
PLANETARY CLIMATE
UNDER POLLUTION STRESS

Agenda

Earth Radiation Balance

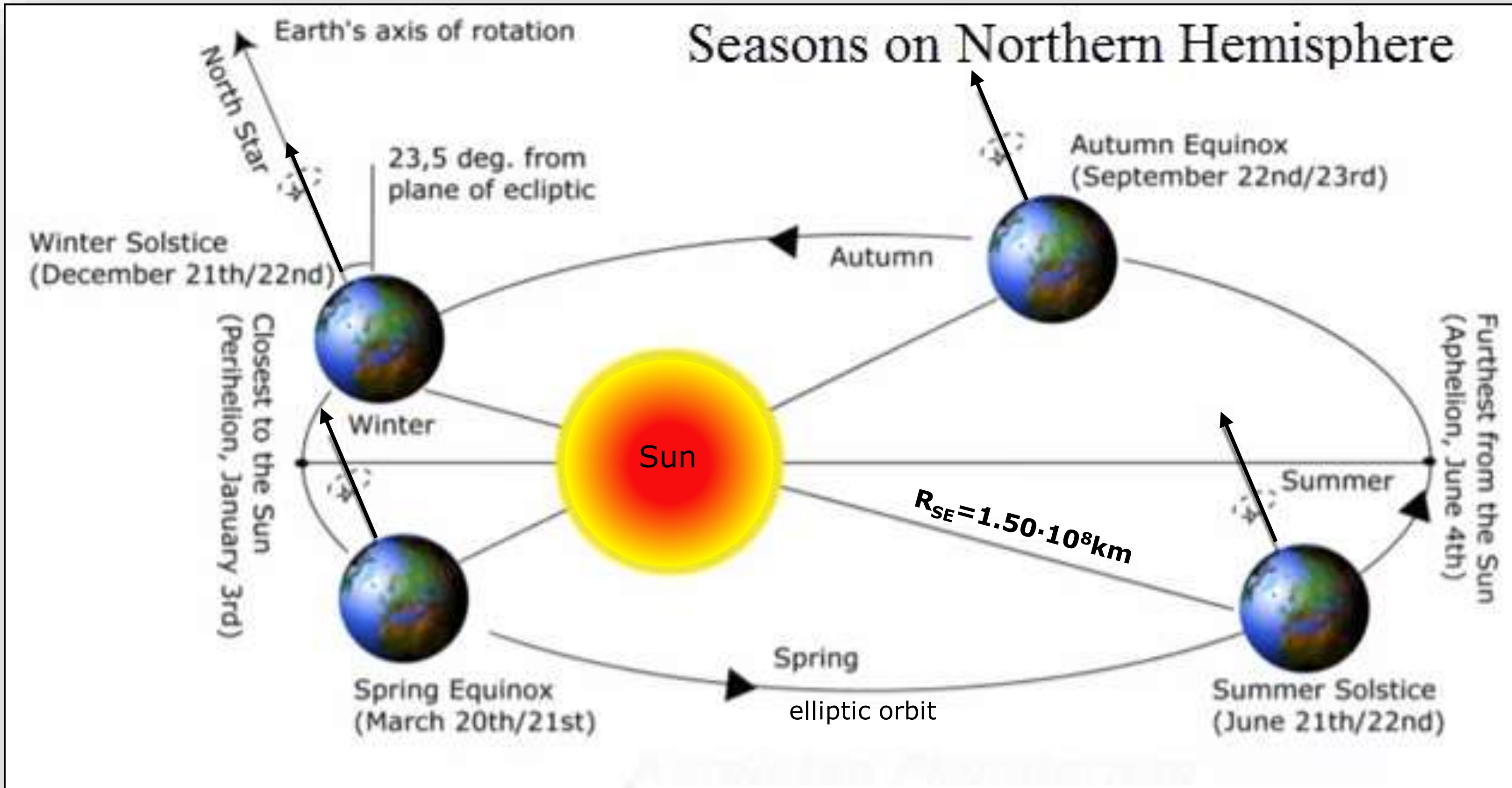
- Potential climate drivers (forcings)
  - Earth planetary motion
  - Extraterrestrial effects on insolation
- Black-body radiation
- Calculate solar insolation, radiation equilibrium
- Basic greenhouse model
  - Radiative forcings, atmospheric effect

  – Selective interactions of elm. radiation with atmosphere (qm tutorial)

- Feedback processes
- Anthropological climate drivers, more greenhouse gases
  - -Sources & sinks
- Projections

Earth In Solar System

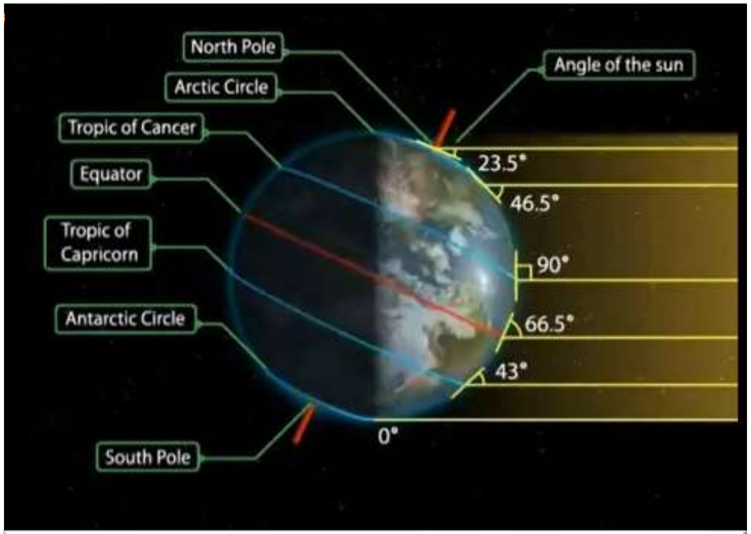
Earth is a spinning gyro with an (approximately) space-fixed orientation now towards North Star. Axis precesses and wobbles with 10ka-100ka periods. Revolution of Earth around Sun in 365.25 d, slightly elliptic orbit (ε~6%). **Now: Axis tilt** against normal to plane of orbit (ecliptic) about Sun (23.5^0).



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**

"Black Bodies" Sun and Earth



Solar radiation incidence during summer on northern hemisphere

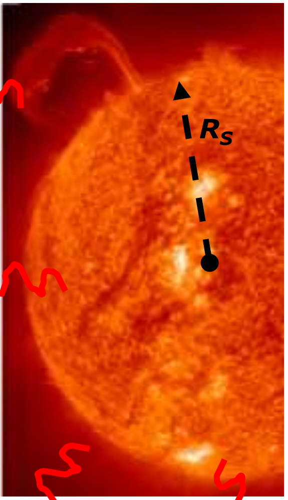
In spite of occasional flares (outbursts/mass ejections), the Sun emits **thermal radiation** like any "black body" at the same temperature T.

Planck's Radiation Law

Light power density per unit wave length λ emitted in random directions (in 4π):

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

$h=6.625\cdot10^{-34}\,J\cdot s$ Planck's constant
$k=1.381\cdot10^{-23}\,J/K$ Boltzmann's constant
$c=2.998\cdot10^{8}\,m/s$ speed of light
$\lambda=$ wave length; $sr=$ solid angle



$R_S=6.96\cdot10^5 km$
$4\pi R_S^2=6.09\cdot10^{12}\,km^2$

Stefan – Boltzmann Radiation Law

$$\text{Total power emitted } S(T)=\int R(\lambda,T)\cdot d\lambda=\sigma\cdot T^4\ \left(W/m^2\right)$$

$SB-constant:$

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

Solar Insolation on Earth

Solar Constant No atmosphere

$$Earth\ surface\ area\ A_E = 4\pi \cdot R_E^2 = 5.1\times 10^8\ km^2$$

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

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

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

Time averaged over spinning earth $\langle A \rangle = A_E/4$

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

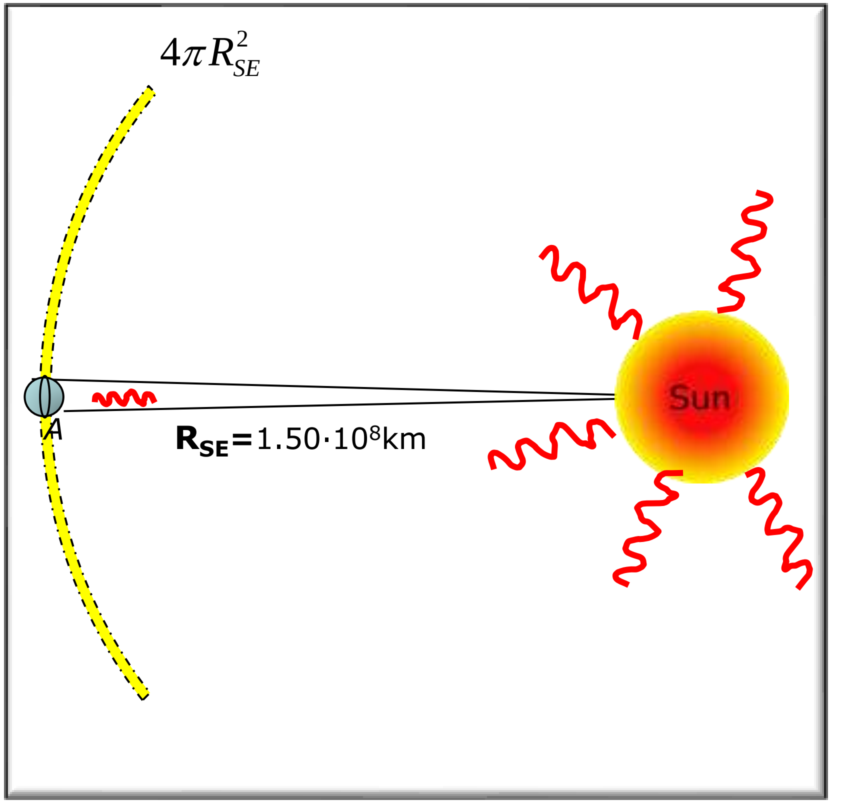
$$\boxed{"Albedo"\ \alpha = reflectivity,\ \alpha_E \approx 0.3\ (expt.)}$$

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

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

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

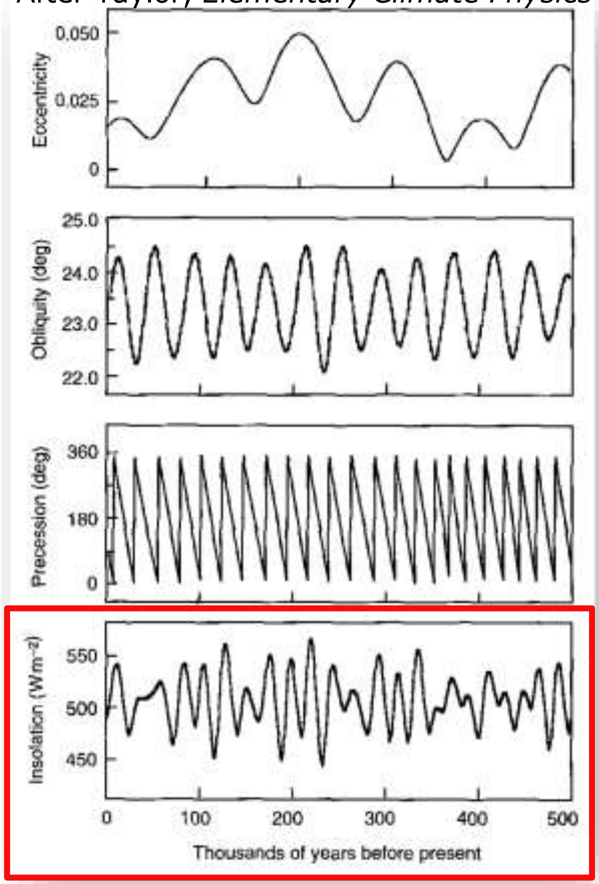
(Need better model for Earth energy balance)



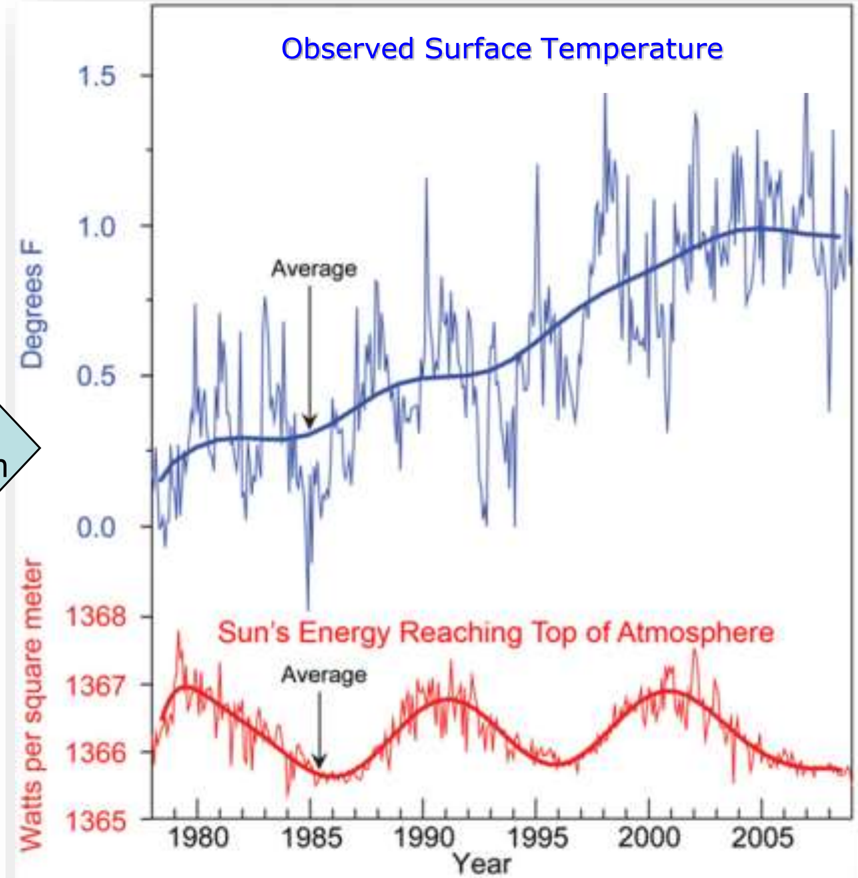
Effect of solar irradiation on Earth surface is non-cumulative, non-linear, possibly unstable.
→ System of several negative and positive feed-back effects.
Possible: Thermal equilibrium (fast)

Orbital Modulation of Insolation

After Taylor, *Elementary Climate Physics*



Acute T Problem

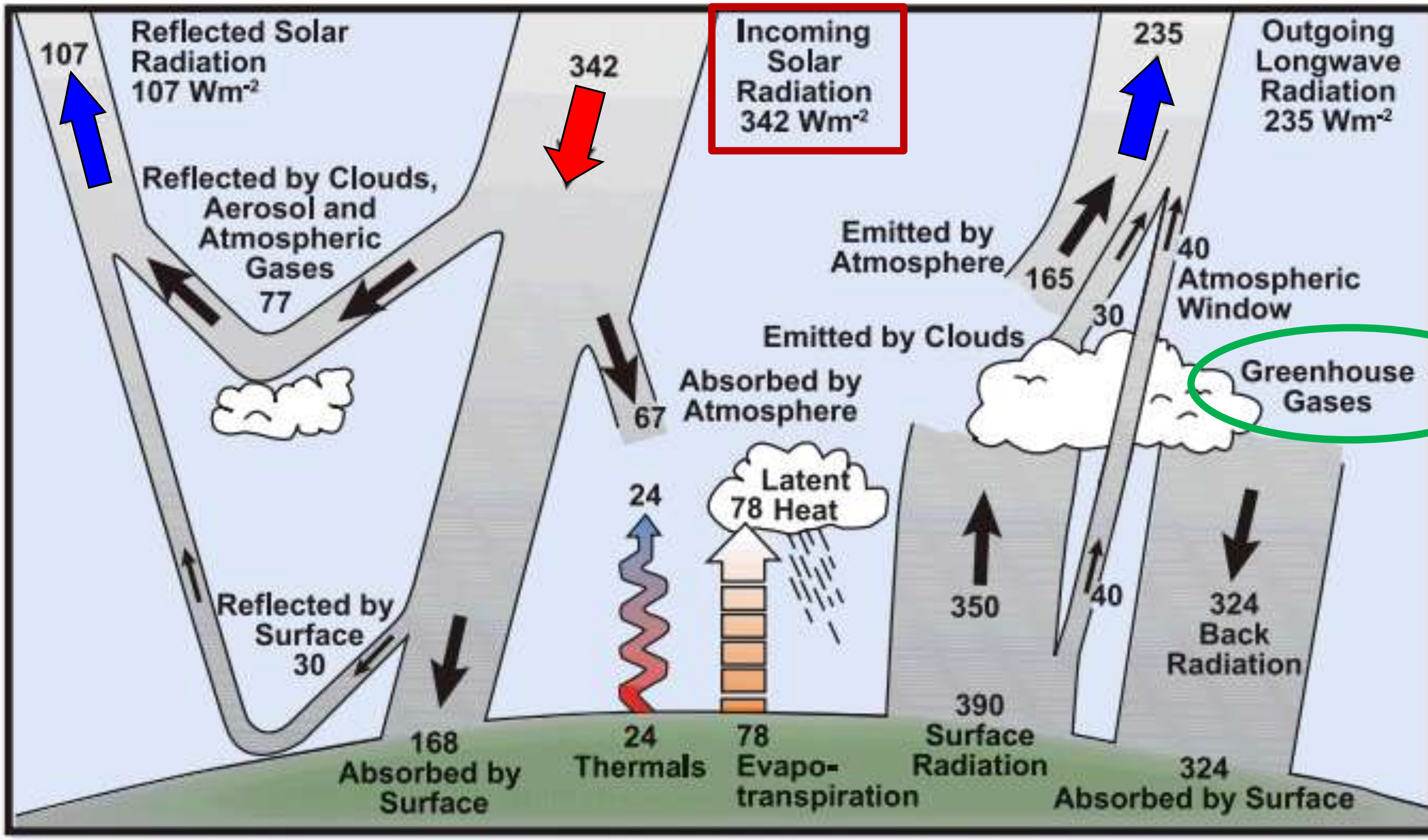


The sun's energy received at the top of Earth's atmosphere has been measured by satellites since 1978. It has followed its natural 11-year cycle of small ups and downs, but with no net increase (bottom). Over the same period, global temperature has risen markedly (top).

