Agenda

The grand picture (Sustainability @ "Anthropocene")

- Human habitat and resources.
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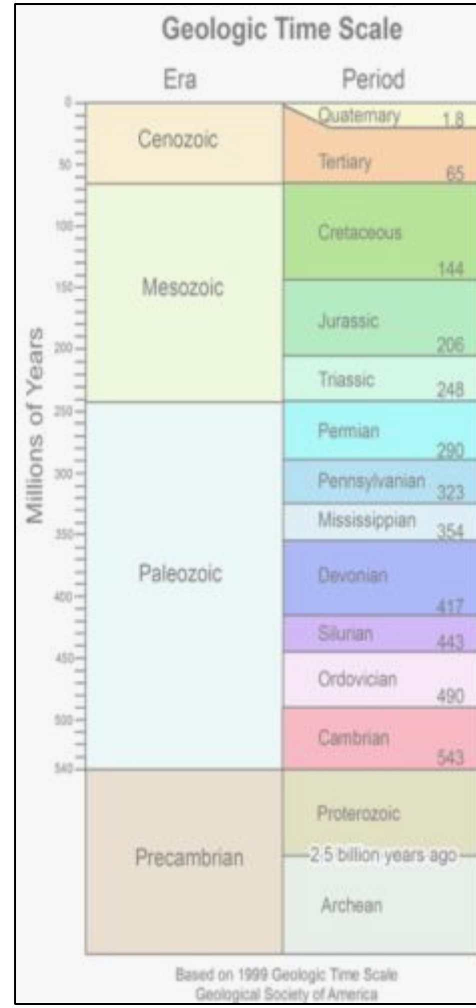
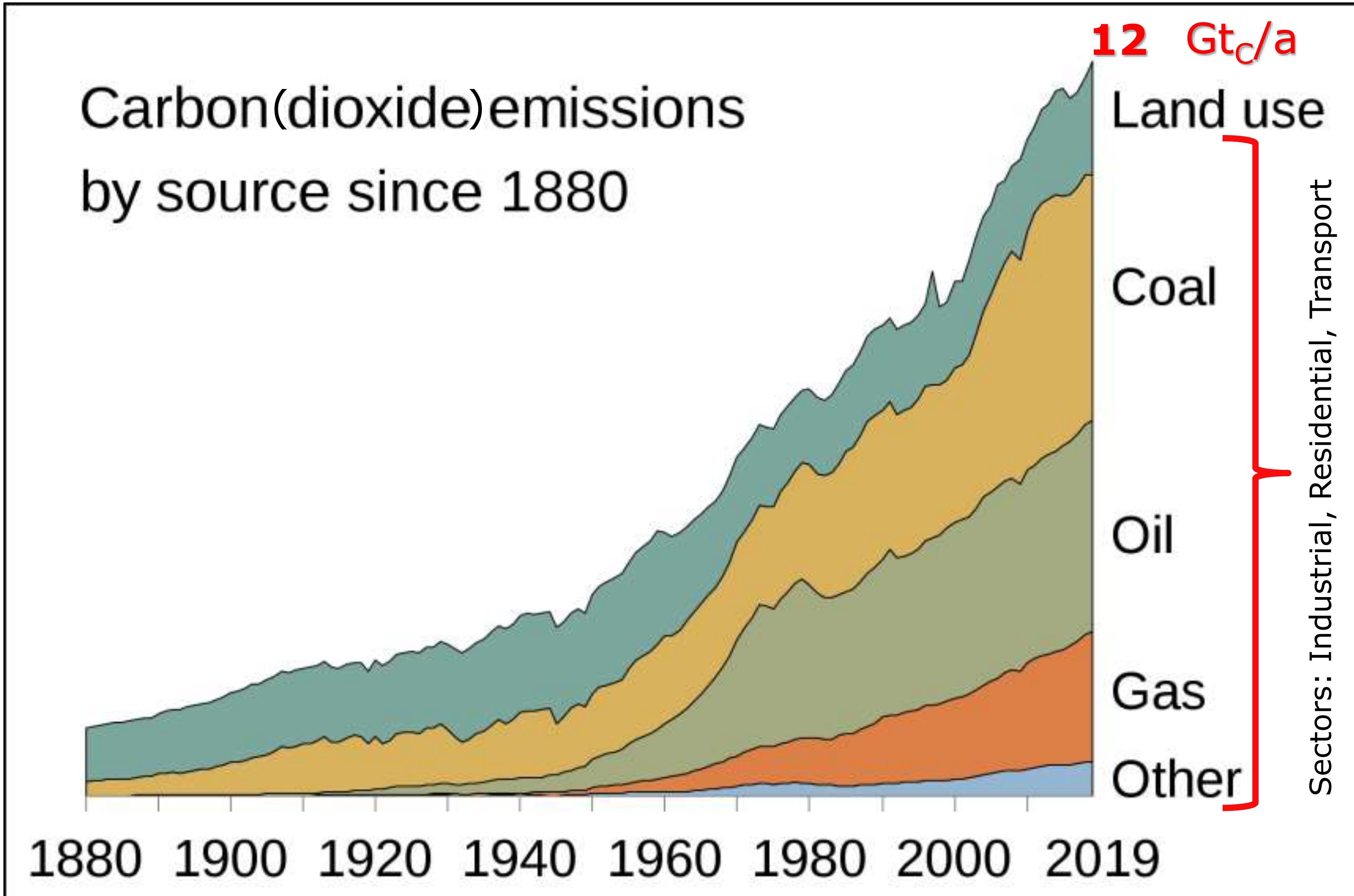
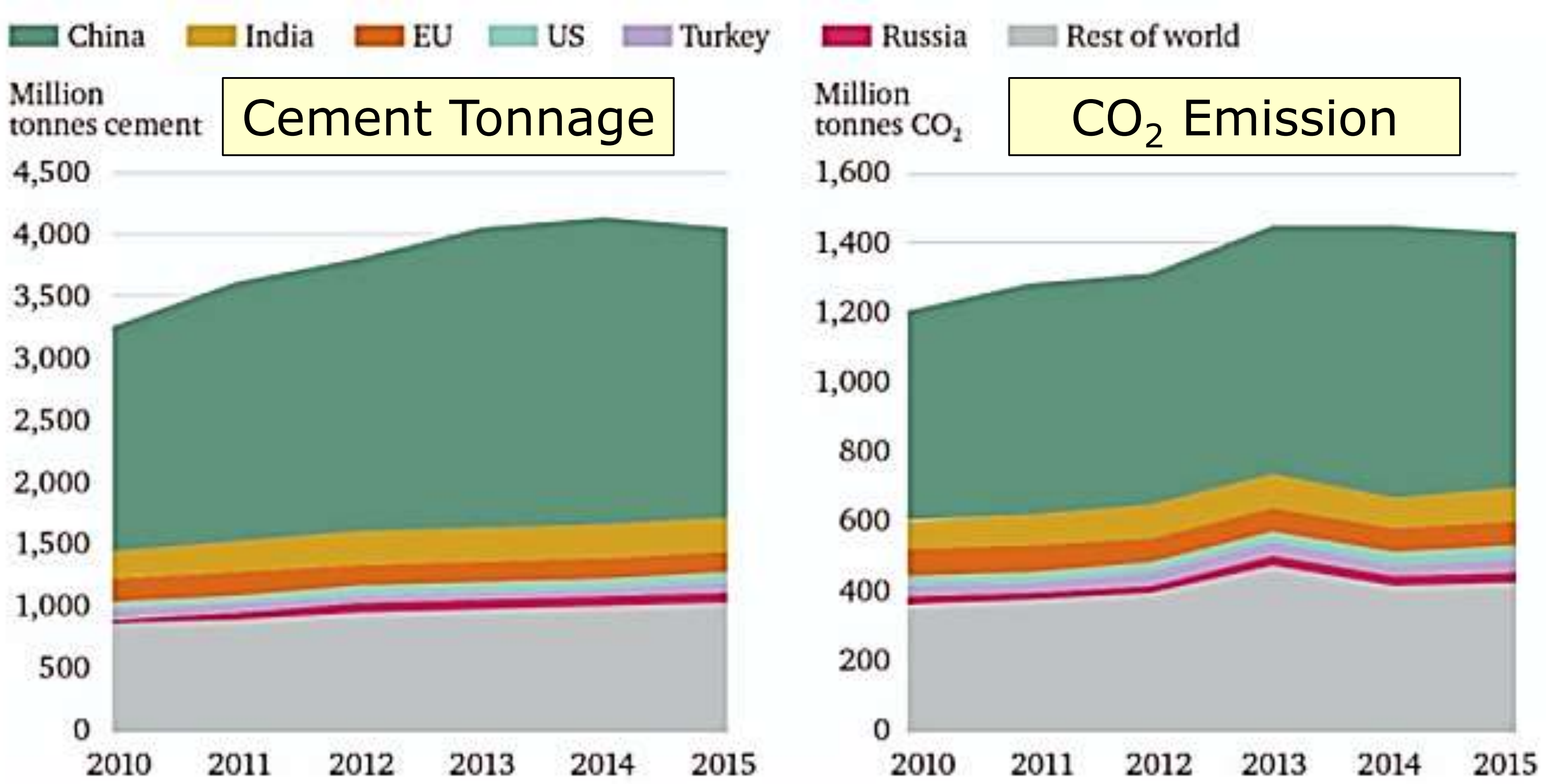


Anthropogenic Carbon Emissions 1880-2019



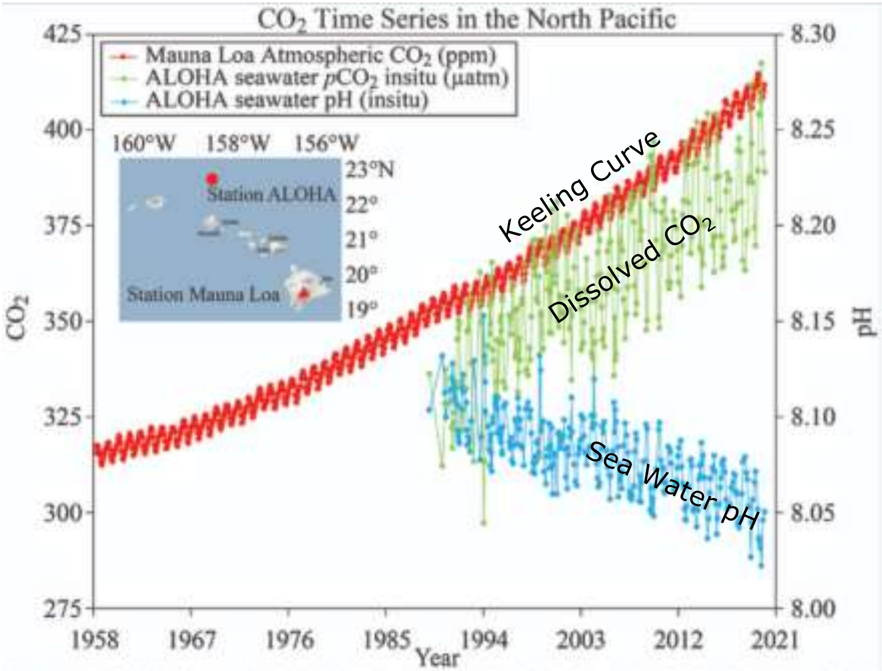
World CO_2 Emission in Cement Production @010-2015)



Cement production and emissions from 2010 to 2015. Source: Analysis of Olivier et al. (2016) by Chatham House.

