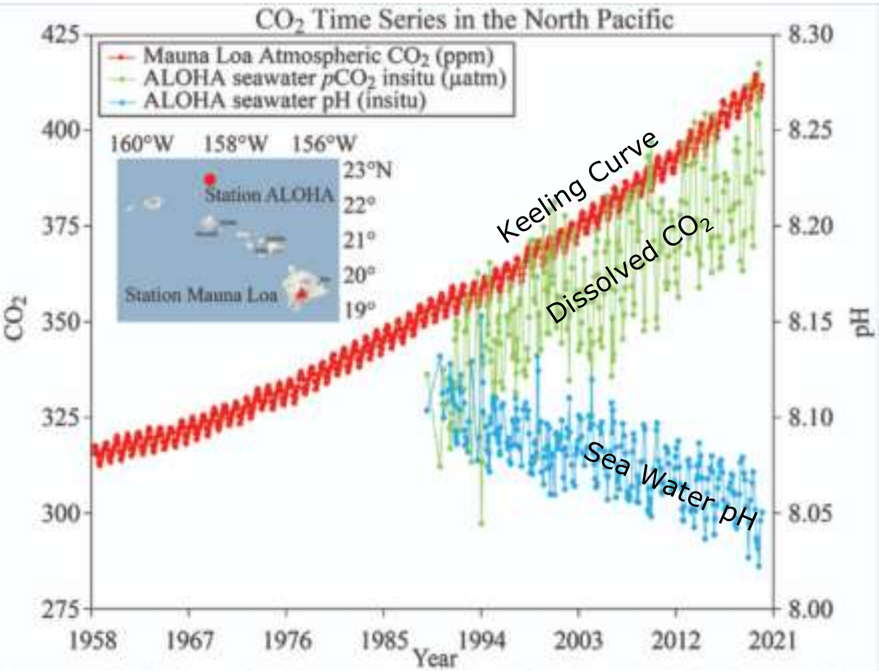
$\Delta H/\Delta\tau$ = (3.0± 0.4)mm/a, Does slightly increase.

Seasonal cycle ($\Delta H=\pm 7$mm) superimposed on general trend.

https://www.climate.gov/maps-data/dataset/global-mean-sea-level-graph

Atmospheric-Aqueous CO_2 Equilibrium and Consequences

$$CO_2(g) + 2H_2O(\ell) \underset{}{\overset{k_1}{\rightleftarrows}} H_2CO_3(aq) + H_2O \overset{k_2}{\rightleftarrows} H_3O^+(aq) + HCO_3^-$$



https://www.pmel.noaa.gov/co2/file/Hawaii+Carbon+Dioxide+Time-Series

Shells Dissolve in Acidified Ocean Water

Henry's Law $p_{CO_2} = k_H(T) \cdot [CO_2]$

Increasing atmospheric concentration of CO_2 → increasing CO_2 solvation in sea water → decreasing pH value (increasing $[H^+]=[H_3O^+]$, complex set of rxns)
NCADAC Report 2013

Consequences of ocean acidity

Bleaching of corals,

Dissolution of shells of marine animals

Example: Pteropod, "sea butterfly": Tiny sea creature (size of pea). Pteropods = food for marine species from krill to whales, major food for North Pacific salmon. Shell slowly dissolves after 45 days.

(Photo credit: National Geographic Images)

Ominous Correlation: Temperature vs. Atmospheric CO_2

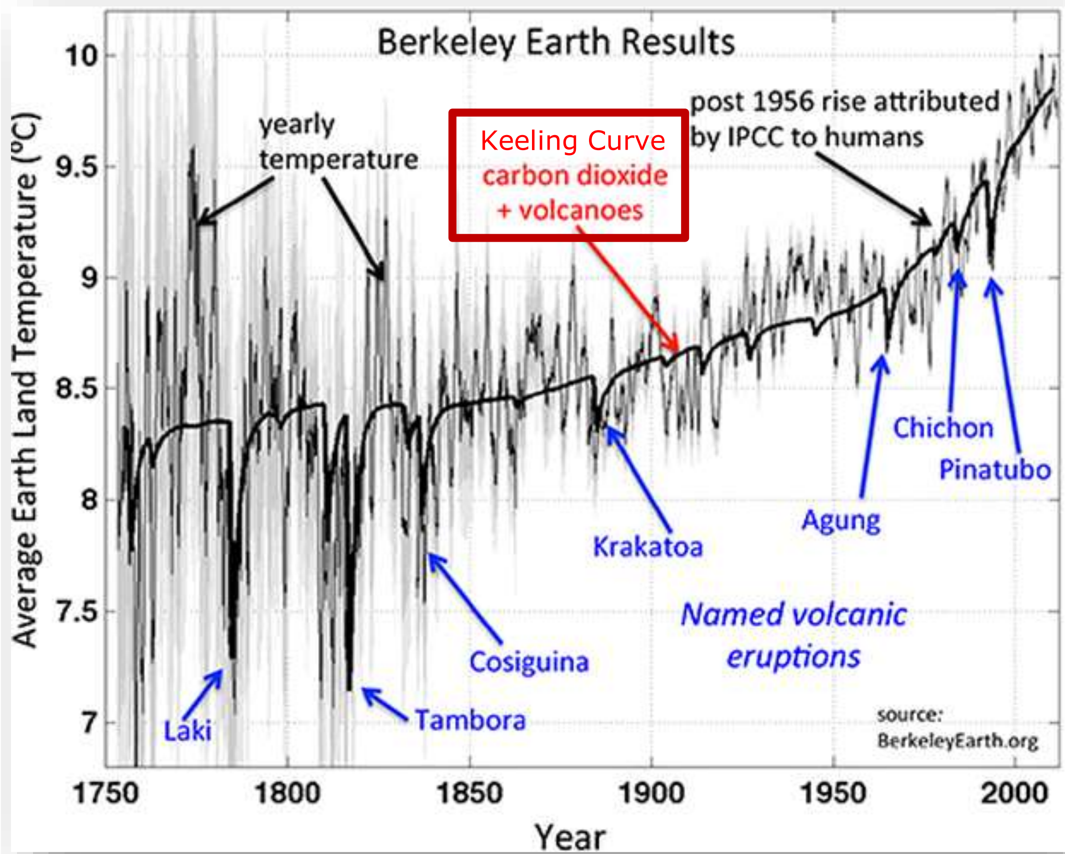
Systematic gradual rise of *T* ($\Delta T \approx 1.6^0$C) correlates with experimental record of atmospheric CO_2, as measured from atmospheric samples and air trapped in polar ice.
Solar variation does not seem to impact the *mean* temperature trend. (Berkeley Earth Surface Temperature study, 2012). Contested by 2025 DOE-Critical Report

Dips in the observed historic temperature pattern match in time of occurrence and amplitude the emissions of known explosive volcanic eruptions.

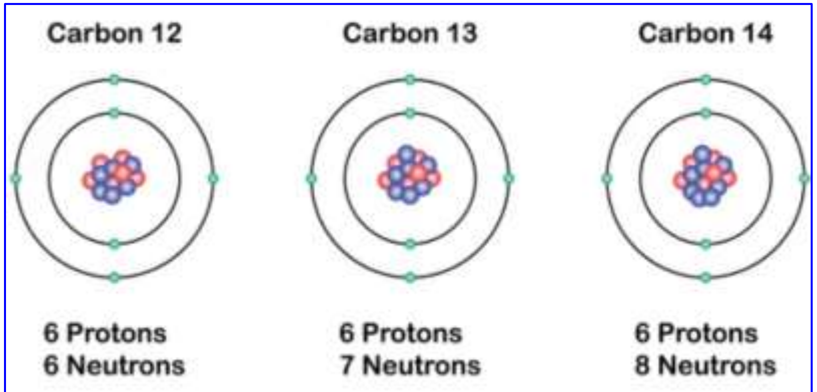
Particulate (aerosol) clouds from volcanic events reflect sunlight and cool the Earth's surface for a few years. Pinatubo 1991: 15-20 Mt SO_2 remained 2 years, - 0.5^0C.

Small rapid variations are attributable to El Nino and other ocean currents such as the Gulf Stream.

