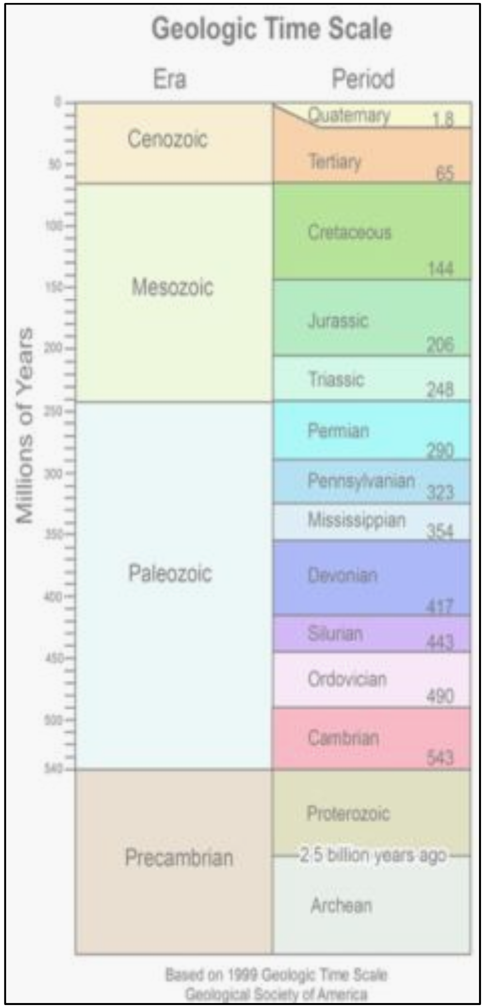
Agenda

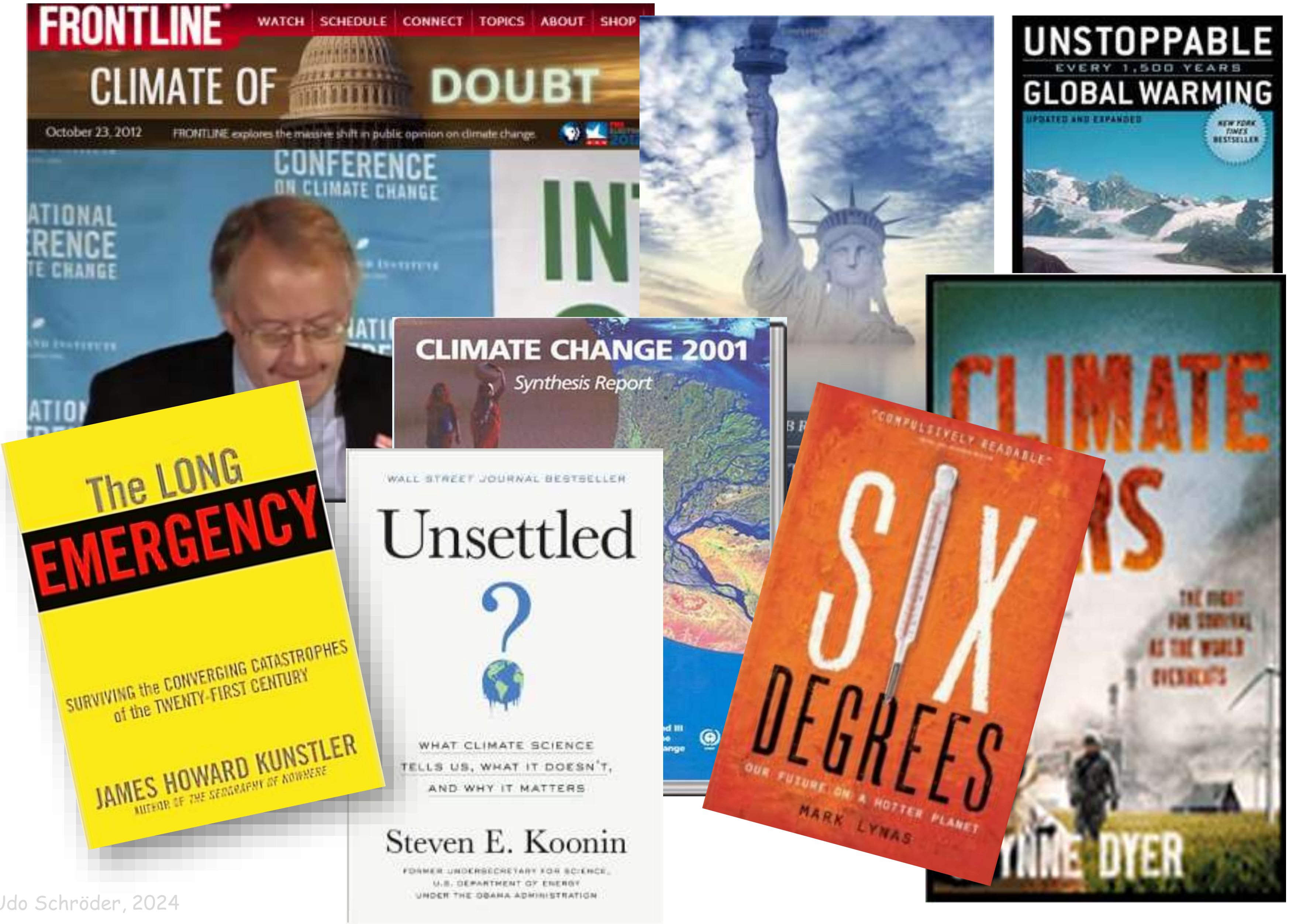
The grand picture (Sustainability @ "Anthropocene")

- Human habitat and resources.
- Sustainability of 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
  Direct & external costs of energy use,
  Climate trend correlations with GHG pollution, extreme weather events, greenhouse effect.
- Stated (aspirational) and actual public policies, mitigation vs. adaptation to environmental & resource challenges.



PLANETARY CLIMATE TRENDS AND CAUSATION

Climate Wars: Apocalypse Soon ?



Extreme Weather Events: Hurricanes, Tornados, Heatwaves

Frequent extreme weather:
Hurricanes Katrina, Irene^{2011},
Sandy,…, Francine^{2024},…
Atmospheric Rivers (PNW, CA),..
Worldwide extreme downpours~$1 L/cm^2$.

Extreme droughts and heatwaves → wildfires, significant loss of human life @ property (GDP), wildlife
Australia (bushfires 2019-20), England (7/2022), Greece, Spain,..
2024 again hottest summer in years: WPost publishes

The Washington Post
Democracy Dies in Darkness

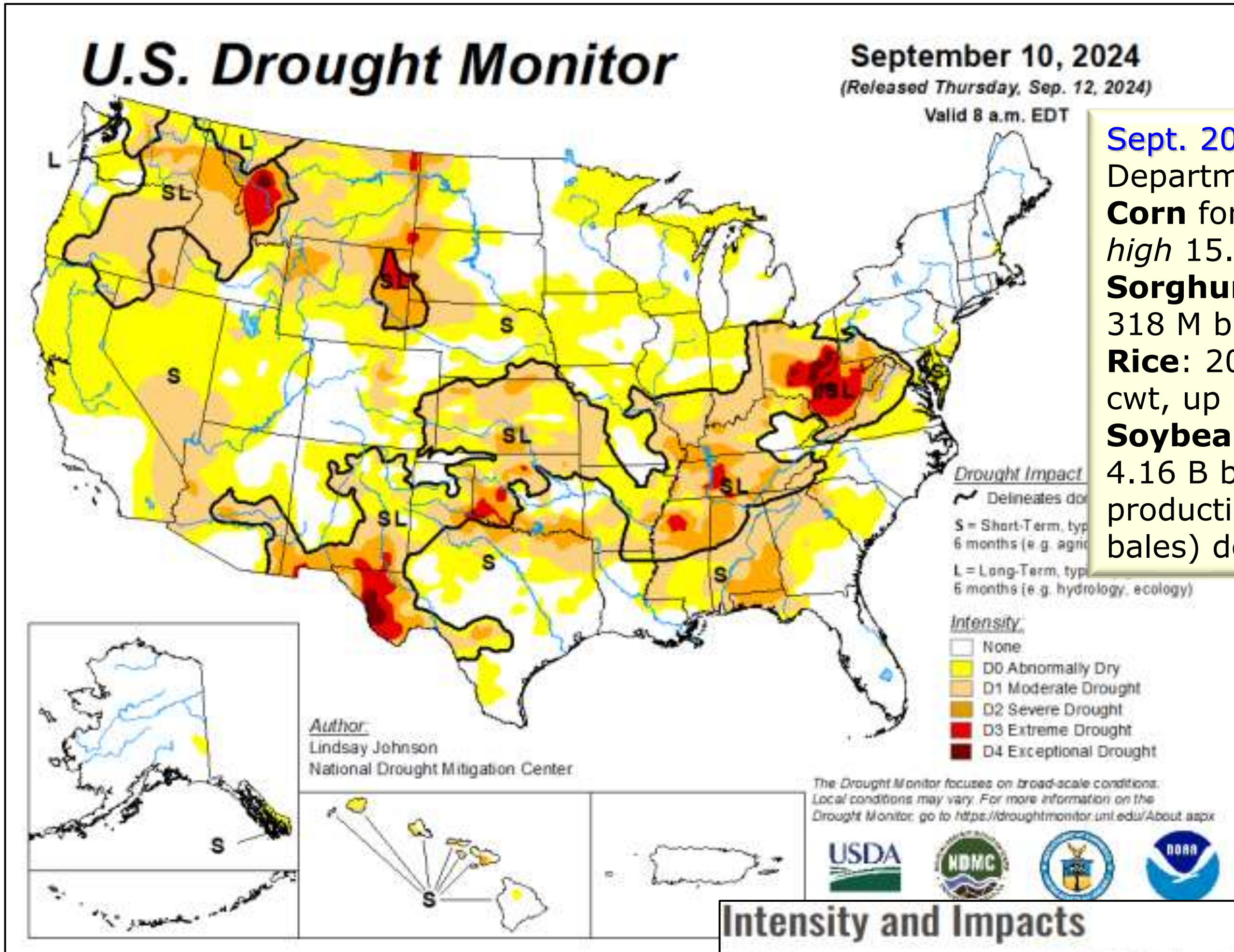
Hottest cities today, by heat index

City	Sat.	Sun.	Mon.	Tue.	Wed.	Thu.	Fri.
Tulsa, Okla.	114°	109°	103°	99°	99°	98°	90°
Oklahoma City, Okla.	113°	106°	101°	96°	96°	98°	93°
Wichita, Kan.	109°	108°	102°	96°	94°	93°	80°
Fort Worth, Texas	106°	102°	104°	104°	104°	106°	106°
Irving, Texas	105°	102°	104°	103°	103°	106°	106°
Dallas, Texas	105°	102°	103°	103°	103°	105°	105°
Arlington, Texas	105°	101°	102°	100°	101°	105°	105°
Corpus Christi, Texas	105°	106°	103°	105°	108°	109°	108°
Lincoln, Neb.	105°	109°	107°	91°	92°	84°	77°
San Antonio, Texas	104°	102°	101°	101°	101°	104°	105°
Plano, Texas	104°	101°	102°	102°	102°	104°	104°
Omaha, Neb.	103°	110°	109°	91°	93°	84°	77°
Tampa, Fla.	103°	105°	105°	102°	105°	102°	102°
St. Petersburg, Fla.	103°	103°	103°	102°	105°	101°	103°
Laredo, Texas	103°	103°	102°	100°	101°	104°	104°
Austin, Texas	103°	103°	102°	102°	104°	106°	107°

Downtown Montpelier, VT July 2023. More frequent floodings of cities.