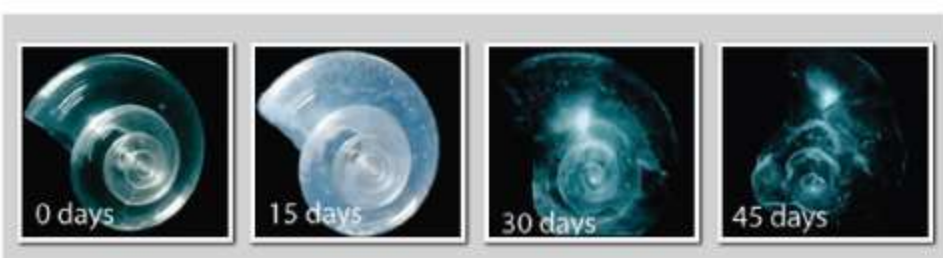
Atmospheric-Aqueous CO_2 Equilibrium and Consequences

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



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

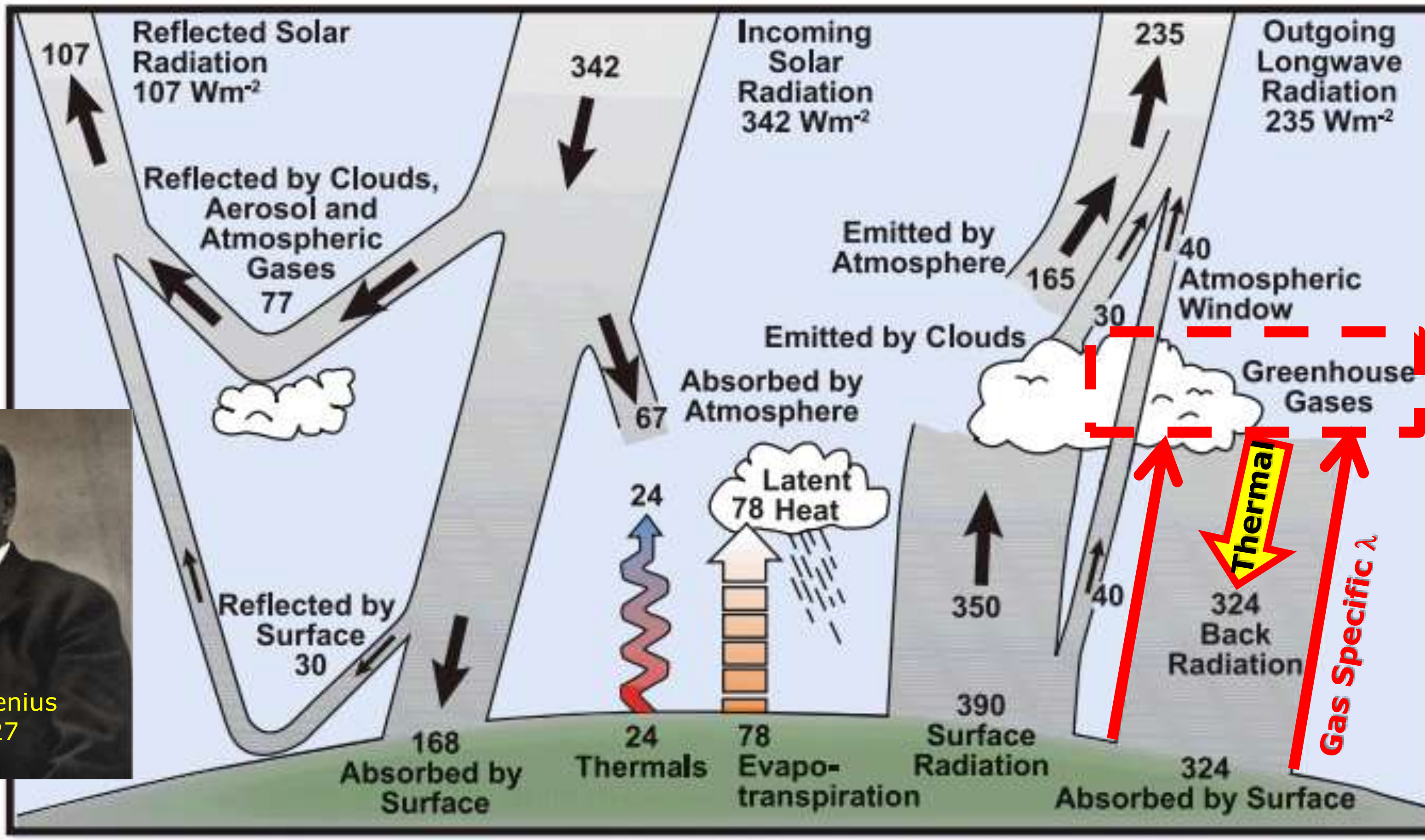
Bleaching of corals,

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)

Earth's Radiation Balance (incl. GH Effect)

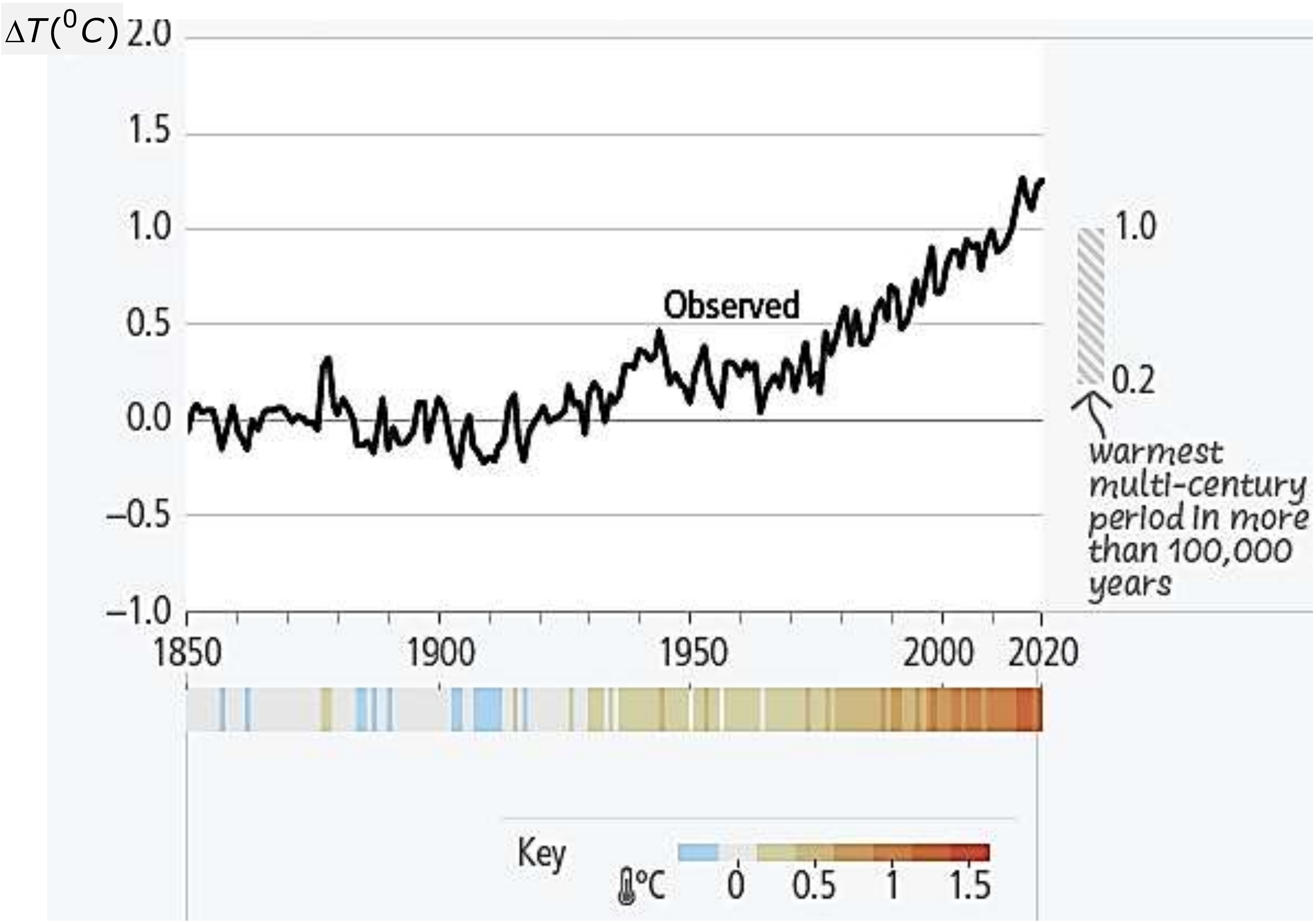


FAQ 1.1, Figure 1. *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space. Source: Kiehl and Trenberth (1997).*