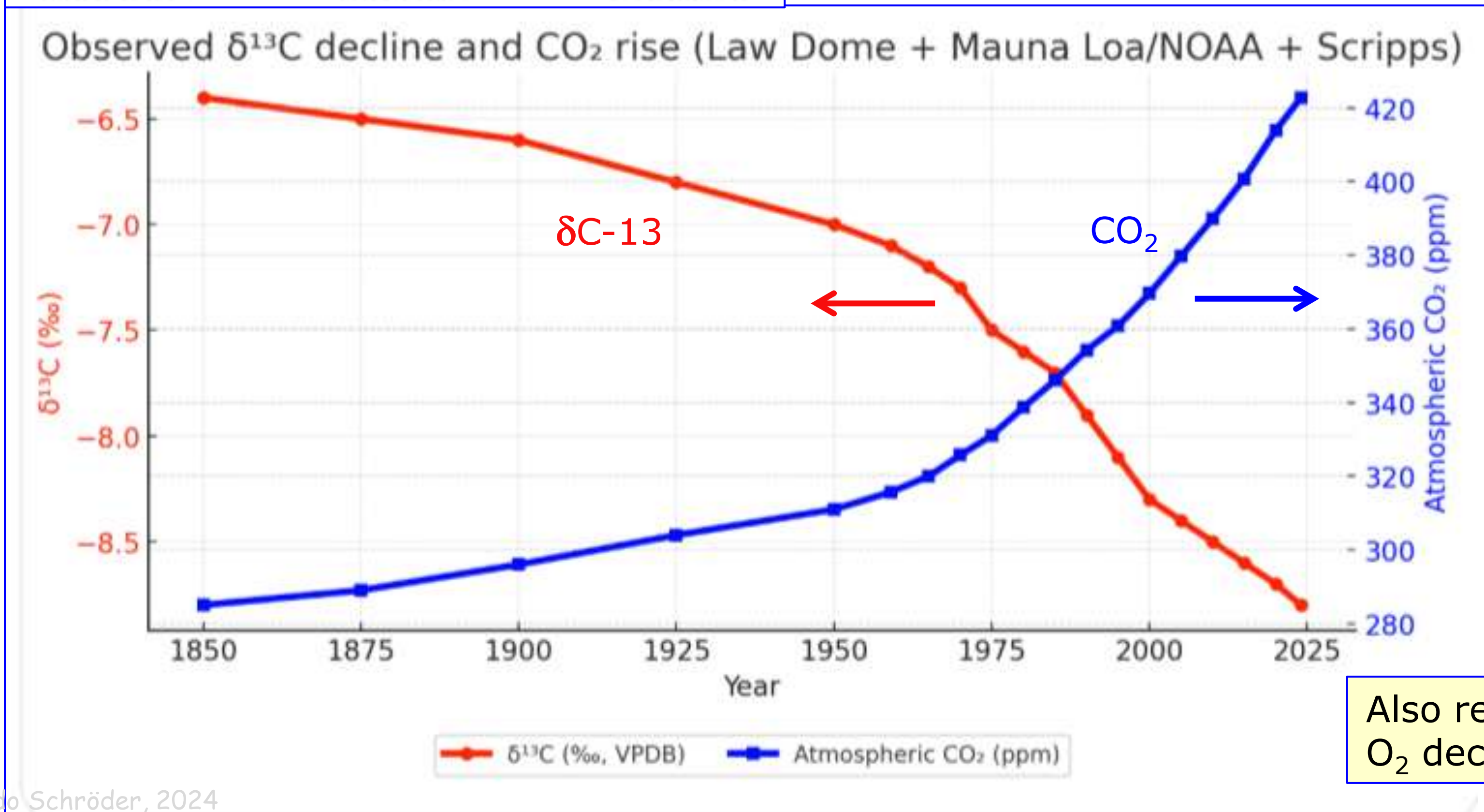
(From BerkelyEarth Project)



$^{13}C/^{12}C$ Isotopic Trend in Atmospheric CO_2



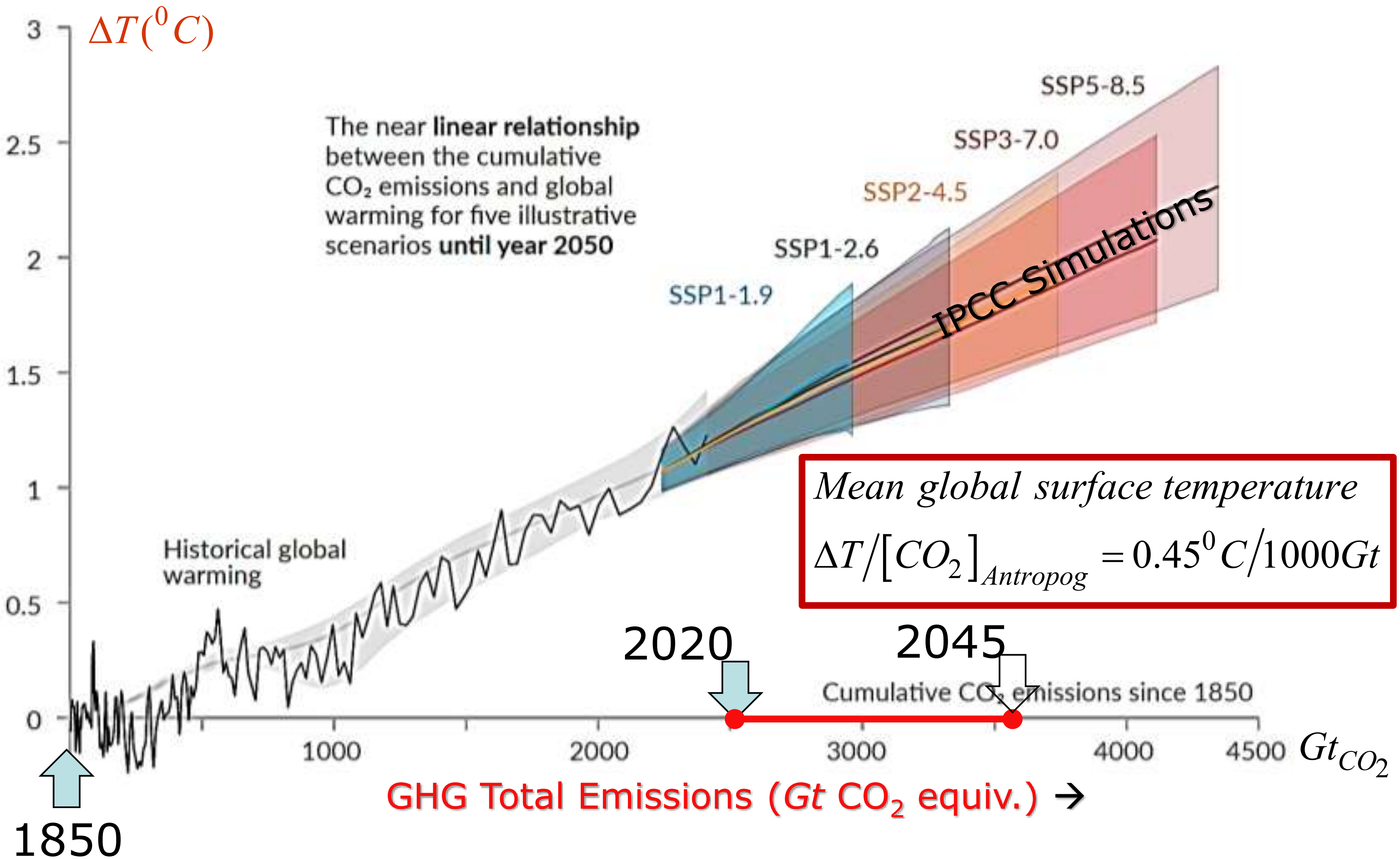
Plant photosynthesis discriminates against C-13, favors C-12 → Plant matter and fossil fuels contain low C-13 levels. → burning fossil fuels emits C-13 poor CO_2.



Also remember O_2 decline

Global Mean Temperature - GHG Inventory Correlation

SSPn-x: **S**hared **S**ocioeconomic **P**athway IPCC Scenario #n with forcing **x**(W/m²)