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.

Understanding Earth's Radiation Balance



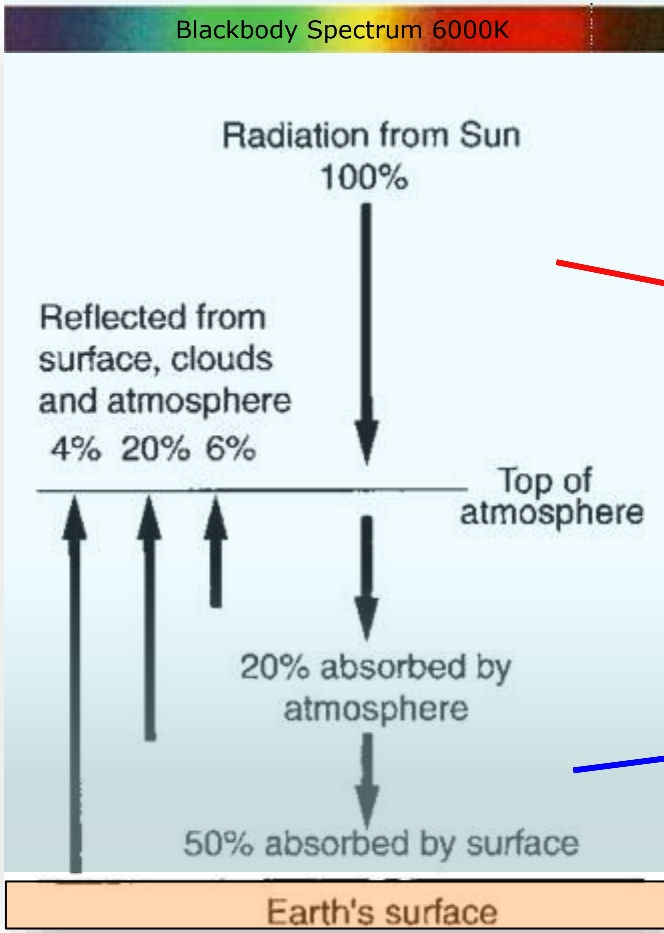
Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming solar radiation is 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).

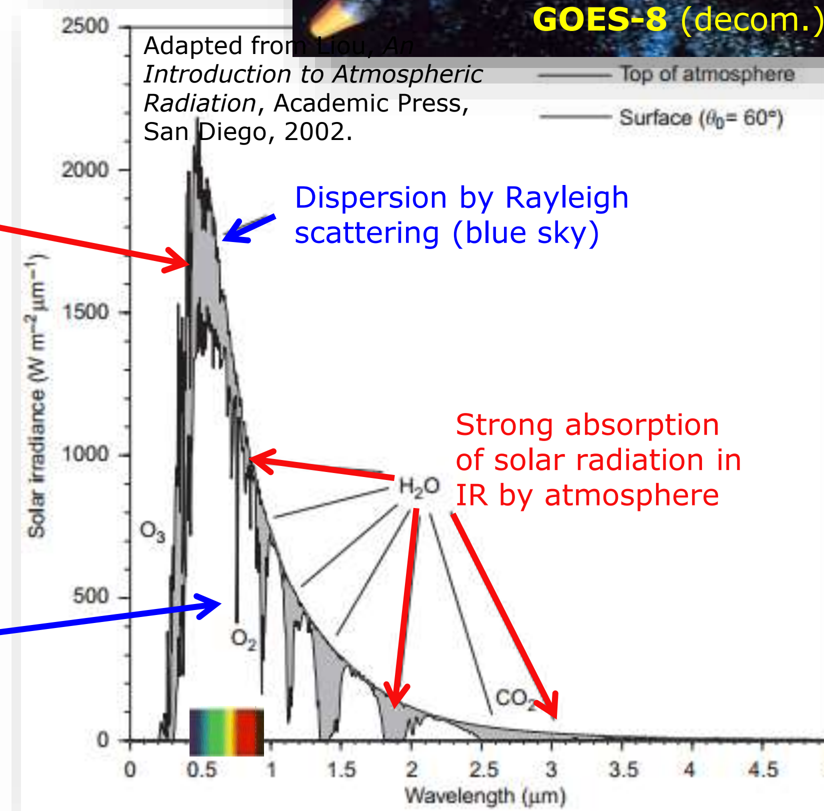
From IPCC AR4 Report, assessed Aug. 2012:
http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter1.pdf

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 !!???

Categorizing Possible Climate (T) "Forcings"

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.

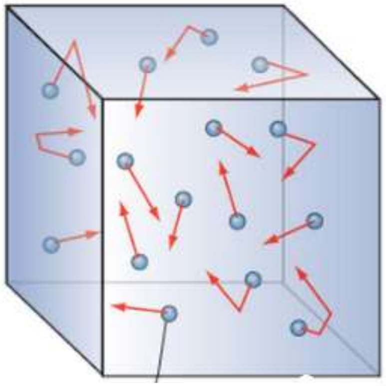
Climate forcing := change imposed on Earth's energy balance/climate due to

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.

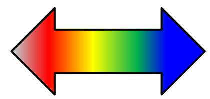
2) Internal causes:
   - a) Volcanic eruptions producing aerosols.
   - b) Changes in oceanic currents.
   - c) Changes in ice and cloud coverage (albedo).
   - d) Human induced changes (emission of greenhouse gases, tropospheric aerosols, CFCs and HCFCs (like those producing "ozone hole").

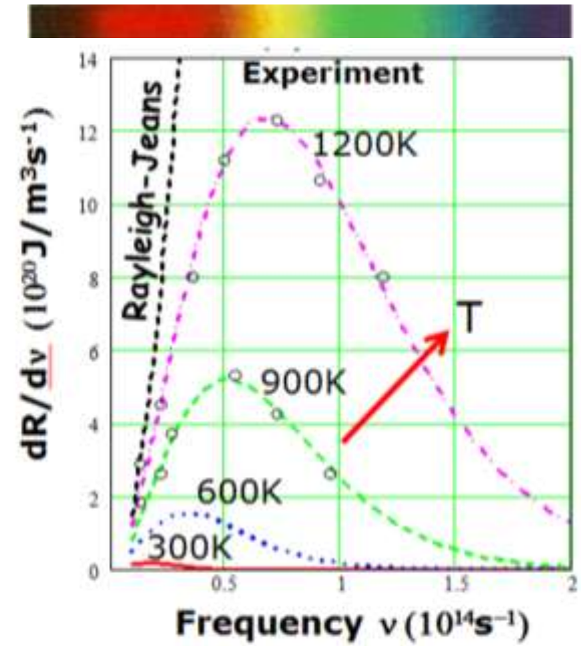
Correlate terrestrial observations with characteristic *t*-dependencies of potential causes.
Look for simplest plausible explanation ("robust" science), eliminate others.

Black Body Radiation



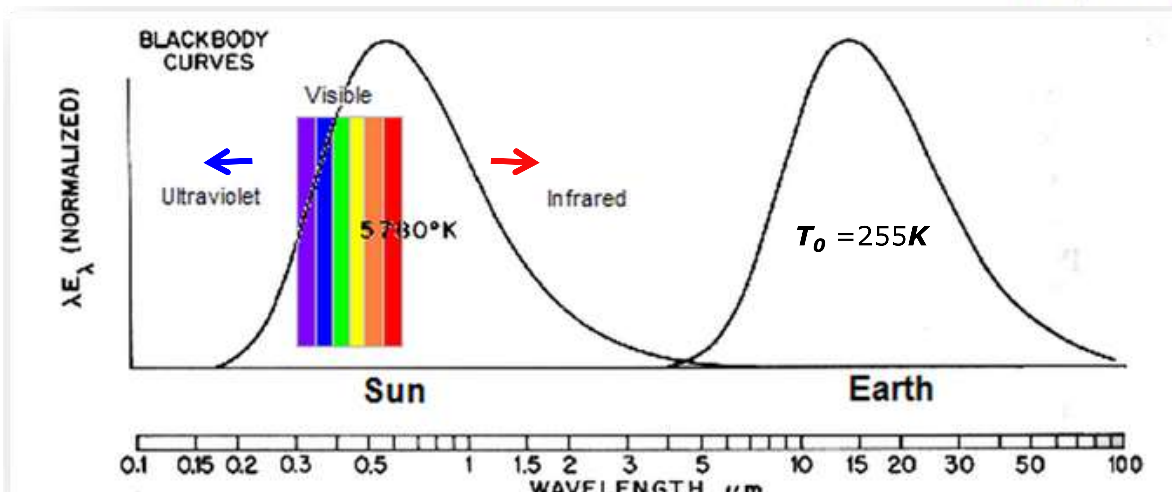
Charged particles in random motion → continuous "thermal" kinetic energy spectrum.
→ Emit photons with continuous energy (ν, λ) spectrum



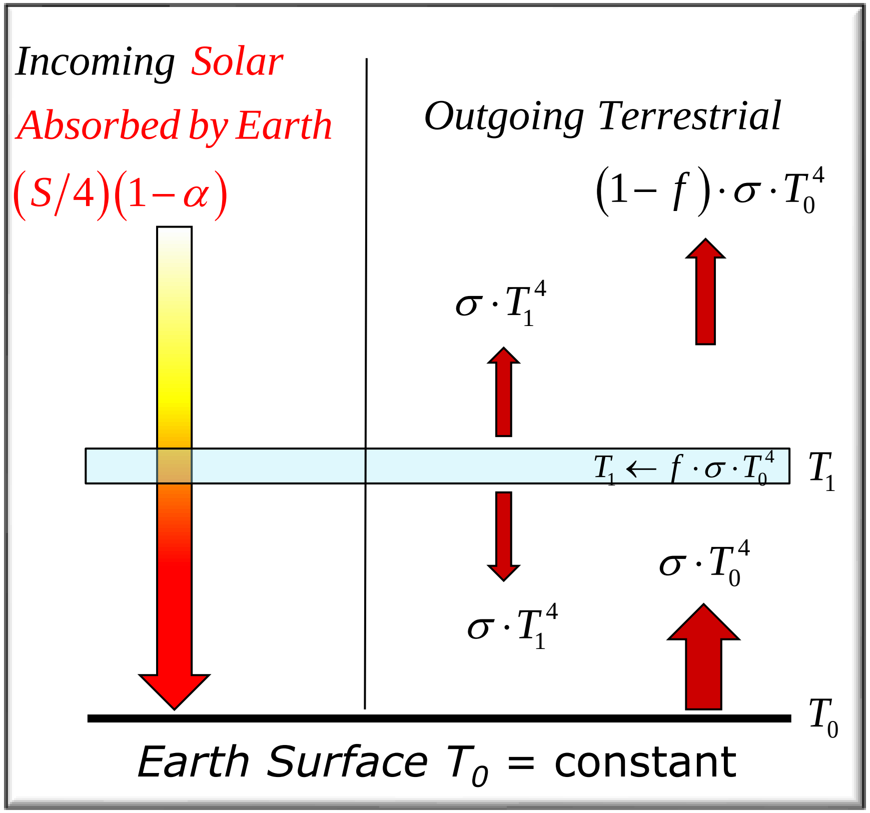


Bare Earth is also approximately a "black body," but with a low temperature, equilibrium (estim.): *T=255 K (-18⁰C).*

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



Basic 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 equilibrates* $T_0 \rightarrow T_1$

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

$$\boxed{\textit{Absorbed} = \textit{Radiated Energy (Power } F)}$$

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

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

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

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

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

Improve model by accounting for altitude dependent, continuous absorption $f(z)$, reduction in T(z).
→ Atmosphere retains more heat.

Radiative Climate "Forcings"

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

(Has additional consequences on H_2O evap., clouds, etc. → "feed backs.")
Model simulation looks for (linear) relation between forcing and ΔT_0.

$$\Delta T_0 = \lambda \cdot \Delta F \qquad \textit{Scale parameter } \lambda$$

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

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

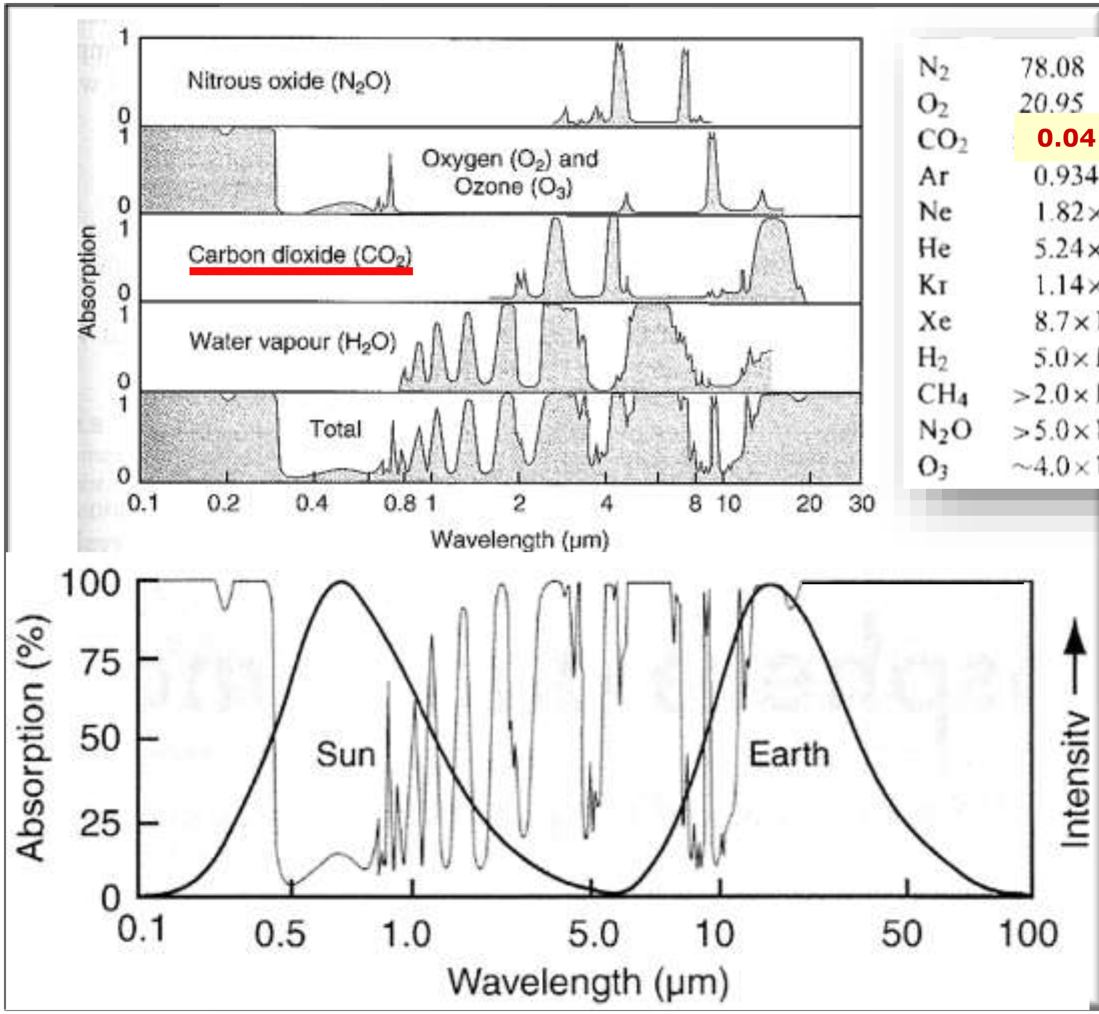
Equilibration of the same absorbed solar flux with $\Delta f : T_0 \rightarrow T_0' = T_0 + \Delta T_0$

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

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

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

Selective Filter Effect of Atmosphere



N_2	78.08
O_2	20.95
CO_2	**0.041**
Ar	0.934
Ne	1.82×10^{-3}
He	5.24×10^{-4}
Kr	1.14×10^{-4}
Xe	8.7×10^{-6}
H_2	5.0×10^{-5}
CH_4	$>2.0\times10^{-4}$
N_2O	$>5.0\times10^{-5}$
O_3	$\sim4.0\times10^{-6}$

Mean composition of dry air and absorption spectra for GHG.