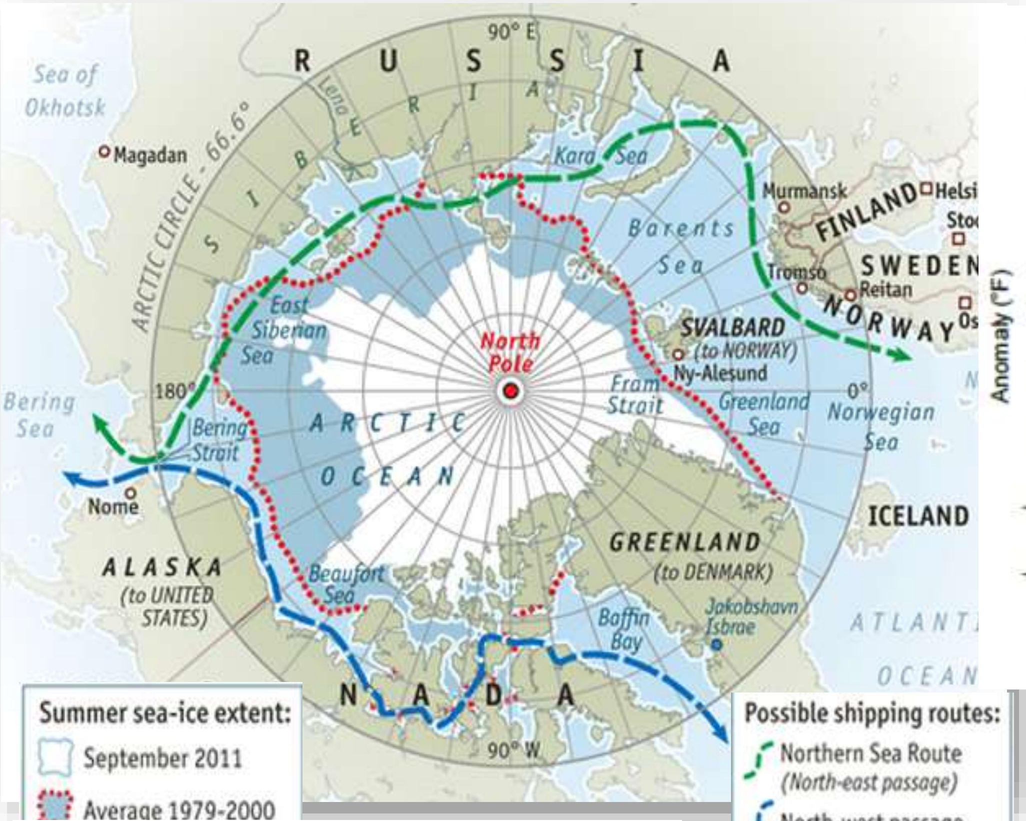
Europe: sustained heavy downpours in various countries.

Extreme Climate Events: Heat Waves & Droughts

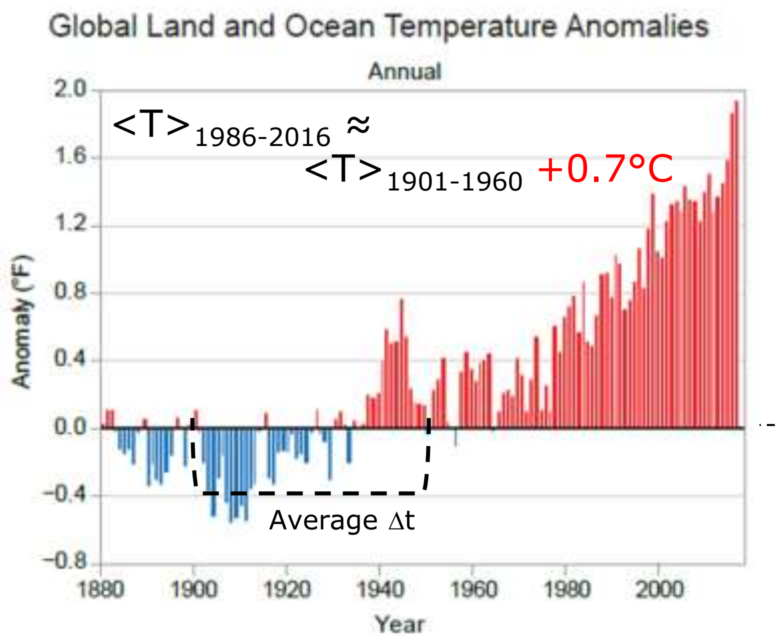


Sept. 2024: U.S.D.A. (Agriculture Department) about 2023 crops: **Corn** for grain production *record high* 15.3 B bushels =+10%. **Sorghum**: Grain production at 318 M bushels +69% from 2022. **Rice**: 2023 production at 218 M cwt, up 36% from 2022. **Soybeans**: 2023 production at 4.16 B bushels, down 2%. Cotton production at 12.4 M (480-pound bales) down 14%.

Evidence for Large-Scale (Global) Changes



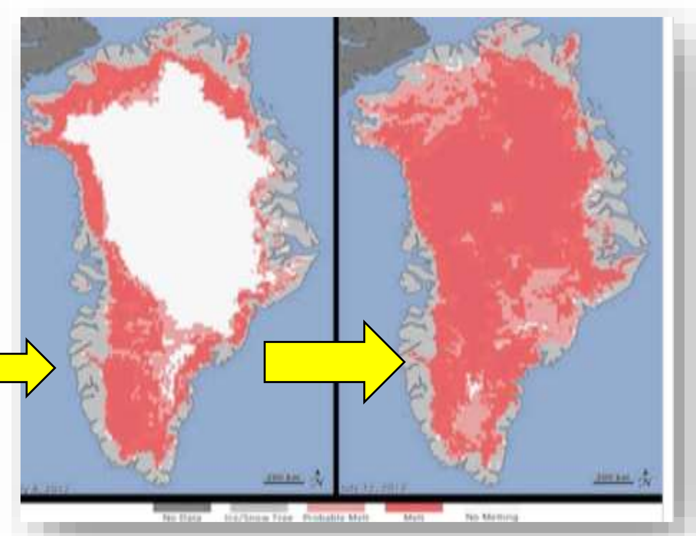
From: IPCC 5th Assessment Report (2014)



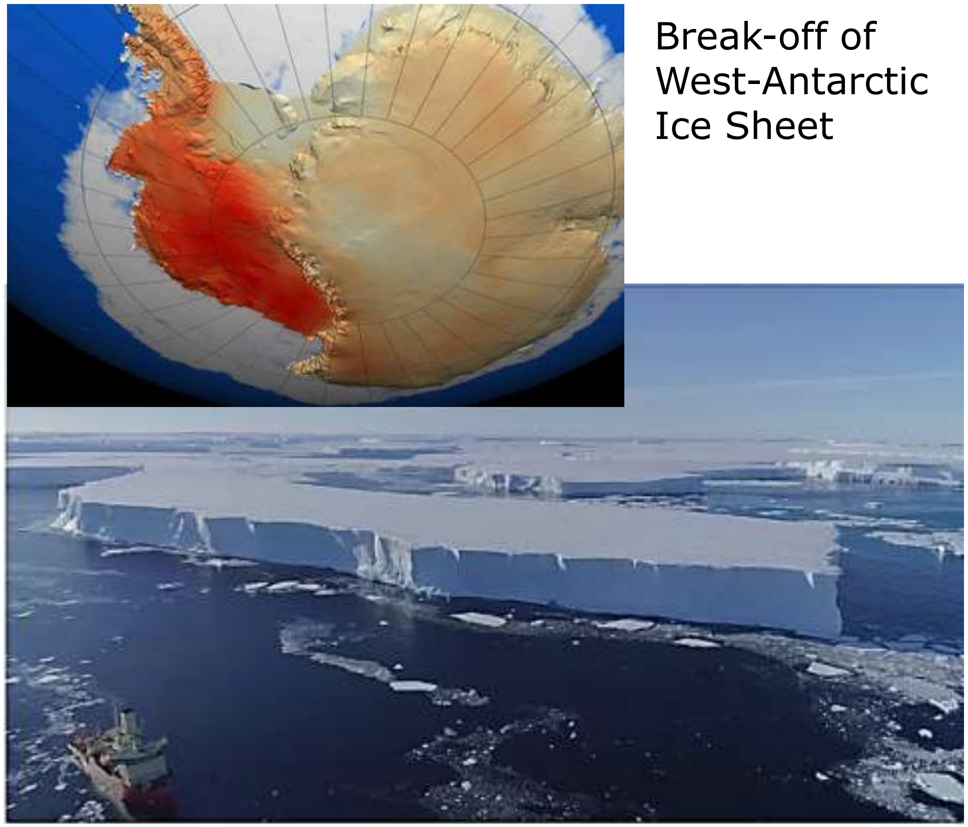
Important Q: Natural vs. man-made ?

Greenland surface ice layer melts 7/8–7/12, 2011=within 4 days!

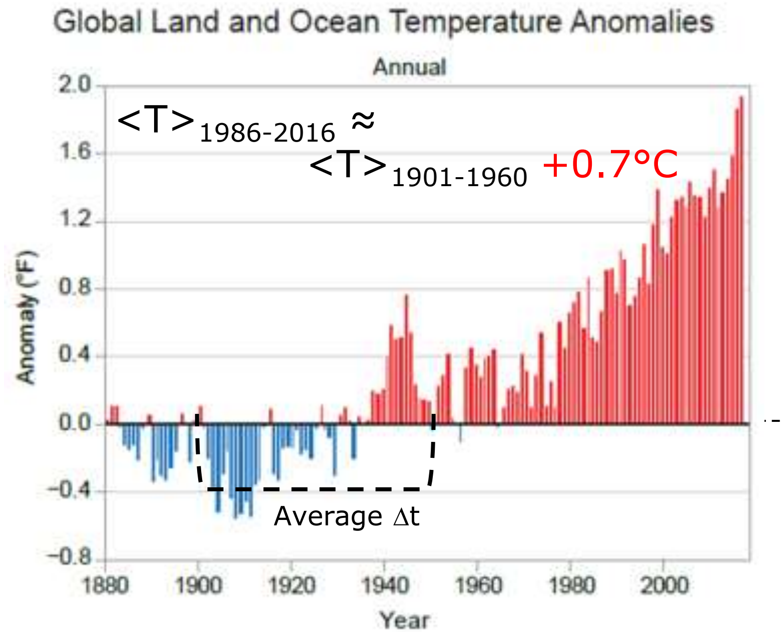
NASA/NOAA satellite image.



Evidence for Large-Scale (Global) Changes



Break-off of West-Antarctic Ice Sheet

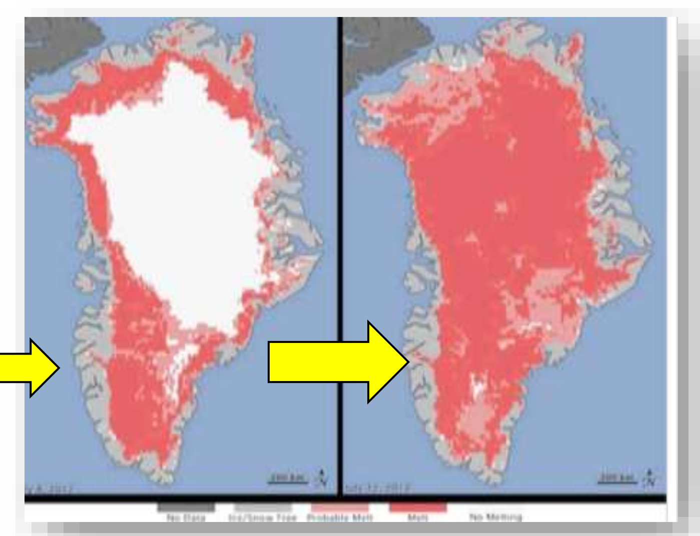


Delaware-size iceberg to break off Antarctica's immense **Larsen C ice shelf** in the Southern Hemisphere winter of 2017.