Mean global surface temperature

$$\Delta T / [CO_2]_{Antropog} = 0.45^0 C / 1000 Gt$$

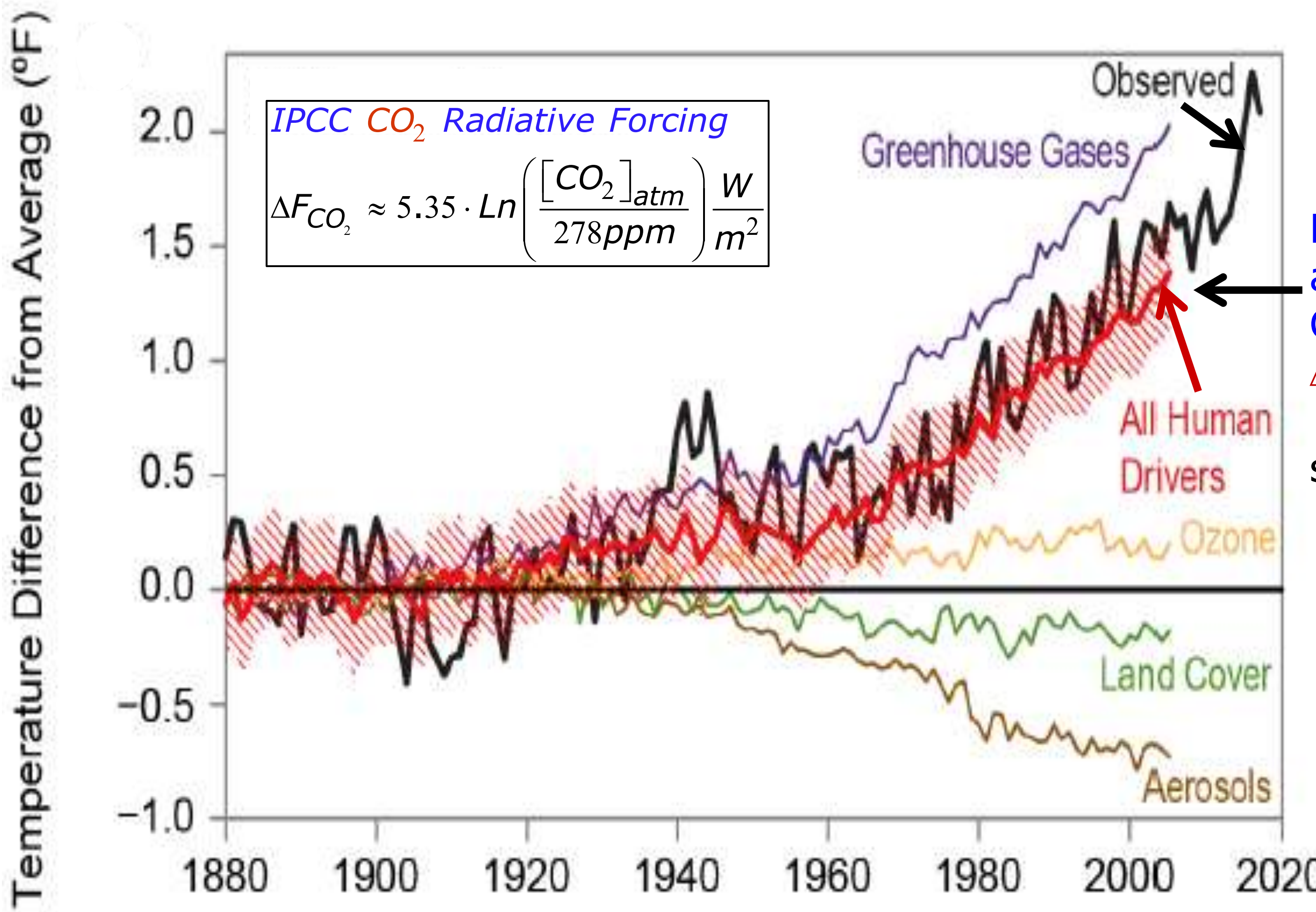
GHG Total Emissions (*Gt* CO_2 equiv.) →

"Budget" Another 10^3 Gt_{CO2} to reach +2°C rel 2000 → +3.1°C rel. 1850,
Now 40Gt_{CO2} per year ≙ 25 years

Anthropogenic Influences on Global Climate (Simulations)

Causal relationships between human caused pollutions and climate parameters
Quantitative relations between [CO2], [CH4],…,[aerosols] and effective W/m².

Need: Quantitative agreement between observation and robust physical model, **plus** absence of plausible competing model explanations.

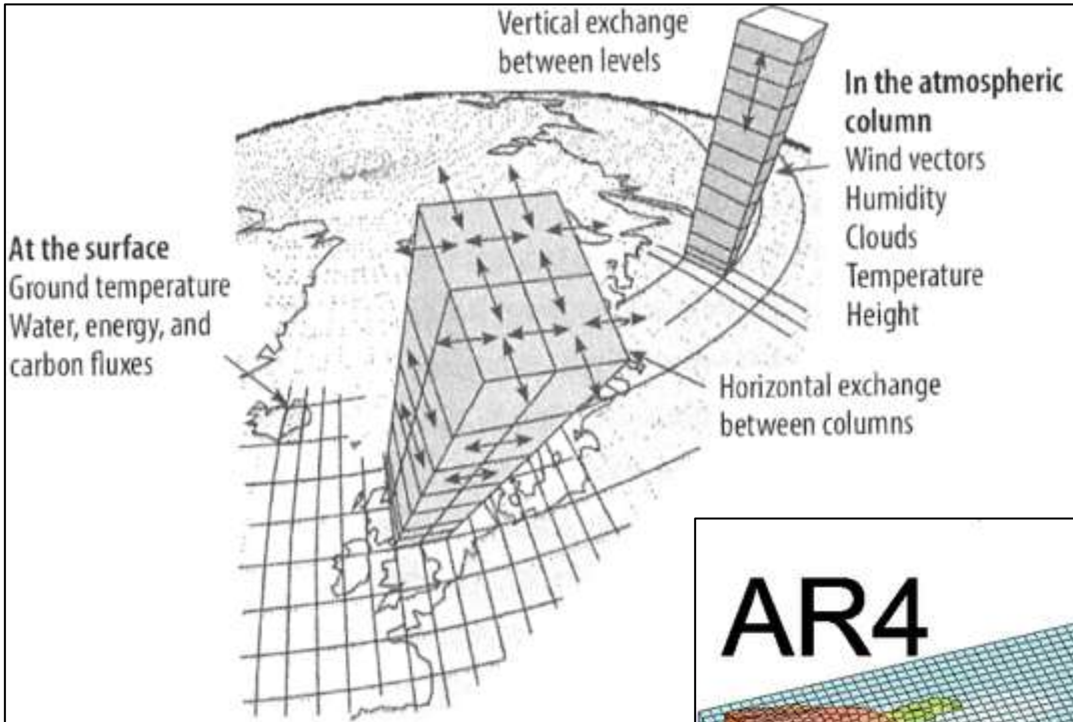


IPCC CO_2 Radiative Forcing

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

Present anthropogenic CO_2 forcing
$\Delta F_{ant} \approx 2.7 W/m^2$
∽ 1% of solar insolation

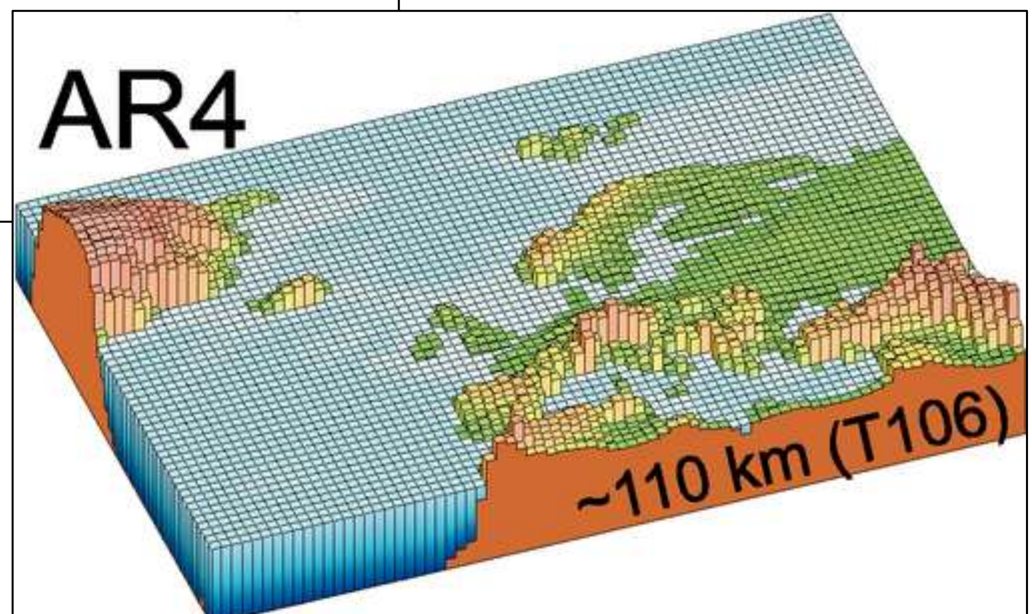
Climate Models: Geographic Resolution



S.E. Koonin, *Unsettled ?*(2021)