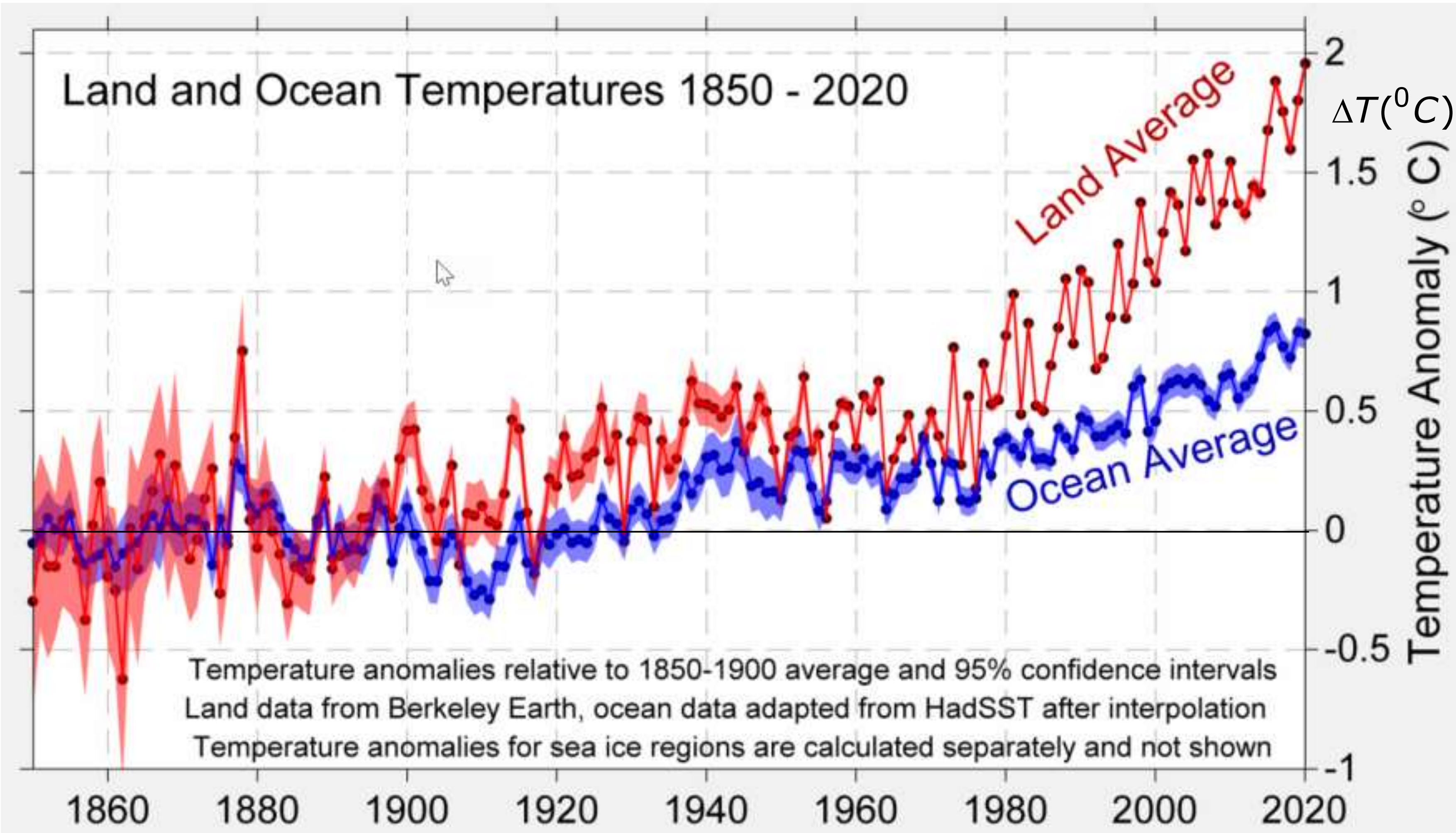
Modifi

http:/

Global Surface Temperature 1850-2020

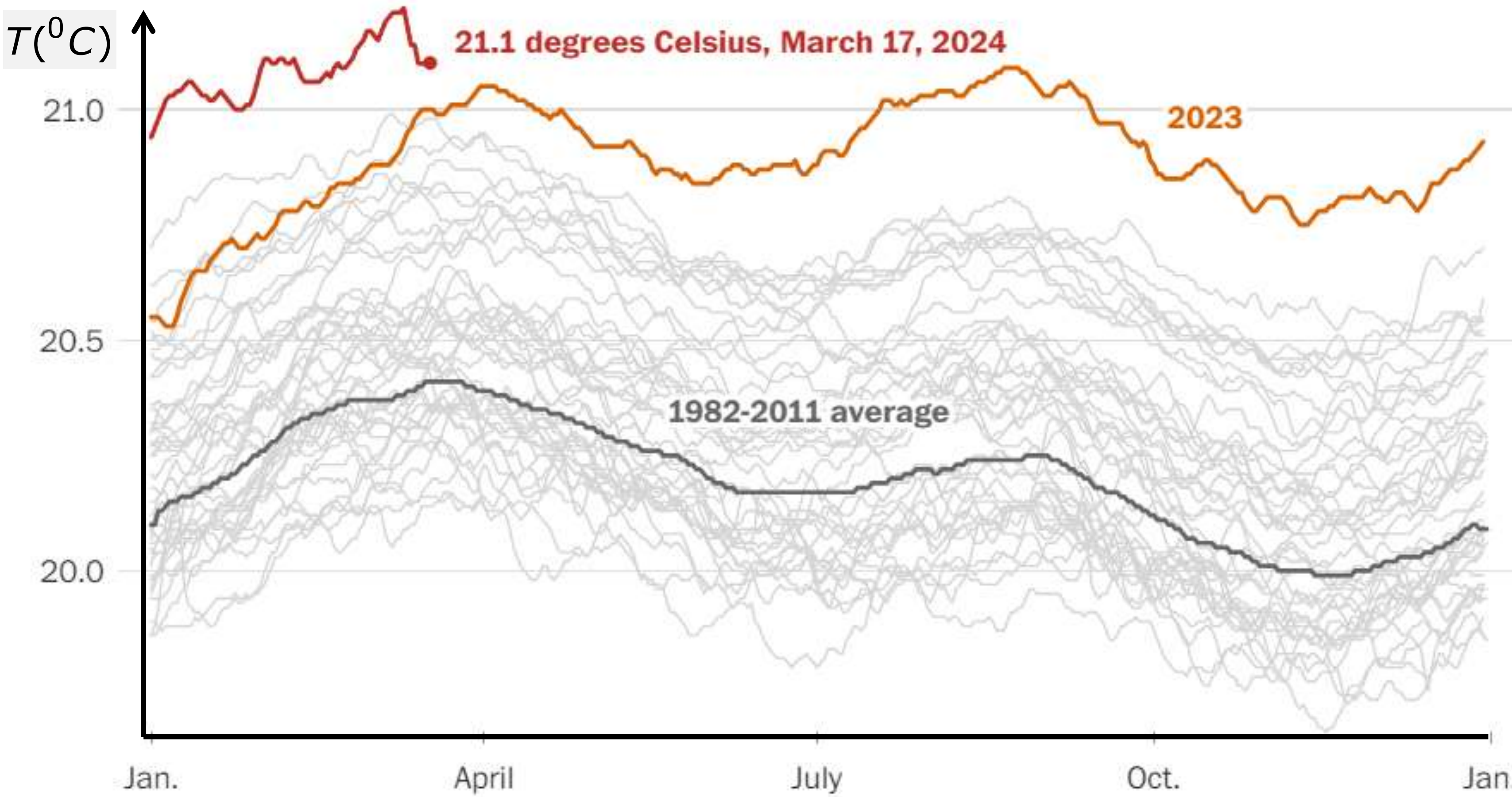


Mean Land and Ocean Temperature Trends



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

Seasonal Trends In Average Global Sea Temperatures



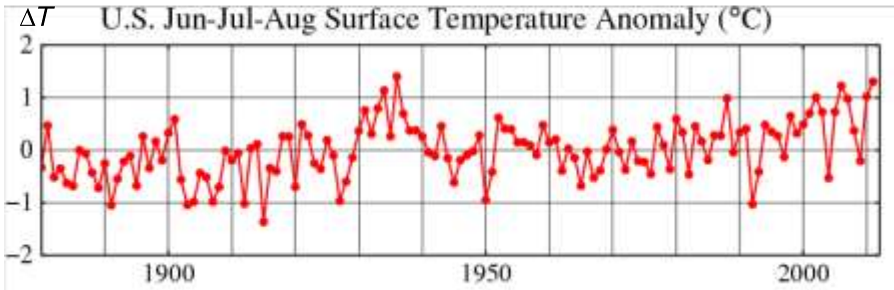
Note: The temperatures shown, in degrees Celsius, include data from 60°S to 60°N across all longitudes.

Source: NOAA OISST v2.1, via ClimateReanalyzer.org, Climate Change Institute, University of Maine.

SCOTT DANCE / THE WASHINGTON POST

Evidence for a Systematically Changing Climate

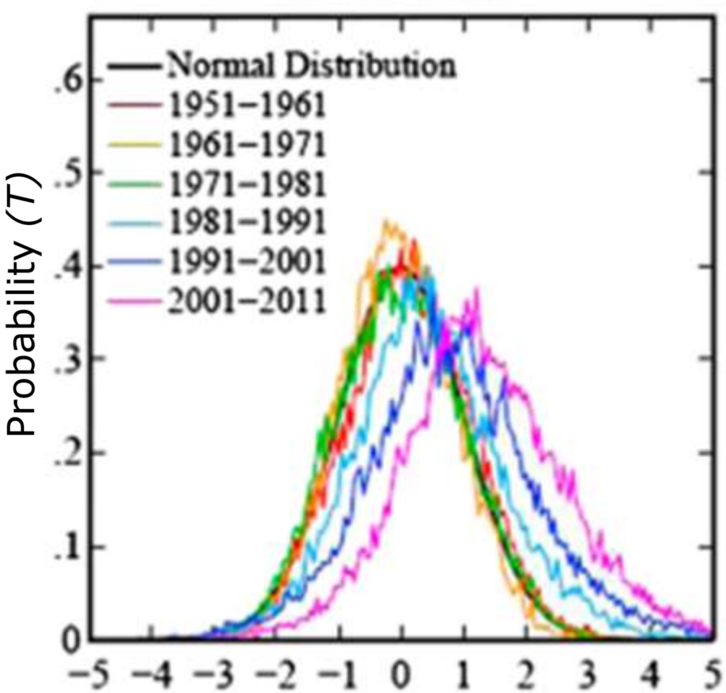
NH Land Surface Temperatures Jun-Aug



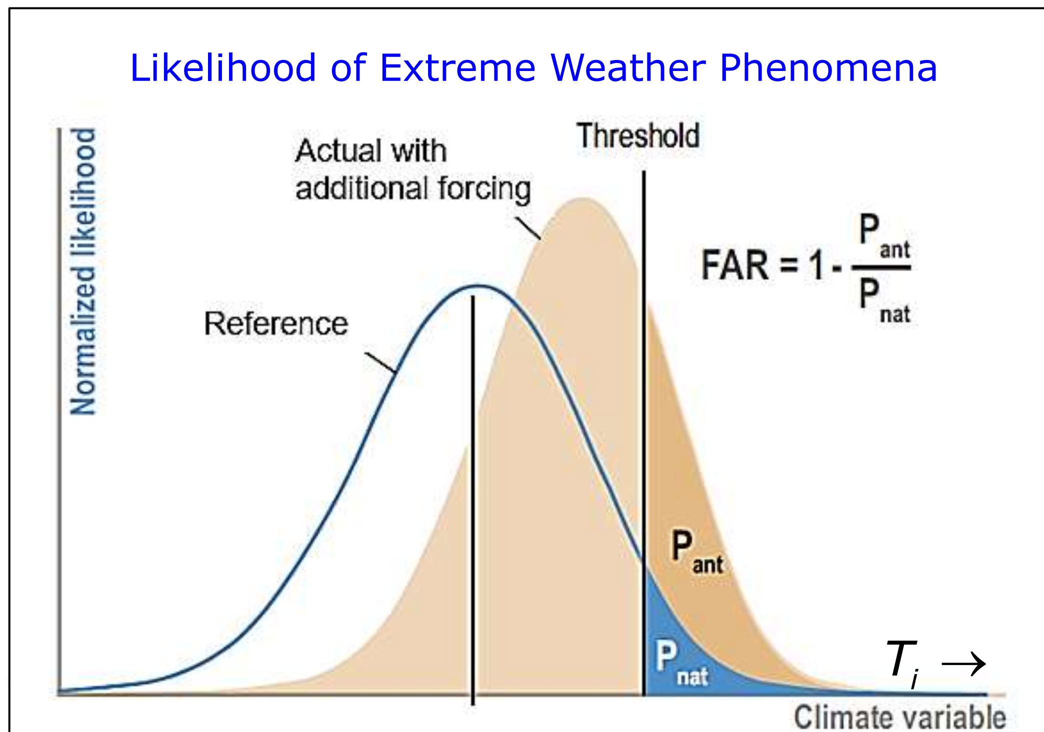
US: World's most extensive weather and climate records publicly available.

2012 statistical study of changing temperature patterns: Report *Perception of climate change* by James Hansen et al., (NASA Goddard Institute for Space Studies & Columbia University Earth Institute

Reference 1951-1980

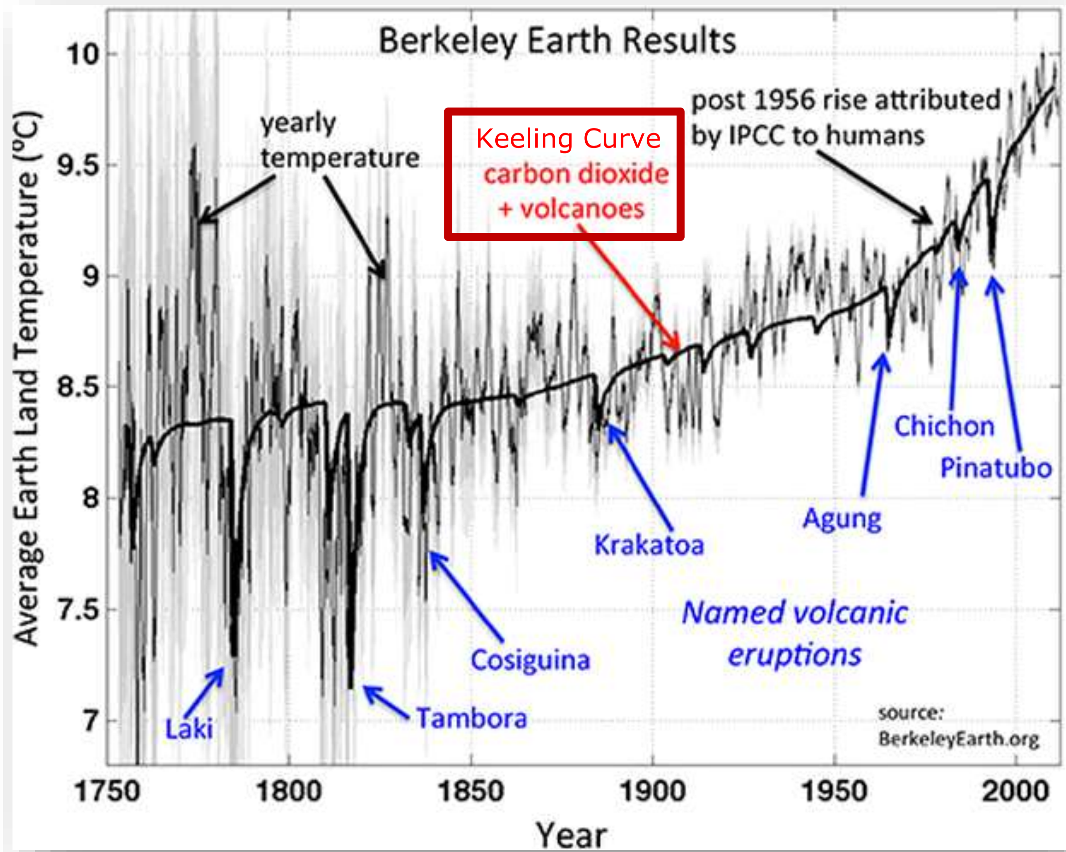


$$\Delta T_i = T_i - \langle T \rangle$$



Ominous Correlation: Temperature vs. Atmospheric CO_2

Systematic gradual rise of $\Delta T=1.5^0C$ 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)



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

Particulate clouds from volcanic events reflect sunlight and cool the Earth's surface for a few years.

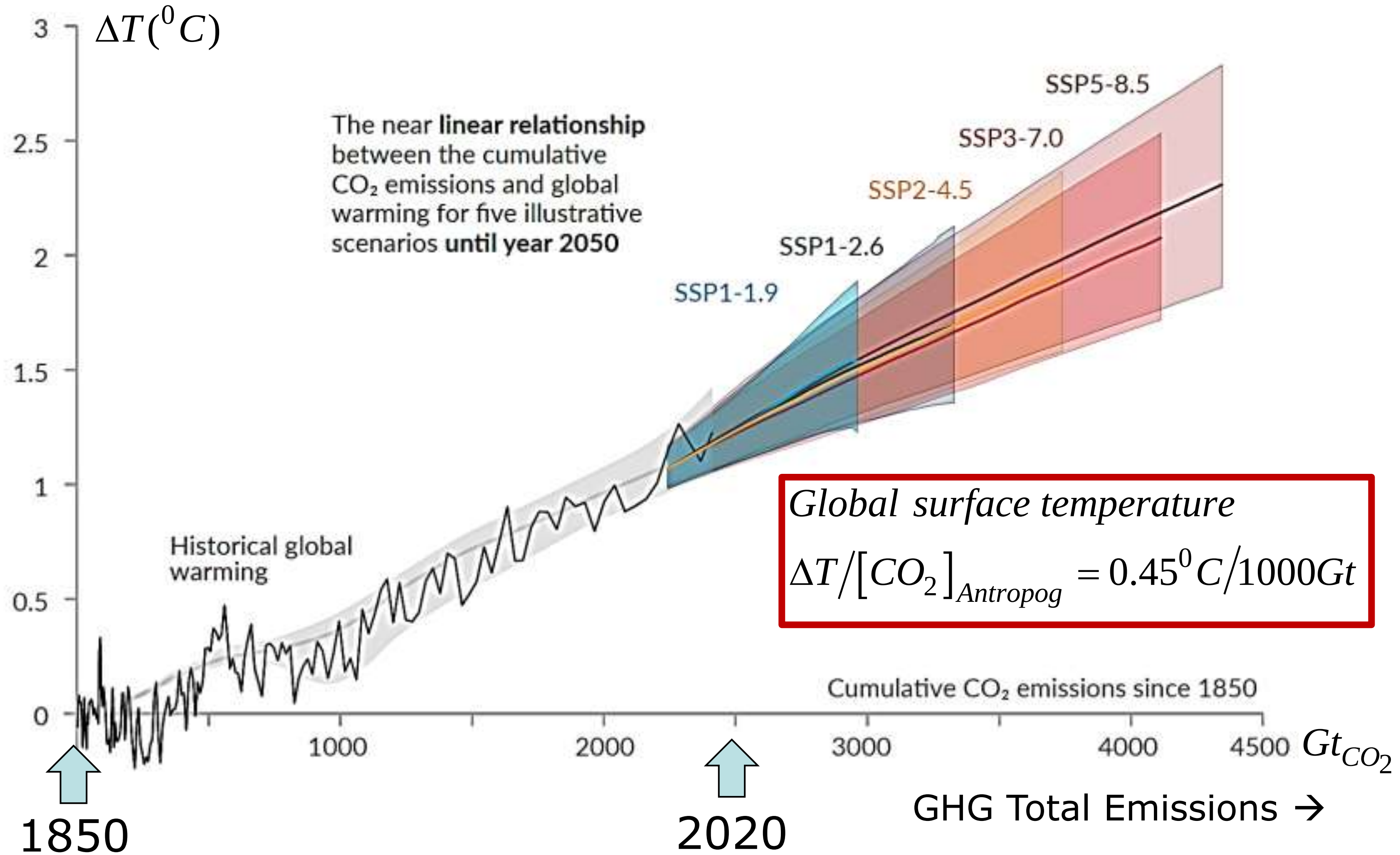
Small rapid variations are attributable to El Nino and other ocean currents such as the Gulf Stream.