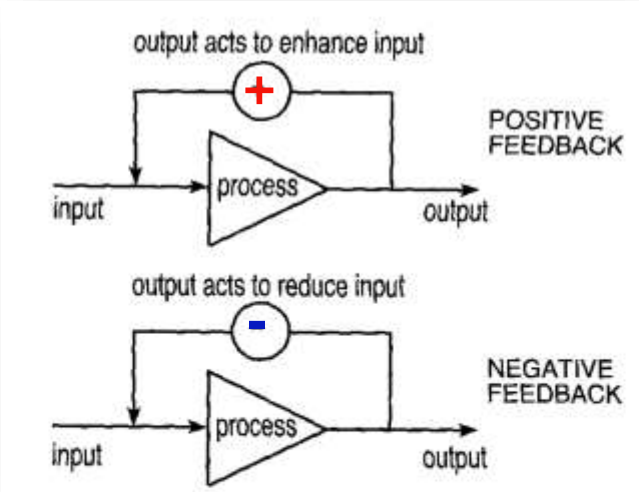
Important Q: Natural vs. man-made ?

Greenland surface ice layer melts 7/8–7/12, 2011=within 4 days!

NASA/NOAA satellite image.



Feedback Effects Find & Establish Equilibria



Important feedback forcing mechanisms considered in climate models:

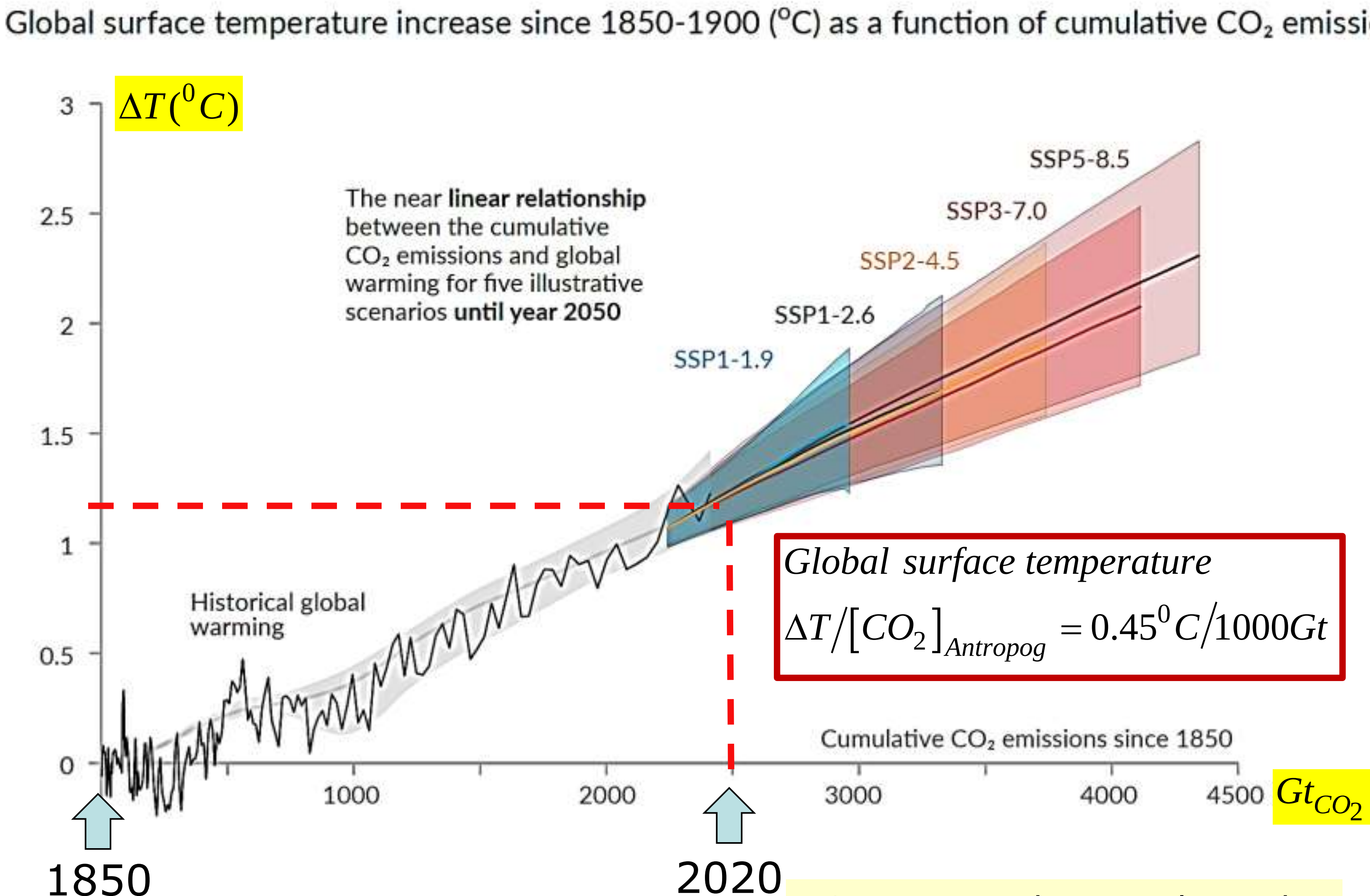
- Changing albedo: Sea water surface reflects less radiation, increases T, more ice melting →
- CO_2 runaway process: Increase $[CO_2]$ → increase T → release additional CO_2 ($+CH_4$) from frozen Tundra and from dissolved seawater →
- H_2O greenhouse effect: More humidity raises atmospheric ***IR*** absorption, higher T, more humidity →
- Cloud effects (dynamical and thermal), complex interaction between radiation, convection, circulation, cloud cover. Similar: Dust/aerosols
- Albedo effect dominates.

H_2O greenhouse effect loses importance if troposphere is already opaque to IR. Then, it only affects heat convection.

Combination of partially canceling positive and negative feedbacks. However:
Complex (non-linear) systems have capacity of sudden irregular (chaotic) response to small changes of parameters.

Is Earth in a non-linear regime @ tipping points?

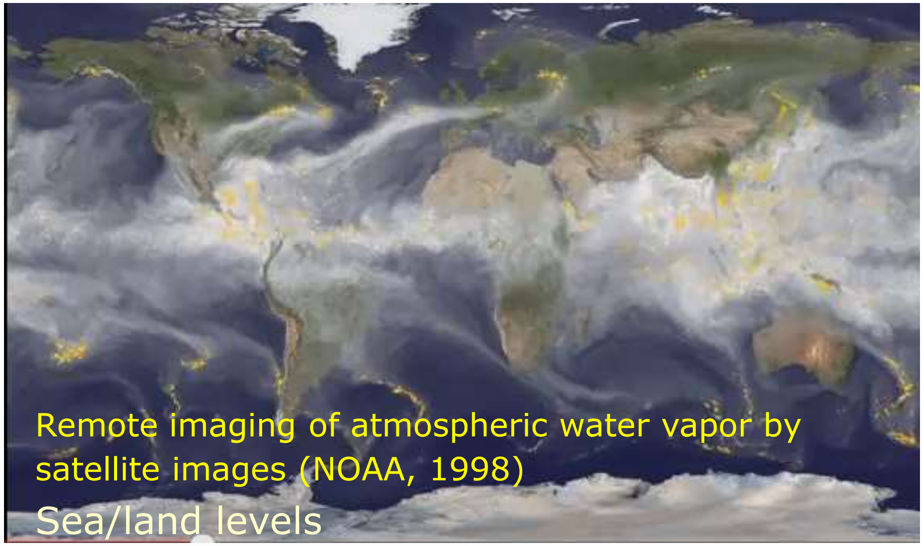
Mean Temperature - GHG Inventory Correlation



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

Compare to historical trends

Big Data: Weather & Climate Information Sources



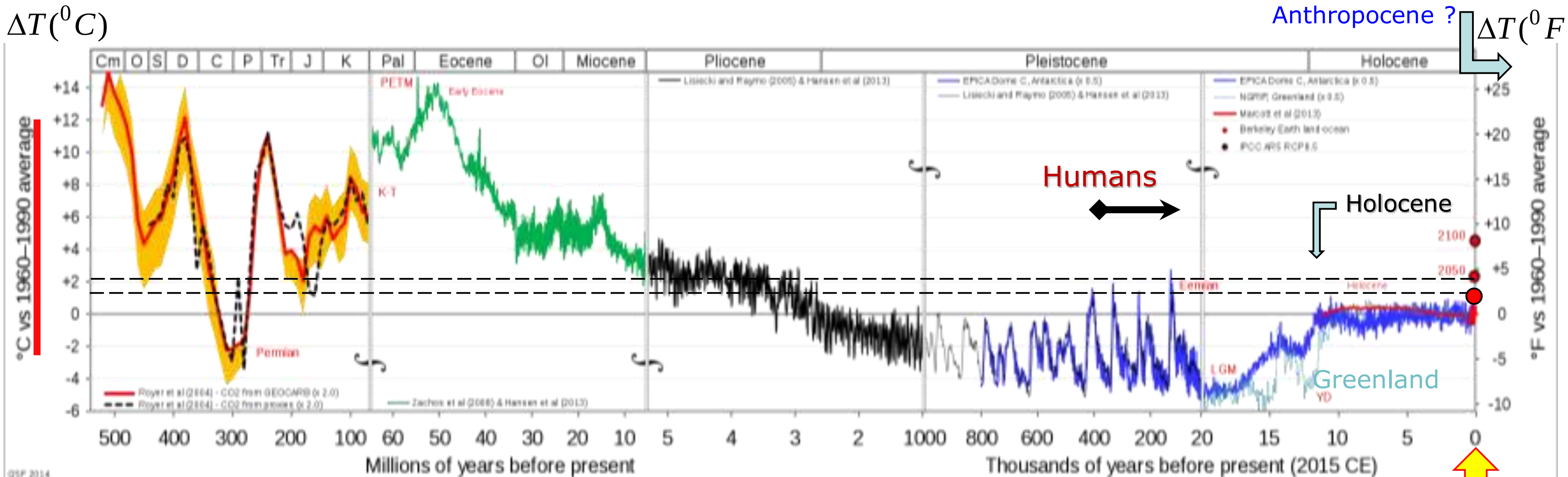
Systematic studies to establish global historic trends require:
Excellent weather/climate information provided by several national/international agencies allows systematic climate evaluation and projection→ Research efforts in National Labs/Univ.

Examples:

1. U.S. *Historical Climatology Network* (USHCN): 1221 observing stations in the 48 contiguous states (Europe equivalent).
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.