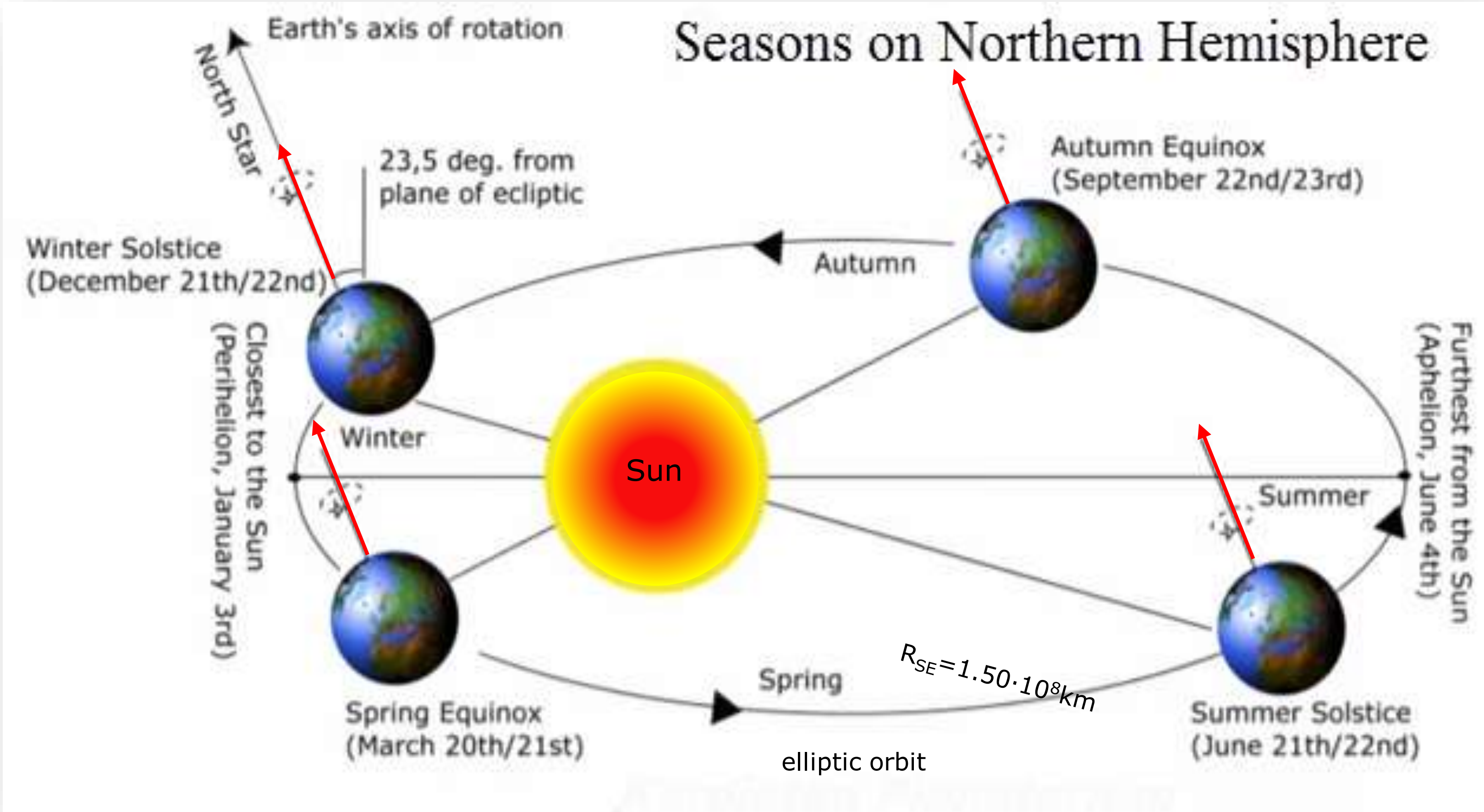
Improved spatial resolution of hydrodynamic simulation codes used for extensive IPCC climate models. Require days of Supercomputer power.

AR6 (2022):
lateral resolution 25 km,
vertical resolution
many oceanic and atmospheric layers. Challenge: clouds.



Earth In Solar System

Energy transfer Sun → Planets via emission and absorption of **electromagnetic radiation**

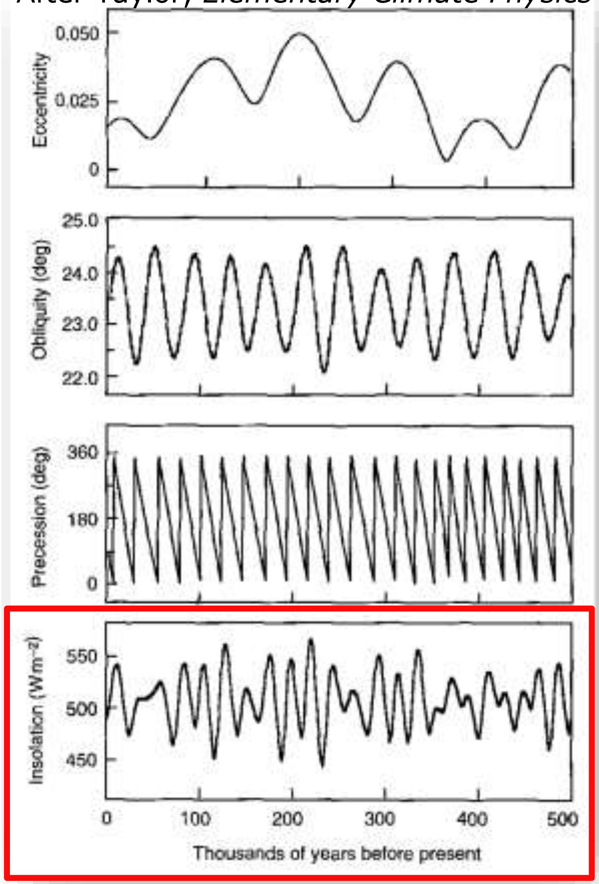


Earth is a spinning gyro with an (approximately) space-fixed orientation now towards North Star. Axis precesses and wobbles with 10ka-100ka periods.

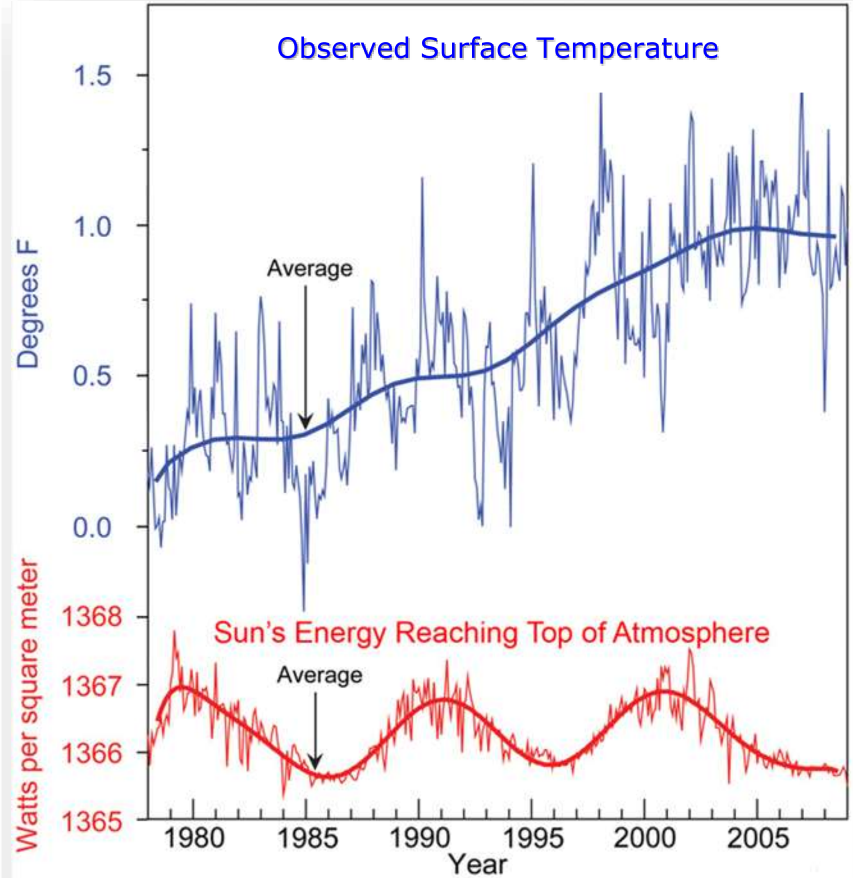
Now: Axis misalignment with normal to plane of orbit (ecliptic) about Sun (23.5^0).

Elimination of Extra-Terrestrial Effects

After Taylor, *Elementary Climate Physics*



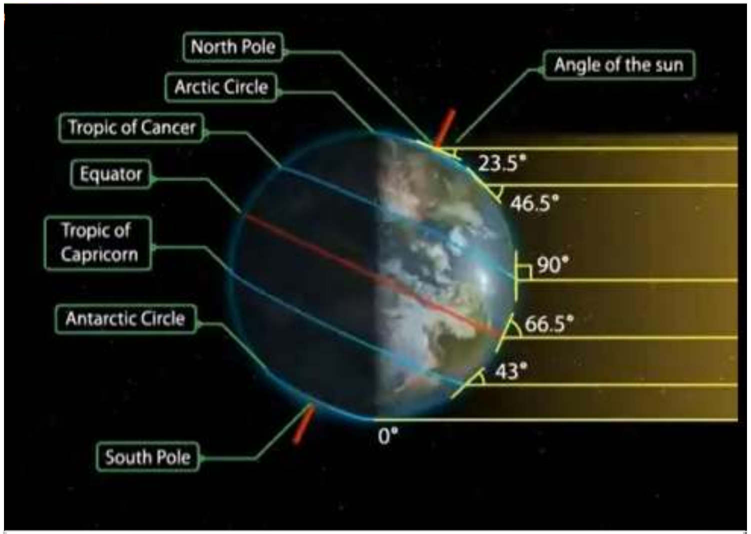
Modeling of influences of peculiarities of Earth planetary orbit and orientation (Milankovich cycles) on solar insolation gives somewhat irregular long-time pattern, approximately accurate (Ice Ages). Predicts no 11-year cycle.



