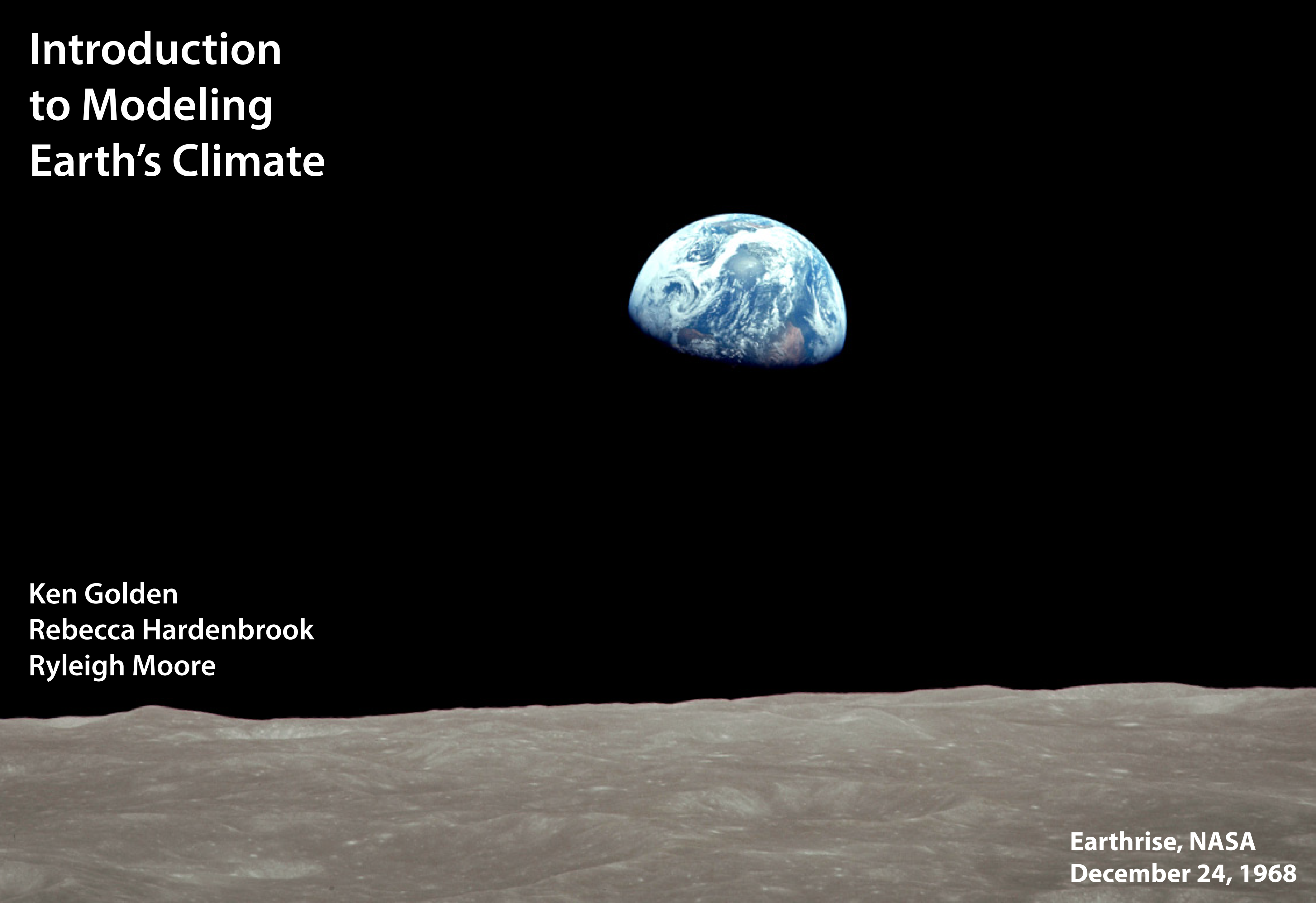
Introduction to Modeling Earth's Climate

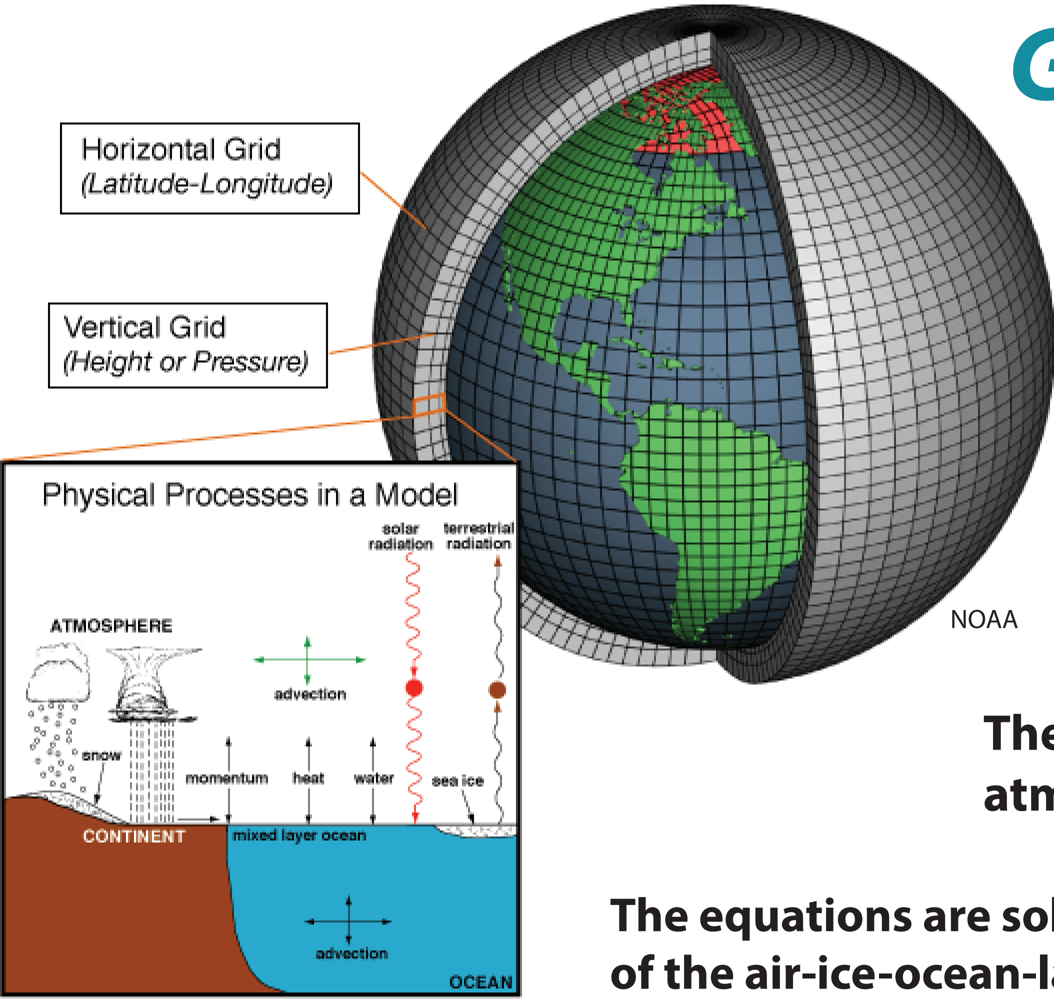
Ken Golden
Rebecca Hardenbrook
Ryleigh Moore