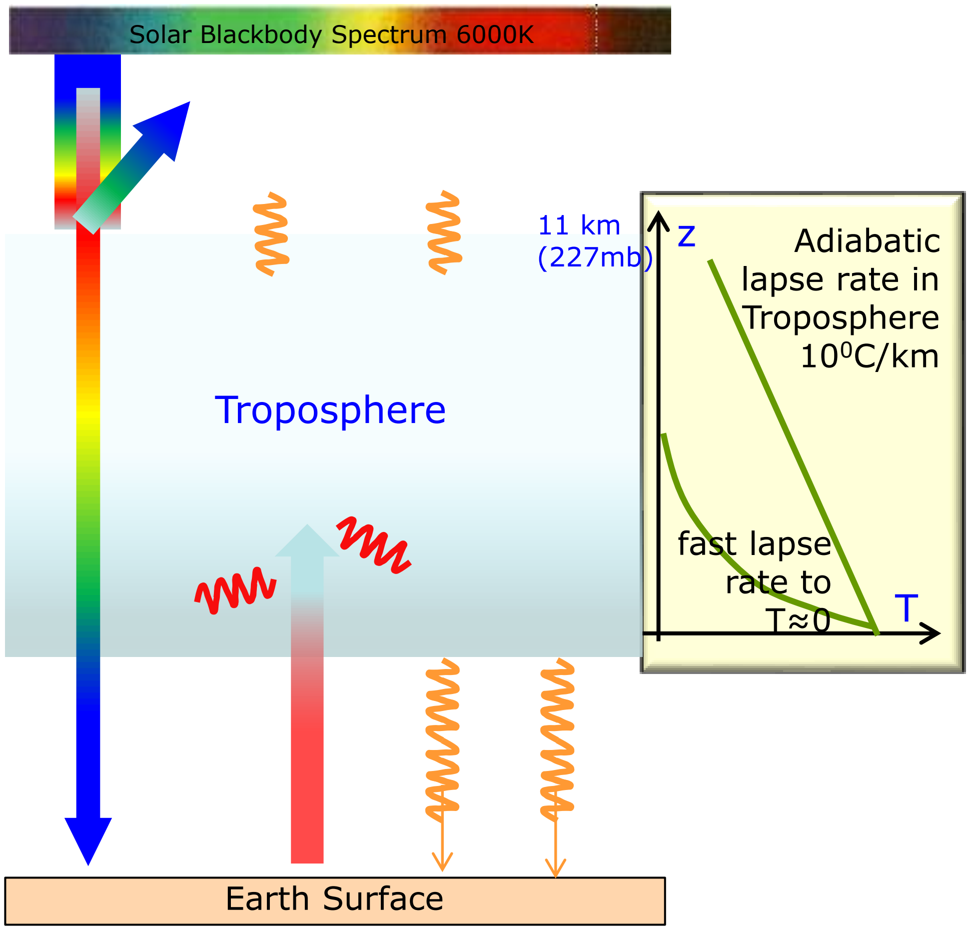
$0\% \le [H_2O] \le 0.4\%$,

GHG concentrations: on the rise during the last century.

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

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

Selective Filter Effect of Atmosphere



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.

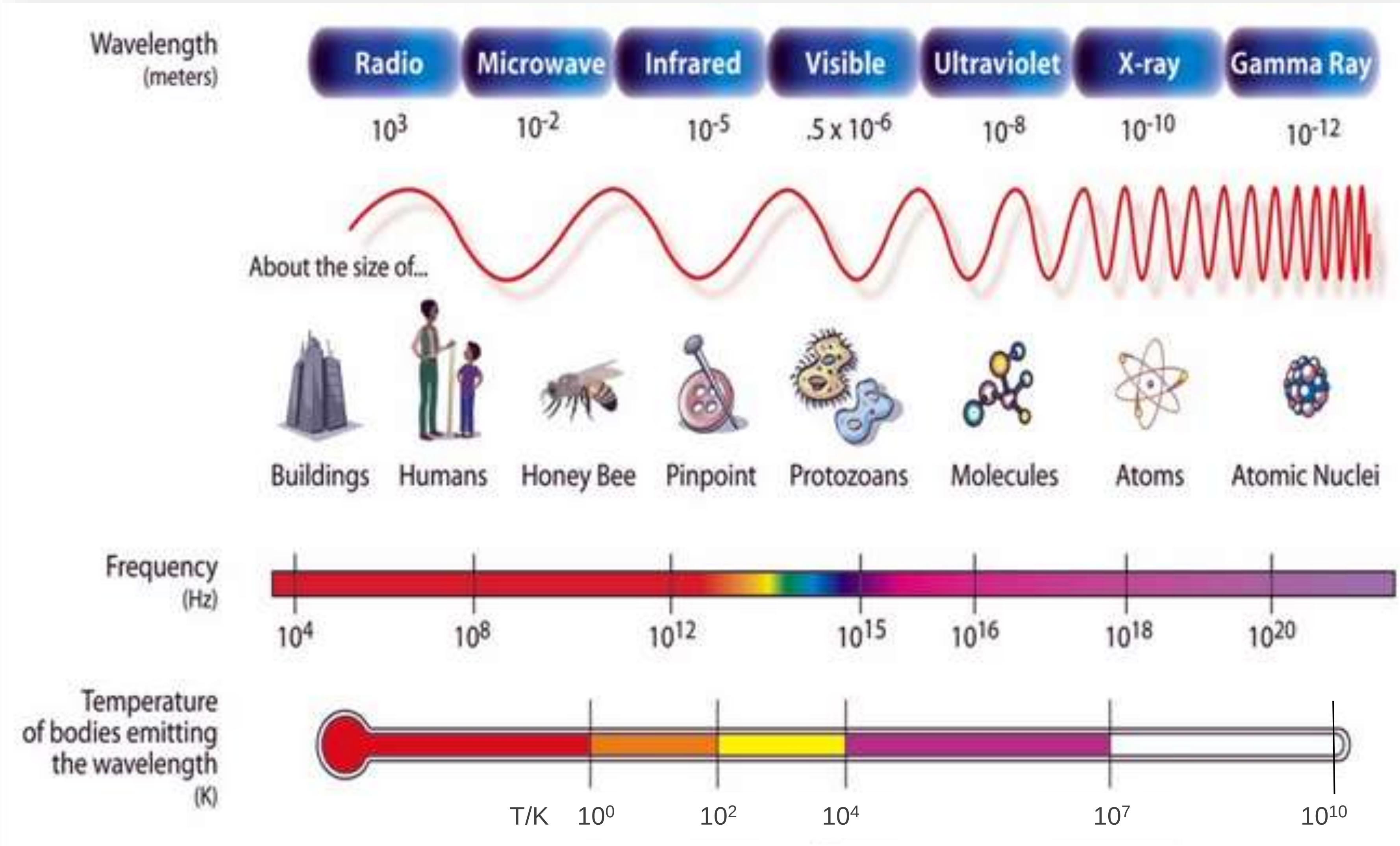
2) Atmosphere radiates P=S(1-a)/4 at low T back into space and at higher T toward surface, heating the surface in addition to direct insolation.

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

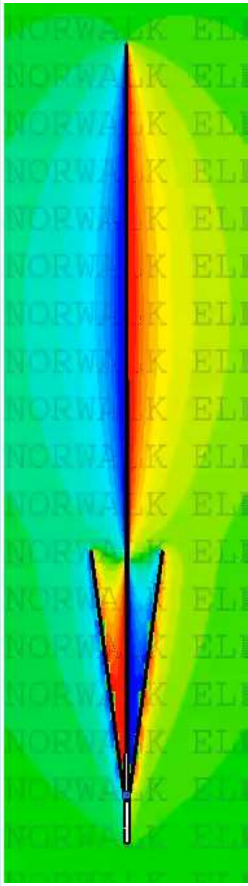
See, e.g., F. P. J. Valero et al., J. GEOPHYS. RES., 105, 4743 (2000)

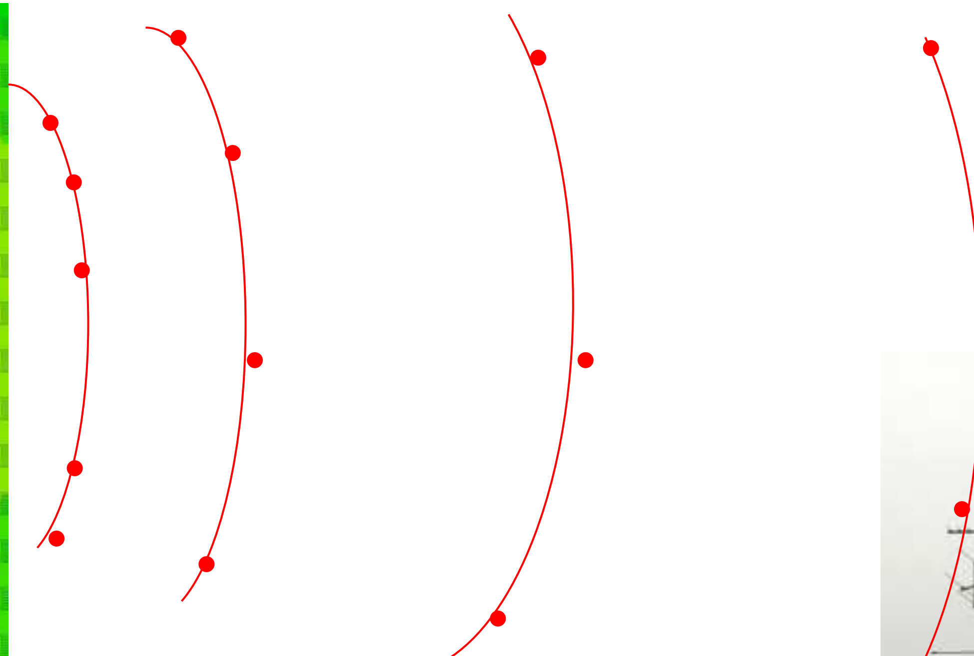
Interaction of elm Radiation With Matter I

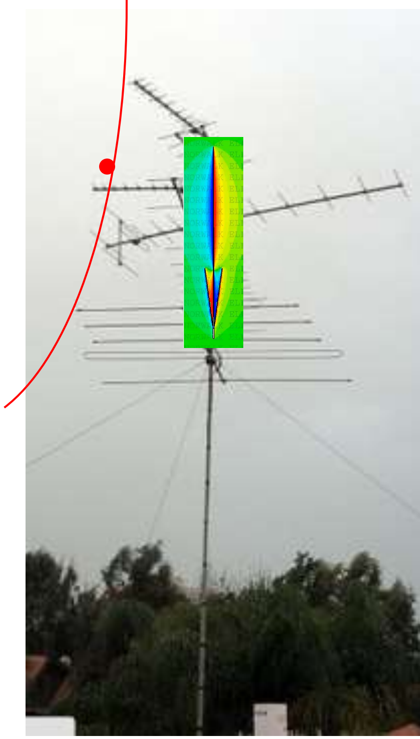
The Electromagnetic Spectrum



Energy Transfer by Photons



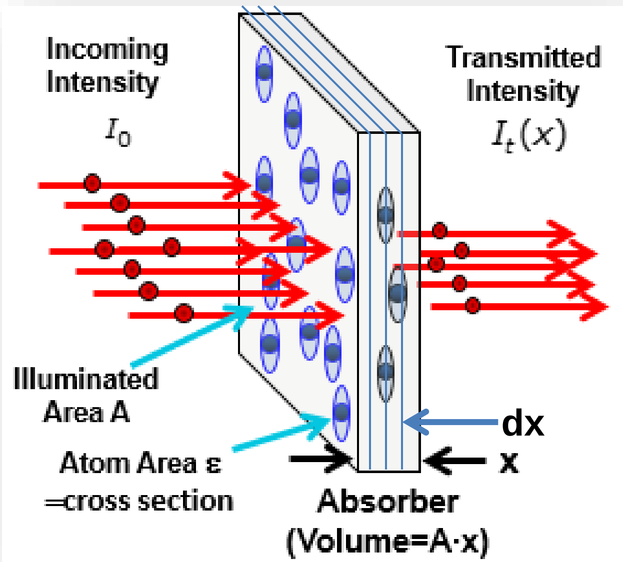




Moving electric charges in broadcast antenna emit electromagnetic radiation fields characteristic (frequency, wave length) of the electric currents

Electromagnetic waves transfer quanta (photons) which can be absorbed by electrons in a receiver antenna, causing them to move in synch with the emitter.

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

.........($\rightarrow$ *simple* calcs)

Probability (= *fraction f*) *for absorption of* dI, *change* $= -dI$

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

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

$$\frac{dI}{dx} = -\mu \cdot I(x) \quad \rightarrow \textit{DEq for exponential}$$

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

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

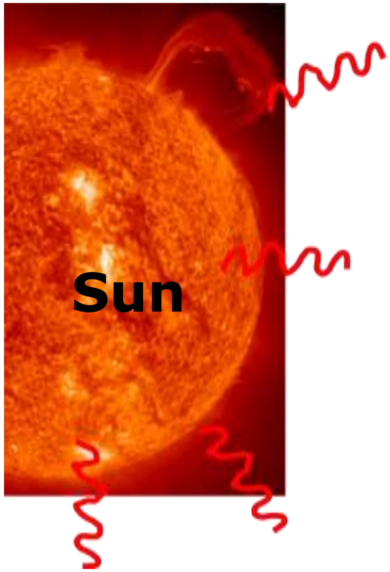
Atomic Cross Section

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

$\rightarrow$ *Absorbance* : $Log_{10}\left(\frac{I_0}{I_t}\right) = \mu \cdot x = \varepsilon \cdot c \cdot x$ 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.

Emission and Absorption of Photons



Unbound electric charges such as electrons in a hot body ("blackbody") of ionized gas (e.g., Sun) emit and absorb electromagnetic spectra with continuous wavelengths (frequencies, photon energies).

Bound electric charges (e.g., electrons in atoms, molecules) emit and absorb discrete ("line") energy (wavelength) spectra.