The sun's energy received at the top of Earth's atmosphere has been measured by satellites since 1978. It has followed its natural 11-year cycle of small ups and downs, but with no net increase (bottom). Over the same period, global temperature has risen markedly (top).

Average temperature trend = superposition of sunspot insolation variation (11-year cycle) on steadily increasing temperature function $T(t)$ not seen in upper atmosphere.

"Black Body" Radiations: Sun and Earth



Solar radiation incidence during summer on northern hemisphere

Except for occasional flares (outbursts/mass ejections), the Sun emits thermal radiation like any "black body" at the same temperature *T*.

Planck's Radiation Law

"Radiance" for light of wave length λ emitted in random directions:

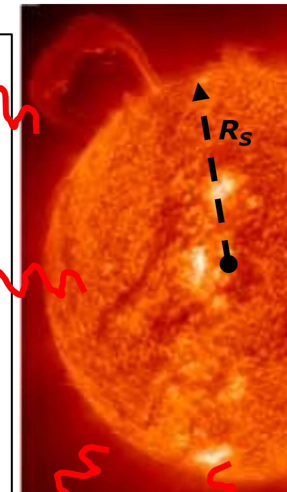
$$R(\lambda,T)=\frac{2hc^2}{\lambda^5}\left[\frac{1}{e^{hc/\lambda kT}-1}\right]\left(\frac{W}{m^3\cdot sr}\right)$$

Total power density emitted

Stefan – Boltzmann Radiation Law

$$F=\int R(\lambda,T)\cdot d\lambda=\sigma\cdot T^4\ \left(W/m^2\right)$$

$$SB-constant:\sigma=5.670\cdot10^{-8}\left(W/K^4m^2\right)$$



$R_S=6.96\cdot10^5 km$

$\pi R_S=6.09\cdot10^{12}\,km^2$

Earth is also an approximately a "black body," but (without atmosphere) @ a low temperature *T=255 K (-18^{0}C).*

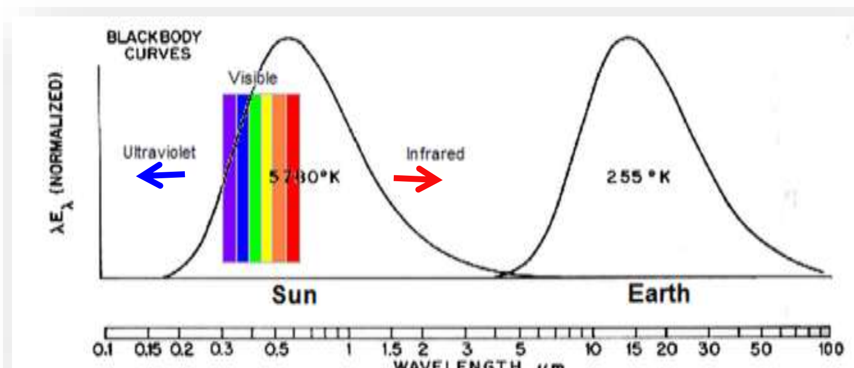
Role of atmosphere → raises ambient temperature ("good" greenhouse effect).

$h=6.625\cdot10^{-34}J\cdot s$ *Planck's constant*

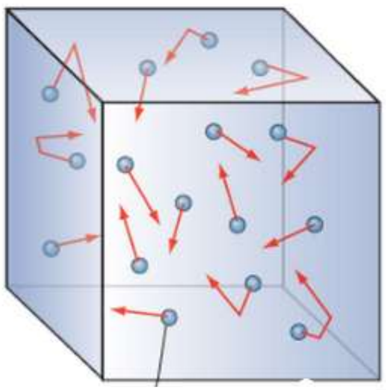
$k=1.3\cdot10^{-34}J\cdot s$ *Boltzmann's constant*

$c=2.998\cdot10^{8}\,m/s$ *speed of light*

sr = *steradians = unit of angular acceptance* $\Delta\Omega=Area/4\pi\cdot distance^2$



Thermal “Black Body” Radiation: Random Particle Motion

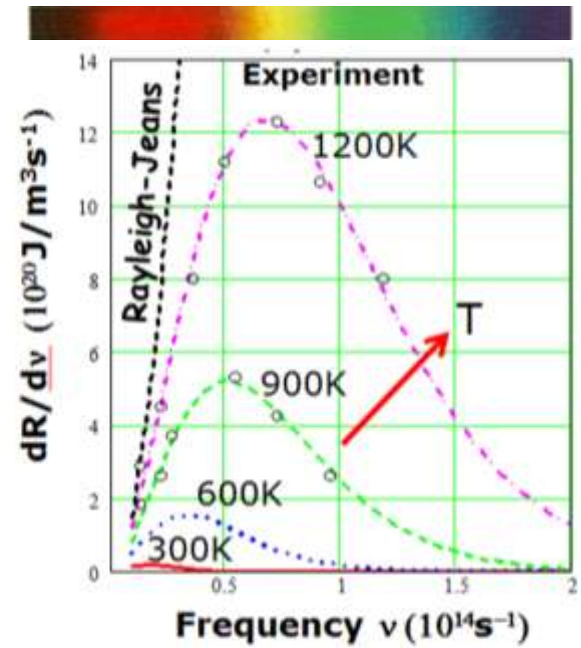


Charged Particles

Charged particles in random motion → continuous “thermal” kinetic energy spectrum.
→ Emit photons with continuous energy E or (ν, λ) spectrum

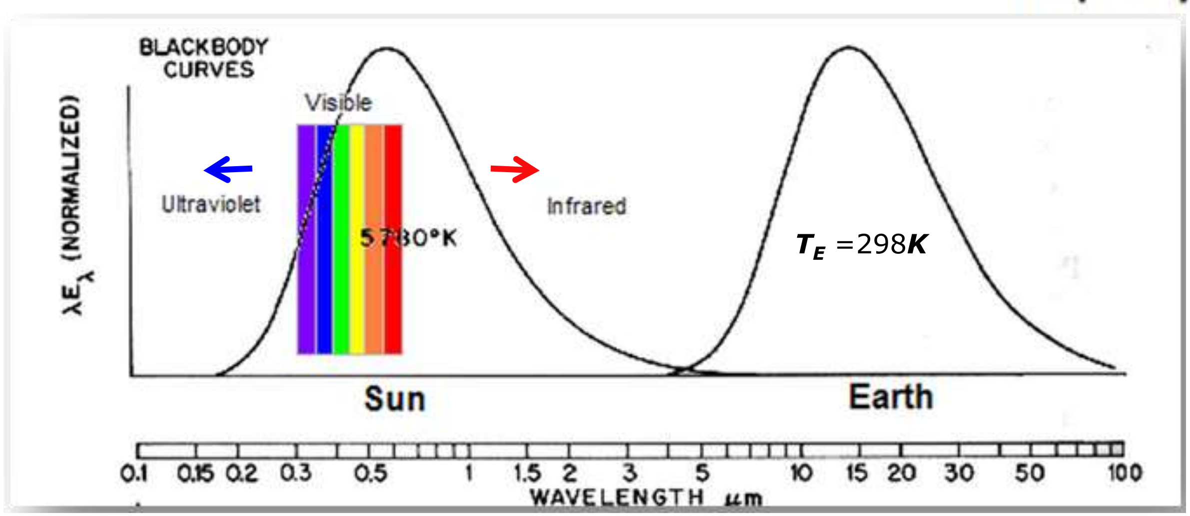
E ⟷ $T \approx \langle E \rangle / part$

Equilibration & Relaxation



Bare Earth is also approximately a “black body,” but with a low temperature, equilibrium (app.): T_E = 298 K (25^0C).