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/

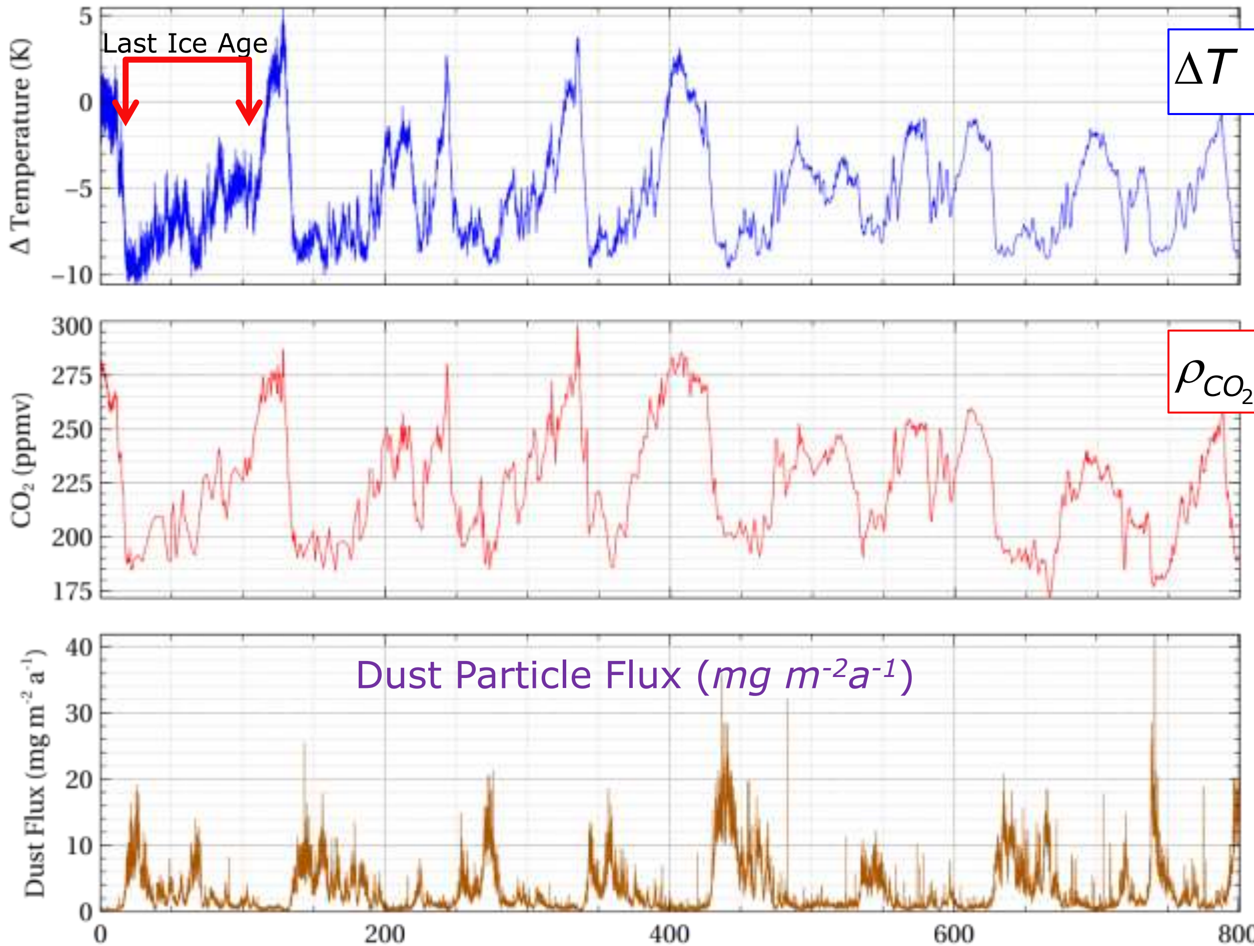
time

NOW

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

Paleo-Climate Correlated Trends: Global Surface Temps

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



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

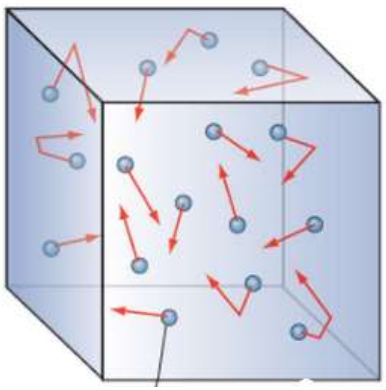
$$\rho_{CO_2}(t)\ (ppm,\ volume)$$

1950

Time Age (in 1000 years before 1950)

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

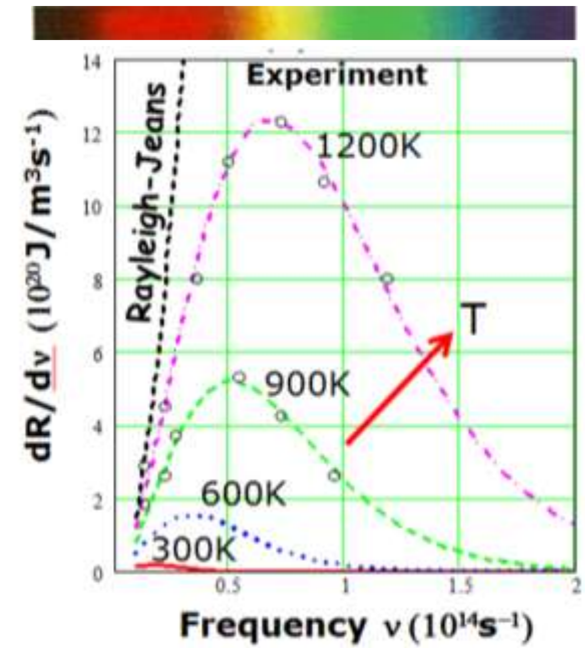
Thermal "Black Body" Radiation: Random Particle Motion



Charged Particles

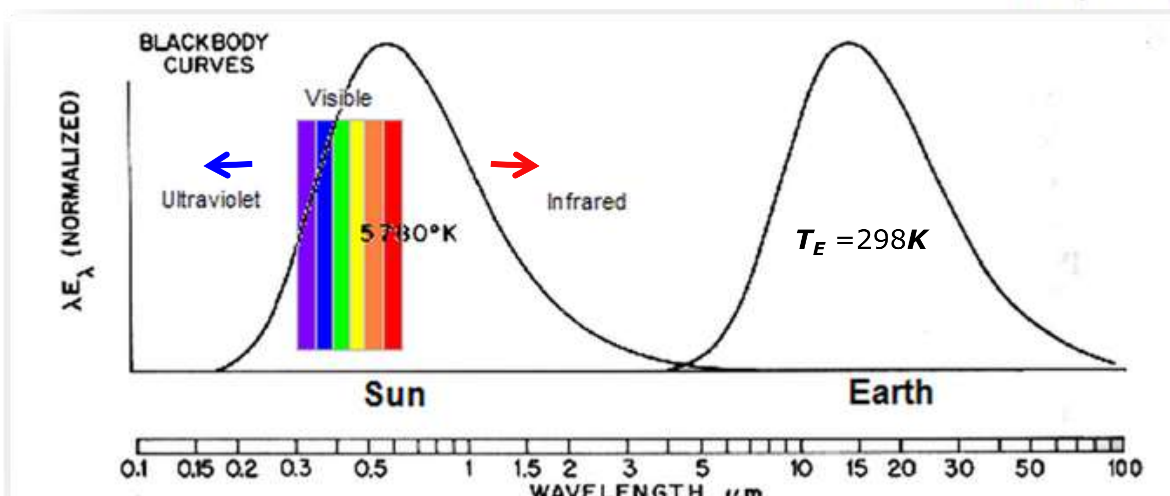
Any charged particles in random motion → continuous "thermal" kinetic energy spectrum.
→ Emit photons with continuous energy (ν, λ) spectrum

Equilibration & Relaxation →

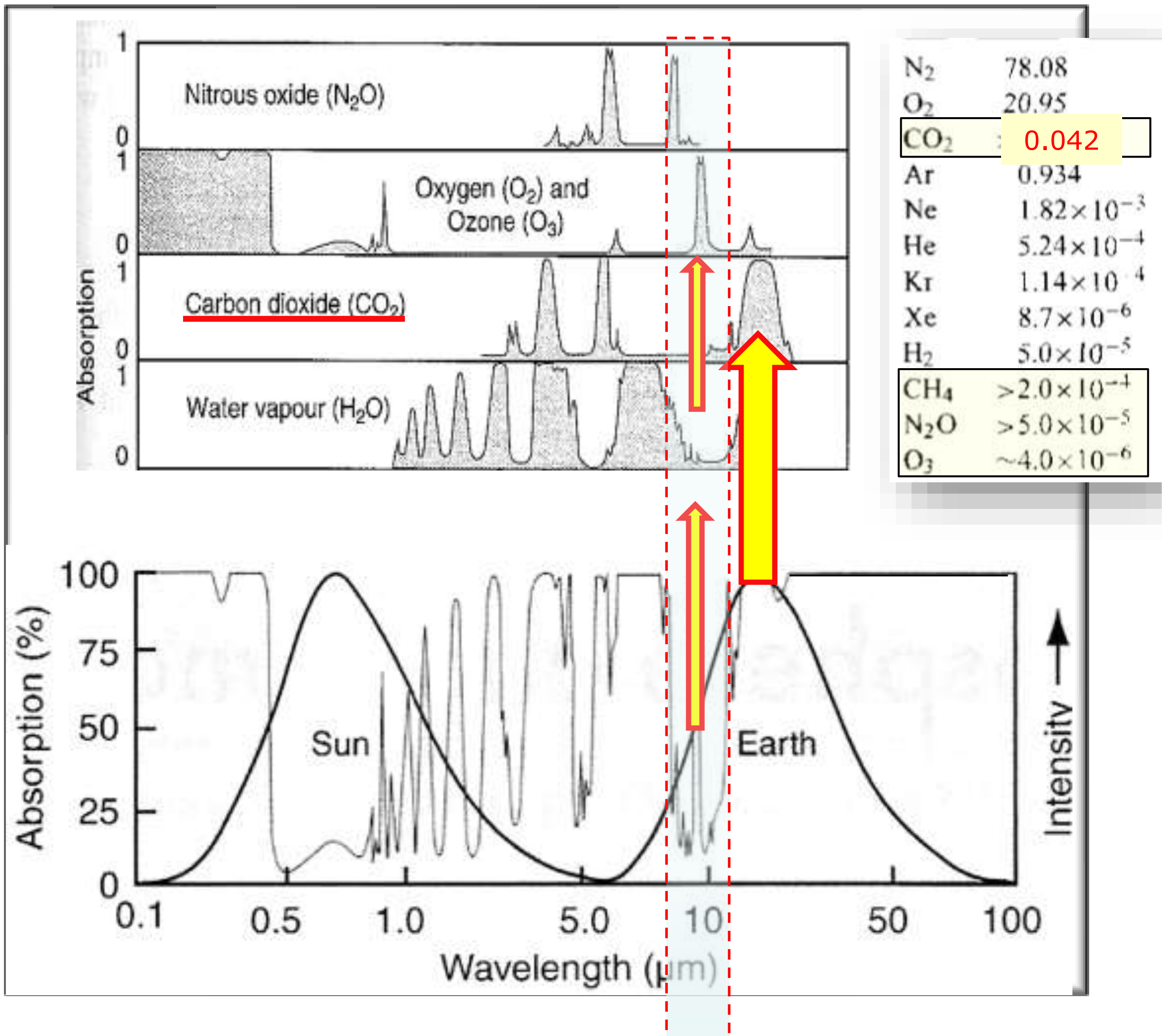


Bare Earth is also approximately a "black body," but with a low temperature, equilibrium (estim.): T_E=298 K (25^{0}C).

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



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 → equilibrates → radiates back to space and to Earth surface.