Energy transfer by photons in bound systems:

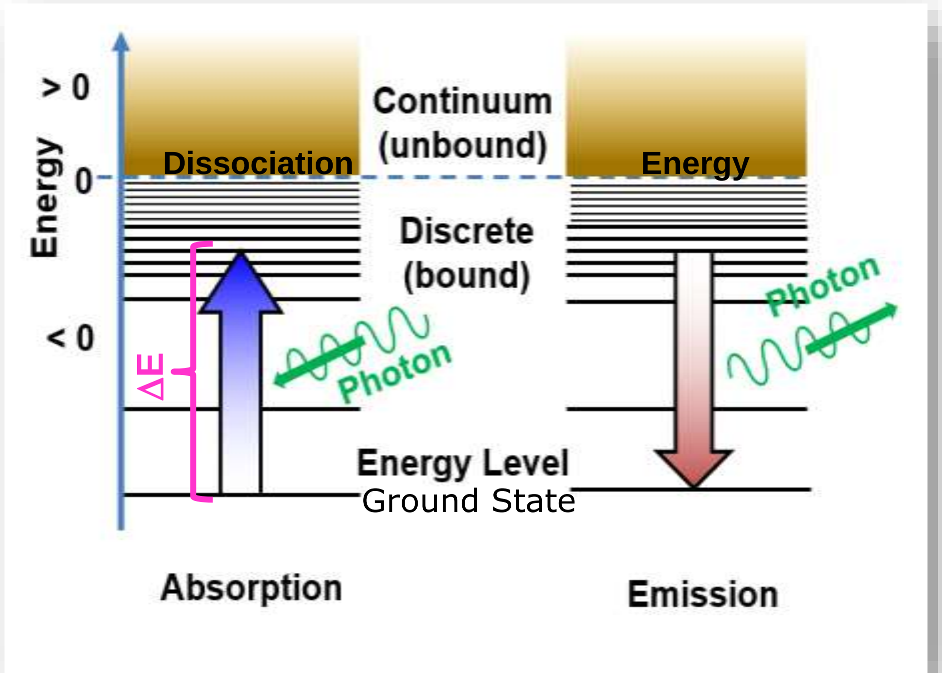
Absorption or emission of light occurs in transitions between discrete energy levels.

Characteristic spacing → spectr. ID

$$|\Delta E| = h\nu = hc/\lambda$$

$h = 6.62606957 \times 10^{-34}\ m^2\ kg\ /\ s$

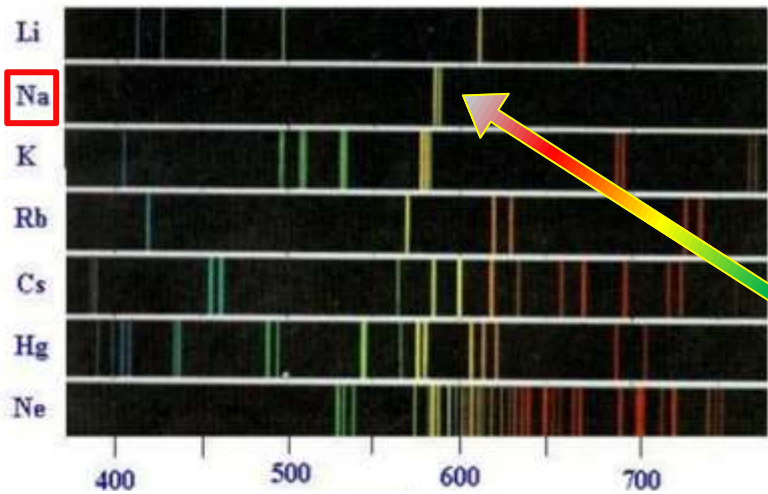
Planck's constant



Energy Transfer Through Radiation

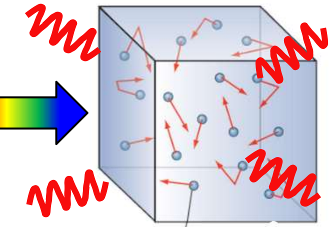
Wave length spectrum for thermal equilibrium

Wave length spectrum for atomic transitions



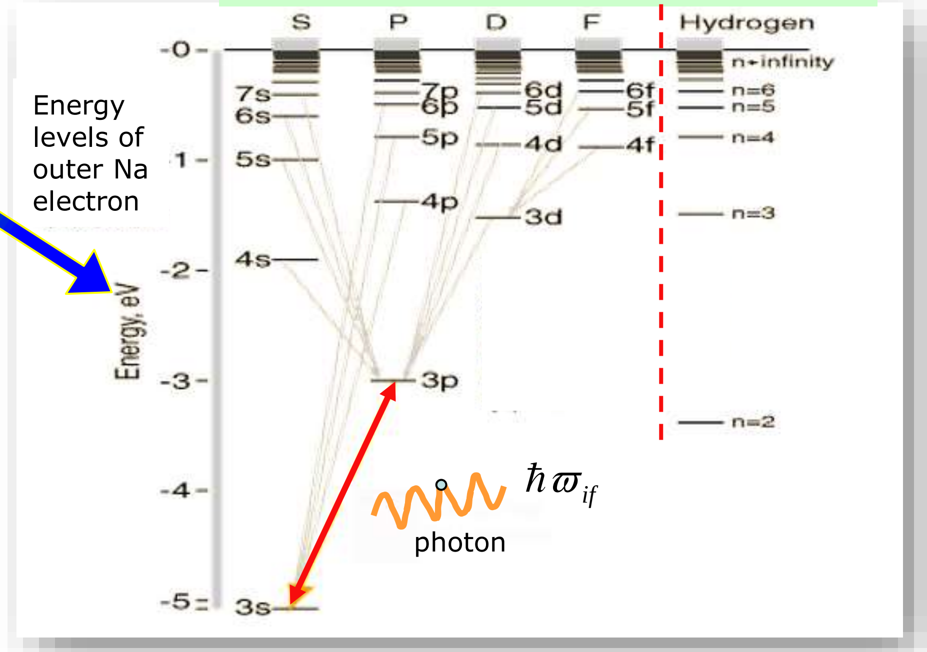
Wave Length λ (nm) →

Continuous thermal spectrum. Emitted and/or absorbed by charged particles in random motion



Charged/Polarized Particles

Energy Levels of Na and H (1-electron atoms)



Internal atomic / molecular energies are quantized

Transition between levels: $i \to f$

$$\Delta E_{if} = E_f - E_i = h\nu_{if} = \hbar\varpi_{if} = hc/\lambda_{if}$$

Planck's constant $h = 6.626 \cdot 10^{-34}\ J \cdot s$

$\hbar = h/2\pi$, $c = 0.2998\, m/ns$ *speed of light*

1 eV = 1.602 176 53(14) × 10^{-19} J (Joule)

Energy related spectroscopic observables

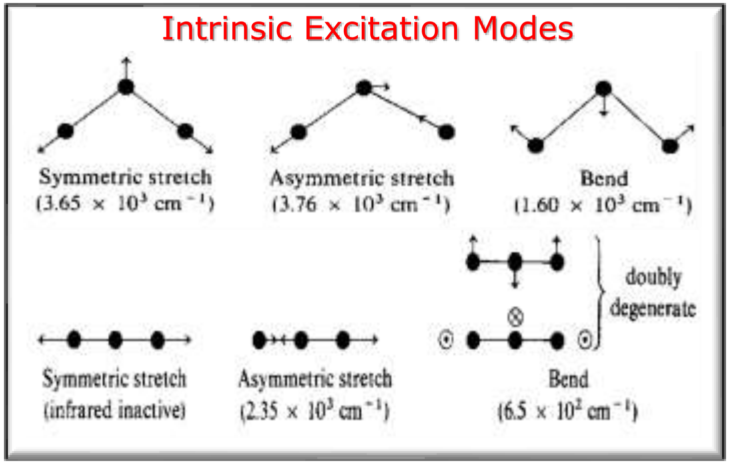
ν: 2.417 989 40(21) × 10^{14} Hz

$\bar{\nu}$: 8 065.544 45(69) cm^{-1}

λ: 1 239.841 91(11) nm

T: 11 604.505(20) K (Kelvin)

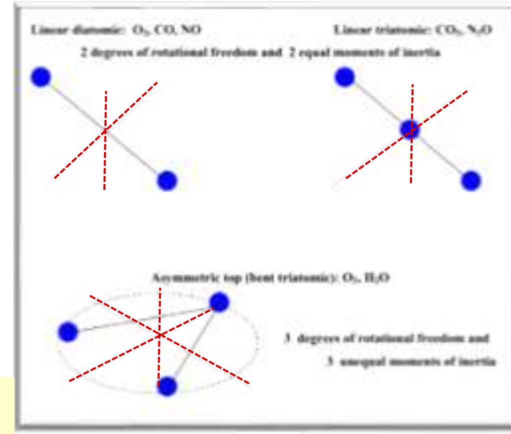
Molecular Emission/Absorption Spectroscopy

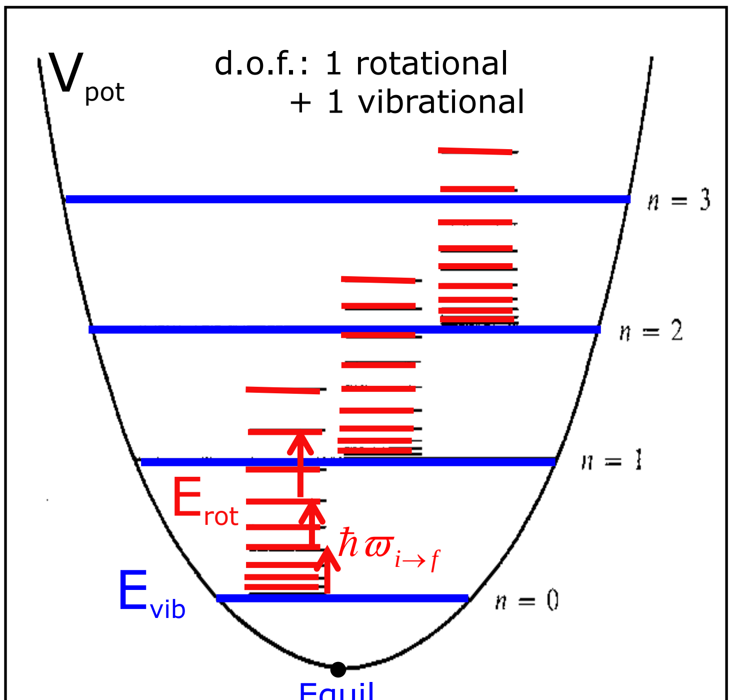


Independent degrees of freedom of motion of a 3-atomic molecule:

1) translational as a whole,
2) rotational (diff. axes),
3) vibrational (diff. modes),
4) electronic.

IR absorption if molecule has electric dipole





$$E = E_{trans}(\upsilon) + E_{rot}(J_i) + E_{vib}(n) + E_{el}(\ldots)$$

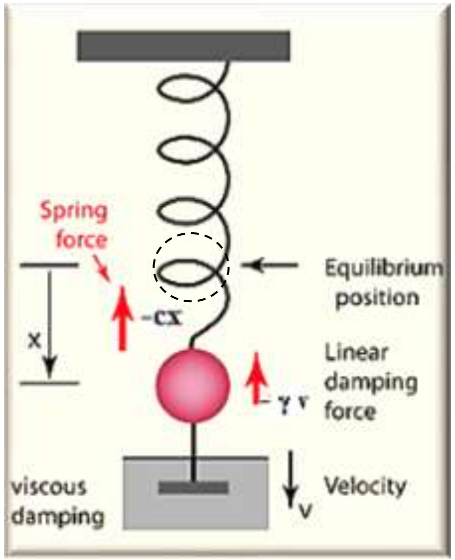
Translation energy E_{trans} has continuous "thermal" spectrum, generated by multiple collisions.
Mean energy about kT≈ 400 cm^{-1} (T =300 K), infrared (IR)
Can absorb or emit any energy amount (E conserved).
Quantized degrees of freedom absorb/emit discrete energy packages $\hbar\varpi_{i\to f} = \pm\left(E_f - E_i\right)$

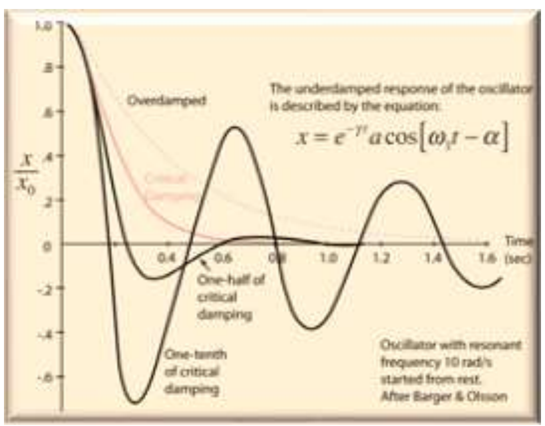
Rotational energy E_{rot} is quantized (line spectrum), typical Energies= (1-500) cm^{-1} (far-IR to microwave)

Vibrational energy E_{vib} is quantized (line spectrum): energy of vibrating nuclei about their equilibrium positions; E ~ (500 to 10^4) cm^{-1} (near-IR to far-IR)

Electronic energy E_{el} is quantized (line spectrum), typical energies (10^4-10^5) cm^{-1} (UV and visible).

Energy Transfer via Collisional Relaxation





Internally rot-vib excited di/poly-atomic molecules in atmosphere suffer multiple collisions with other particles in random (thermal) motion, which act as a "viscous heat bath."

Energy is transferred back and forth between all (***f***) degrees of freedom, until equi-partition

$$\langle E_i \rangle_{eq} = \frac{1}{2} k \cdot T \quad (i = 1, 2..., f)$$

$$3D\ translational\ motion\ \langle E \rangle_{eq} = \langle E_x \rangle_{eq} + \langle E_y \rangle_{eq} + \langle E_z \rangle_{eq} = 3 \cdot \frac{1}{2} k \cdot T$$

Consequently: for damped oscillation of mass m on a spring

$$Undamped:\ x_{free}(t) = x(t=0) \cdot \cos(\varpi \cdot t) \qquad \varpi = \sqrt{c/m}$$

$$Damping\ coefficient\ \gamma \rightarrow x_{damped}(t) = x(t=0) \cdot e^{-\gamma \cdot t} \cdot \cos(\varpi \cdot t)$$

Energy (E(*t*) ~ x(t)²) transfer to bath particles and back until equilibrium is attained (bath heats up).

$$\frac{d}{dt}\langle E \rangle = -\left[\langle E \rangle - E_0\right] / \tau_{relax} \quad ,\ with\ \tau_{relax} \propto \tau_{coll}$$