Atmosphere =blanket → raises ambient T (“good” GHE)



Solar Insolation on Earth

Solar Constant

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

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

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

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

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

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

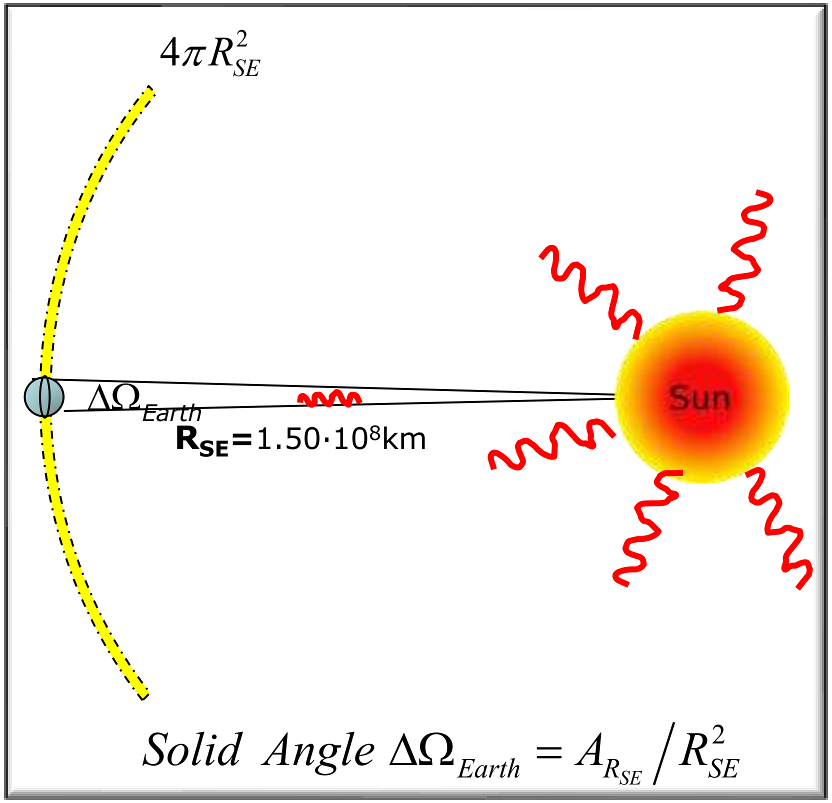
$$Albedo\ \alpha = reflectivity,\ \alpha_E \approx 0.3\ (expt.)$$

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

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

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

(More sophisticated models for Earth energy balance are available)

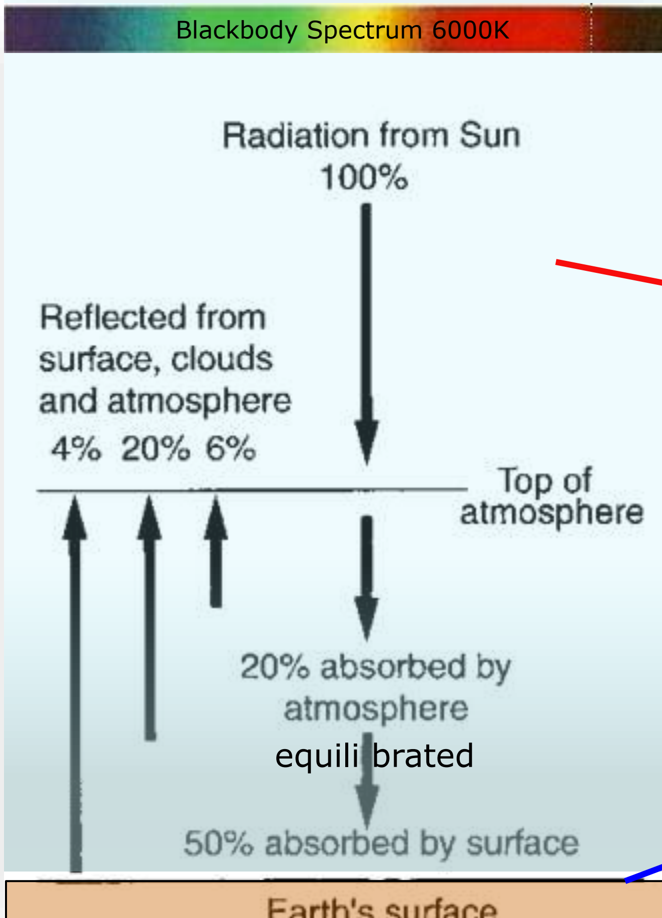


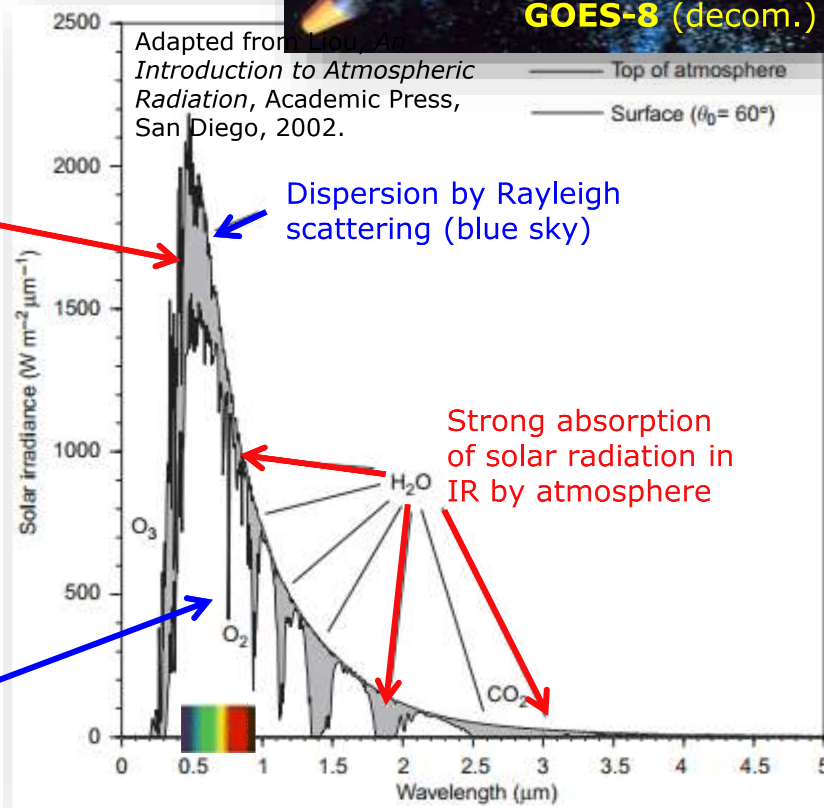
Effect of solar irradiation on Earth surface is non-cumulative, non-linear, possibly unstable.
System of several negative and positive feed-back effects.
Possible: Thermal equilibrium ?

Selective Filter Effect of Atmosphere

Absorption of solar radiation by the atmosphere is determined using spectroscopic satellite, aircraft, and surface data. See recent Atmospheric Radiation Measurement Enhanced Shortwave Experiment (ARESE)

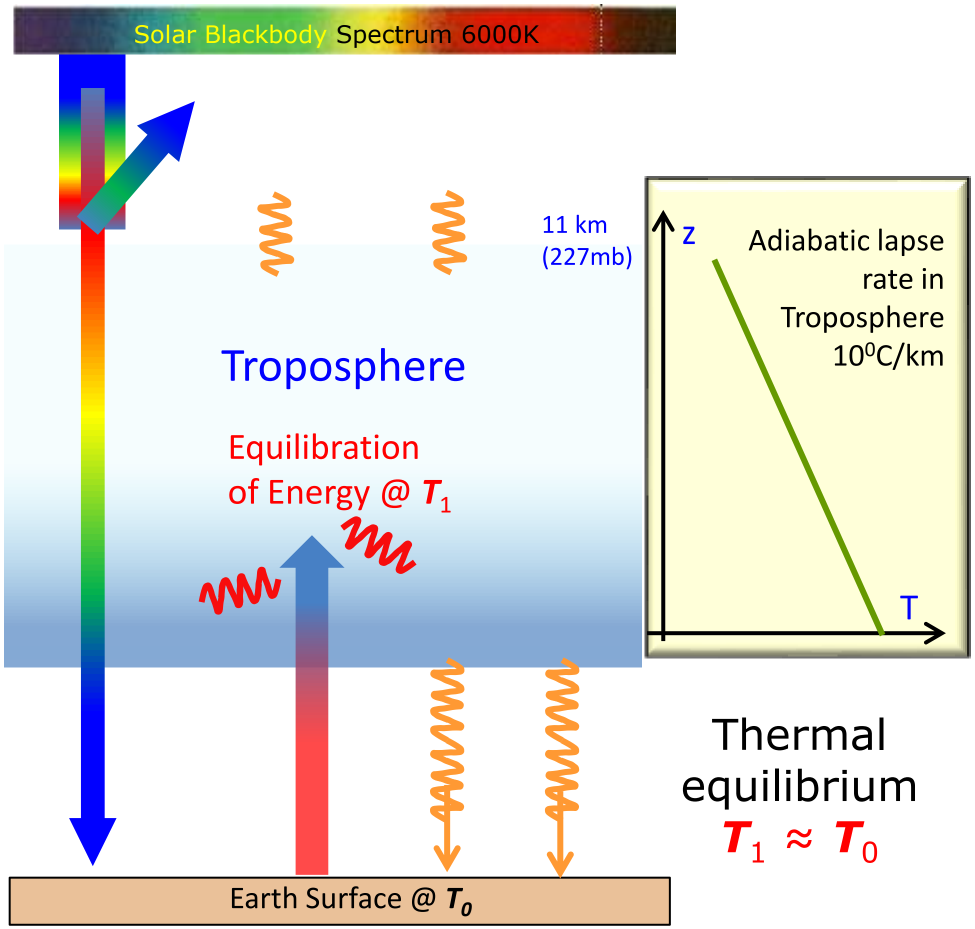
See, e.g., F. P. J. Valero et al., J. GEOPHYS. RES., 105, 4743 (2000)





Scattered or absorbed radiation not available for warming Earth surface. → T_E < 255K !!???