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

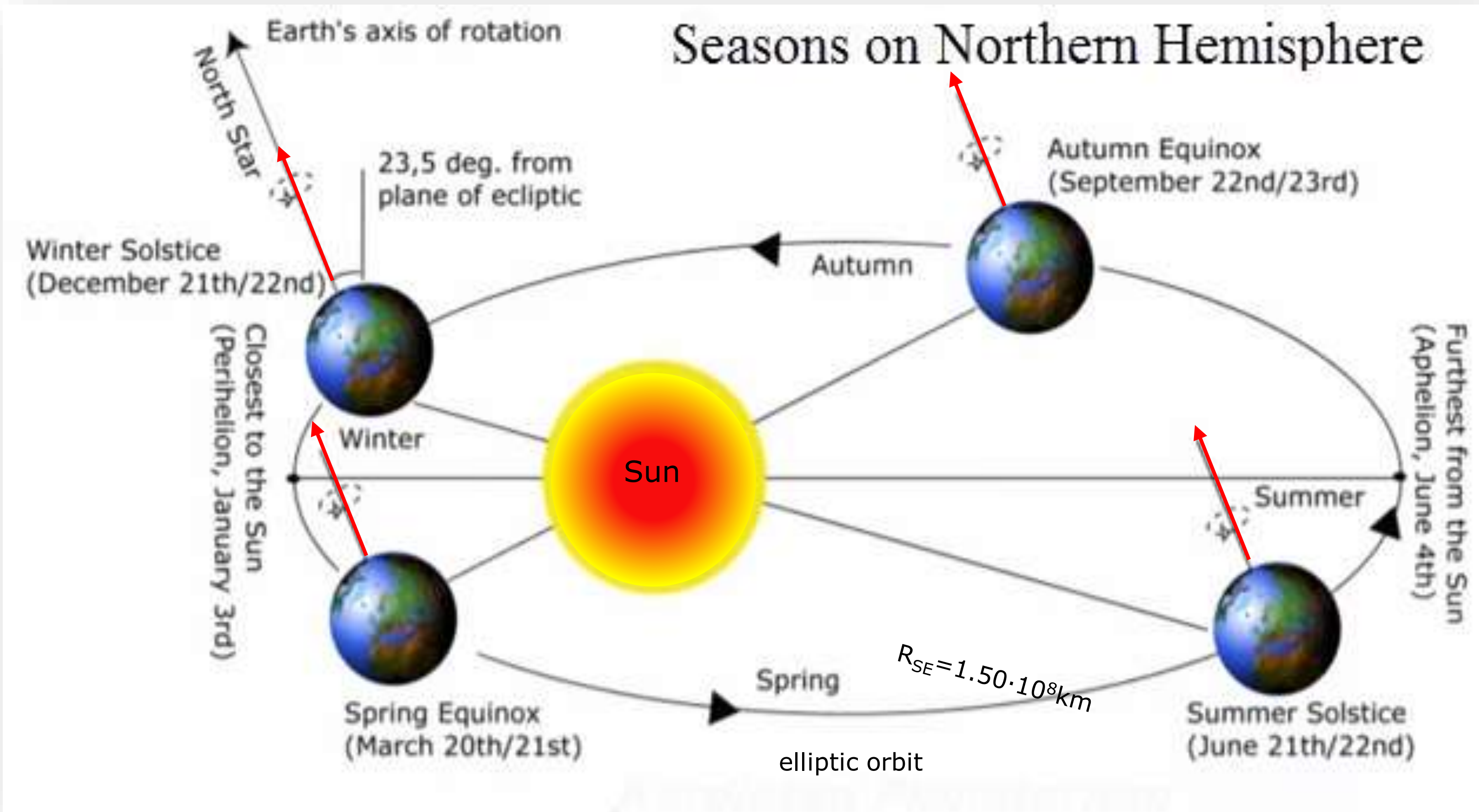
N_2O and CH_4 absorb in atmospheric escape hole for radiation.

GHG concentrations on the rise during the last century.

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

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).

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

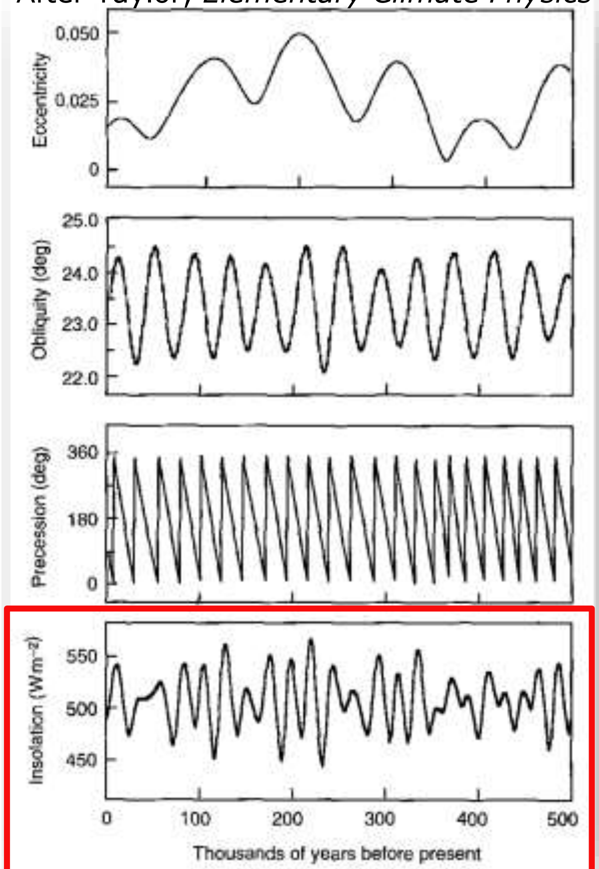
1) External causes (solar radiation influx):
   - a) changes in Earth orbital eccentricity ($\Delta e \sim (0.01\text{-}0.2)\%$, $T_{ecc} \sim 110{,}000$ a),
   - b) orbital precession ($T \sim 20{,}000$ a)
   - c) obliquity ($\Delta\theta = \pm 1^0$, $T_{obl} \sim 40{,}000$ a) of rotational axis.
 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

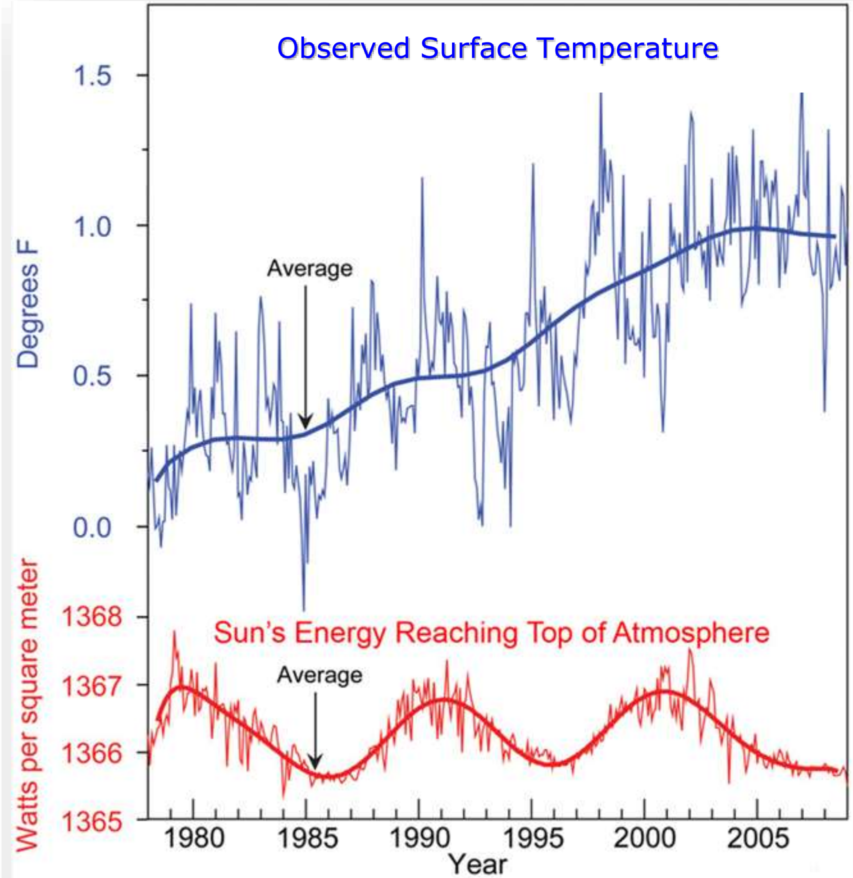
2) Internal causes:
   - a) Volcanic eruptions producing aerosols.
   - b) Changes in oceanic currents.
   - c) Changes in ice and cloud coverage (albedo).
   - d) Human induced changes (emission of greenhouse gases, tropospheric aerosols, CFCs and HCFCs producing "ozone hole").

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

Elimination of Extra-Terrestrial Effects

After Taylor, *Elementary Climate Physics*



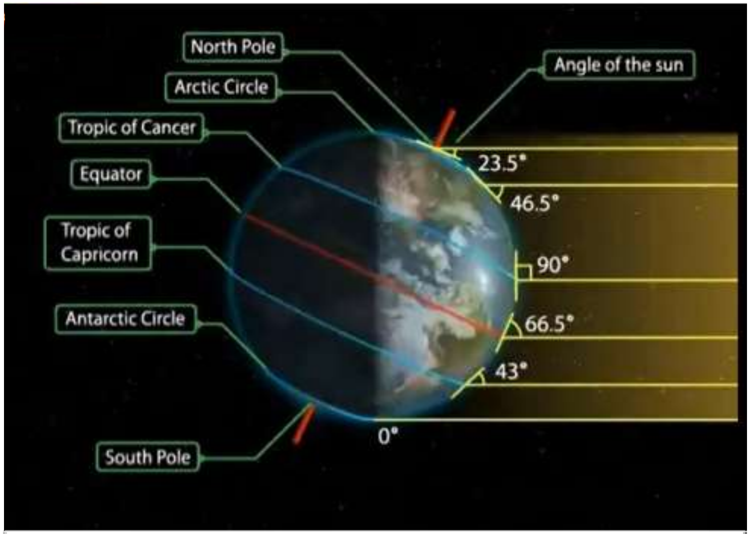


The sun's energy received at the top of Earth's atmosphere has been measured by satellites since 1978. It has followed its natural 11-year cycle of small ups and downs, but with no net increase (bottom). Over the same period, global temperature has risen markedly (top).

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.

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:

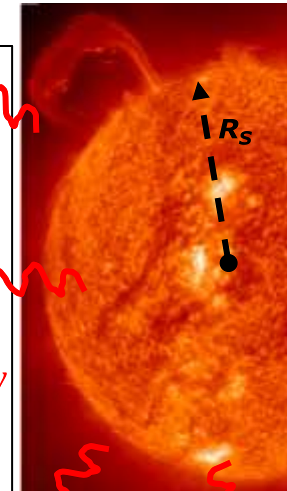
$$\boxed{R(\lambda,T)=\frac{2hc^2}{\lambda^5}\left[\frac{1}{e^{hc/\lambda kT}-1}\right]\left(\frac{W}{m^3\cdot sr}\right)}$$

Stephan – Boltzmann Radiation Law

Total power emitted

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

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



R_S=6.96·10^5 km

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

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

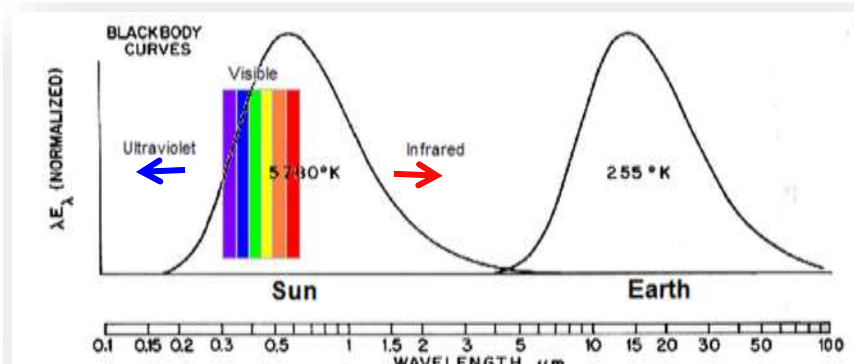
Role of atmosphere → raises ambient temperature ("good" greenhouse effect).