Earthrise, NASA
December 24, 1968

Math ACCESS Week, June 18 - 21, 2019

Global Climate Models



NOAA

climate fueled by the nonuniform spatial distribution of incoming solar radiation.

Stute et al., PNAS 2001

Climate models are systems of partial differential equations (PDE) derived from the basic laws of physics, chemistry, and fluid motion.

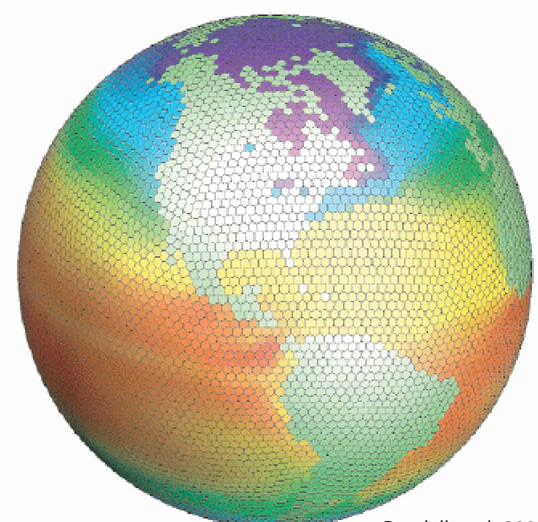
They describe the state of the ocean, land, ice atmosphere, biosphere, and their interactions.

The equations are solved on 3-dimensional grids of the air-ice-ocean-land system (with horizontal grid size ~ 100 km), using very powerful computers.

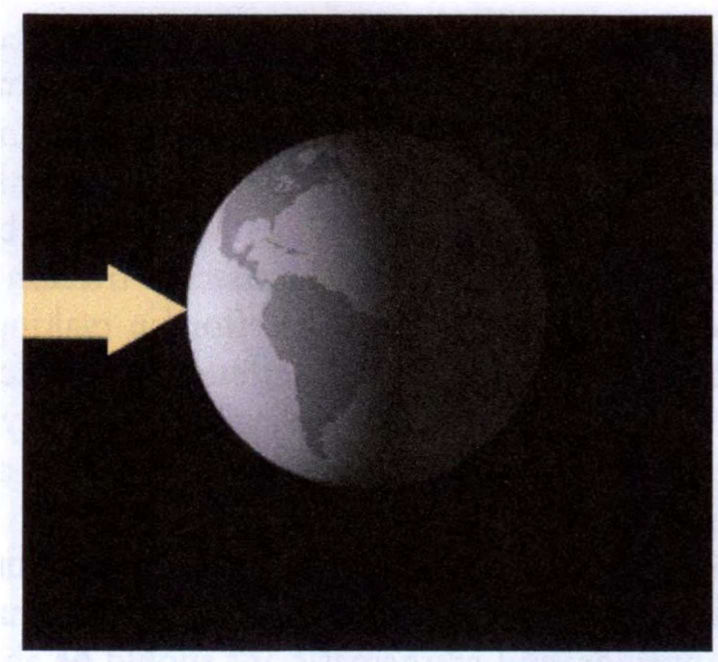
key challenge :

incoming sub - grid scale processes

linking scales

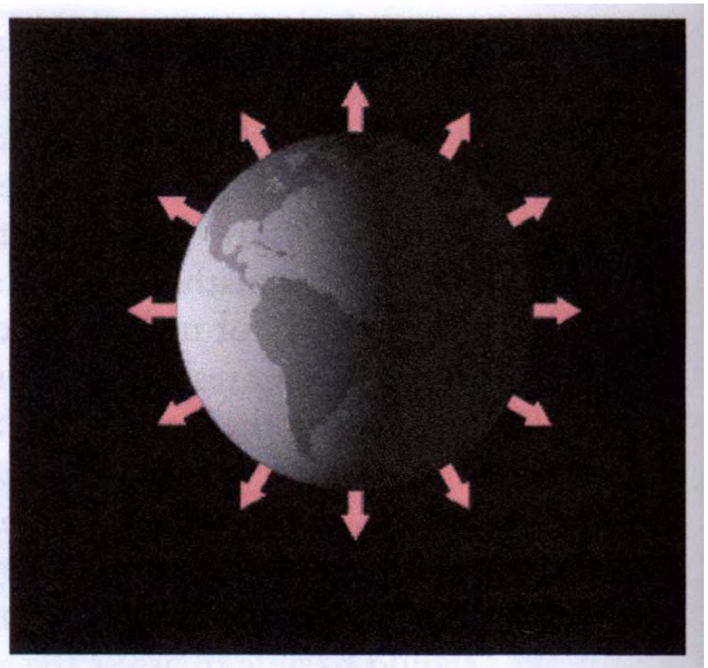

Randall *et al.*, 2002

Earth's energy balance



E_{in}

incoming shortwave radiation
sunlight



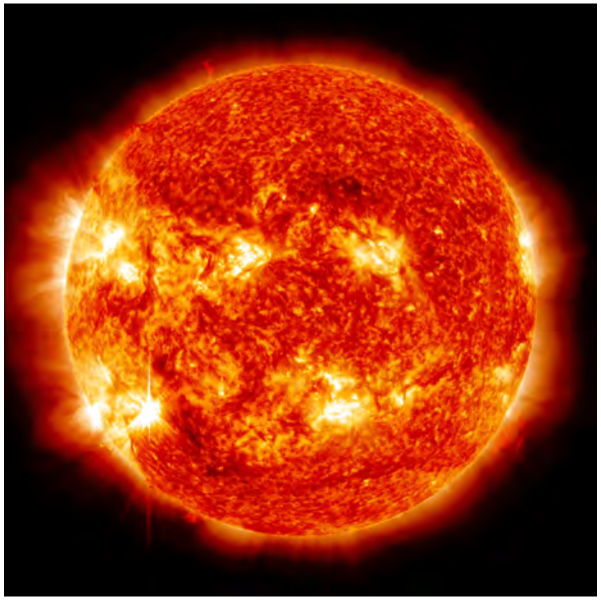
E_{out}

outgoing longwave radiation
heat

if $E_{out} > E_{in}$ **planet cools**

if $E_{out} < E_{in}$ **planet warms**

climate system parameters



$$S_0 = 1,368\,\mathrm{W m^{-2}}$$

solar enery flux per unit area

solar "constant"

depends on sun's strength
and average distance from
Earth to Sun

MODEL INPUT

$$T(t) = \langle \mathrm{Temperature}(x,t) \rangle$$

global mean
surface temperature

How to predict ??