Near-Surface Energy Equilibration



Thermal equilibrium
$T_1 \approx T_0$

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.

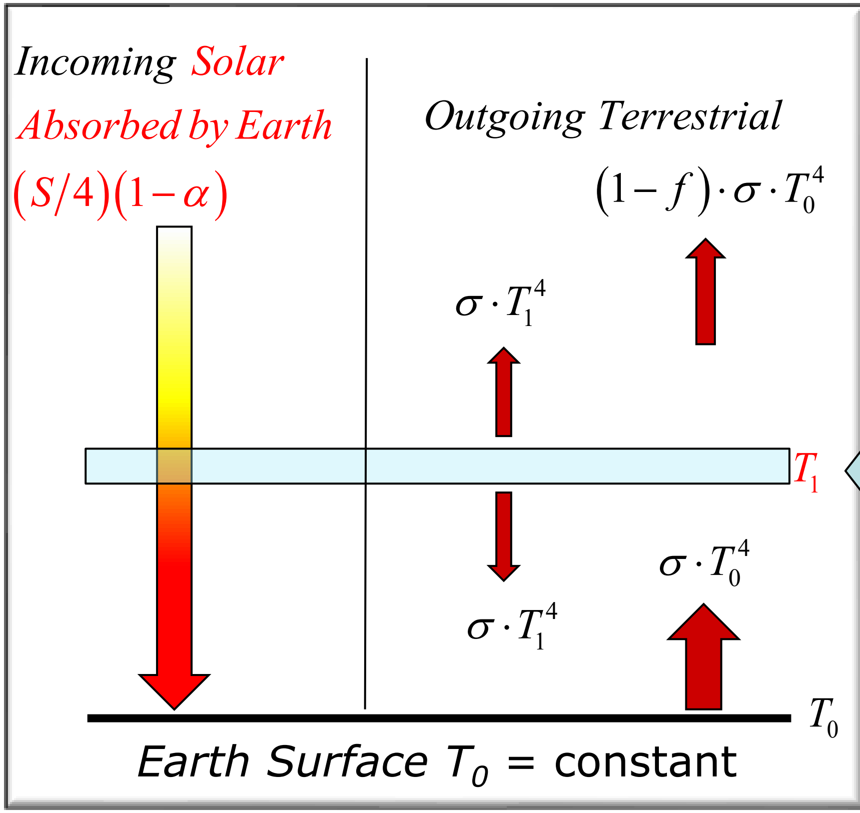
IR radiation from surface is absorbed by atmosphere, heating it up.

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

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

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

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

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

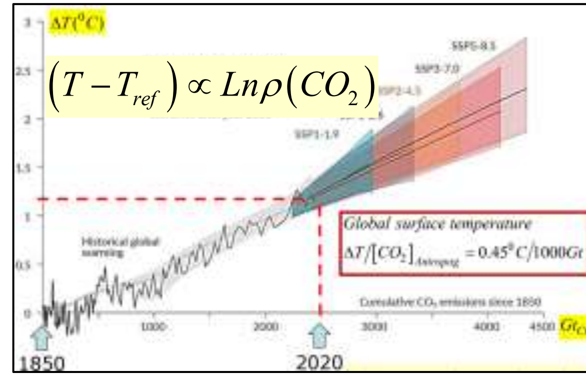
$$Observed: T_0 = 288\,K \rightarrow f = 0.77$$

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

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

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

Atmospheric Perturbations (adding GHG) produce changes in heat absorption $f \rightarrow f+\Delta f$ $\quad \Delta f \propto \Delta\rho_{CO_2}$



→ ***Forcing = ΔF*** = *hypoth.* change in *power* flux *onto surface to explain* ΔT_0 *(reflects surface T_0)*.

Check with simple GH model **if**: $\quad \Delta T_0 = \lambda \cdot \Delta f$

disregard absorption by atmosphere

For a fixed T_0, perturbation Δf changes the emitted power flux by

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

Equilibration of the same absorbed solar flux : $T_0 \rightarrow T_0' = T_0 + \Delta T_0$

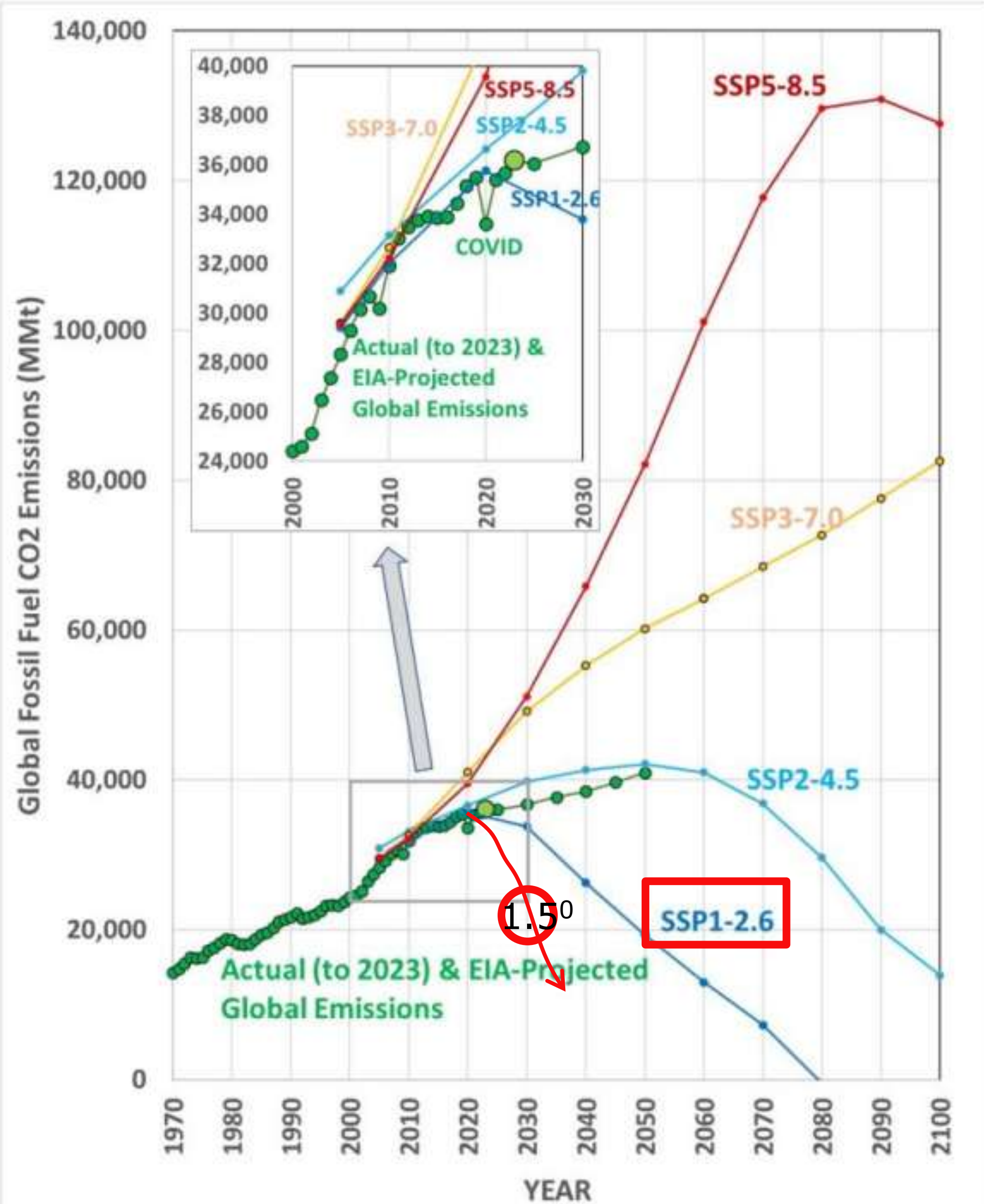
$$F = (S/4)(1-\alpha) \overset{!}{=} (1 - f/2)\cdot\sigma\cdot T_0^4 = \left[1 - \left(f + \Delta f\right)/2\right]\cdot\sigma\cdot\left[T_0 + \Delta T_0\right]^4$$

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

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

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

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

Different scenarios SSPn-x simulated by IPCC collaboration.