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

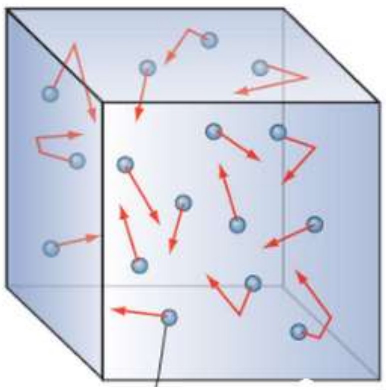
$k=1.3\cdot10^{-34}\ J\cdot s$ Boltzmann's constant

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

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



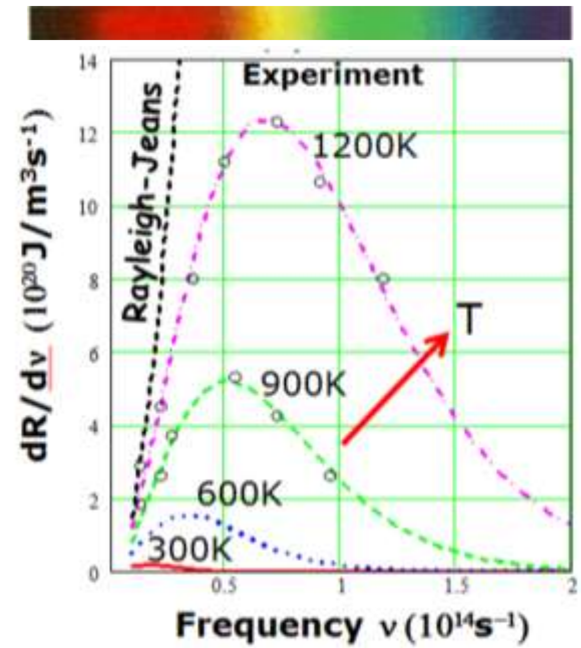
Random Motion → Black Body Radiation



Charged Particles

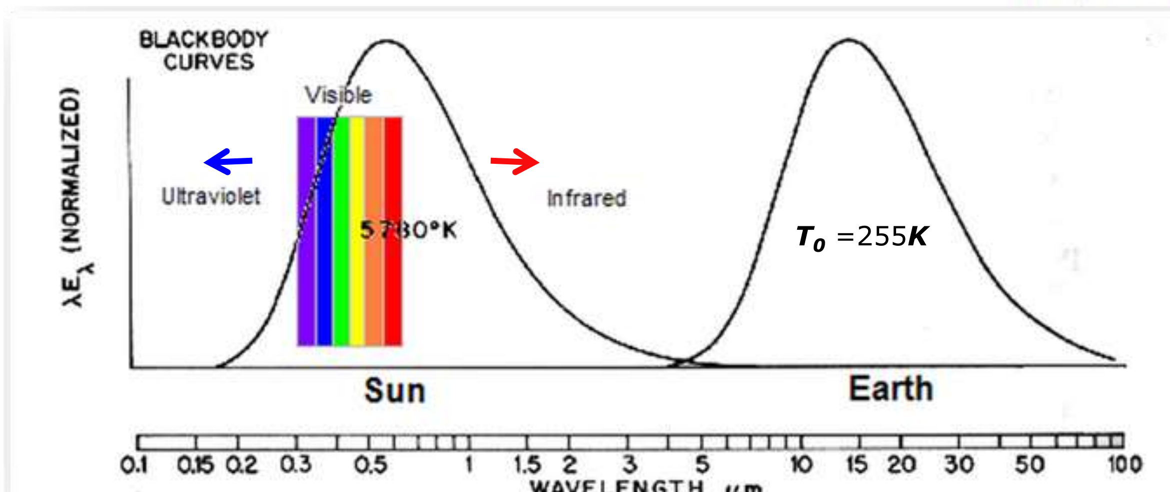
Charged particles in random motion → continuous "thermal" kinetic energy spectrum.
→ Emit photons with continuous energy (ν, λ) spectrum

Equilibration & Relaxation →



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

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



Solar Insolation on Earth

Solar Constant

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

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

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

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

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

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

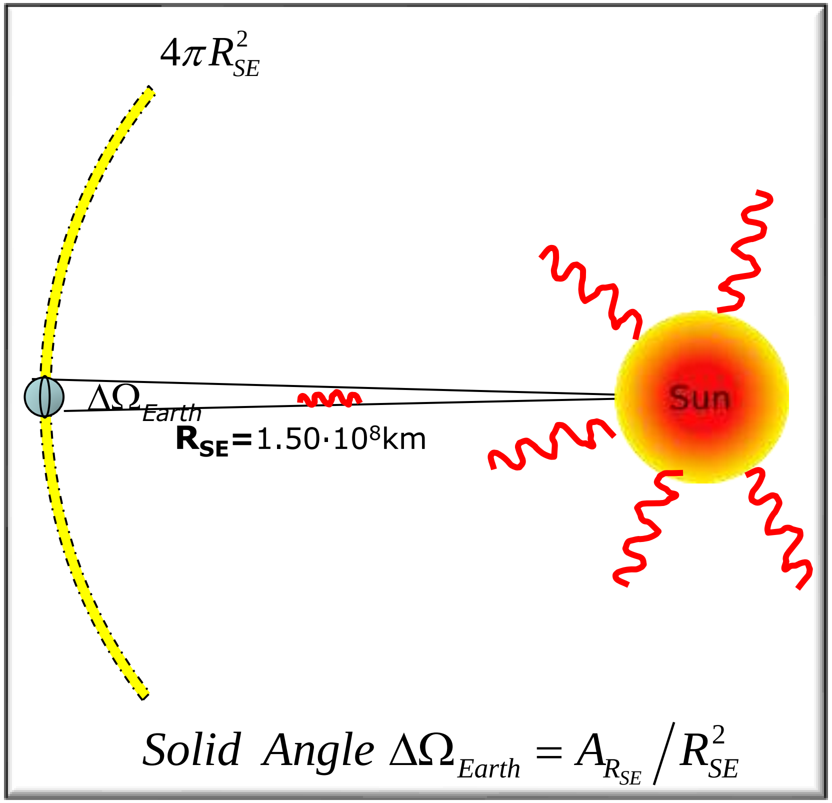
$$Albedo\ \alpha = reflectivity,\ \alpha_E \approx 0.3\ (expt.)$$

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

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

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

$$(More\ sophisticated\ models\ for\ Earth\ energy\ balance\ are\ available)$$

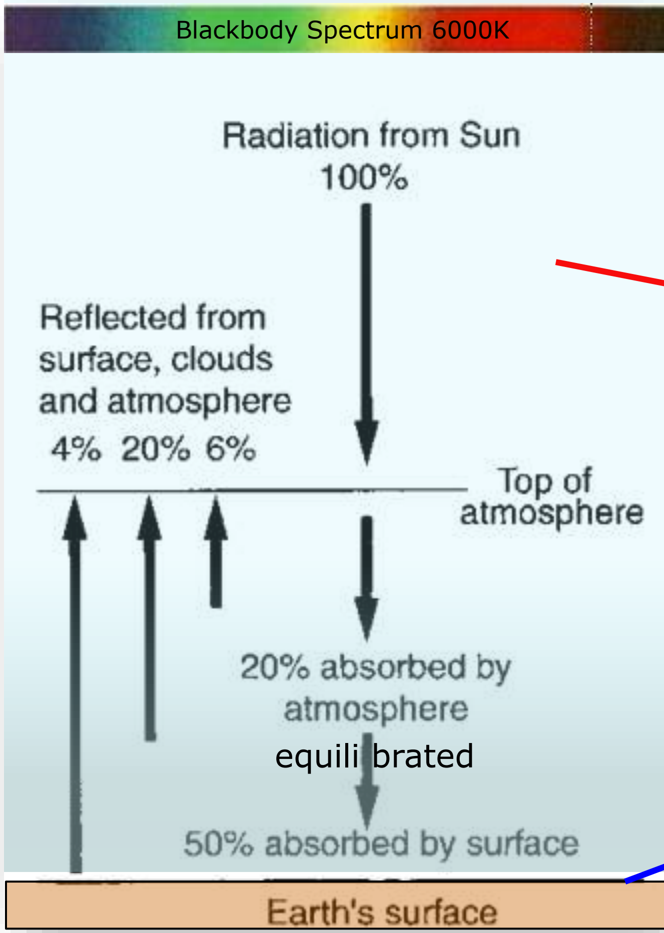


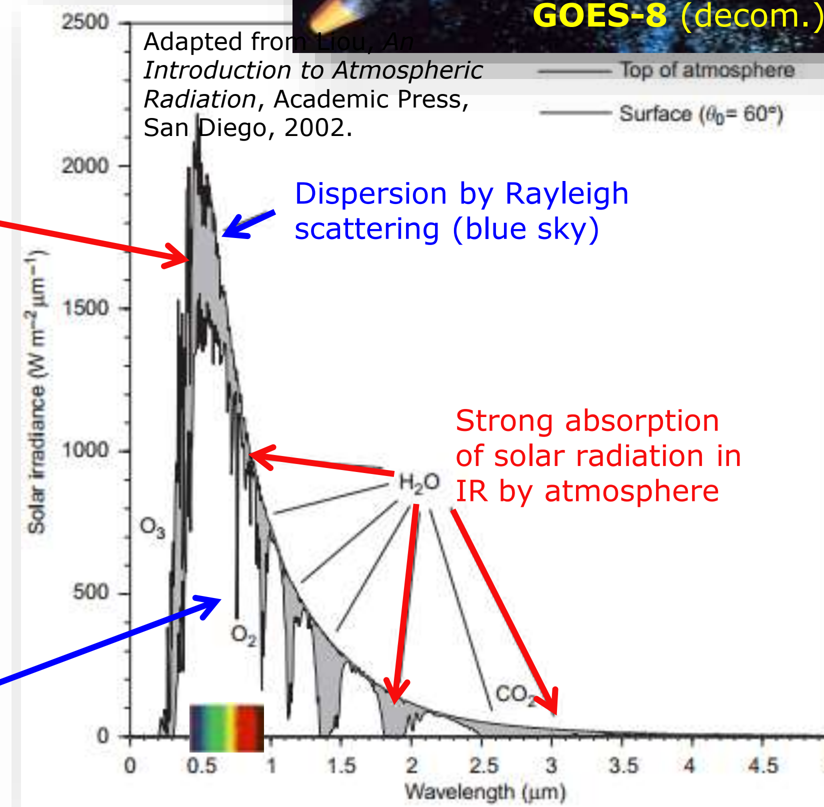
Effect of solar irradiation on Earth surface is non-cumulative, non-linear, possibly unstable.
System of several negative and positive feed-back effects.
Possible: Thermal equilibrium ?