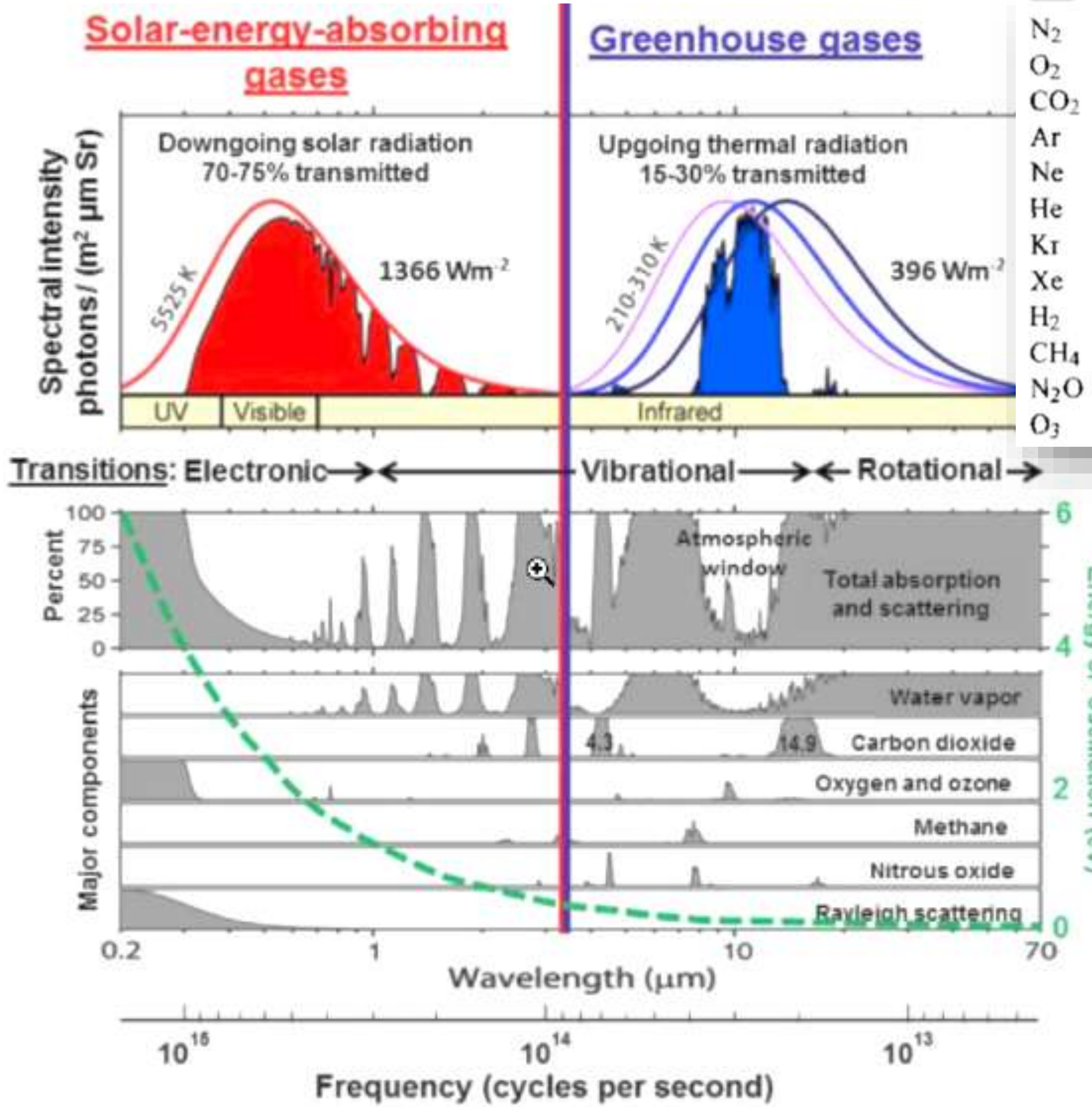
$$collision\ time\ \tau_{coll} = function(density, T)$$

$$\tau_{coll} = \frac{mean\ \ free\ path\ \lambda}{mean\ thermal\ speed} \approx \left(\frac{5 \cdot 10^{-3} cm}{p / Torr}\right) \sqrt{\frac{m}{8\pi kT}} \sim 10^{-10} s$$

Fast relaxation/ attainment of equilibrium

Internal molecular energy dissipated quickly and heats surrounding gas @ equilibrium

Selective Filter Effect of Atmosphere



N_2	78.08
O_2	20.95
CO_2	**0.041**
Ar	0.934
Ne	1.82×10^{-3}
He	5.24×10^{-4}
Kr	1.14×10^{-4}
Xe	8.7×10^{-6}
H_2	5.0×10^{-5}
CH_4	$>2.0\times10^{-4}$
N_2O	$>5.0\times10^{-5}$
O_3	$\sim4.0\times10^{-6}$

Mean composition of dry air and absorption spectra for GHG.

$0\% \le [H_2O] \le 0.4\%$,

GHG concentrations rising during past century.

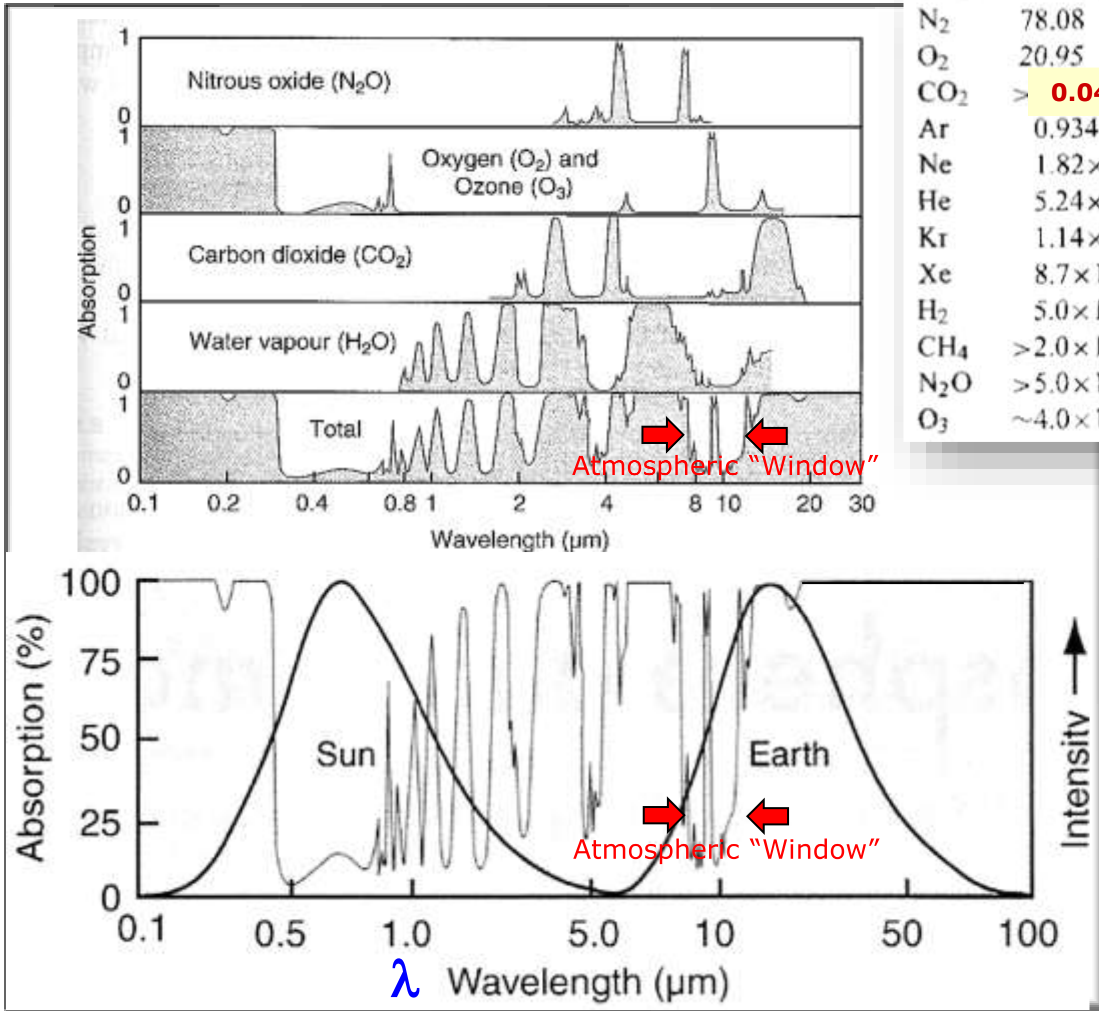
Adapted from F.W. Taylor, *ECP*.

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

Radiation within the "Atmospheric Window" $\Delta\lambda$ is not absorbed by atmosphere → emitted directly into space. Specific Greenhouse gases may absorb in $\Delta\lambda$ and reflect radiation back to Earth surface→ "warming potential"

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6174548/

Selective Filter Effect of Atmosphere



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GHG concentrations: on the rise during the last century.

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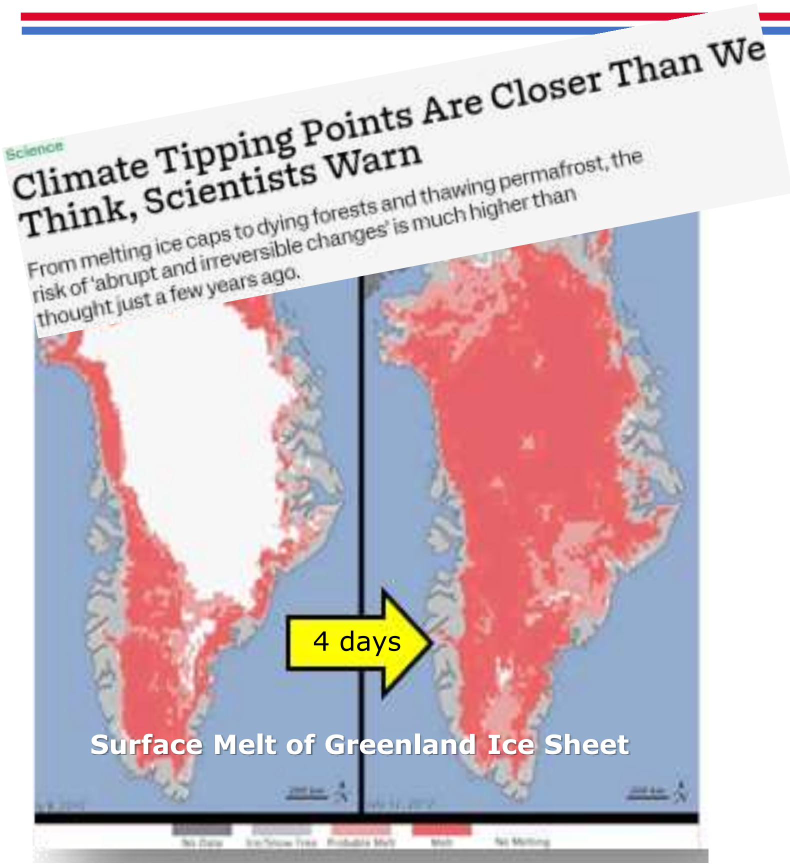
Scattered or absorbed radiation energy is not available for warming Earth surface. → $T_E < 255K$

Radiation within the "Atmospheric Window" Δλ is not absorbed by atmosphere → emitted directly into space. Specific Greenhouse gases may absorb in Δλ and reflect radiation back to Earth surface→ "warming potential"

Tutorial

End
Interaction of elm Radiation
With Matter I

Tipping Points in Earth Climate ?



Non-linear and coupled effects in Earth current climate evolution → global warming, melting of sea ice , ice cap, desertification, ocean acidification, sea level rise,……

Historic climate facts:

Earth climate has alternated between Ice ages (little and major) and greenhouse periods. Transition speed?

Do we have time to adapt or change pace?

Mind the fate of planet Venus (NYT 012921)

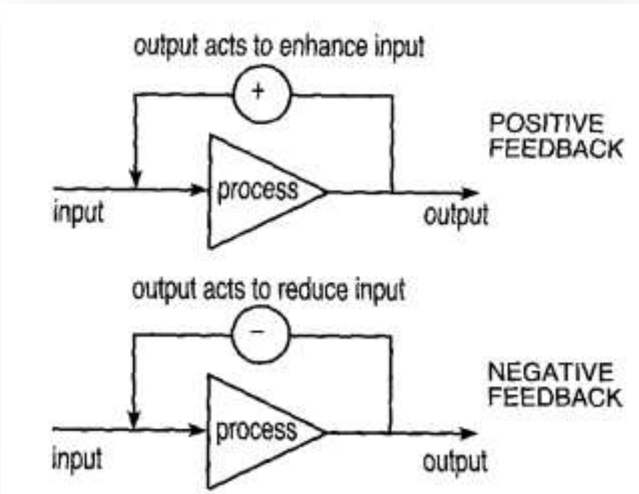
Earth albedo or surface reflectivity ε = important in maintaining radiation balance

Glaciation: increasing ice cover $\Delta\varepsilon > 0 \rightarrow$ *surface temperature change* $\Delta T < 0$

Warming: decreasing ice cover $\Delta\varepsilon < 0 \rightarrow$ *surface temperature change* $\Delta T > 0$

Albedo is non-monotonic function of important driving parameters, has extrema!

Non-Linear Forcings: Feedback Effects



Important feedback forcing mechanisms considered in climate models:

- CO_2 runaway process: Increase [CO_2] → increase T → release additional CO_2 from frozen Tundra →
- Ice – albedo: White Ice surface reflects more radiation, lowers T, more freezing →
- 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. Albedo effect dominates.

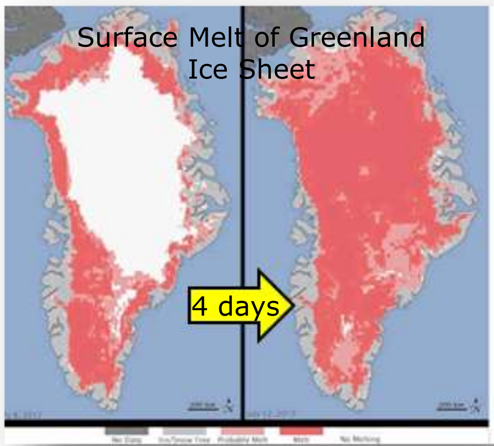
H_2O greenhouse effect looses importance if troposphere is already opaque to IR. Then, it only affects heat convection.

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

Examples

Non-Linear Climate Forcings

Time dependent Earth albedo, rapid change in Greenland



Thawing Tundra (Area =1.1x Area_of US) → time dependent CO_2/CH_4 emitter

After Taylor (ECP)

Earth albedo $a = a(T(t)) \rightarrow T = T(t)$ = *surface temperature*

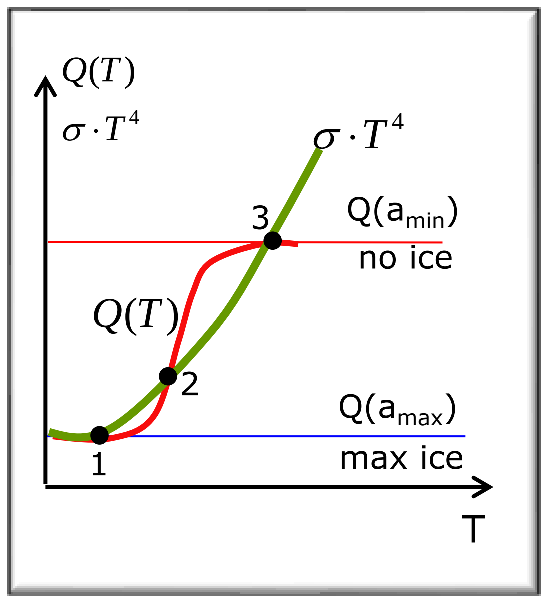
C = *effective surface heat capacity : abs.heat energy* $Q = C \cdot T$

Differential equation for $T(t)$

$$C \cdot \frac{d}{dt} T(t) = (1 - a(T)) \cdot \frac{S}{4} - \sigma \cdot T^4(t) \quad \text{with } S, \sigma \text{ constants}$$

T *increases, and* a *decreases (more ice melting), as long as*

$$(1 - a(T)) \cdot \frac{S}{4} > \sigma \cdot T^4(t) \;\; or \;\; 1 - 4\frac{\sigma}{S} \cdot T^4(t) > a(T) > 0$$



Stable states : $T(t) = const.? \rightarrow$

$dT(t)/dt = 0$ *at* $T = T_i \;\; (i = 1, 2...)$

$$Q(T_i) = (1 - a(T_i)) \cdot \frac{S}{4} = \sigma \cdot T_i^4$$

But $d^2T(t)/dt^2 < 0 \rightarrow$ *unstable*

Assume gen. dependence $a(T)$

$a(T) = a_0 + c_1 \cdot T + c_2 \cdot T^2 + ...?$

$T \rightarrow 0 : a \rightarrow a_{max}, T \rightarrow \infty : a \rightarrow a_{min}$

Stable states 1) ice age or 3) ice free. State 2) is meta stable, unstable against small changes in ***a***.

Sudden climate changes !

Speculation: Earth Albedo Model

Albedo is non-monotonic function of important driving parameters.