(From BerkelyEarth Project)

What is Human role in *T* increase?

Mean Temperature - GHG Inventory Correlation

Global surface temperature increase since 1850-1900 (°C) as a function of cumulative CO_2 emissi



Global surface temperature

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

GHG Total Emissions →

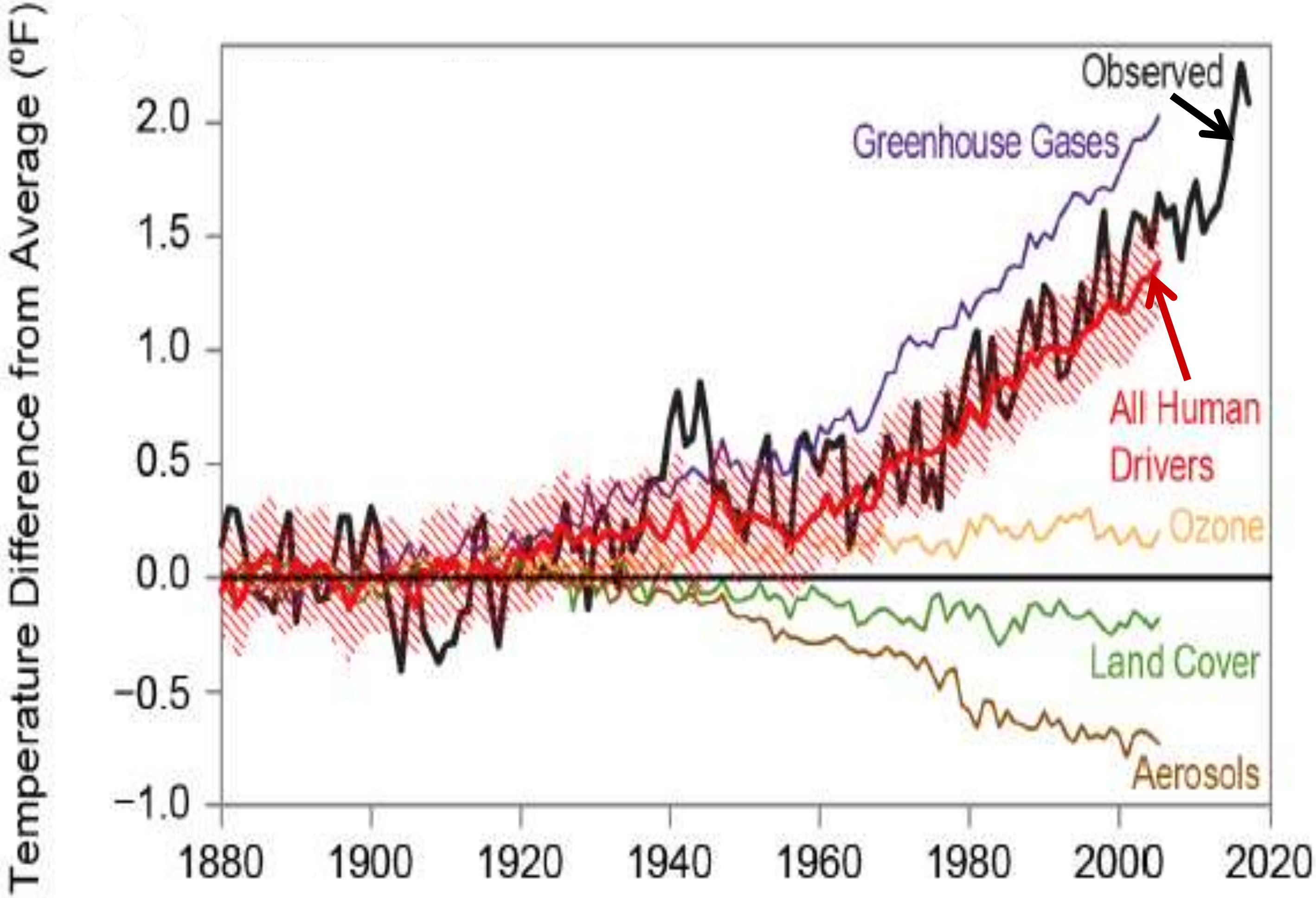
W. Udo Schröder, 2024

Anthropogenic Influences: Global Climate

Many correlations exist between human caused pollution and global climate parameters: To what extent are there causal relationships ?

→ Quantitative agreement between observation and robust physical models

→ Absence of plausible competing scenarios



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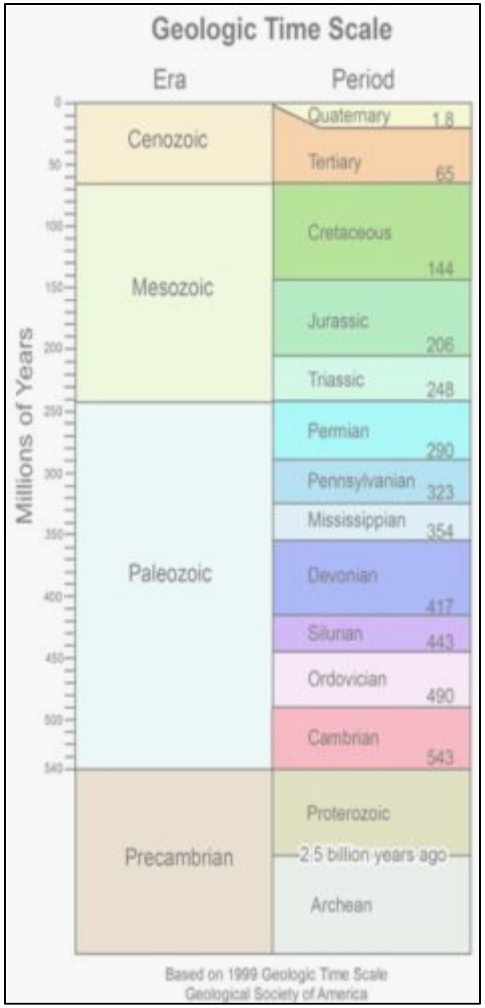
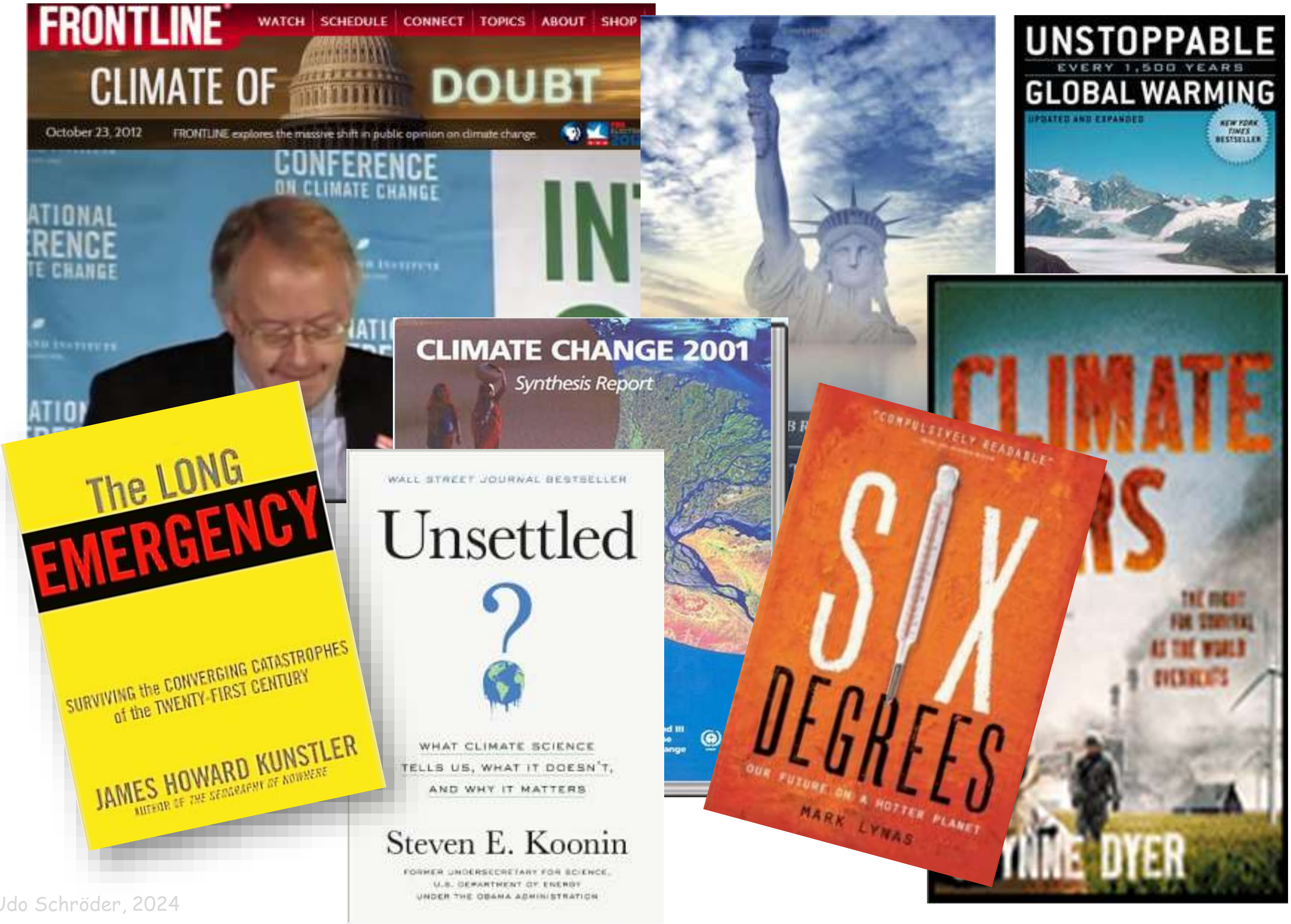


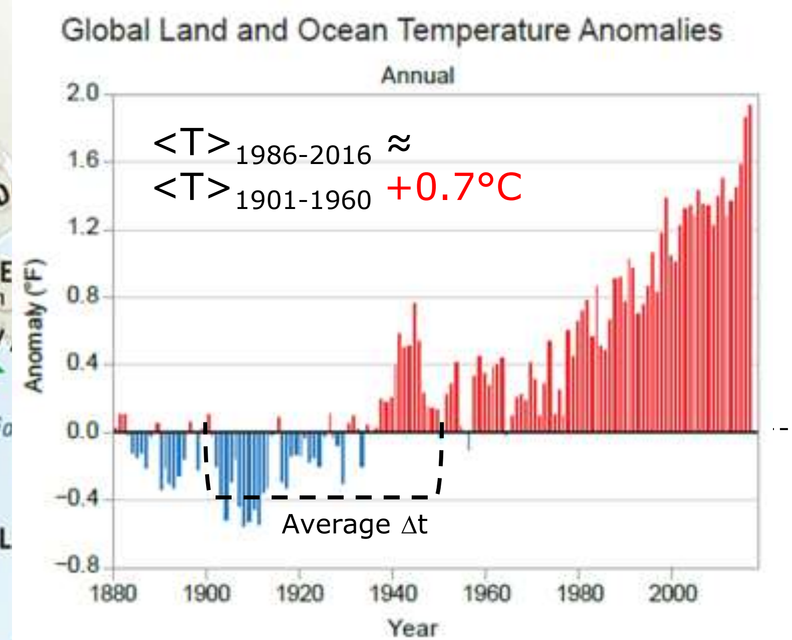
PLANETARY CLIMATE TRENDS AND CAUSATION

Climate Wars: Apocalypse Soon ?