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)

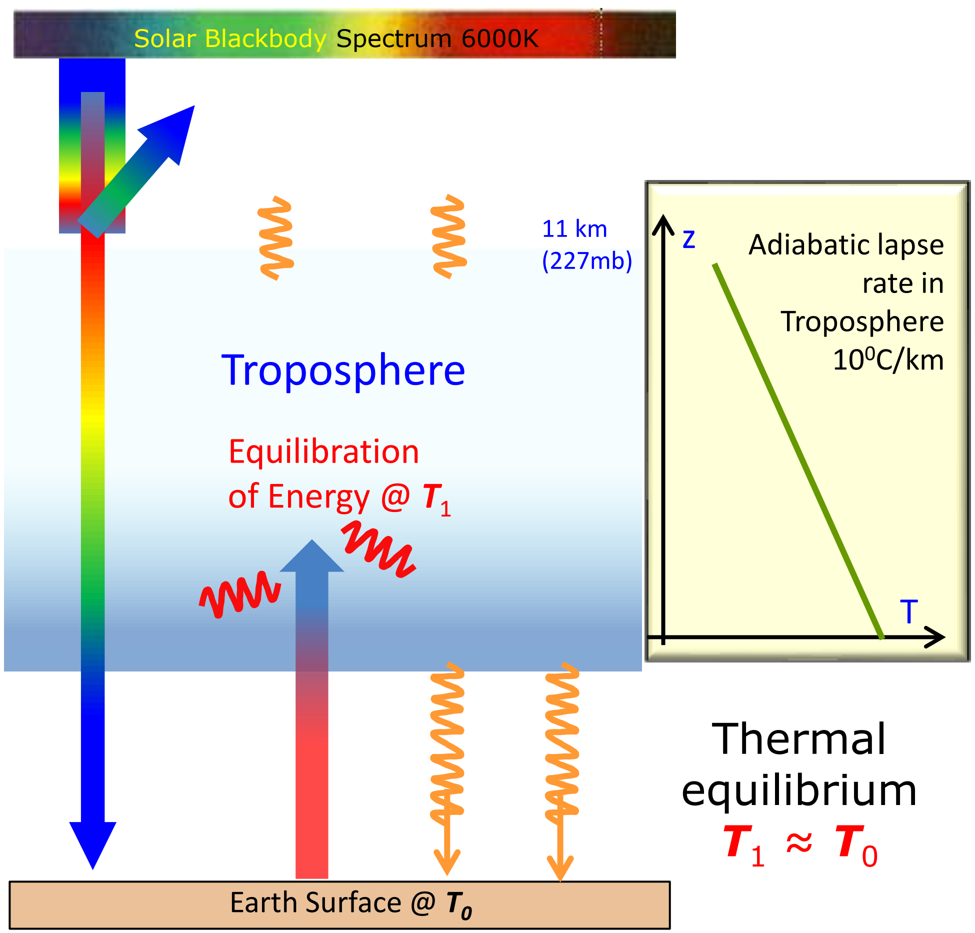
See, e.g., F. P. J. Valero et al., J. GEOPHYS. RES., 105, 4743 (2000)





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.

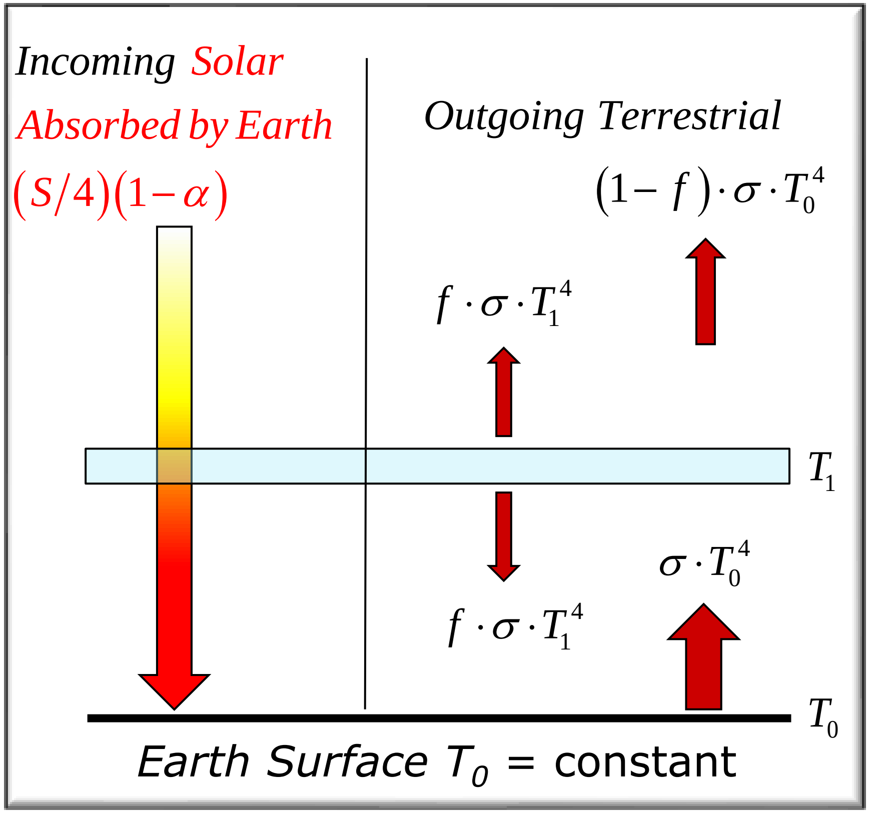
IR radiation from surface is absorbed by atmosphere, heating it up.

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 : $T_0 \rightarrow T_0' = T_0 + \Delta T_0$

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

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

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

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 : $T_0 \rightarrow T_0' = T_0 + \Delta T_0$

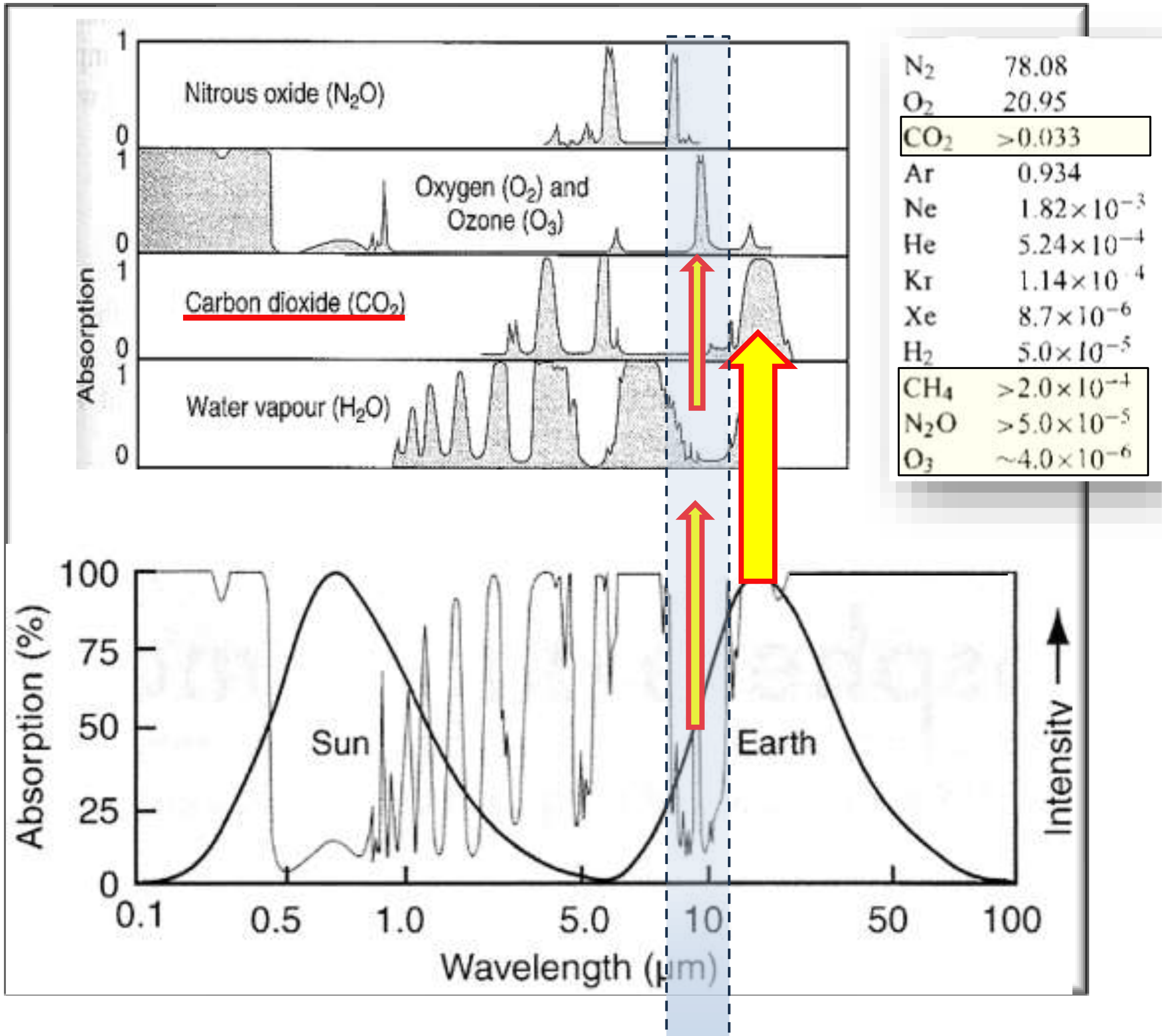
$$F = (S/4)(1-\alpha) = (1-f/2)\cdot\sigma\cdot T_0^4 = \left[1-(f+\Delta f)/2\right]\cdot\sigma\cdot\left[T_0+\Delta T_0\right]^4$$

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

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

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

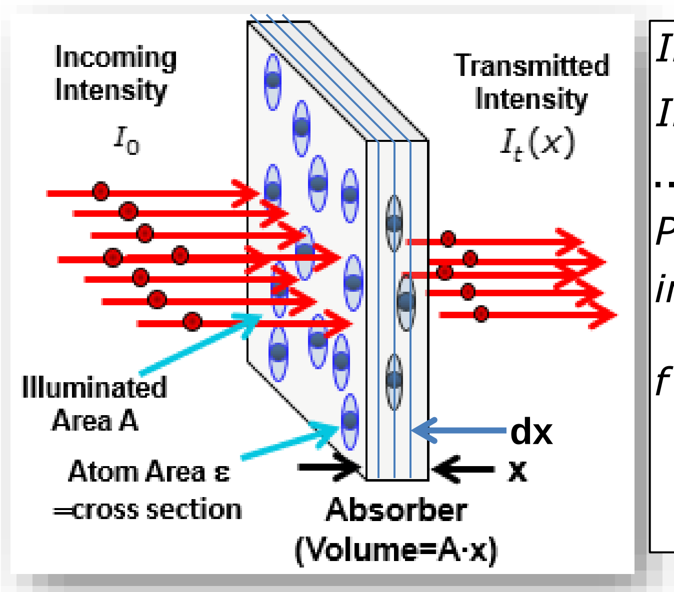
Absorption of radiation in atmosphere → equilibrates → radiates back to space and to Earth surface.

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*.