Combine ε parameter dependence to model *non-linear* dependence on history:

$$\varepsilon\left(t+\Delta t\right)=\alpha\cdot\varepsilon\left(t\right)-\beta\cdot\varepsilon^{2}\left(t\right)+......;\quad parameters\ \alpha,\beta=f(CO_{2},...)?$$

$$Since\ \varepsilon\left(t\right)\ is\ non-monotonic\ and\ must\ have\ an\ extremum$$

$$\rightarrow sign\left(\alpha\right)=sign\left(\beta\right),\ choose\ \alpha,\beta>0$$

$$Adopt\ discrete\ time\ steps\ t_{n}\ \ (days,\ months,\ years,....,centuries)\rightarrow$$

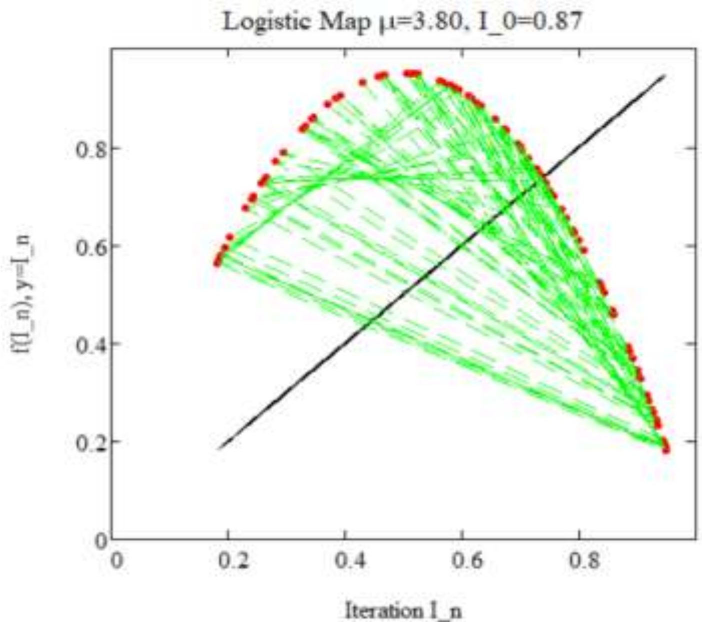
$$\varepsilon_{n+1}=\varepsilon_{n}\left(t+n\cdot\Delta t\right)\approx\alpha\cdot\varepsilon_{n}-\beta\cdot\varepsilon_{n}^{2}\qquad "Iteration"$$

$$Variable\ transformation\rightarrow$$

$$Profile\ function\ \boxed{f(\varepsilon)=\mu\cdot\varepsilon\cdot\left(1-\varepsilon\right)}\qquad "Logistic\ Map"$$

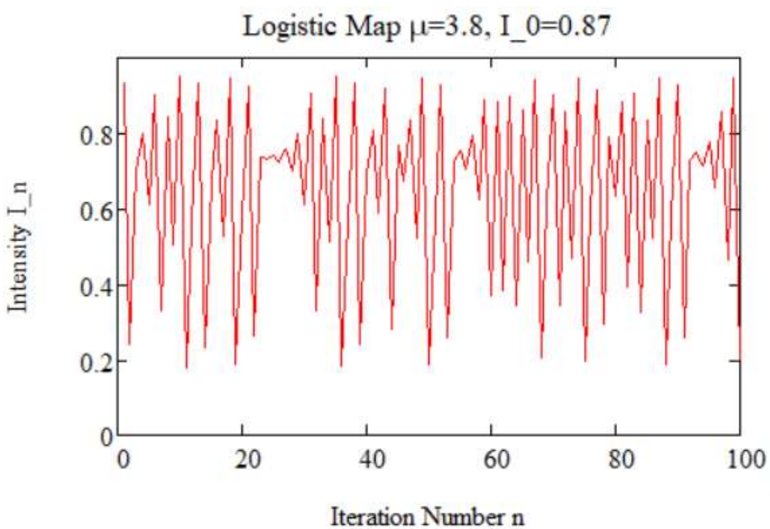
$$\varepsilon_{n+1}=f(\varepsilon_{n})=f(f(\varepsilon_{n-1}))=f(f(f(\varepsilon_{n-2})))=f^{3}(\varepsilon_{n-2})\quad Iterative\ Logistic\ Map$$

Chaotic Map Trajectories



Same example as above, plot showing only the iterative intensities I_n on the curve representing the map profile function $f(I)$.

A large part of the brightness spectrum is covered by the trajectory already after 500 iteration. No apparent intensity pattern.
Intensity flashes between bright and dim.



Same example as above, plot shows iterative intensities I_n vs n. Some, but not exact similarities, intermittency domains, strongly dependent on initial condition I_0.

Linear and Non-Linear Dynamical Regimes

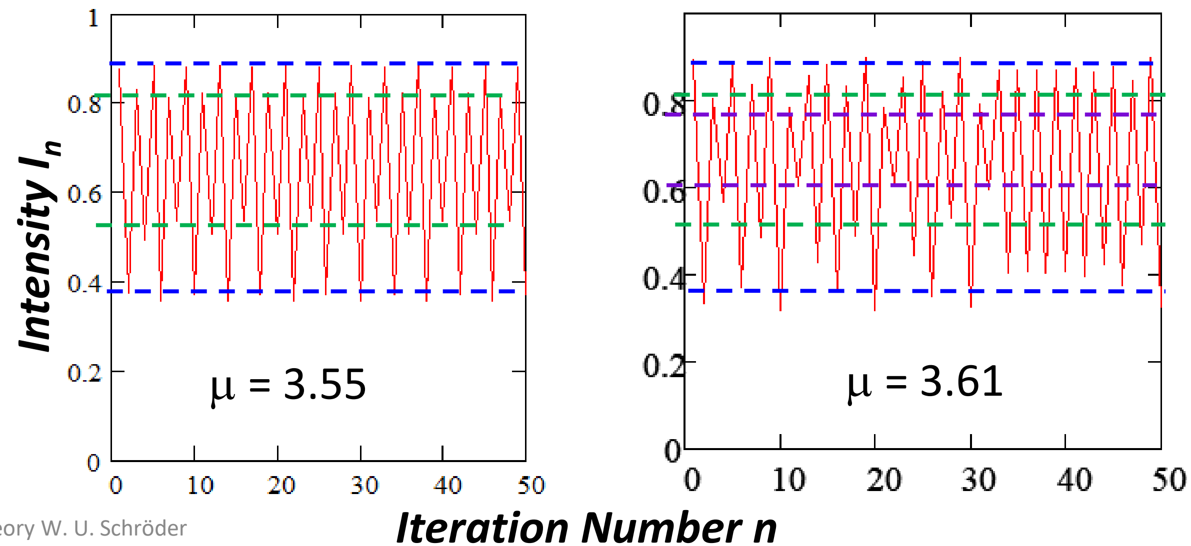
$0.0 \le \mu \le 1.0$: *No non – trivial fixpoints* $\rightarrow I_n \underset{n\to\infty}{\rightarrow} 0$

$1.0 < \mu \le 3.0$: *1 non – trivial attractor fixpoint, "deterministic chaos"*
Trajectory deterministic for precise initial condition

$3.0 < \mu \le 3.6$: *1 non – trivial repellor fixpoint, "deterministic chaos"*
bi – stable flickering with alternating intensities,
several n – frequency doublings (bifurcations)

$3.6 < \mu < 3.8$: *1 non – trivial repellor fixpoint, intermittent flicker*

$3.8 \le \mu < 4.0$: *1 non – trivial repellor fixpoint, chaotic dynamics*

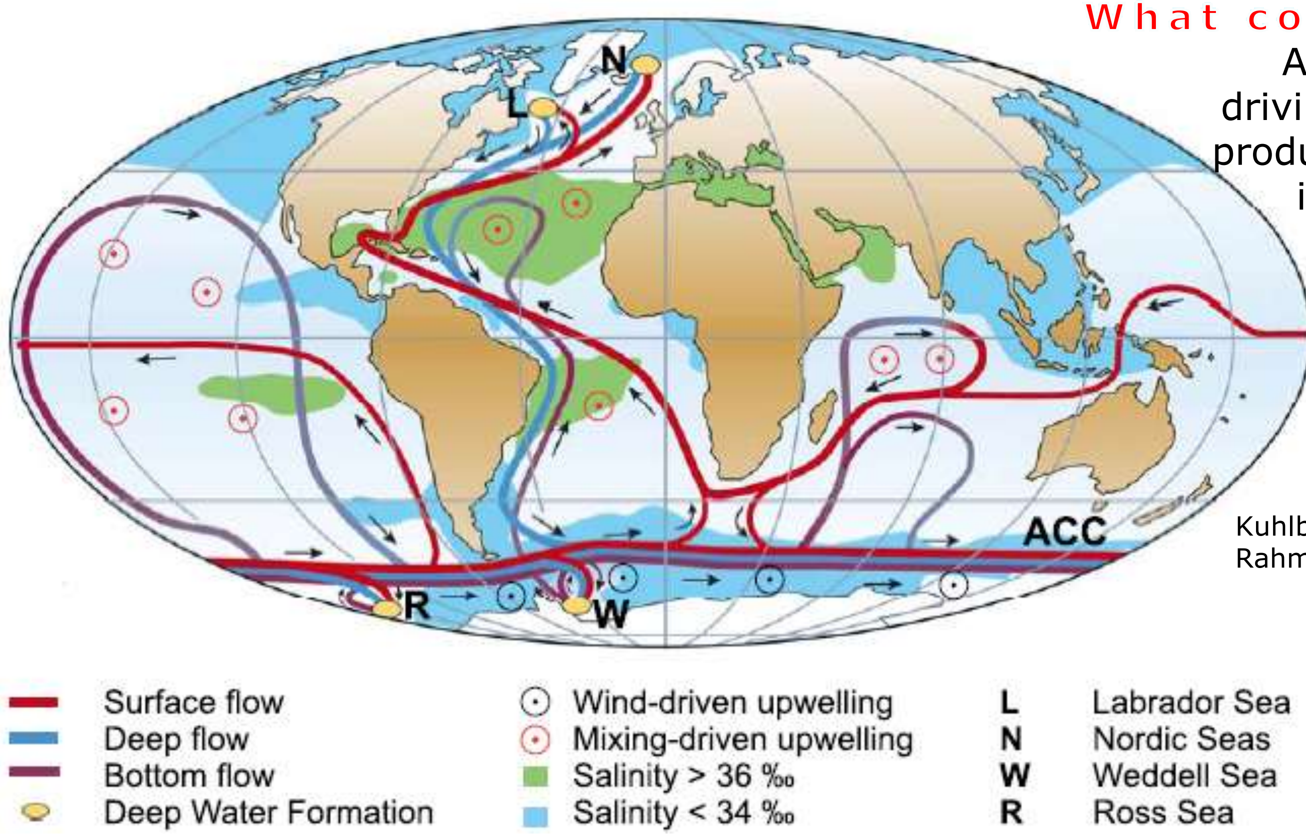


Left: Frequency doubling

Right: Two frequency doublings with intermittency.

Fragile Thermohaline Ocean Circulation

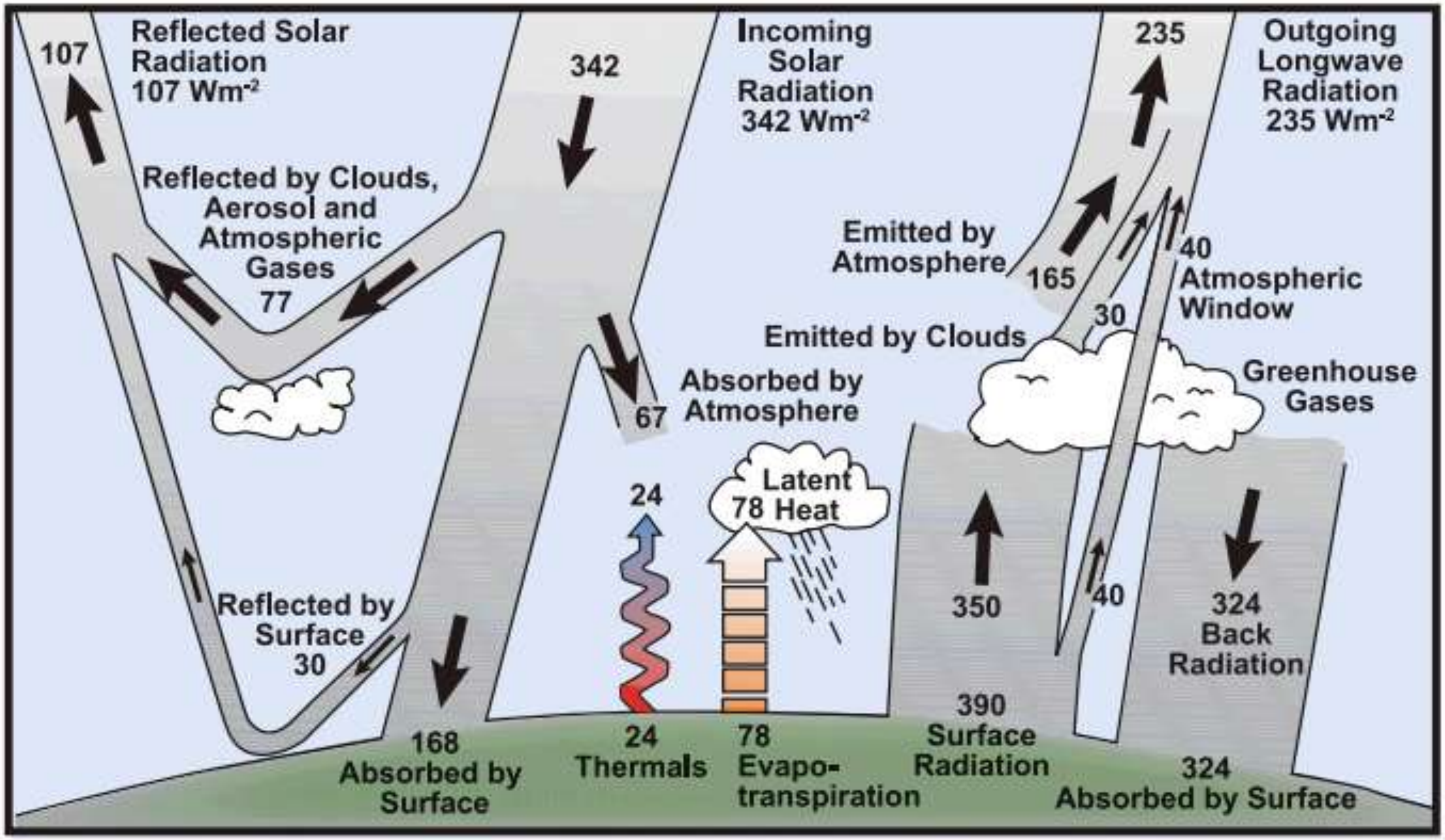
What could happen with Atlantic "conveyor belt" driving Gulf Stream, which produces moderate climate in Western Europe and North America.



Kuhlbrodt et al., Rahmstorf et al.

Atlantic: Warm saline (sea) water flows north, cools and sinks into deeper waters. Cold saline water returns southward. Possible scenario from glacial ice melting: saline water dilutes with fresh water, which does not sink readily. → backflow to south interrupted, circulation blocked → stops Gulf Stream: consequences for European and North American climate.