Current annual emissions

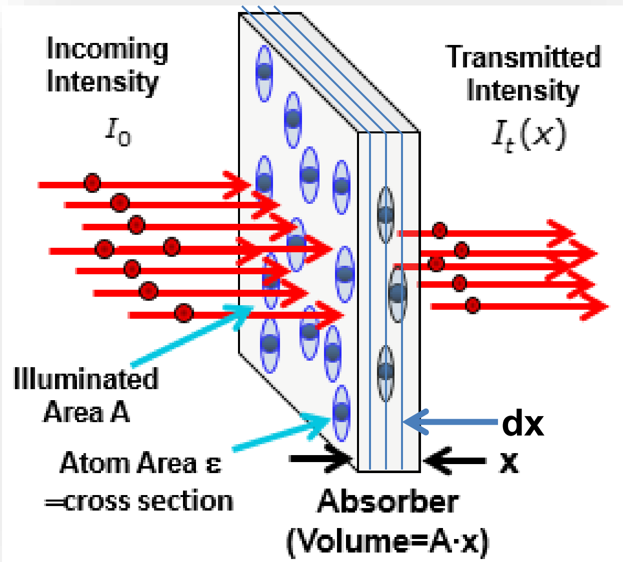
$39Gt_{CO2}/a \triangleq 2.7W/m^2$

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.

Absorption of *elm* Radiation: Beer-Lambert Law



Incoming intensity $I_0 = I(x=0)$ *blocked by* ε *per atom*

Intensity absorbed along path length Δx : $-\Delta I = f \cdot I \cdot \Delta x$

.........(→ calculus)

Probability (fraction) f for absorption of $-dI$

in the next slice of absorber dx : $\underline{dP_{abs}(x) \propto dx}$

$$f = dP_{abs}(x) = \frac{-dI}{I(x)} = \mu \cdot dx \quad \text{(fraction of } I \text{ abs.)}$$

$$\frac{dI}{dx} = -\mu \cdot I(x) \quad \rightarrow \text{DEq for power law}$$

Transmitted : $I_t = I(x) = I_0 \cdot e^{-\mu \cdot x}$ $\quad \mu := \rho_{particle} \cdot \varepsilon$

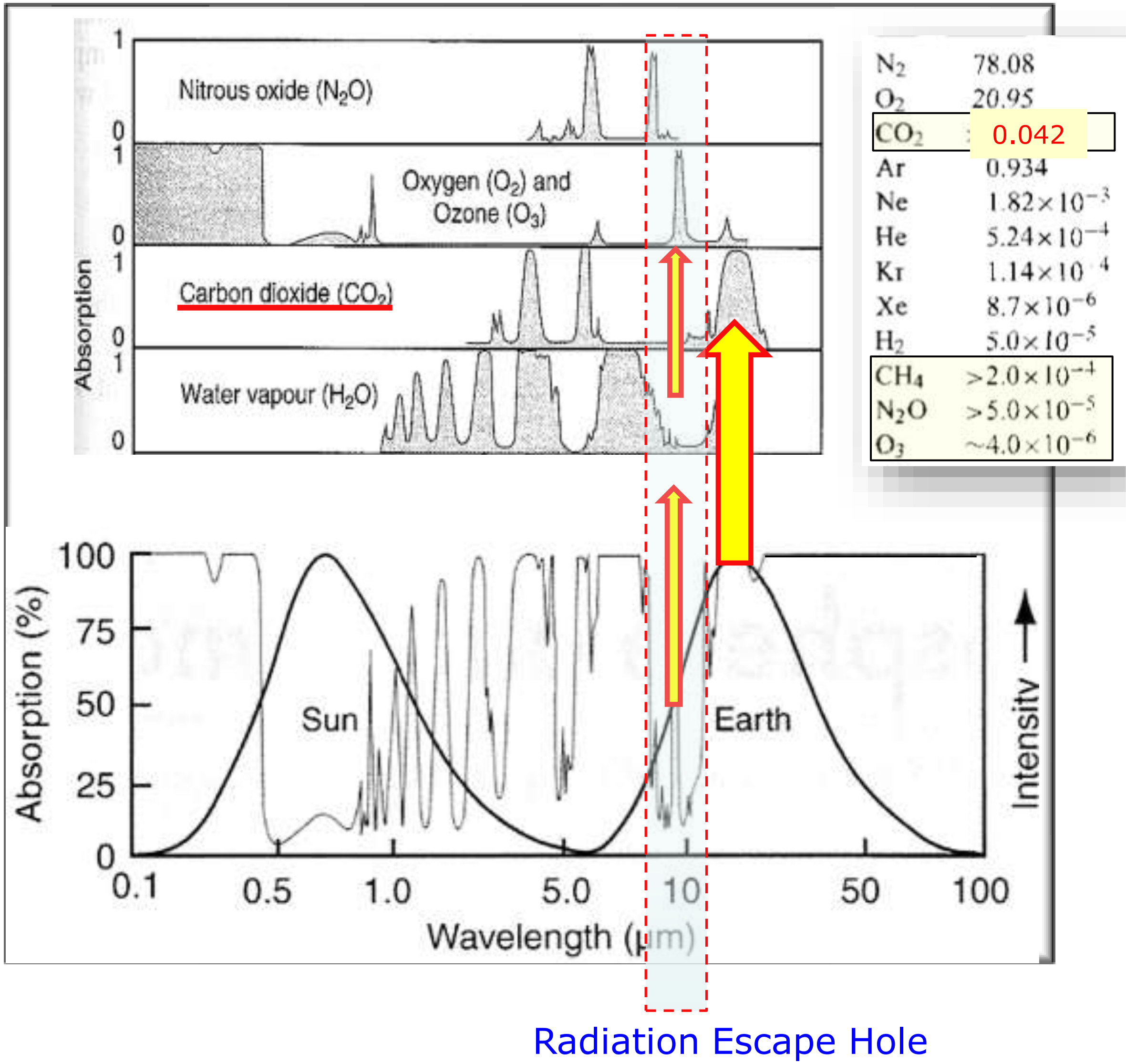
Absorbed : $I_a = I_0 - I(x) = I_0\left(1 - e^{-\mu \cdot x}\right)$

Can use base ***10*** instead of base ***e=2.718….***
Customary: use $\log_{10}$ instead of ***ℓn***.

$\rightarrow$ *Absorbance* : $Log_{10}\left(\frac{I_0}{I_t}\right) = \mu \cdot x = \varepsilon \cdot x \cdot c$ Units of μ and ε depend on unit of *c*.

Specific for absorber material, depends on internal structure, electric dipole moment. Otherwise, μ ≠ 0 only for ionized ideal gas.

Selective Absorption of Atmospheric GHG



Scattered radiation is not fully available for warming Earth surface.
→ $T_E < 255K$

Absorption of radiation in atmosphere → equilibrates → radiates back to space and to Earth surface.

CO_2 absorbs efficiently @ maximum of the Earth' surface spectrum;

N_2O and CH_4 absorb in atmospheric escape hole for radiation.

GHG concentrations on the rise during the last century.

Adapted fro F.W. Taylor, *ECP*.

Global Warming Potentials: Data

Species	Chemical formula	Lifetime (years)	Global Warming Potential (Time Horizon)		
			20 years	100 years	500 years
CO_2	CO_2	variable §	1	1	1
Methane *	CH_4	12±3	56	21	6.5
Nitrous oxide	N_2O	120	280	310	170
HFC-23	CHF3	264	9100	11700	9800
HFC-32	CH2F2	5.6	2100	650	200
HFC-41	CH3F	3.7	490	150	45
HFC-43-10mee	C5H2F10	17.1	3000	1300	400
HFC-125	C2HF5	32.6	4600	2800	920
HFC-134	C2H2F4	10.6	2900	1000	310
HFC-134a	CH2FCF3	14.6	3400	1300	420
HFC-152a	C2H4F2	1.5	460	140	42
HFC-143	C2H3F3	3.8	1000	300	94
HFC-143a	C2H3F3	48.3	5000	3800	1400
HFC-227ea	C3HF7	36.5	4300	2900	950
HFC-236fa	C3H2F6	209	5100	6300	4700
HFC-245ca	C3H3F5	6.6	1800	560	170
Sulphur hexafluoride	SF6	3200	16300	23900	34900
Perfluoromethane	CF4	50000	4400	6500	10000
Perfluoroethane	C2F6	10000	6200	9200	14000
Perfluoropropane	C3F8	2600	4800	7000	10100
Perfluorobutane	C4F10	2600	4800	7000	10100
Perfluorocyclobutane	c-C4F8	3200	6000	8700	12700
Perfluoropentane	C5F12	4100	5100	7500	11000
Perfluorohexane	C6F14	3200	5000	7400	10700

United Nations
Framework Convention on
Climate Change

http://unfccc.int/ghg_data/items/3825.php

End: Global Climate