(How to define and measure??)

MODEL OUTPUT

most important climate parameter:
how much energy reflected *vs.* how much energy absorbed

reflection

albedo $\alpha = \dfrac{\text{reflected sunlight}}{\text{incident sunlight}}$

absorption

co- albedo $1-\alpha$

fraction of energy that reaches Earth's surface

amount of solar energy intercepted by Earth per unit time (as a flat disk) $\pi R^2 S_0$

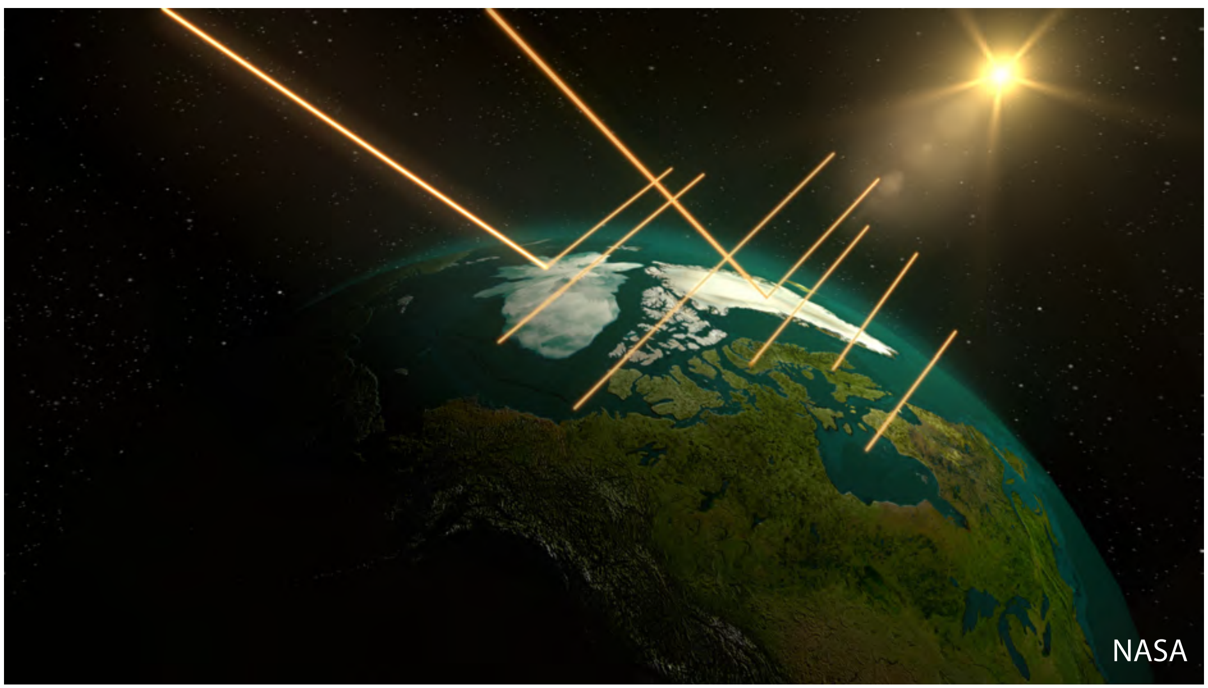
amount of solar energy reaching Earth's surface per unit time $(1-\alpha)\pi R^2 S_0$

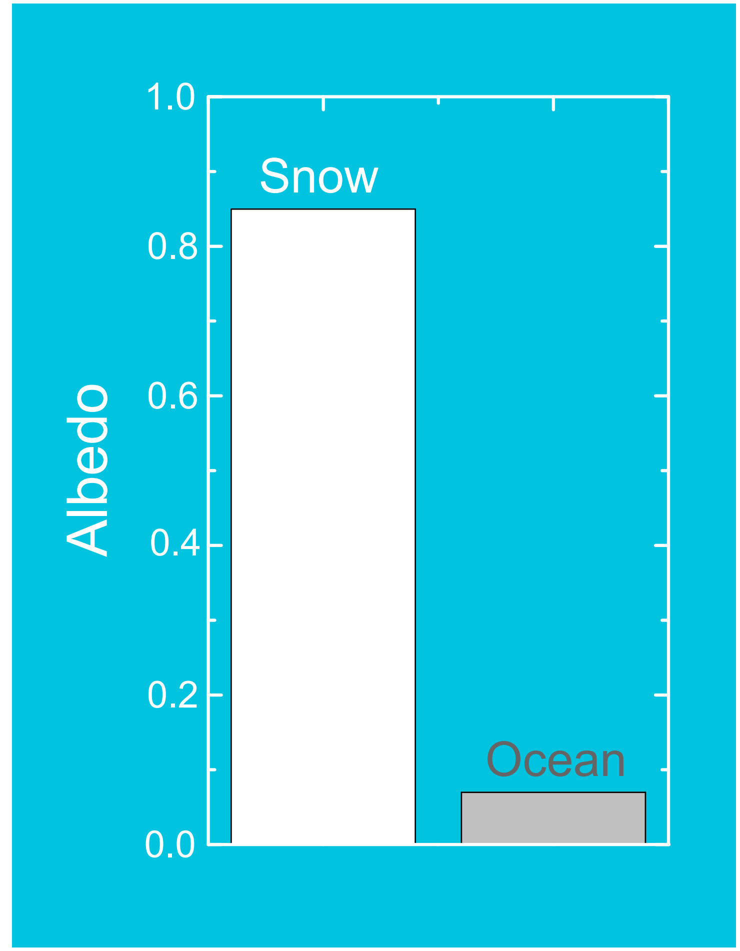
amount of solar energy reaching Earth's surface per unit time / unit area