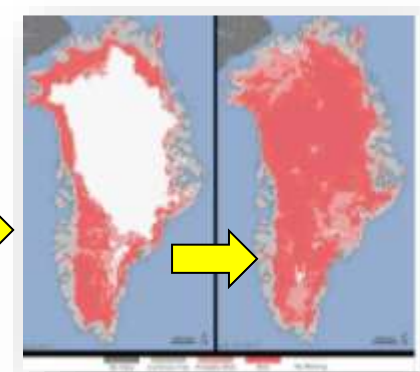
Evidence for Large-Scale Changes

From: IPCC 5th Assessment Report (2014)



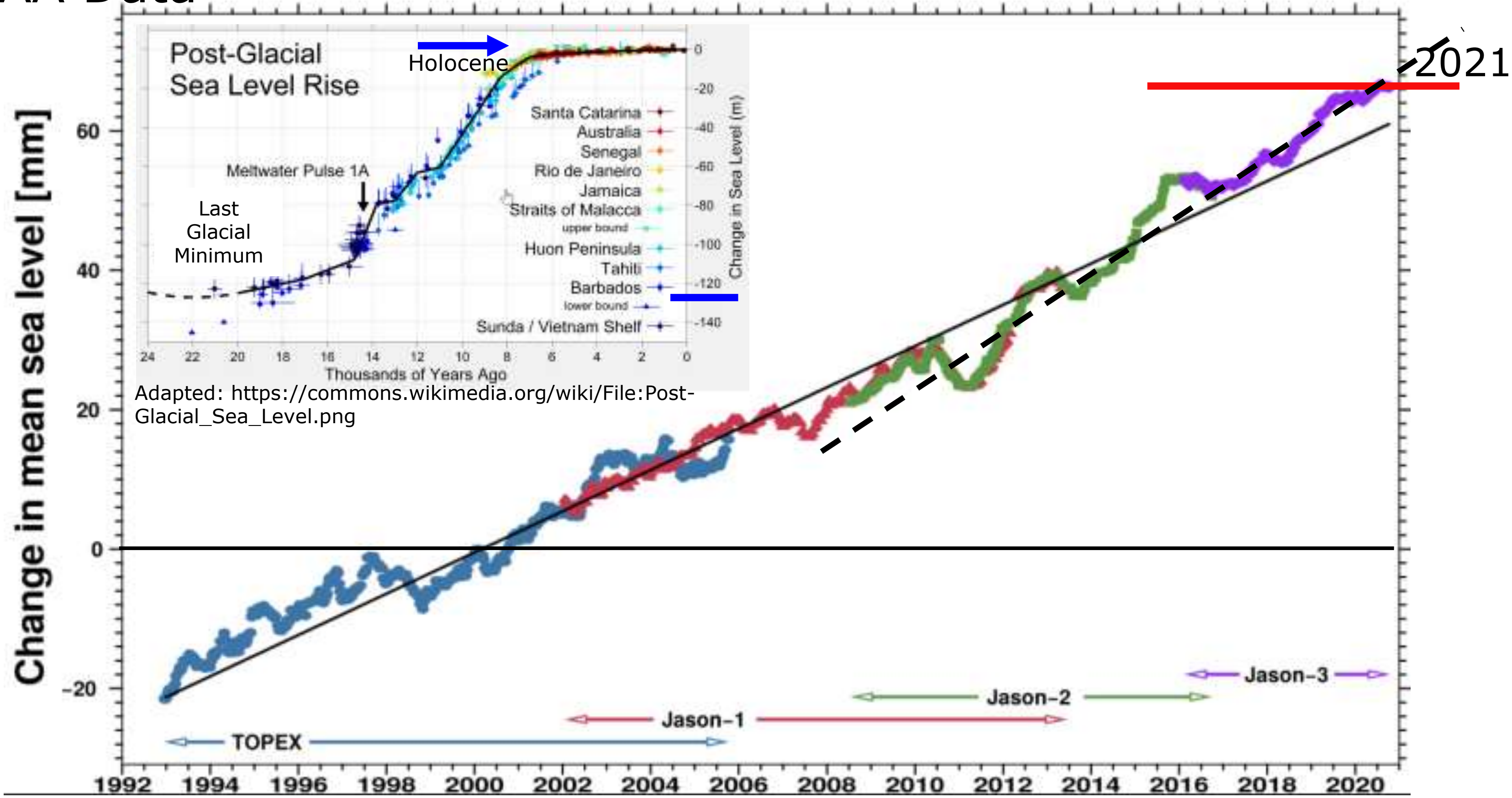
Important Q:
Natural vs. man-made
→
Economic Implications

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



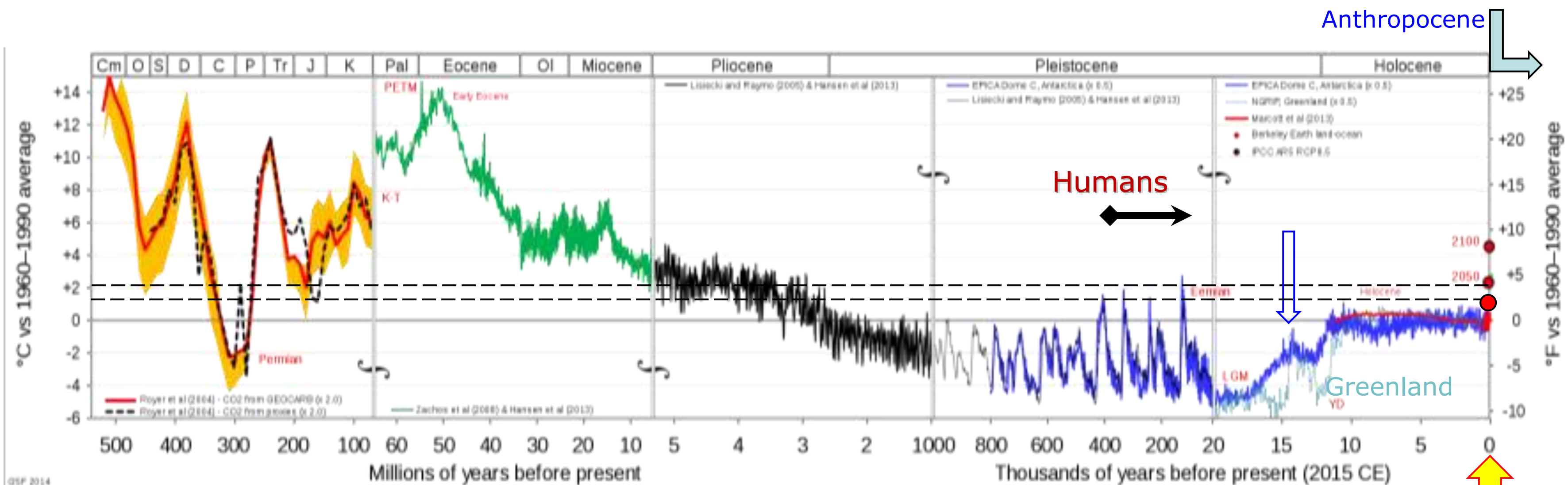
Recent and Ancient Sea Level Trends

NOAA Data

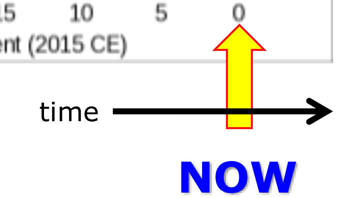


2021: Δh= + 67 mm since 1850, mean rate: (3.0± 0.4)mm/a, slightly increasing. Seasonal cycle (ΔH=±7mm) is superimposed on general trend. Comparison (inset) sea levels since last glacial minimum (-125 m !), now probably in pre-glacial rise (uncertainty ΔH=±10m), modified by anthropogenic influences.

Context Paleo-Climate: Global Surface Temps

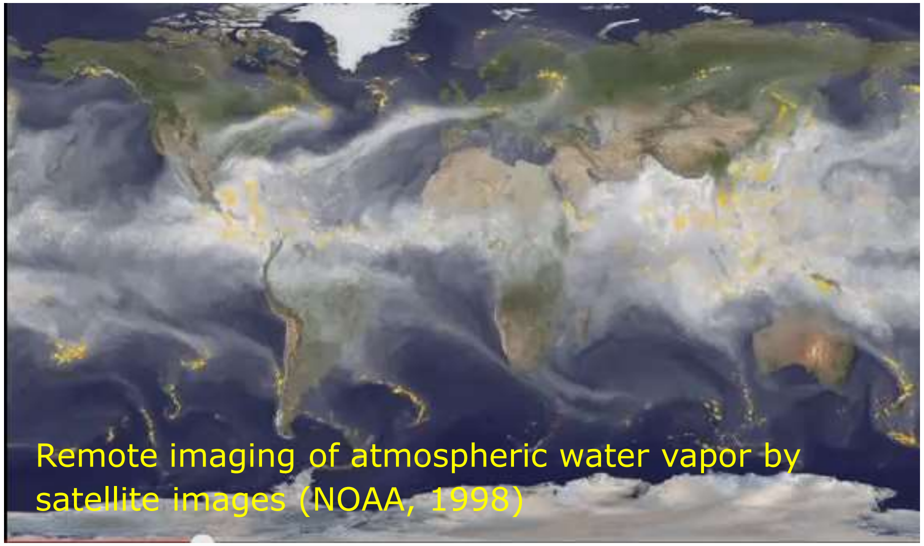


Cited by S.E. Koonin, Glen Fergus: data sources are cited below, CC BY-SA 3.0,
https://commons.wikimedia.org/w/index.php?curid=31736468
https://en.wikipedia.org/wiki/Paleoclimatology#/media/File:All_palaeotemps.svg/



Different methods to determine temperatures (etc.) of paleoclimate, ice cores (≈3Ma), isotopic ratios, ocean sediments (≈100Ma) → direct satellite T measurements (±0.1^{0}C)

Big Data: Weather & Climate Information Sources



Remote imaging of atmospheric water vapor by satellite images (NOAA, 1998)

One of many weather stations (Albany) of US Network.

Ice cores stored in the U.S. Geological Survey **National Ice Core Lab** (NAS 2010)

Systematic studies to establish global historic trends require:
Excellent weather/climate information provided by several national/international agencies allows systematic climate evaluation and projection→ Research efforts in Nat'l Labs/Univ.

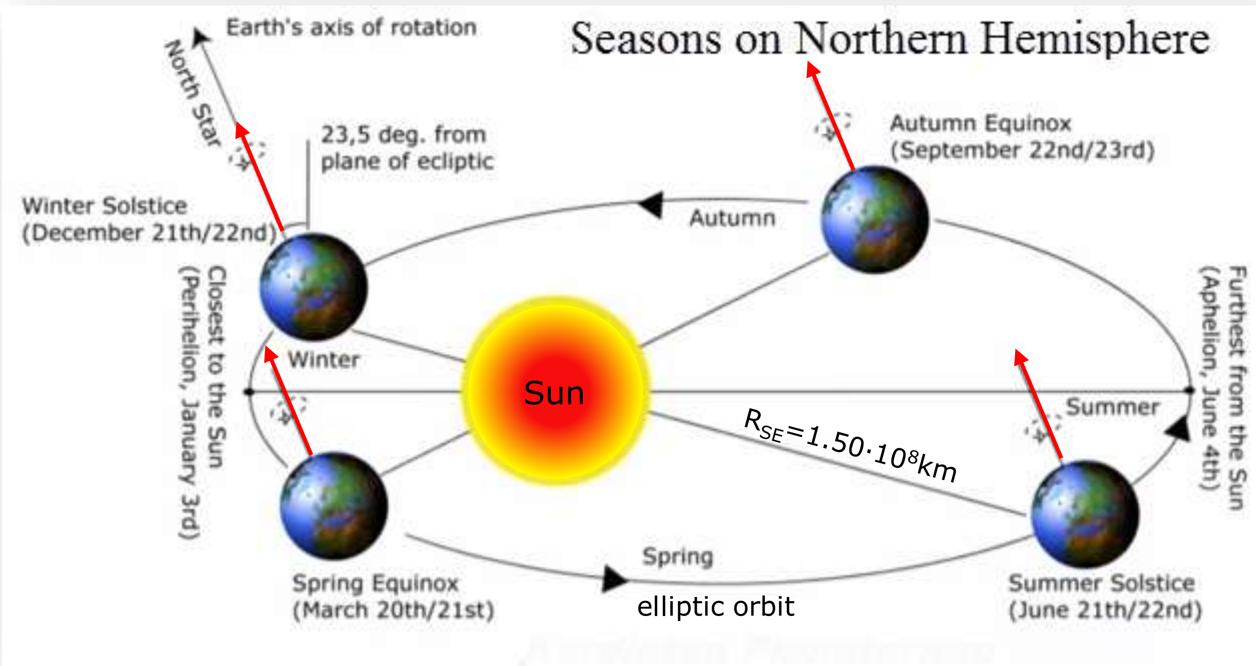
Examples:

1. U.S. *Historical Climatology Network* (USHCN): 1221 observing stations in the 48 contiguous states (Europe equiv).
2. Complex, remote measurements of atmospheric temperatures, composition, flows, ocean temperatures, etc., via many NOAA/NASA/ESA/EUMETSAT satellites.
3. Check theoretical models against known history.

Paleo-climate information: isotope ratios, air bubbles in Greenland or Antarctic ice cores, tree rings, coral reefs, historical records.

Earth In Solar System

Earth climate is driven by solar radiation influx from Sun. Sun gets energy from nuclear fusion reactions. Solar radiation is dominated by approximate thermal equilibrium of photons with solar matter ("black body" @ T = 5,780 K). Solar activity (sun spots) and insolation on Earth vary in an 11-year cycle.



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).

Revolution of Earth around Sun in 365.25 d, slightly elliptic orbit (ε~6%).
Seasons are caused by tilt of rotational axis (spin angular momentum), determining angle of incidence and intensity of solar insolation, as well as length of day/night.

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

Climate Forcing Categories

Paleoclimatology achieved via study of Antarctic and Greenland ice cores, geological sedimentation, tree rings, coral reefs, records, …

Recent past via human records, oral history, temperature records

Now: various geophysical measurements on land and sea, e.g., remote satellite sensing.