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 : $\underline{dP_{abs}(x) \propto dx}$

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

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

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

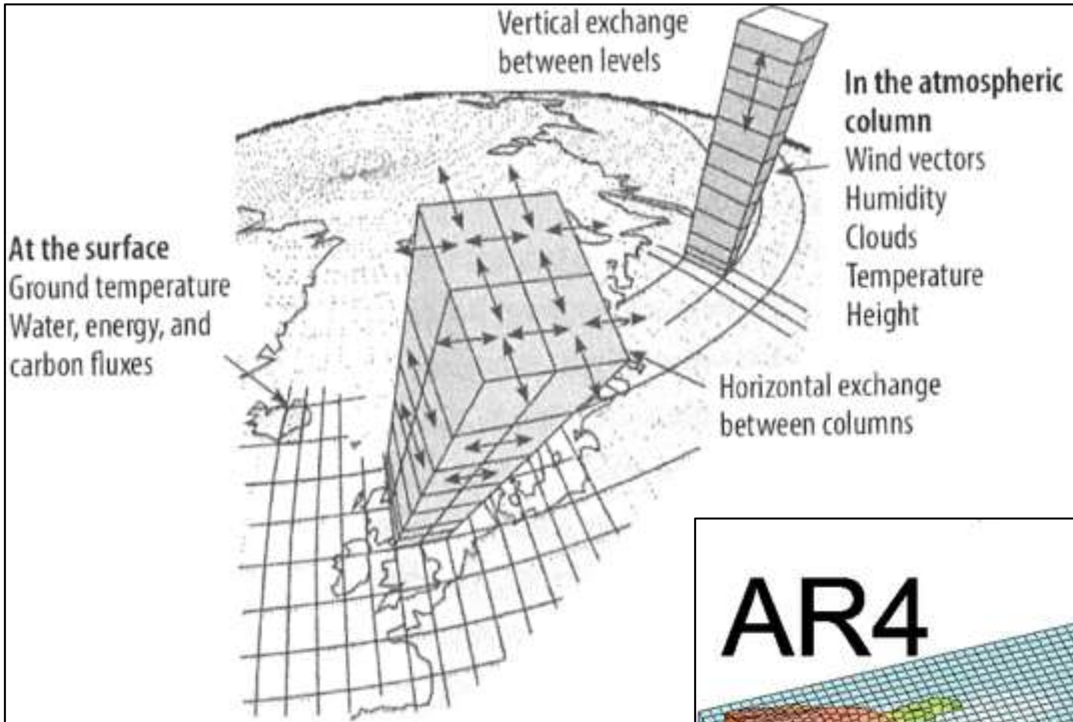
Absorbed : $\boxed{I_a = I_0 - I(x) = I_0 \left(1 - e^{-\mu \cdot x}\right)}$

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.

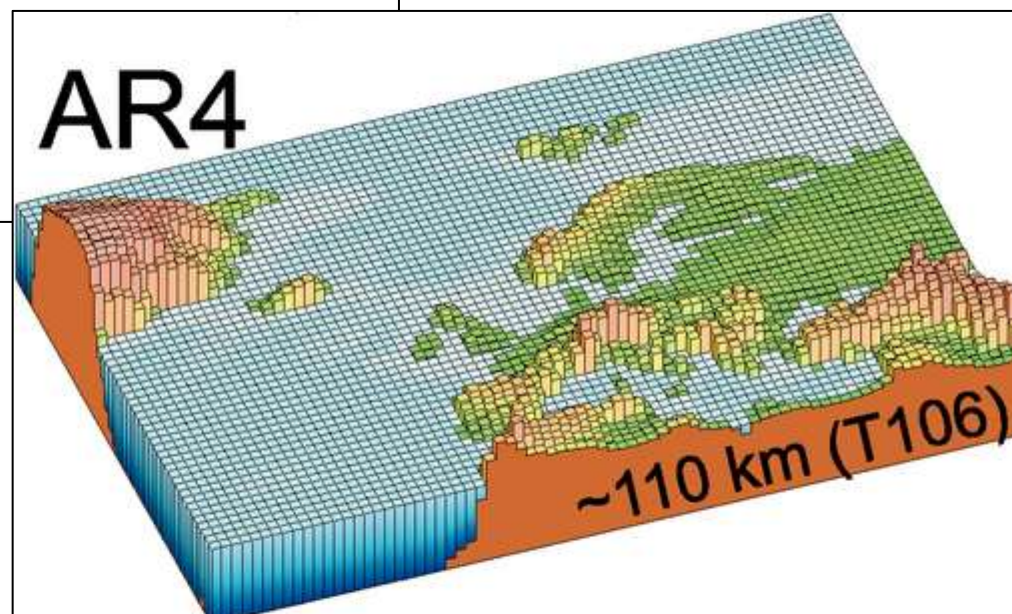
Climate Models: Geographic Resolution



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

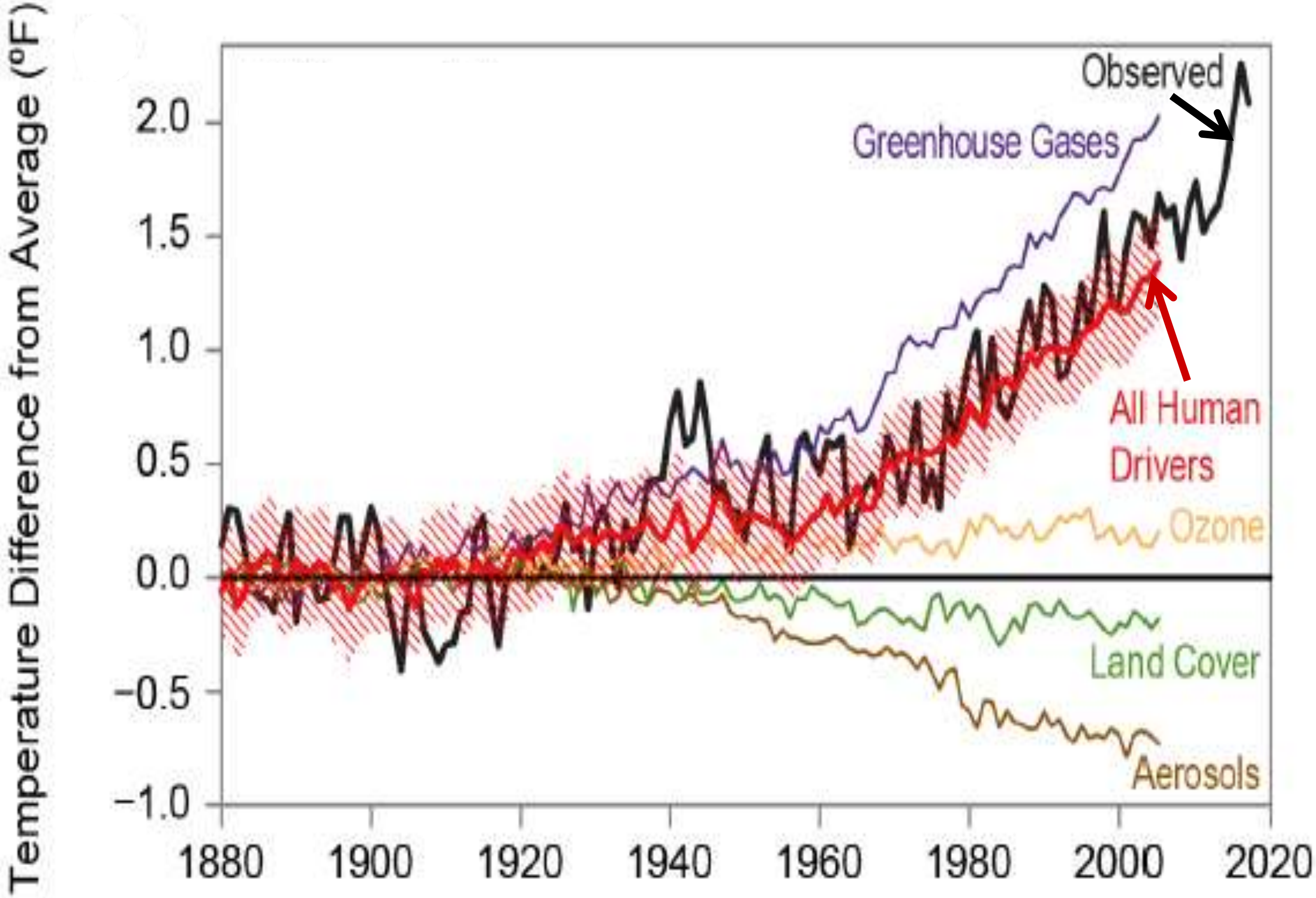


Anthropogenic Influences: Global Climate

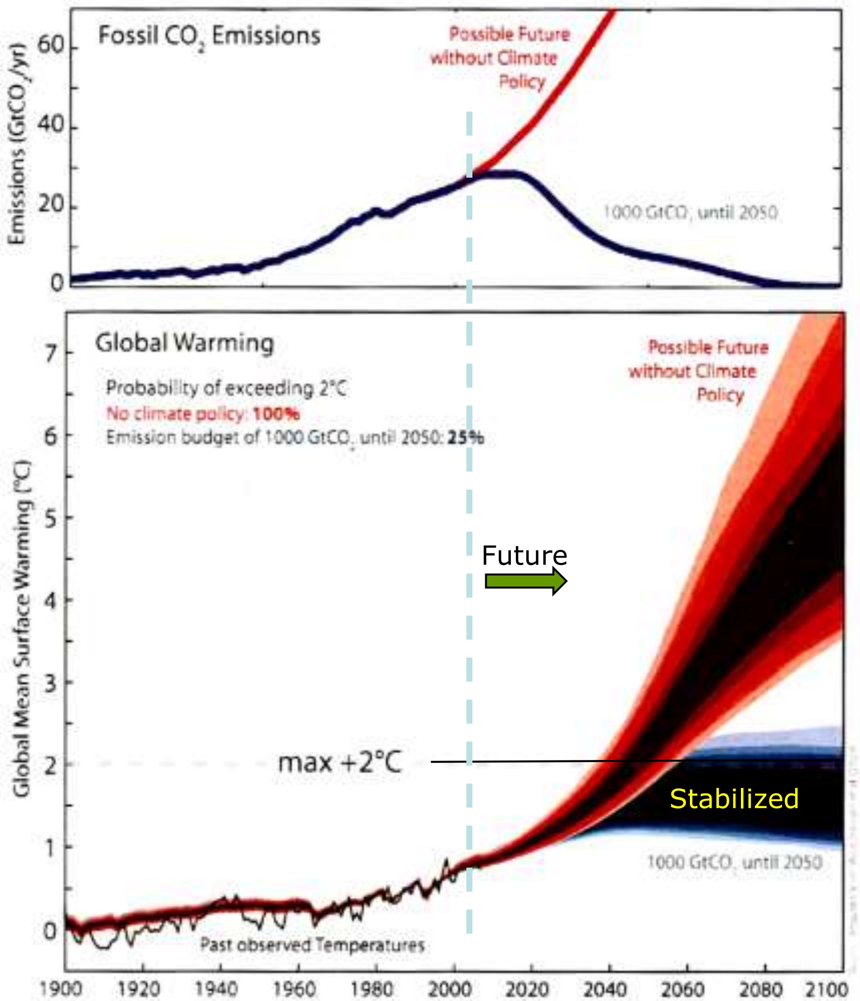
Many correlations exist between human caused pollution and global climate parameters: To what extent are there causal relationships ?

→ Quantitative agreement between observation and robust physical models

→ Absence of plausible competing scenarios



Possible Climate Futures



Correlated with scenarios of constant, decreased or increased emissions of greenhouse gases.

Changing climate → changes in frequency, intensity, spatial extent, duration, timing of extreme weather and climate events, even produces unprecedented extreme weather and climate events. (NAS report).

Examples: Extensive heat waves and droughts, super-storms/hurricanes, extreme downpours, flash flooding, coastal flooding due to rising sea levels, atmospheric rain channels, troughs,…. Global: stopping the Gulf Stream.

$\Delta T \leq 2^0C$ until 2050 are relatively well manageable.

Larger temperature increases (4^0-6^0) are likely catastrophic.

By themselves, anecdotal (individual) weather events do not make a case for climate change. → Need systematic statistics over extended period to discover abnormalities and an understanding within a comprehensive overall picture (model of Earth).