$$E_{in} = \frac{(1-\alpha)\pi R^2 S_0}{4\pi R^2} = \frac{(1-\alpha)S_0}{4} = (1-\alpha)Q$$

polar ice caps critical to global climate in reflecting incoming solar radiation

white snow and ice reflect





dark water and land absorb

$$\textbf{\textit{albedo}}\ \alpha = \frac{\text{reflected sunlight}}{\text{incident sunlight}}$$

albedo of Earth's surface

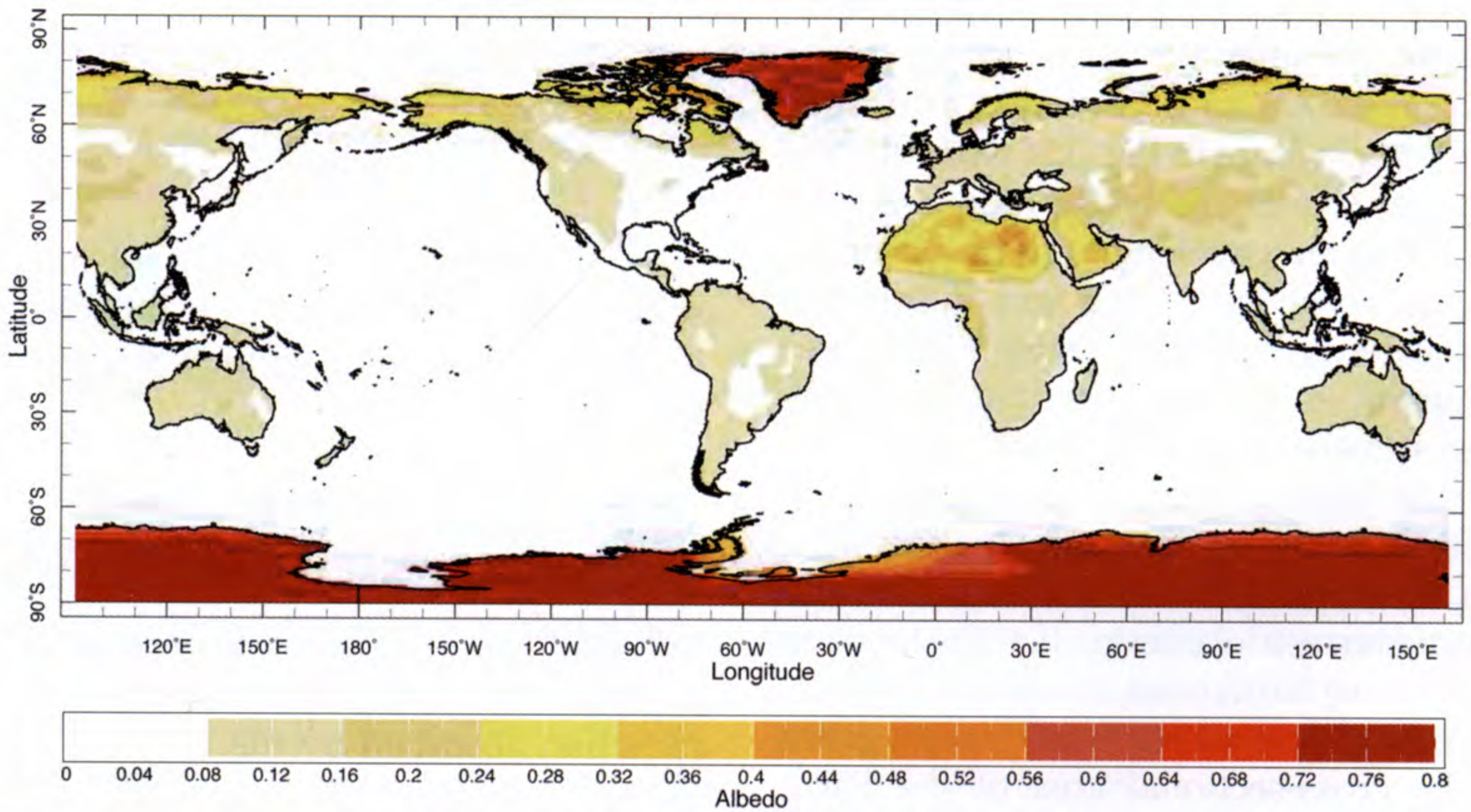


FIGURE 2.5. The albedo of the Earth's surface. Over the ocean the albedo is small (2–10%). It is larger over the land (typically 35–45% over desert regions) and is particularly high over snow and ice (~80%) (see Table 2.2).

average albedo ~ 0.3

Marshall and Plumb 2008

How much energy radiates out into space from a ball at temperature T?

Earth radiates mostly in infrared spectrum, energy radiated depends on T
(approximate as a "black body")

$$E_{out} = \sigma T^4$$

$$\sigma = 5.67 * 10^{-8}\,\mathrm{Wm^{-2}K^{-4}}$$

Stefan - Boltzmann constant

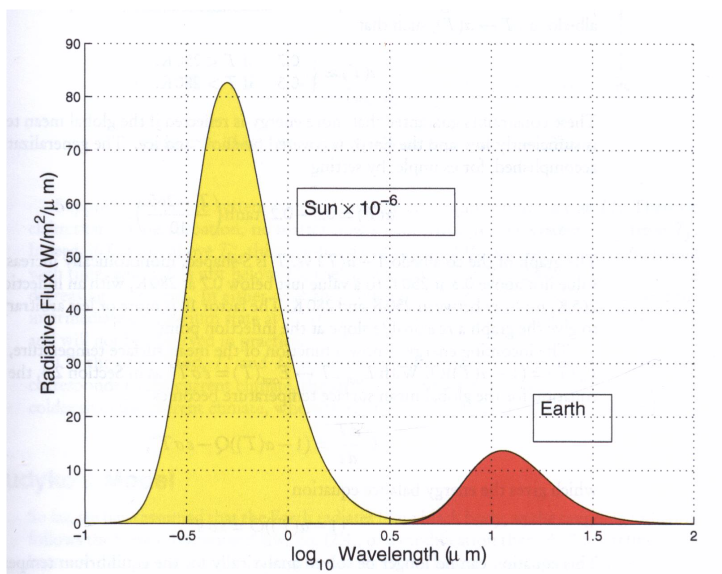


Figure 2.4. *Black-body emission curves of the Sun and the Earth. Reprinted courtesy of NASA.*