Climate forcing := change imposed on Earth's surface energy balance/climate due to

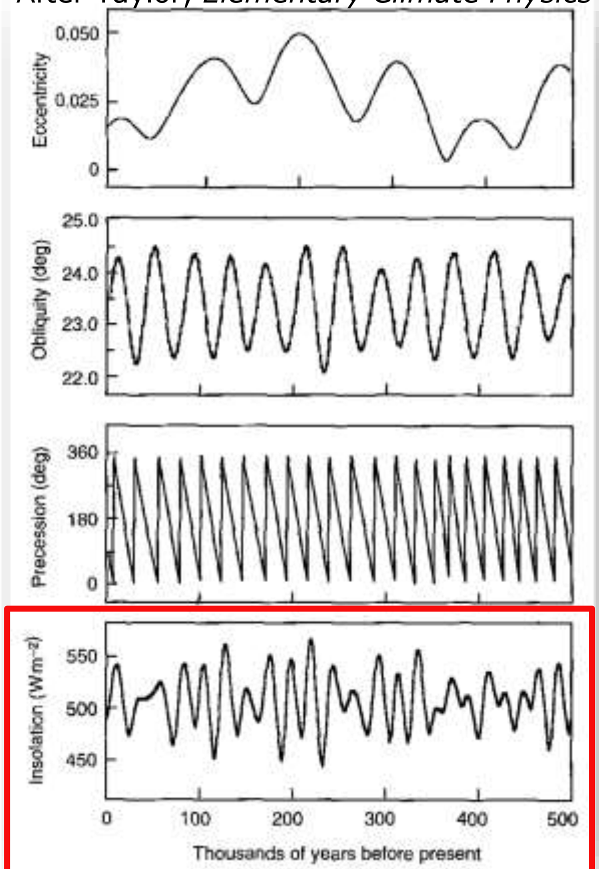
1) External causes (solar radiation influx):
   - a) changes in Earth orbital eccentricity (Δe~(0.01-0.2)%, T_{ecc} ~ 110,000 a),
   - b) orbital precession (T ~ 20,000 a)
   - c) obliquity ($\Delta\theta = \pm 1^0$, T_{obl} ~ 40,000 a) of rotational axis.
   - d) Solar activity, sunspots (T_{Sol}~ (9-14) a)
   - e) Impact of meteorites, asteroids.

2) Internal causes:
   - a) Volcanic eruptions producing aerosols.
   - b) Changes in oceanic currents.
   - c) Changes in ice and cloud coverage (albedo).
   - d) Human induced changes (emission of greenhouse gases, tropospheric aerosols, CFCs and HCFCs producing "ozone hole").

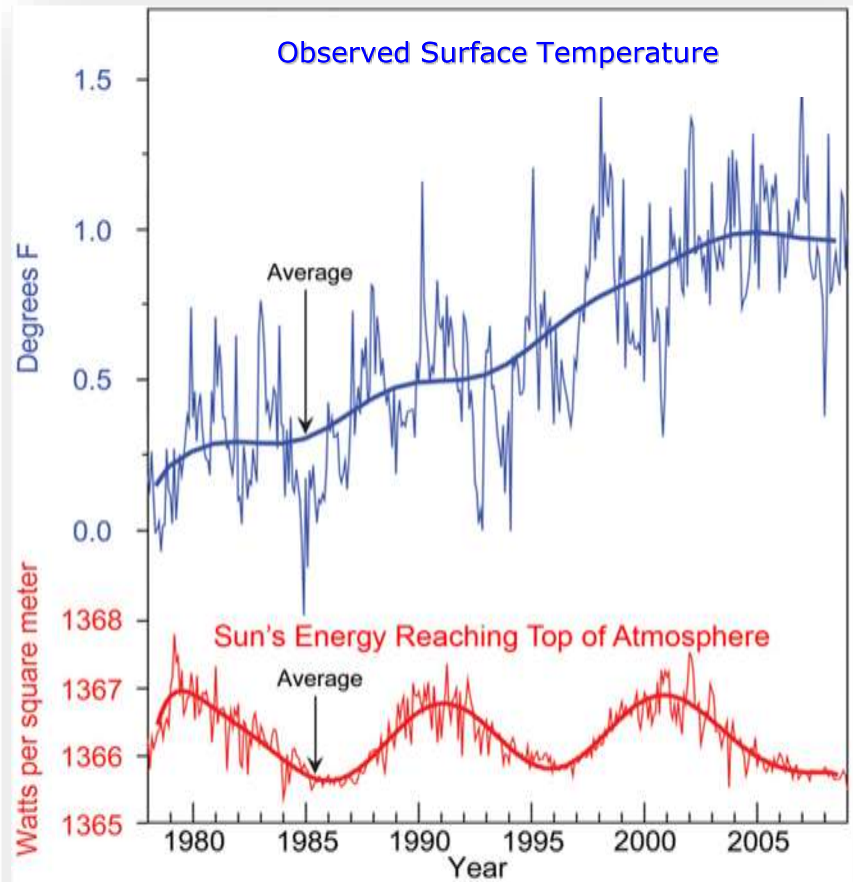
Correlate terrestrial observations with characteristic *t*-dependencies of potential causes

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.

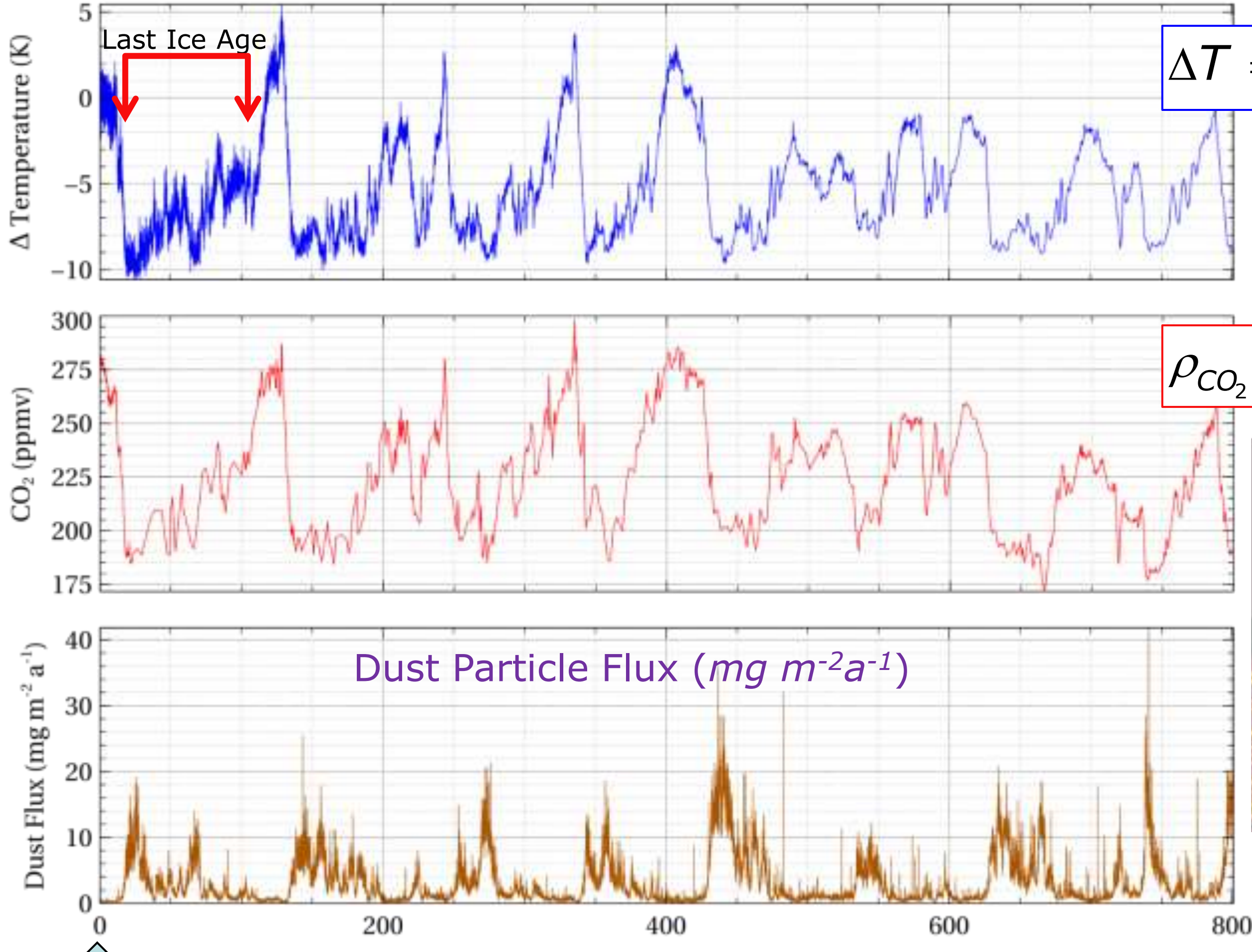


The sun's energy received at the top of Earth's atmosphere has been measured by satellites since 1978. It has followed its natural 11-year cycle of small ups and downs, but with no net increase (bottom). Over the same period, global temperature has risen markedly (top).

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

Paleo-Climate Correlated Trends: Global Surface Temps

Ice core data for past 800,000 years (x-axis values represent age before 1950



$$\Delta T = T(t) - \langle T(1950) \rangle$$

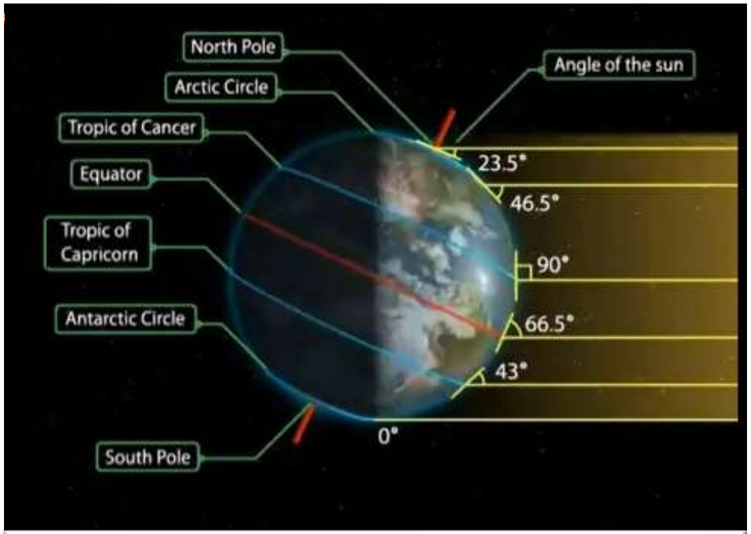
$$\rho_{CO_2}(t)\ (ppm,\ volume)$$

Age (in 1000 years before 1950

1950

Note length of glacial-interglacial cycles averages ~100,000 years.

"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:

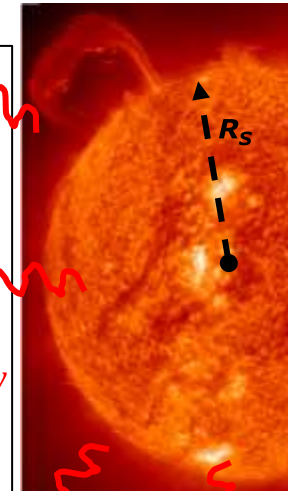
$$R(\lambda,T)=\frac{2hc^2}{\lambda^5}\left[\frac{1}{e^{hc/\lambda kT}-1}\right]\left(\frac{W}{m^3\cdot sr}\right)$$

Stephan – Boltzmann Radiation Law

Total power emitted

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

$$SB-constant:\sigma=5.670\cdot 10^{-8}\ \left(W/K^4m^2\right)$$



$R_S=6.96\cdot 10^5 km$

$\pi R_S^{}=6.09\cdot 10^{12}\ km^2$

Earth is also an approximately a "black body," but with a low temperature *T=255 K (-18⁰C).*

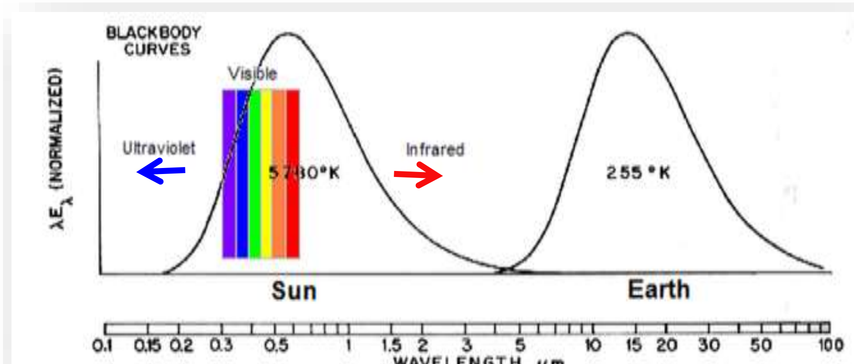
Role of atmosphere → raises ambient temperature ("good" greenhouse effect).