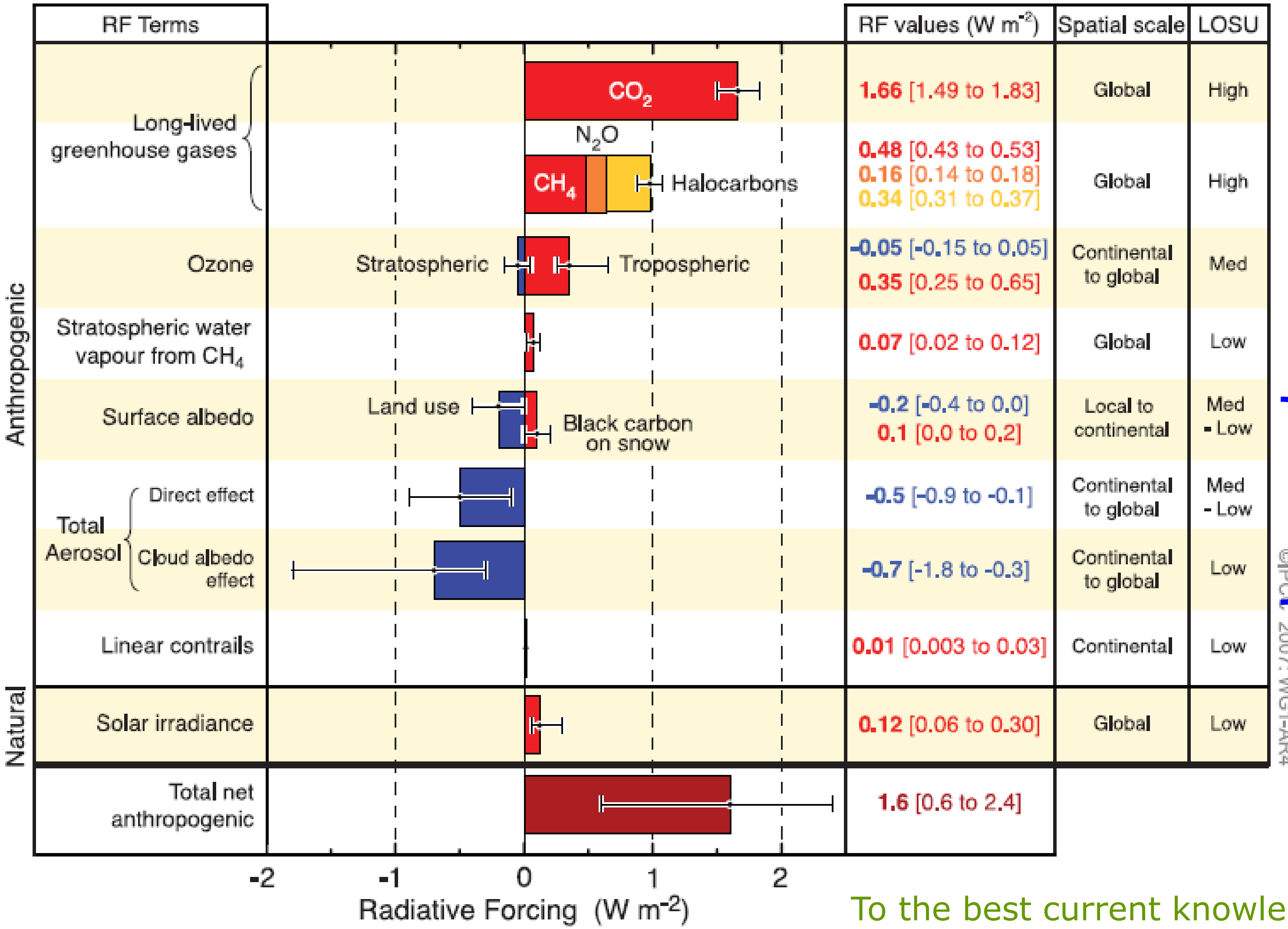
Understanding Earth's Radiation Balance



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).*

From IPCC AR4 Report, assessed Aug. 2012:
http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter1.pdf

Anthropogenic vs. Natural Forcings



Reduce

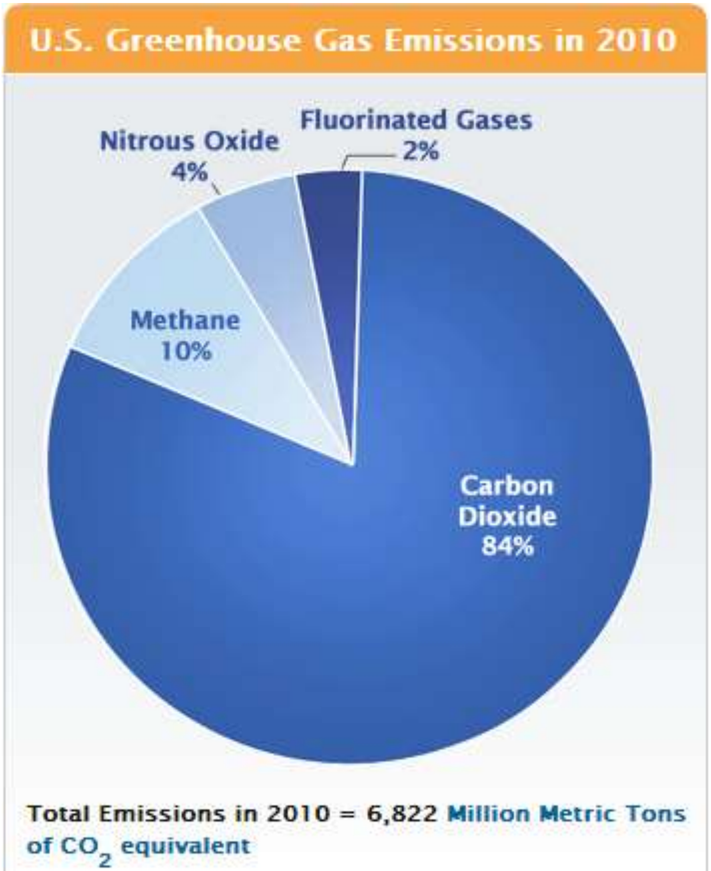
Geo Engineering?

To the best current knowledge:

Human activities (GHG) cause climate change

Greenhouse gas emissions

Greenhouse Gas Emission



EPA Report on Climate Change, GHG
http://www.epa.gov/climatechange/ghgemissions/gases.html

Greenhouse Gases (GHG) = gases that trap heat (IR) in the atmosphere and heat surface.

Carbon dioxide (CO_2) from burning fossil fuels (coal, natural gas, oil), solid waste, biomass (plants, wood, animal products), manufacture of cement. 0.035% in atmosphere.

Methane (CH_4) emitted in production (mining) and transport of coal, natural gas, oil, from livestock, agricultural practices, decay of organic waste in municipal solid waste landfills.

Nitrous oxide (N_2O) from agricultural and industrial activities, combustion of fossil fuels and solid waste.

Fluorinated gases = (HFCs, CFCs, PFCs = hydro/chloro-fluorocarbons, per-fluorocarbons, halon, SF_6) from industrial processes.
→ potent greenhouse gases = High Global Warming Potential gases ("High GWP gases").

Water (H_2O) vapor: >65% responsible for GH effect, but atmospheric content= Humidity is function of *temperature* : Clausius-Clapeyron Law,
H_2O *not directly* affected by anthropogenic activities, but indirectly via CO_2 emission.
Positive feed-back loop T ←→ water-vapor, but clouds stabilize !

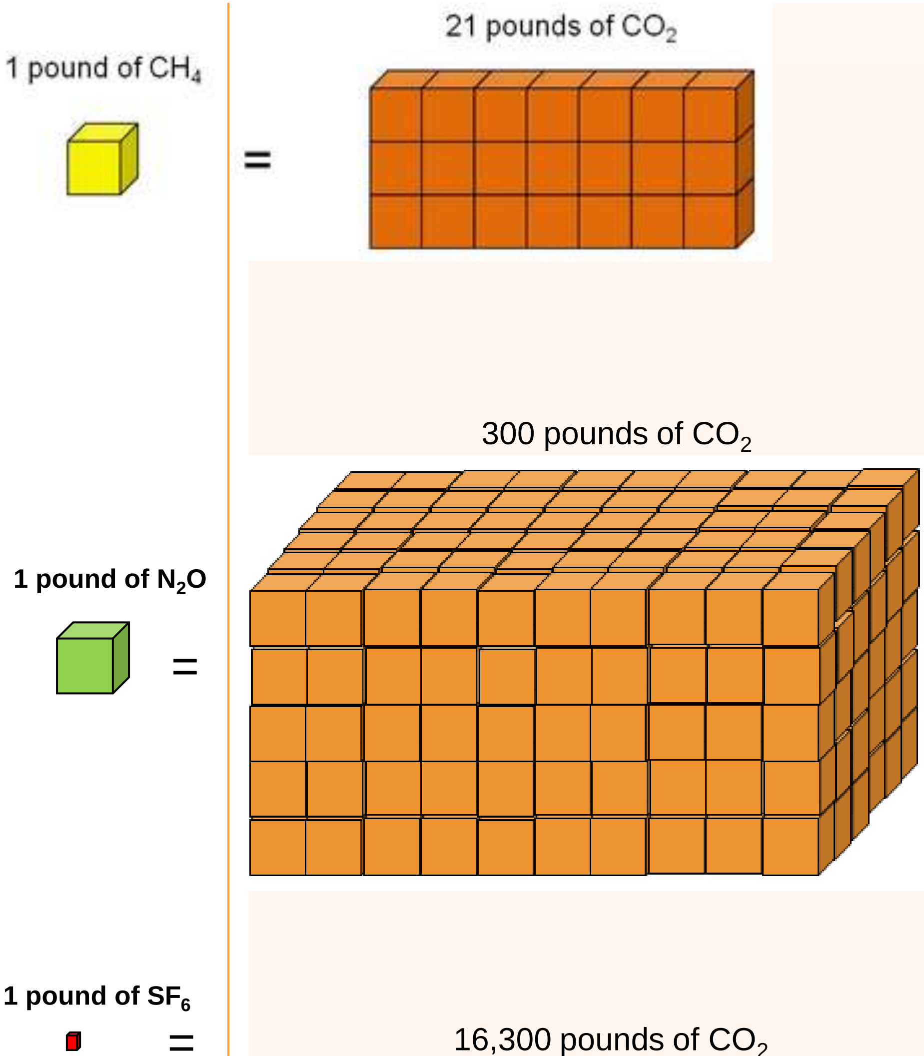
Global Warming Potentials: Data

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

Global Warming Potential (GWP)



Main factors:

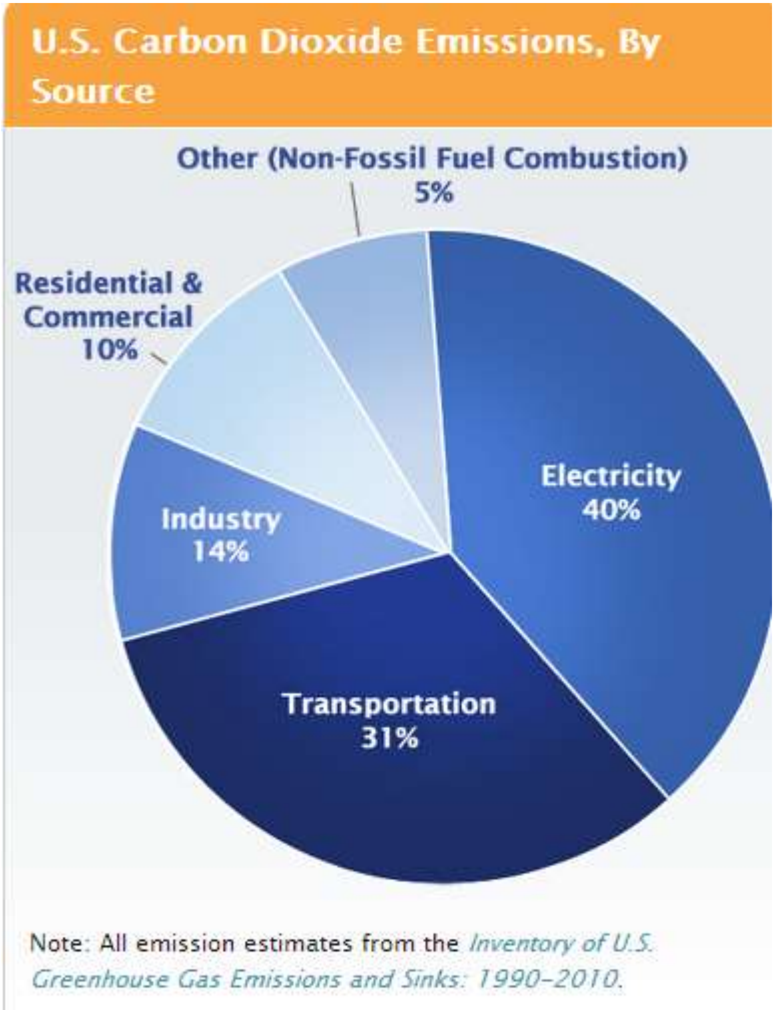
1) Effectiveness to trap heat (GWP#)
2) Abundance in atmosphere
3) Residence/lifetime in atmosphere

CO_2: GWP := 1 (reference).
Lifetime in Earth's atmosphere ~100 a.

CH_4: GWP = 21
Lifetime in Earth's atmosphere ~12 a.

N_2O: GWP = 300
Lifetime in Earth's atmosphere ~120 a.

US GHG Emission Sources (2010)



Electricity (40% of total CO_2, 33% of GHG emission) via combustion of fossil fuels. Coal produces more CO_2 than oil or natural gas.

Transportation (31% of CO_2 , 26% of GHG), via combustion of fossil fuels. This category includes transportation sources such as highway vehicles, air travel, marine transportation, and rail.

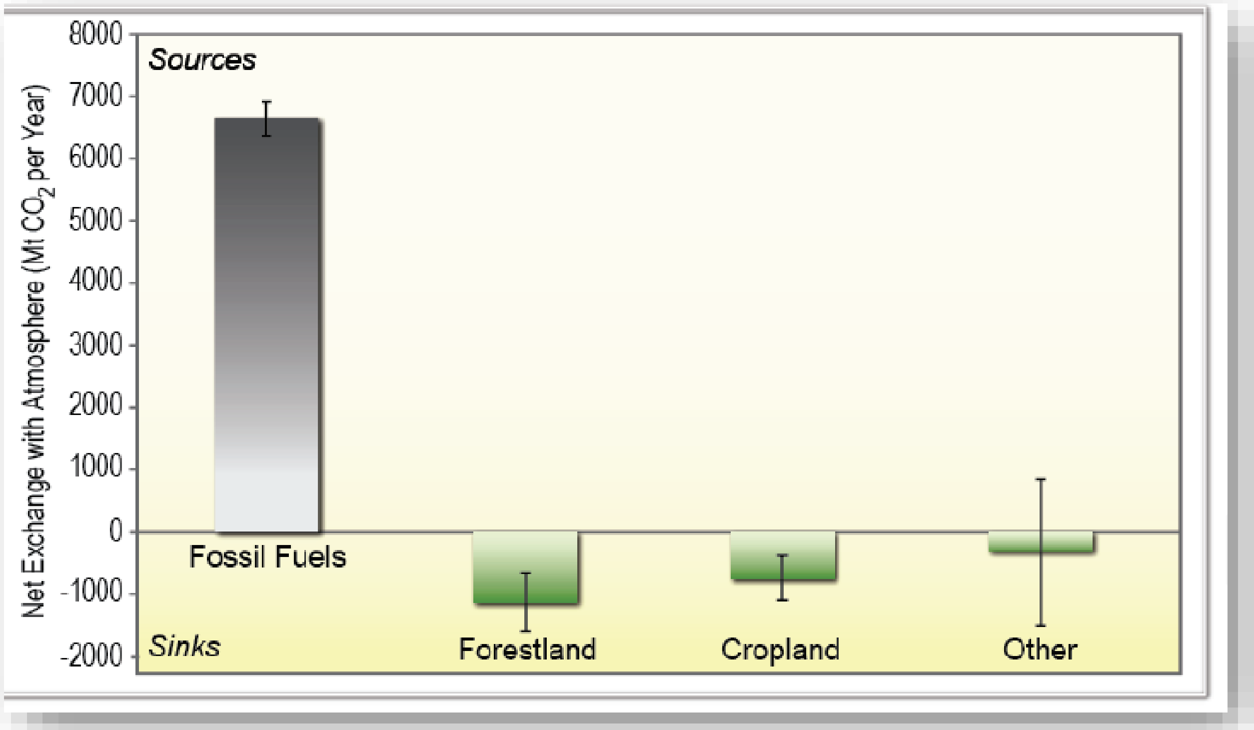
Industry (14% of CO_2 , 20% of GHG) mostly via fossil fuel combustion. Some important processes also produce CO_2 via chemical reactions (not combustion).

Examples: production and consumption of mineral products (e.g., cement), production of metals (e.g., iron, steel, etc.), production of certain chemicals.

Indirect CO_2 production via use of electricity (e.g., aluminum, composites,…).

1990-2010: U.S. Trends relatively stable (app. 6 Gt CO_2/a) → contra Kyoto Protocol !!