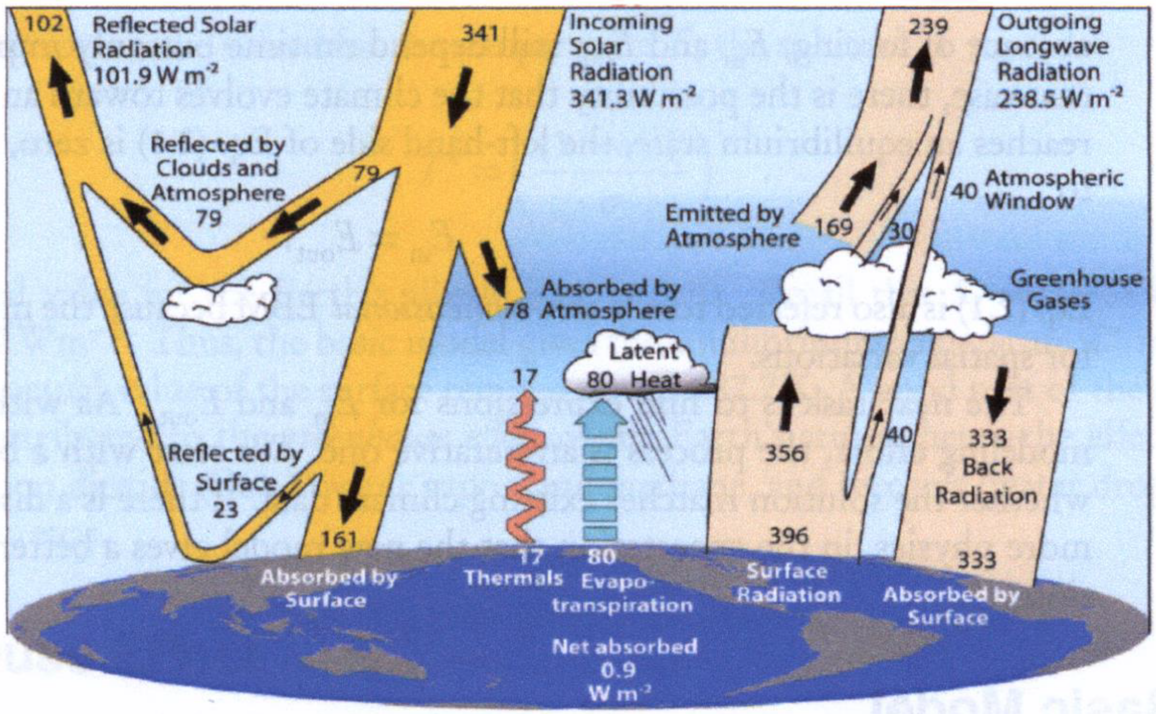


Figure 2.3. *Detailed radiative energy balance* [112].

Energy Balance Model

$$C\,\frac{dT}{dt} = E_{in} - E_{out}$$

C = ***heat capacity***
= energy needed to raise temperature by one Kelvin

rate of change of mean global temperature

$$C\,\frac{dT}{dt} = (1-\alpha)Q - \sigma T^4$$

Find steady-state **equilibrium** temperature: $C\frac{dT}{dt} = E_{in} - E_{out}$

$$\frac{dT}{dt} = 0$$

constant temperature rate of change = 0

$$E_{in} = E_{out}$$

solve $$\sigma T^4 = (1 - \alpha)Q$$

$$T_{eq} = \left(\frac{(1-\alpha)\,Q}{\sigma}\right)^{1/4}$$

$T_{eq} \approx 254.8\,\mathrm{K} = -1.03\,^{\circ}\mathrm{F}$, which is quite cold!

The actual measured temperature of the surface of the Earth is $287.89\,\mathrm{K} = 58.5\,^{\circ}\mathrm{F}$

Pretty good .... but what are we missing?