$h=6.625\cdot 10^{-34}\ J\cdot s$ *Planck's constant*

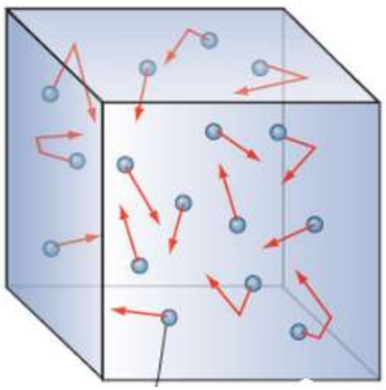
$k=1.3\cdot 10^{-34}\ J\cdot s$ *Boltzmann's constant*

$c=2.998\cdot 10^{8}\ m/s$ *speed of light*

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



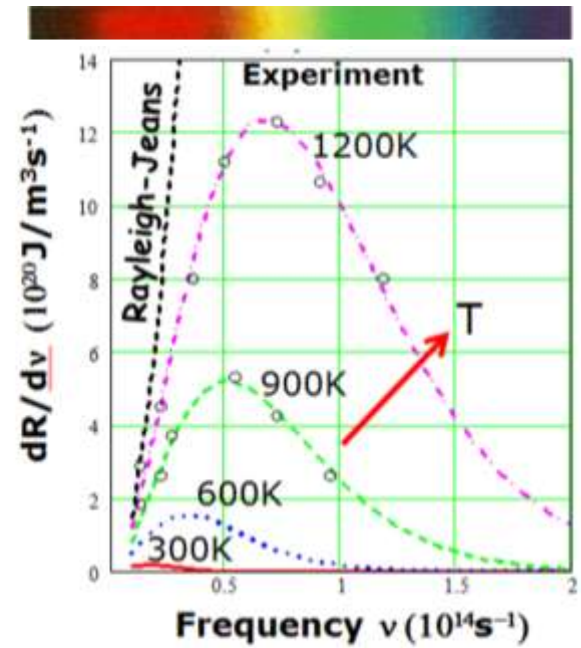
Random Motion → Black Body Radiation



Charged Particles

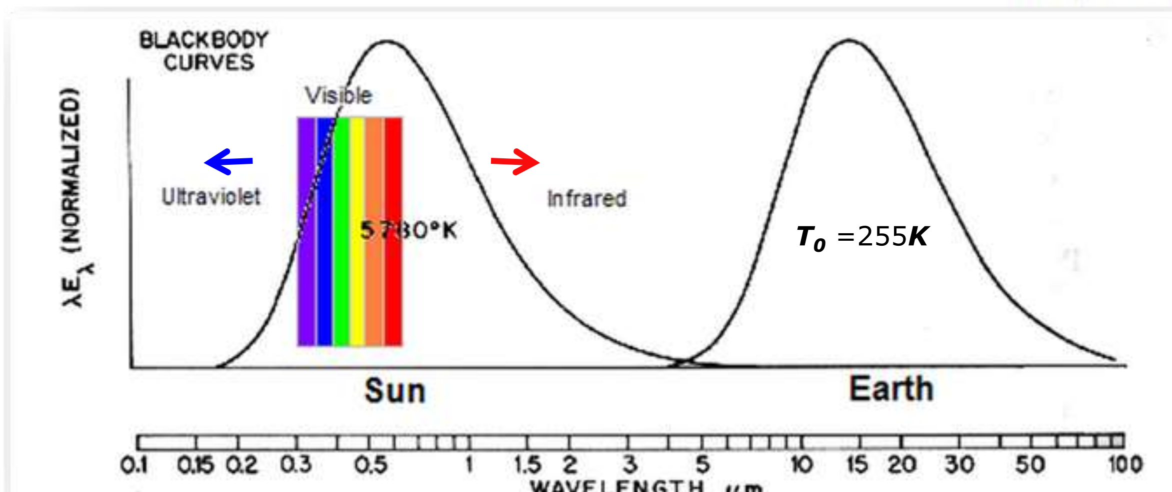
Charged particles in random motion → continuous "thermal" kinetic energy spectrum.
→ Emit photons with continuous energy (ν, λ) spectrum

Equilibration & Relaxation →



Bare Earth is also approximately a "black body," but with a low temperature, equilibrium (estim.): *T=255 K (-18^{0}C).*

Atmosphere =blanket → raises ambient ***T*** ("good" GHE)



Solar Insolation on Earth

Solar Constant

$$Earth\ area\ A_E = 5.1\times10^8\ km^2$$

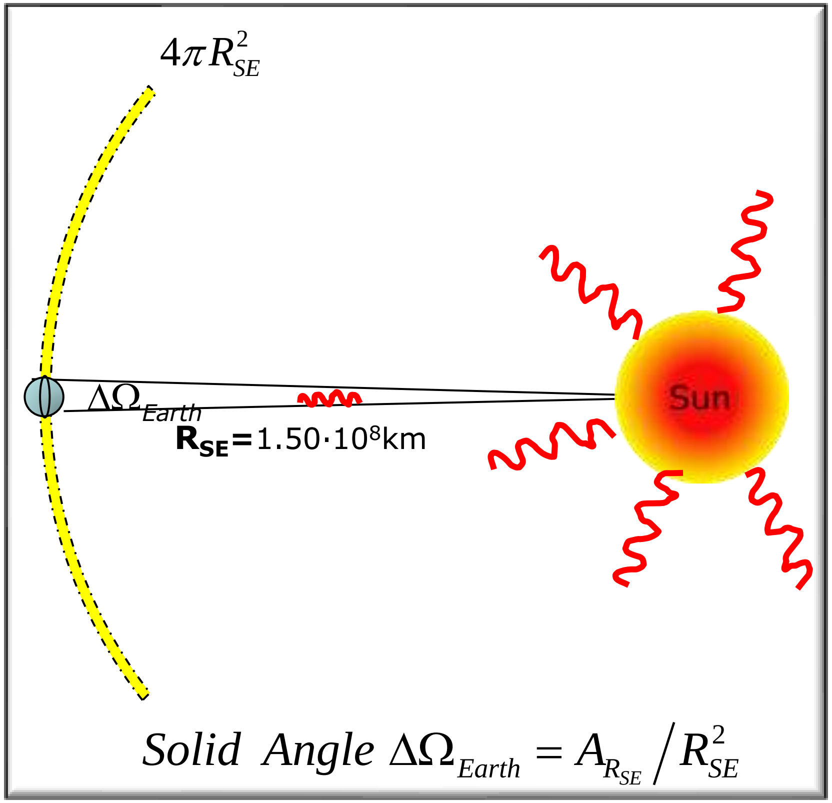
$$exposed\ to\ Sun = disk\ of\ area\ A_{R_{SE}} = \pi R_E^2 = \frac{1}{4}A_E$$

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

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

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

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



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

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

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

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

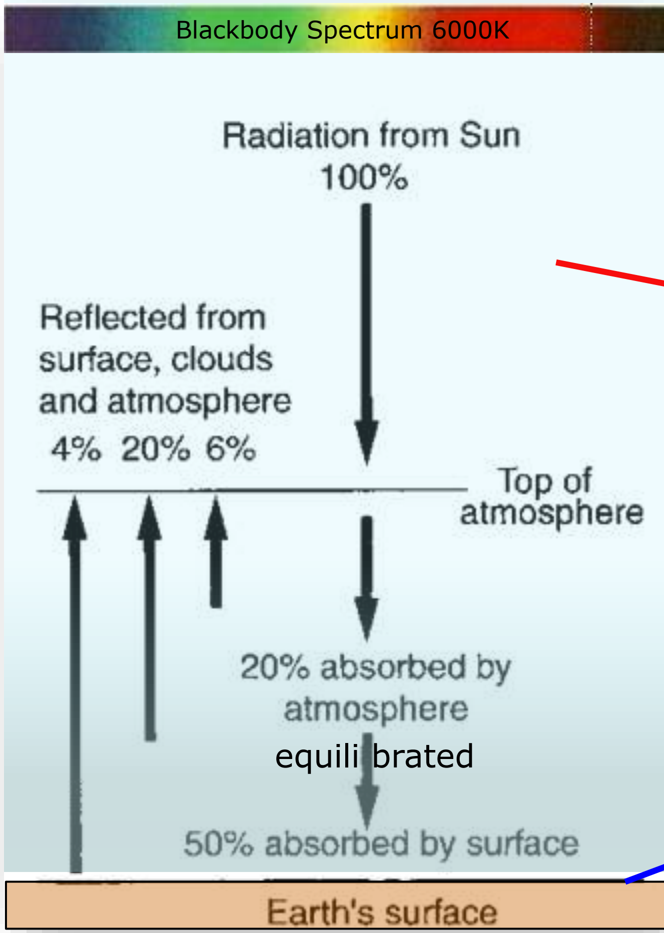
(*More sophisticated models for Earth energy balance are available*)

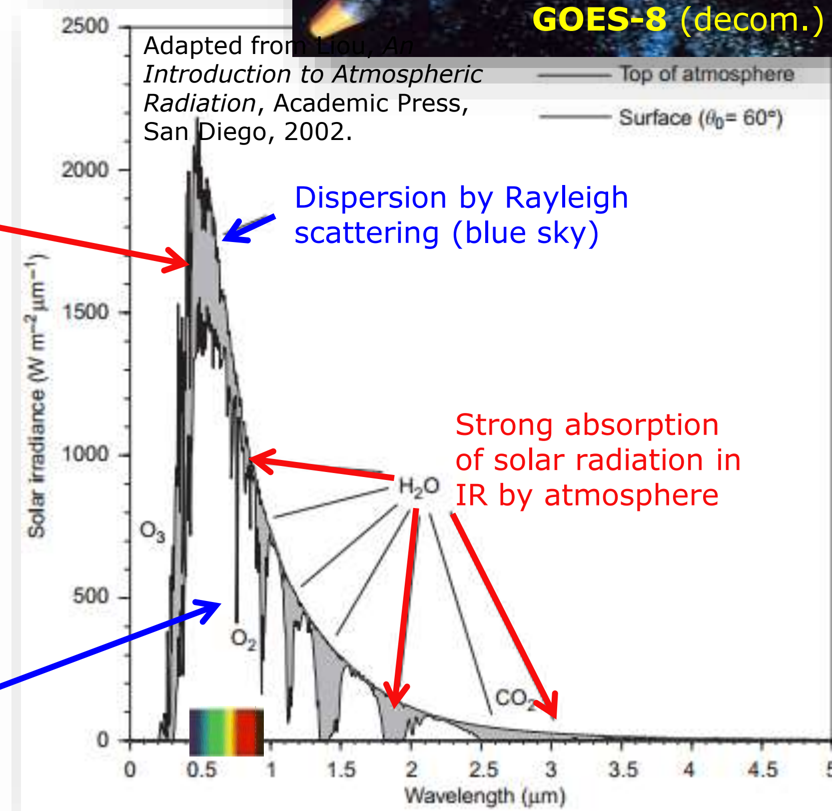
Effect of solar irradiation on Earth surface is non-cumulative, non-linear, possibly unstable.
System of several negative and positive feed-back effects.
Possible: Thermal equilibrium ?

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)

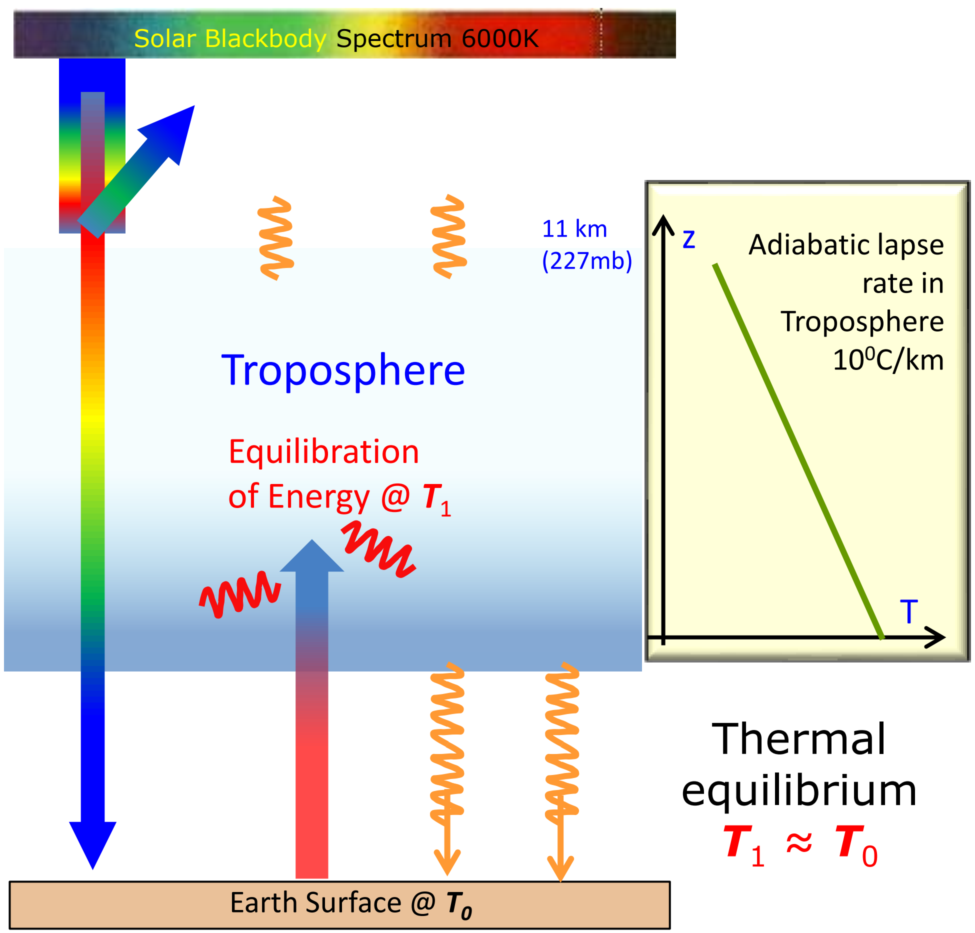
See, e.g., F. P. J. Valero et al., J. GEOPHYS. RES., 105, 4743 (2000)





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

Near-Surface Energy Equilibration



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.