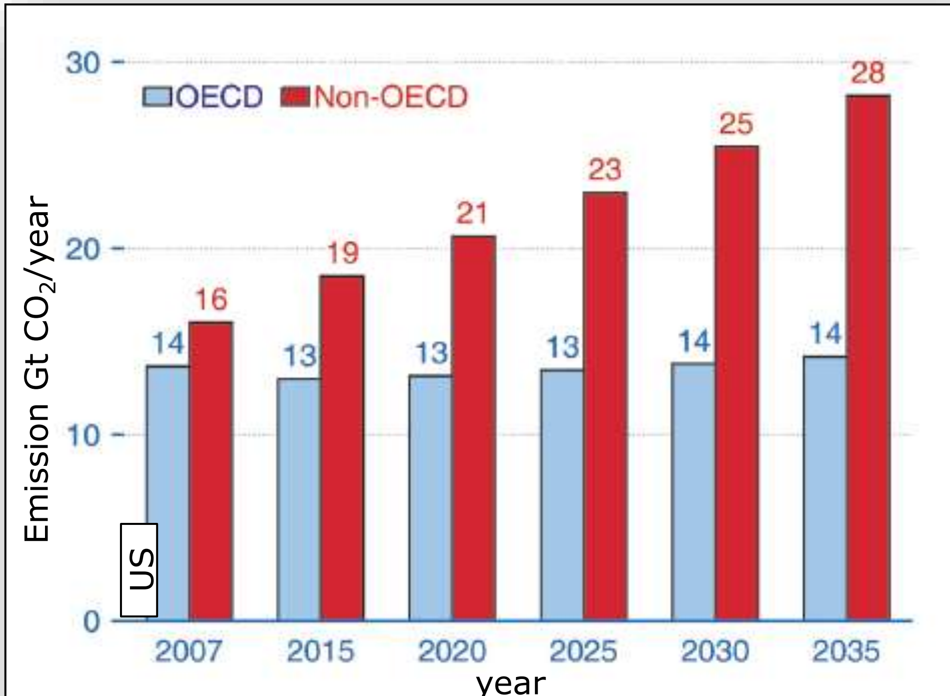
North American CO_2 Sources and Sinks



"At the continental scale, there has been a large and relatively consistent increase in forest carbon stocks over the last two decades (Woodbury et al. 2007), due to recovery of forests from past disturbances, net increases in forest area, and faster growth driven by climate or fertilization by CO_2 and nitrogen (King et al. 2012; Williams et al. 2012). However, emissions of CO_2 from human activities in the U.S. continue to increase and exceed ecosystem CO_2 uptake by more than three times. As a result, North America remains a net source of CO_2 into the atmosphere (King et al. 2012) by a substantial margin."

After NCADAC report 2013

Projections for CO_2 Emissions

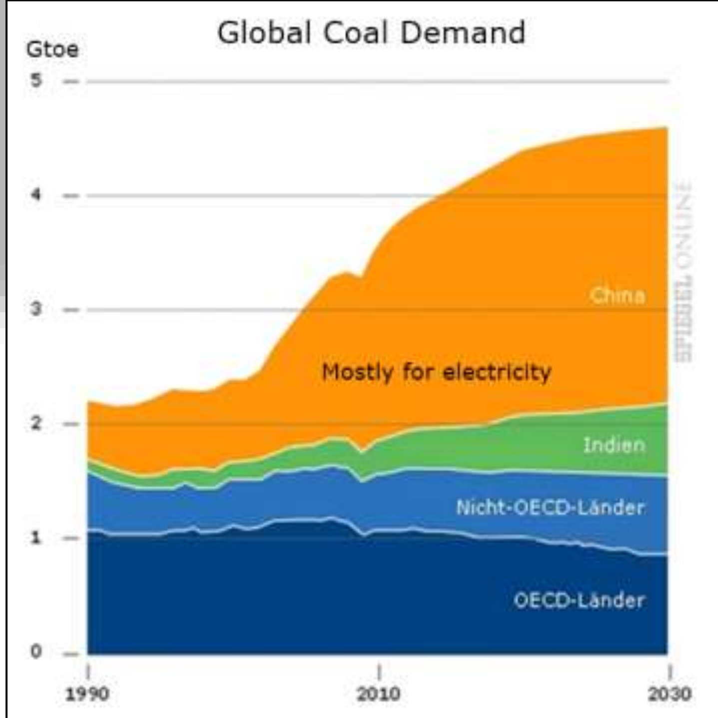


Energy Information Administration / International Energy Outlook. 2010

World energy-related CO_2 emission projections (in billion metric tons CO_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.



After: Spiegel online, Oct. 2012/ Sources BP, IEA

1 ton of oil equivalent (toe) = 42 GJ =energy released by burning 1 ton of crude oil.

National Climate Assessment and Development Advisory Committee

Summary Findings (edited):

1) Global climate is changing, apparent in a wide range of observations. The climate change of the past 50 years due primarily 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.

3) Human-induced 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 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, particularly the Southwest, the Great Plains, the Southeast, the islands of the Caribbean and the Pacific, including the state of Hawai.

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 more acidic.

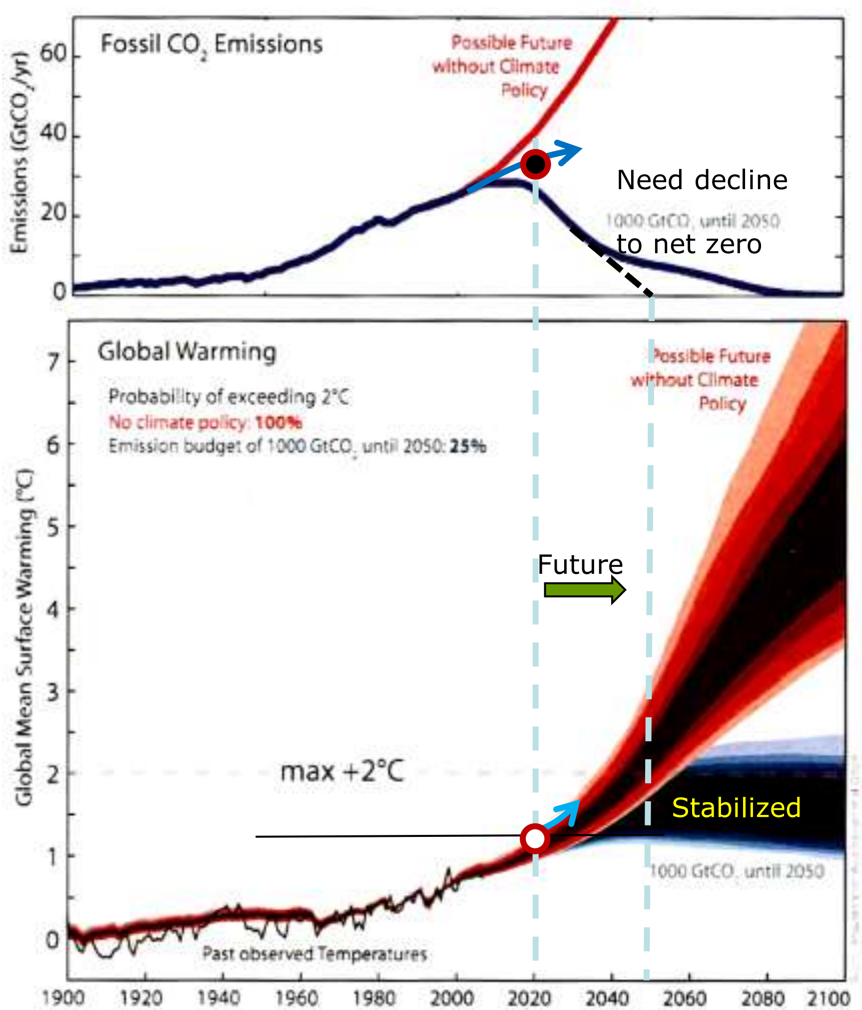
11) Planning for adaptation (address and prepare for impacts) and mitigation (reduce emissions) is increasing, but progress with implementation is limited.

Mitigation Goals

limiting global mean temperature increase (e.g. 2°C, 3°C)	What is a 'safe' amount of climate change? *Depends on the risks associated with given temperature targets, and decisions about willingness to tolerate these risks*
↓ limiting global atmospheric GHG concentrations (e.g. 450 ppm, 550 ppm)	How does GHG concentration translate into global temperature change and other impacts? *Depends on climate sensitivity and the strength of other forcing factors (e.g., aerosols)*
↓ limiting global GHG emissions (e.g. global emission budget or percent reduction)	How does a given level of emissions translate into an atmospheric GHG concentration? *Depends on carbon cycle dynamics and the timing of emission reductions*
↓ limiting U.S. GHG emissions (e.g. national emission budget or percent reduction)	What is a reasonable share of U.S. emission reductions relative to the global targets? *Depends on political, economic, and ethical judgments*

Developing nations find requests by the US to limit emissions unjustified because current per-capita emissions and standard of living in the United States and other developed nations are the highest and because US is responsible for largest share of historical increase in atmospheric GHG, and because the US have not yet enacted a restrictive emission policy or ratified Kyoto Protocol.

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 probably "relatively well manageable."

Larger temperature increases (4^0-6^0) are likely catastrophic (T, sea level).

We are on a dangerous path !

National Climate Assessment and Development Advisory Committee

Summary Findings (2017, 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.

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10) Life in the oceans is changing as ocean waters become warmer and more acidic.

11) 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

Literature

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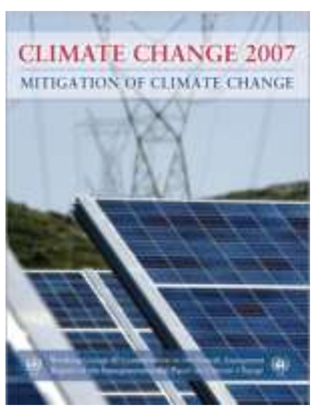
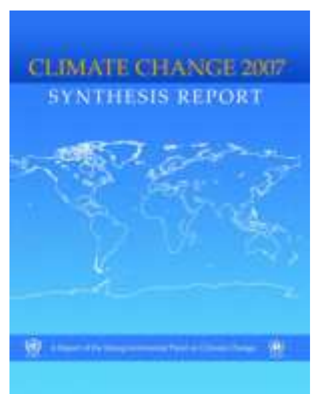
Climate Change 2007: Mitigation of Climate Change and Synthesis Report
http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4_wg3_full_report.pdf
http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf

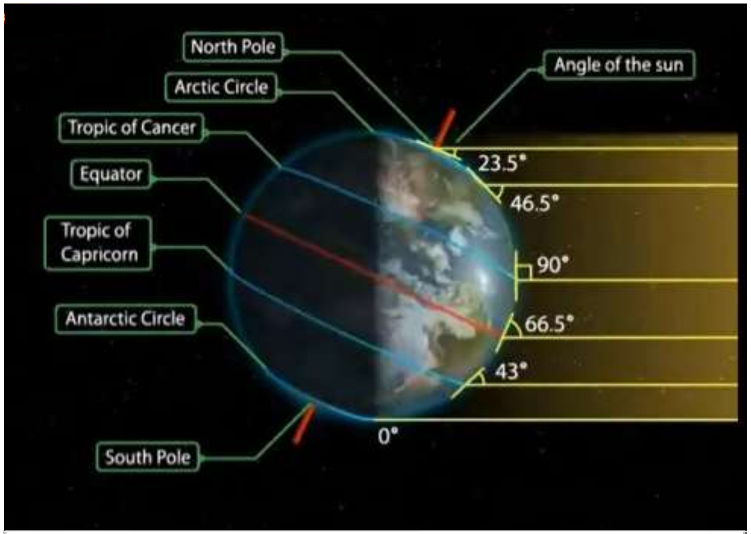
National Climate Assessment and Development Advisory Committee, Draft Report 2013, http://ncadac.globalchange.gov/download/NCAJan11-2013-publicreviewdraft-fulldraft.pdf





The End

“Black Bodies” Sun and Earth



Solar radiation incidence during summer on northern hemisphere

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

$k = 1.381 \cdot 10^{-23}\ J/K$ *Boltzmann's constant*

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

sr = *steradians = unit of angular acceptance*

$\Delta\Omega = Area/(4\pi \cdot distance^2)$

In spite of occasional flares (outbursts/mass ejections), the Sun emits **thermal radiation** like any “black body” at the same temperature *T*.

Planck's Radiation Law

Light power density per unit wave length λ *emitted in random directions (in* 4π*):*

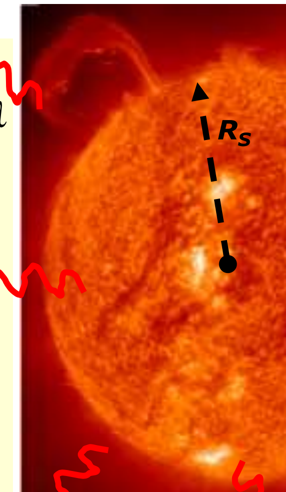
$$\boxed{R(\lambda,T) = \frac{2hc^2}{\lambda^5}\left[\frac{1}{e^{hc/\lambda kT}-1}\right]\left(\frac{W}{m^3 \cdot sr}\right)}$$

Stephan – Boltzmann Radiation Law

Total power emitted

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

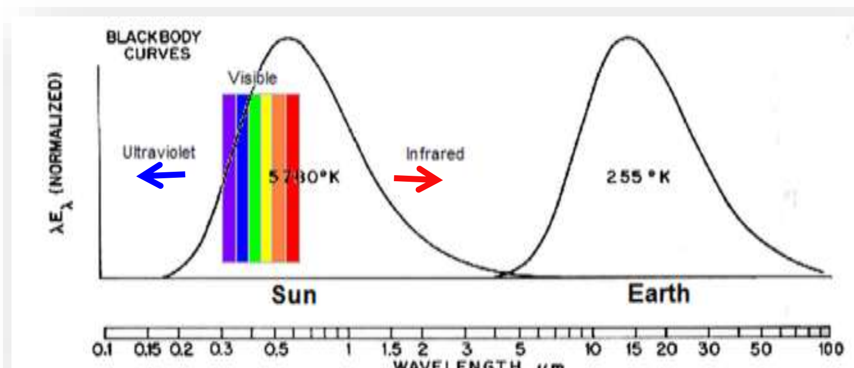
$$SB-constant: \boxed{\sigma = 5.670 \cdot 10^{-8}\ \left(W/K^4 m^2\right)}$$



$R_S = 6.96 \cdot 10^5 km$

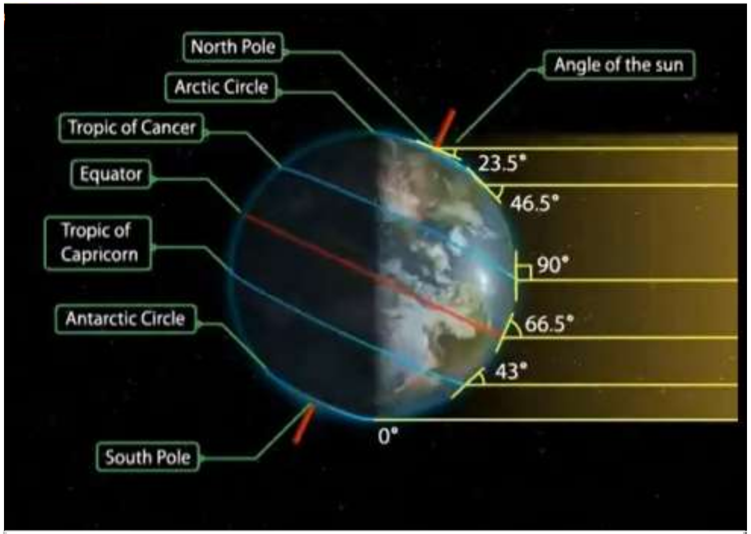
$4\pi R_S^2 = 6.09 \cdot 10^{12}\ km^2$

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



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

"Black Bodies" Sun and Earth



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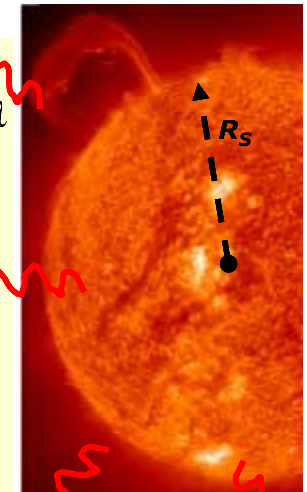

R_S=6.96·10⁵km

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