greenhouse effect

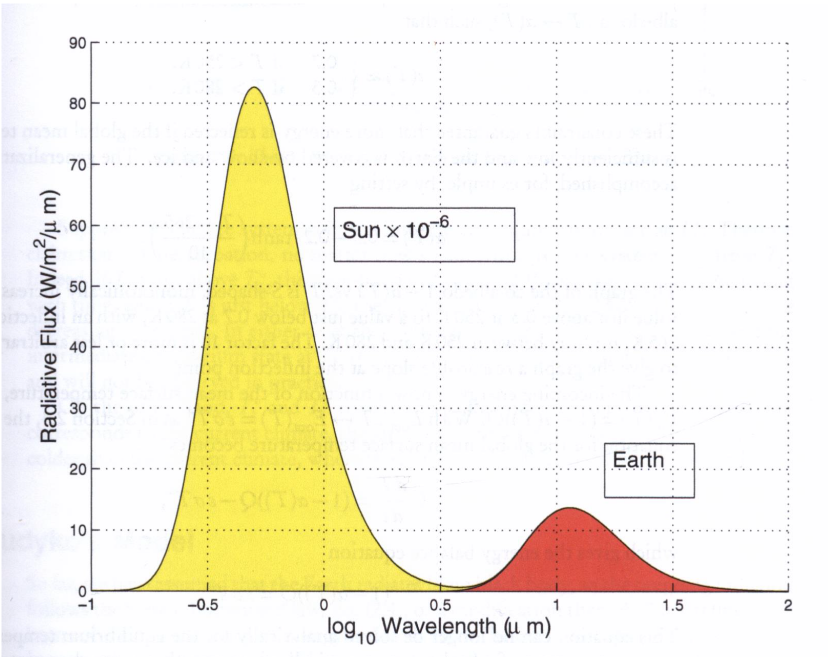
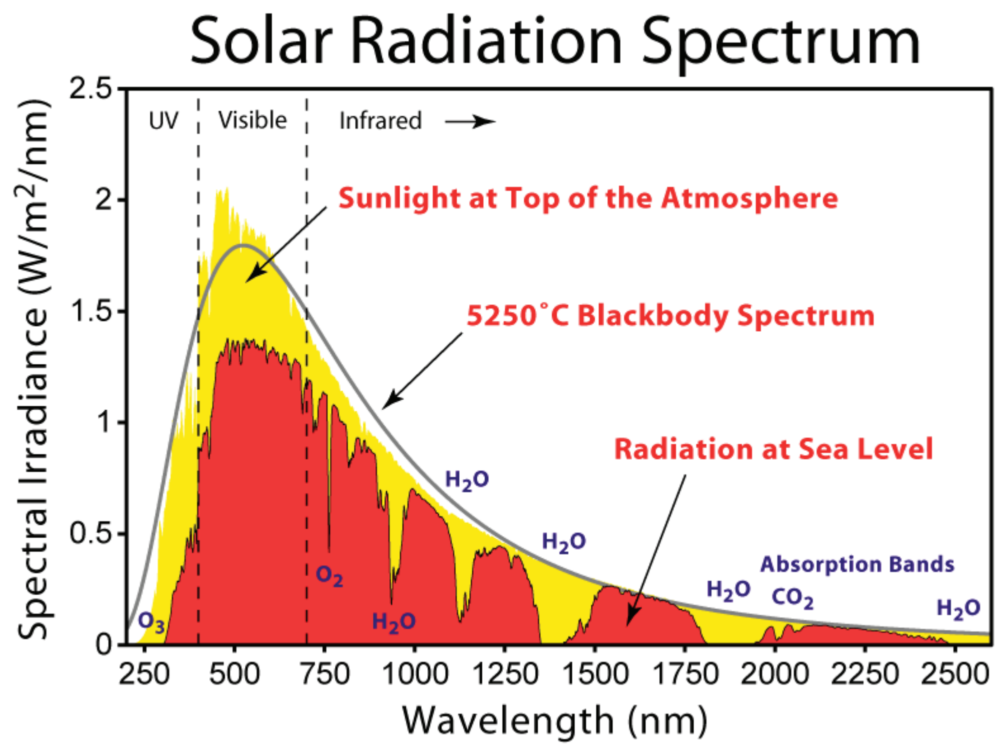
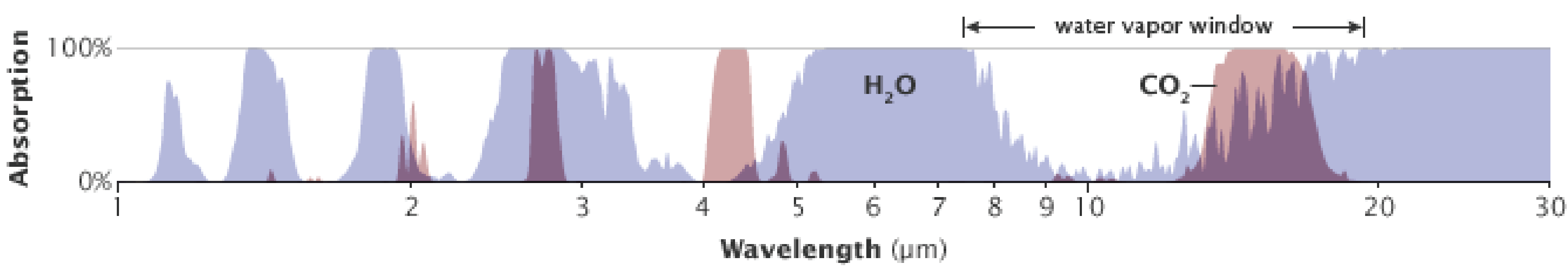


Figure 2.4. *Black-body emission curves of the Sun and the Earth. Reprinted courtesy of NASA.*