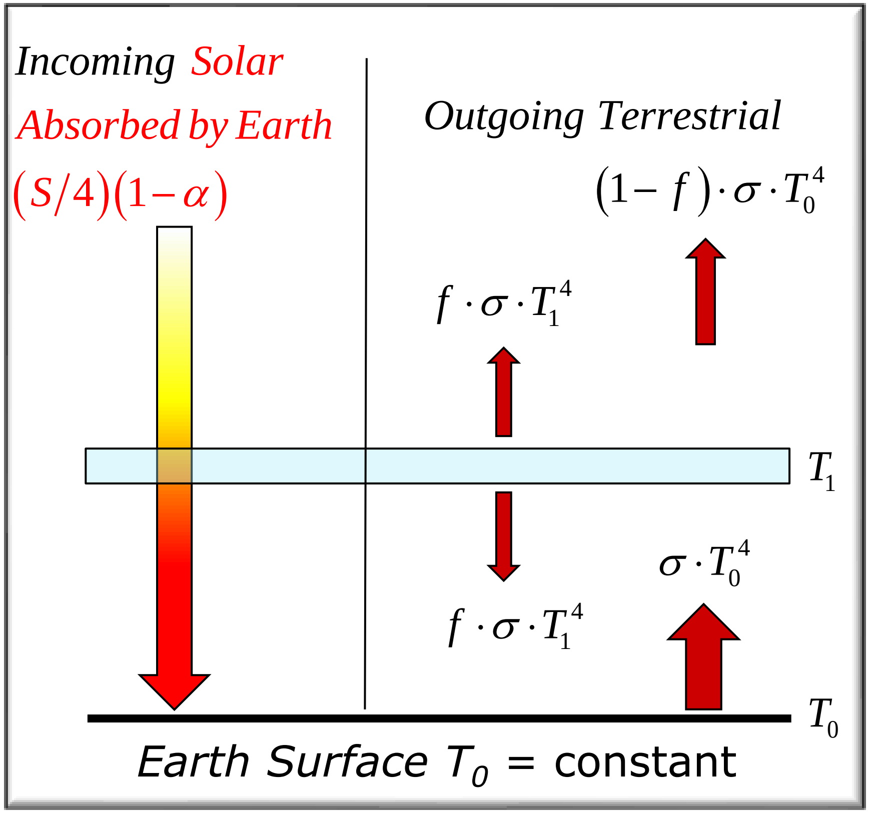
IR radiation from surface is absorbed by atmosphere, heating it up.

2) Atmosphere radiates P=S(1-a)/4 at 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.

← *Energy Content*

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

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

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

$$F = (1-f/2)\cdot\sigma\cdot T_0^4$$

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

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

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

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

Radiative Forcing

Perturbations in the atmosphere (different amounts of GHG) produce changes in atmospheric absorption ($f \rightarrow f + \Delta f$) at a given (fixed) T_0

→ ***Forcing = ΔF*** = change in outgoing power flux

Additional consequences on H_2O evap., clouds, etc. → "feed backs."

Experience with model simulations: linear relation forcing and T_0.

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

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

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

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

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

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

$$\rightarrow \Delta T_0 \approx \frac{T_0}{8(1 - f/2)} \cdot \Delta f = \frac{1}{4(1 - f/2)\sigma T_0^3} \cdot \Delta F =: \lambda \cdot \Delta F \qquad \Rightarrow \quad \Delta T_0 \approx \Delta f$$

Increasing GHG concentration → increases absorption of surface radiation → increases surface temperature T_0

Radiative Forcing

Perturbations in the atmosphere (additions of GHG) change atmospheric absorption ($f \rightarrow f + \Delta f$) of thermal spectrum for a given (fixed) T_0

→ ***Forcing = ΔF*** = change in outgoing flux

(Additional consequences on H_2O evap., clouds, etc. → "feed backs.")
Model simulations start with linear relation between forcing and T_0.

$$\Delta T_0 = \lambda \cdot \Delta F \qquad Scale\ parameter\ \lambda$$

For a given T_0, perturbation Δf in absorbance changes emitted power flux F by

$$\Delta F := \left[1-(f+\Delta f)/2\right]\cdot\sigma\cdot T_0^4 - \left[1-f/2\right]\cdot\sigma\cdot T_0^4 = -\frac{\Delta f}{2}\cdot\sigma\cdot T_0^4 \quad (T_0 = const. \neq equil.)$$

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

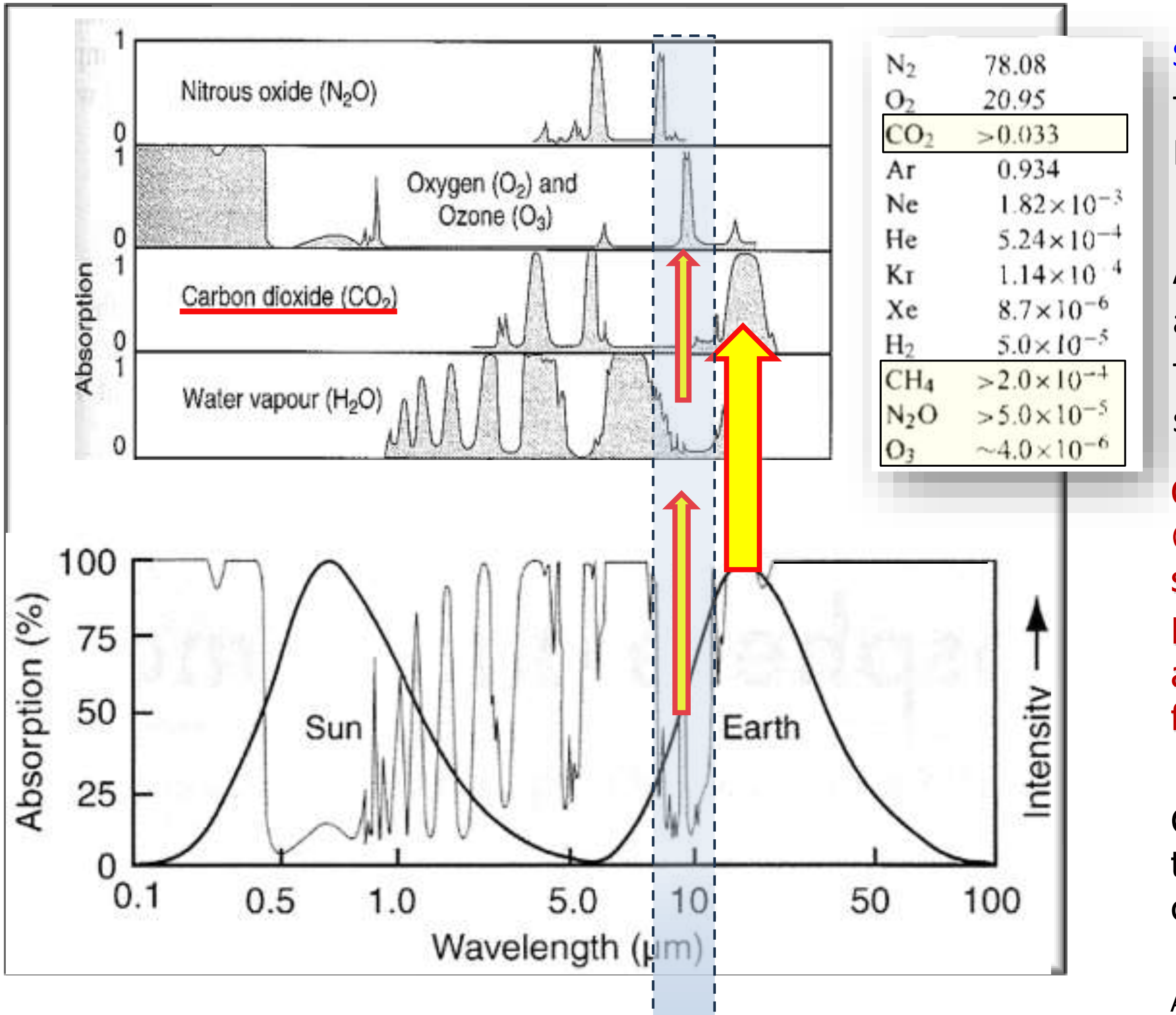
$$F = (S/4)(1-\alpha) = (1-f/2)\cdot\sigma\cdot T_0^4 = \left[1-(f+\Delta f)/2\right]\cdot\sigma\cdot\left[T_0+\Delta T_0\right]^4$$

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

$$\rightarrow \Delta T_0 \approx \frac{T_0}{8(1-f/2)}\cdot\Delta f = \left[\frac{1}{4(1-f/2)\sigma T_0^3}\right]\cdot\Delta F =: \lambda\cdot\Delta F \quad \begin{cases} first\ order\ in\ \Delta f, \Delta T_0 \\ Can\ do\ numerically\ exact. \end{cases}$$

Increasing GHG concentration → increases absorption of surface radiation
→ increases surface temperature T_0

Selective Absorption of Atmospheric GHG



Radiation Escape Hole

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

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

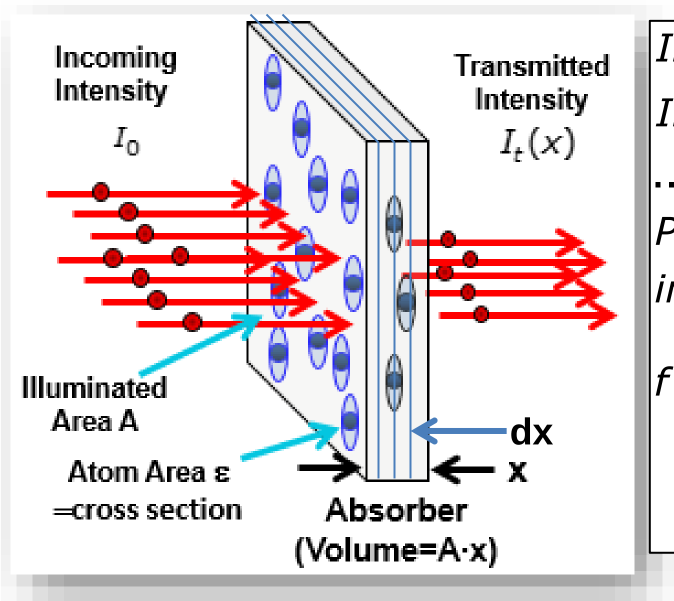
CO_2 absorbs efficiently @ maximum of the Earth' surface spectrum;

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*.

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 : $-\Delta I = f \cdot I \cdot \Delta x$

.........($\rightarrow$ calculus)

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

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

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

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

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

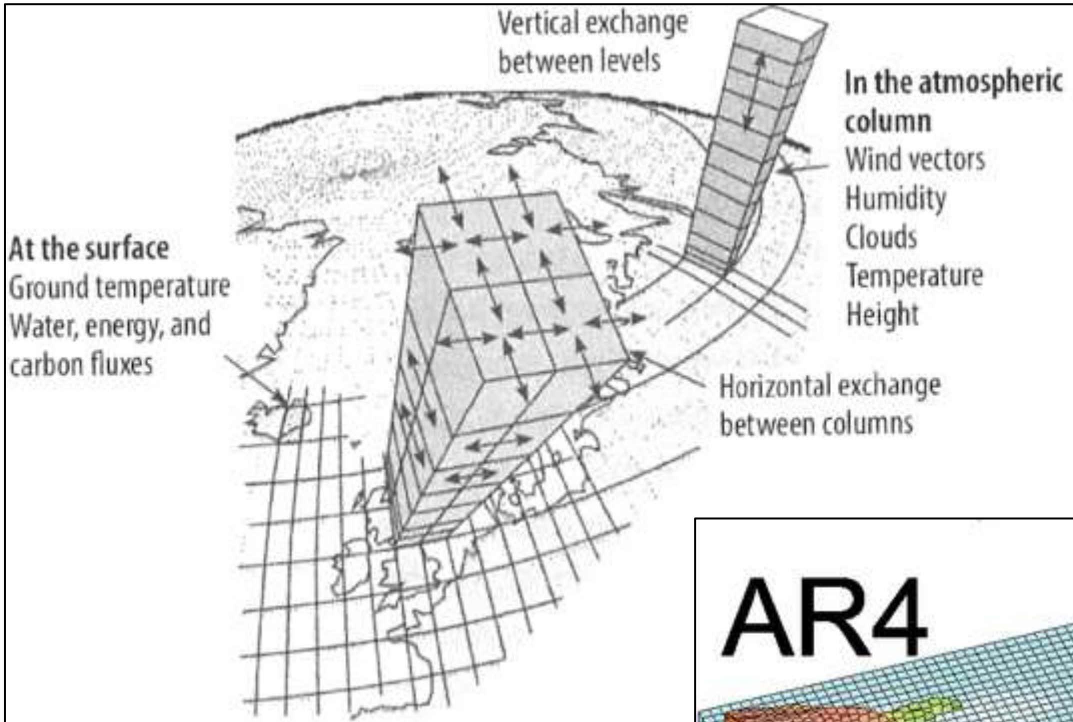
Absorbed : $I_a = I_0 - I(x) = I_0\left(1 - e^{-\mu \cdot x}\right)$

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 $\boldsymbol{\mu}$ and $\boldsymbol{\varepsilon}$ depend on unit of *c*.

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

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