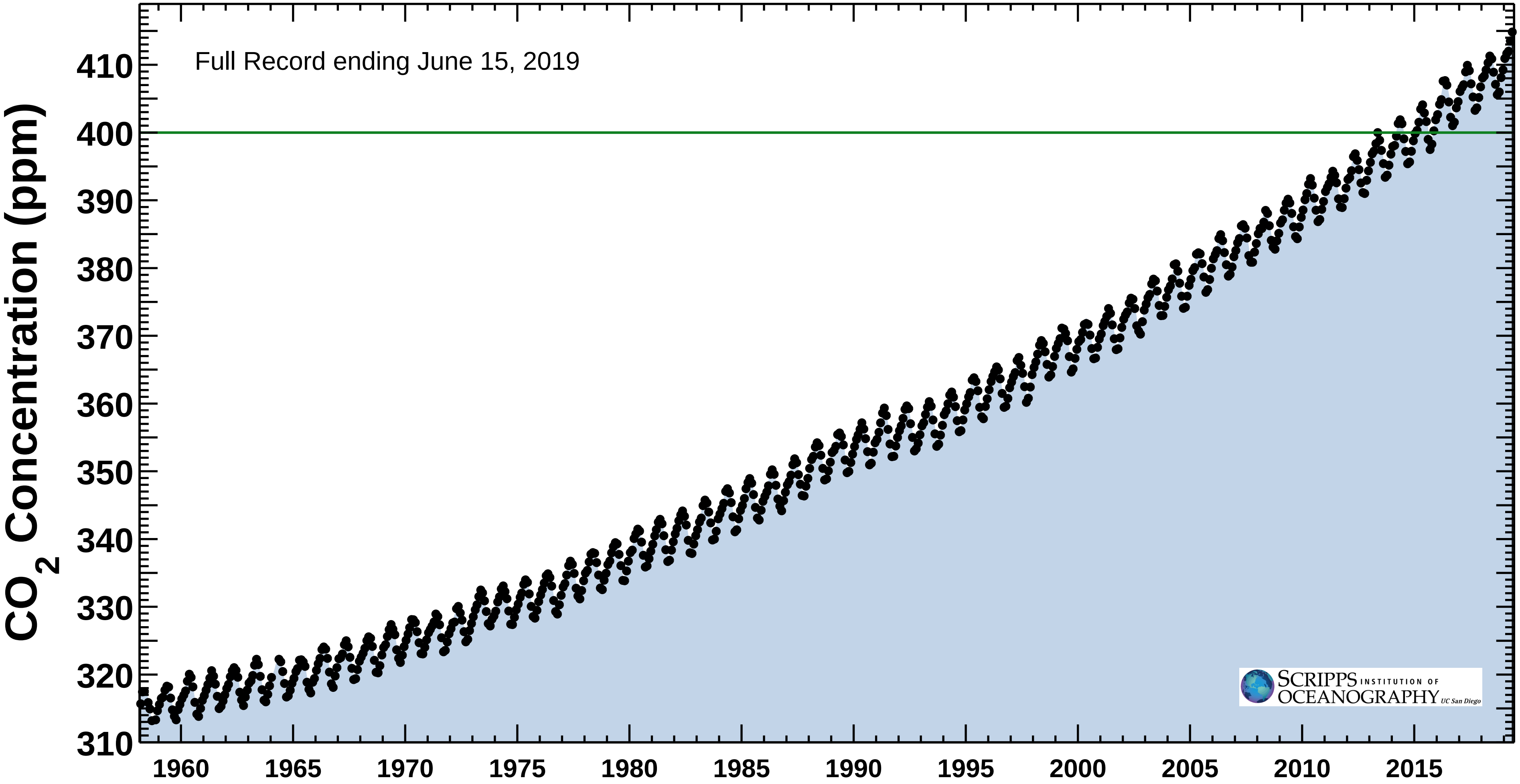


Earth's emission spectrum in far infrared > 5 µm

Latest CO_2 reading
June 13, 2019

414.71 ppm

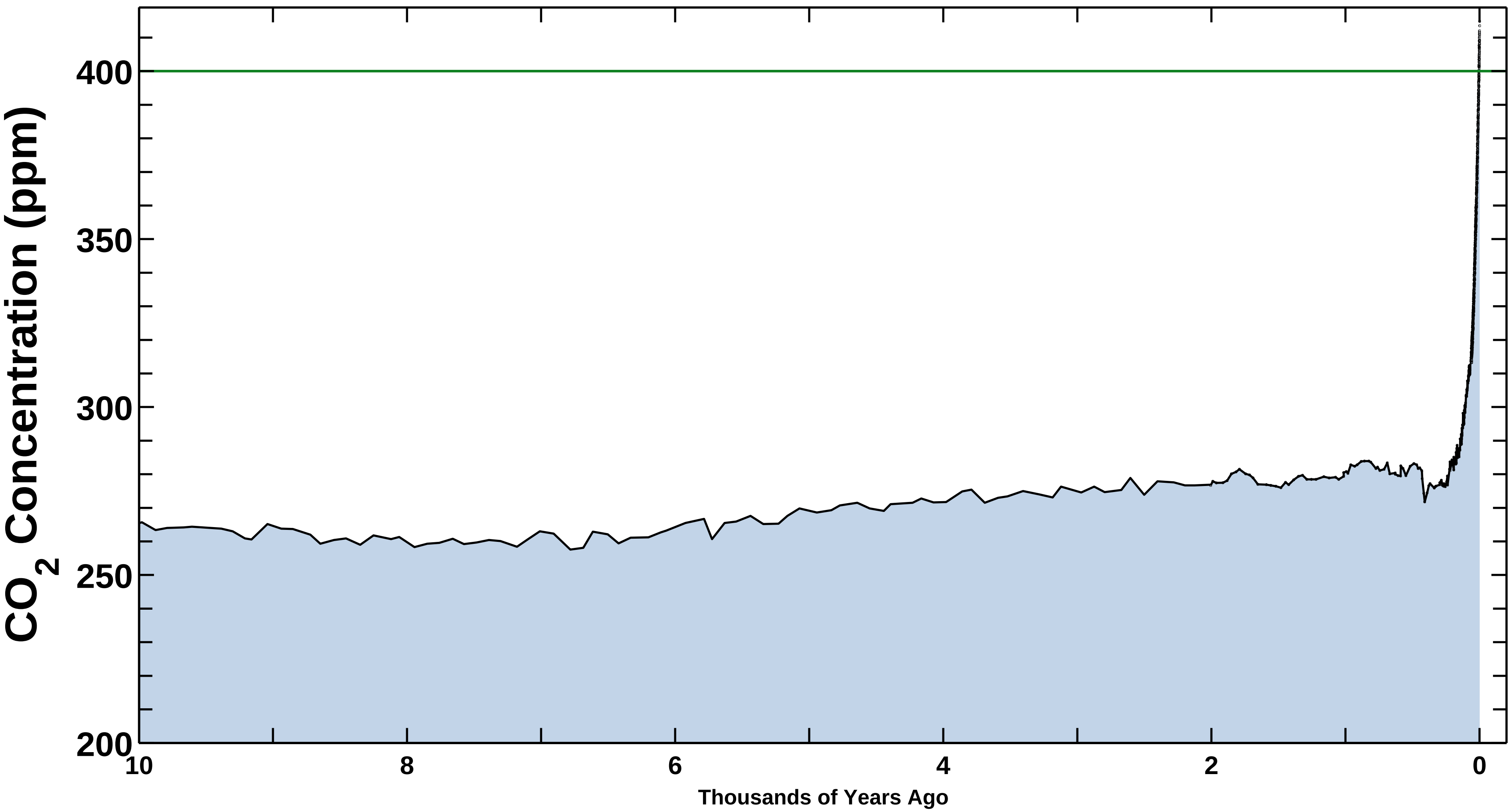
Carbon dioxide concentration at Mauna Loa Observatory

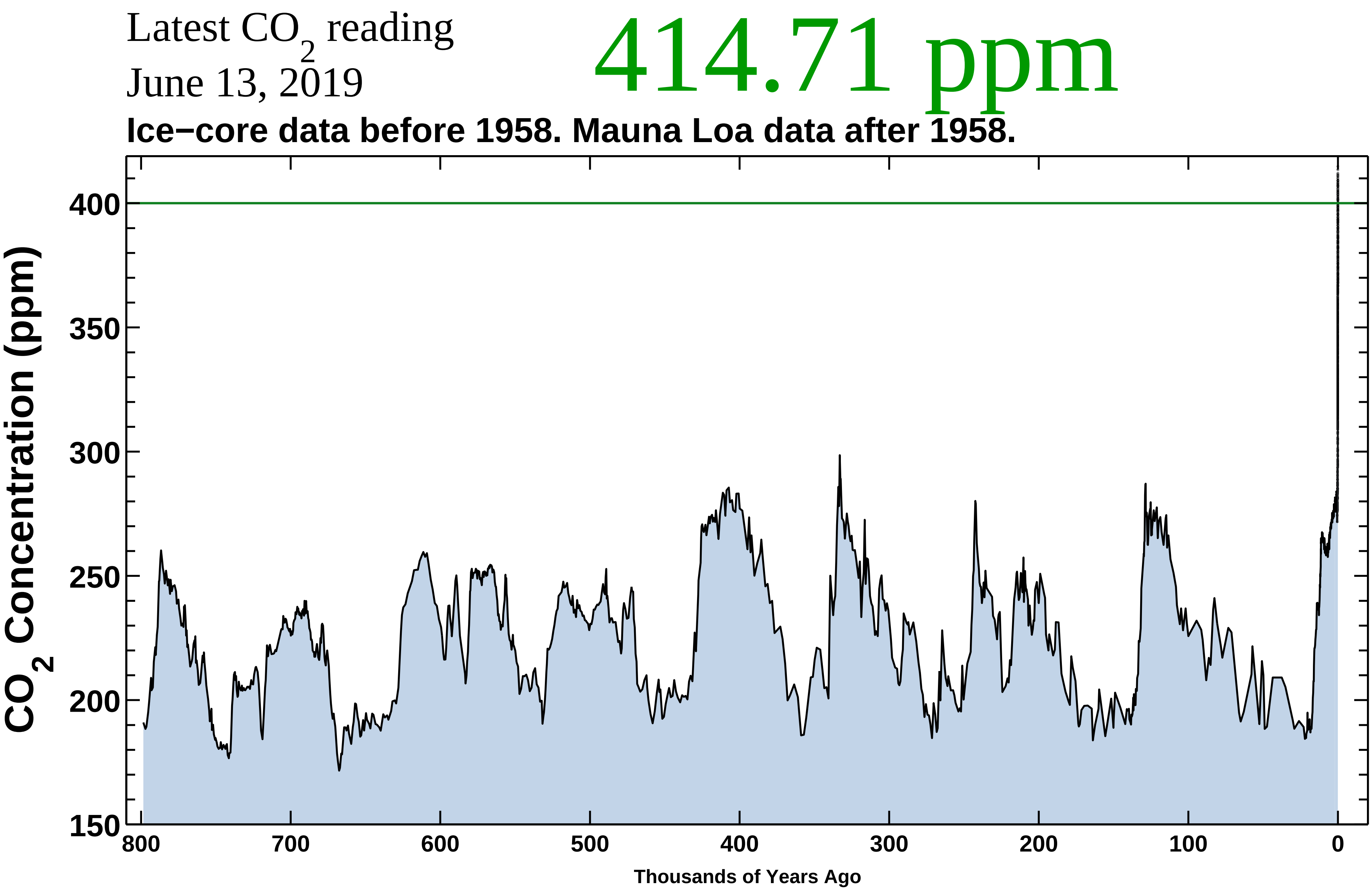


Latest CO_2 reading
June 13, 2019

414.71 ppm

Ice−core data before 1958. Mauna Loa data after 1958.



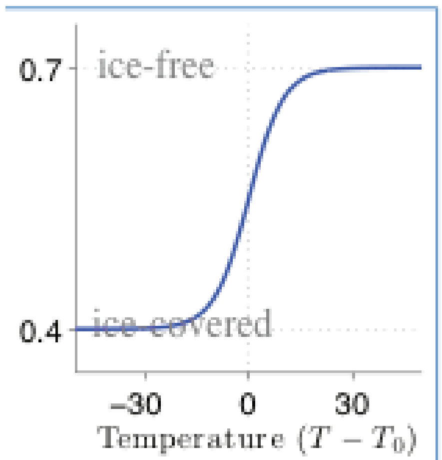


Latest CO_2 reading
June 13, 2019
414.71 ppm
Ice−core data before 1958. Mauna Loa data after 1958.
CO_2 Concentration (ppm)
400
350
300
250
200
150
800
700
600
500
400
300
200
100
0
Thousands of Years Ago

Assuming albedo independent of Earth's temperature too simplified....

planetary co-albedo

$$1 - \alpha$$



cold icy reflective

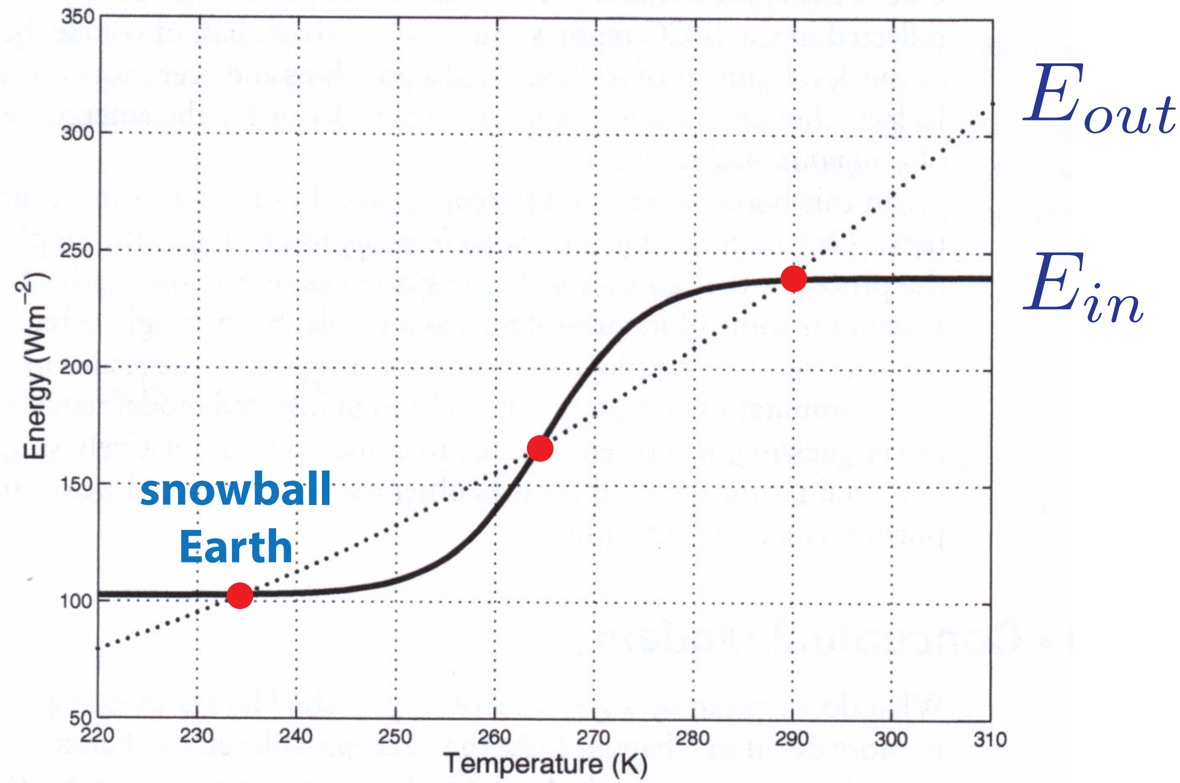
warm watery absorptive

albedo nonlinear in temperature

Now solve for equilibrium temperature $E_{in} = E_{out}$

$$\sigma T^4 = (1 - \alpha(T))Q$$

3 solutions!
multiple equilibria



stable *vs.* unstable equilibria

Bifurcation Diagram

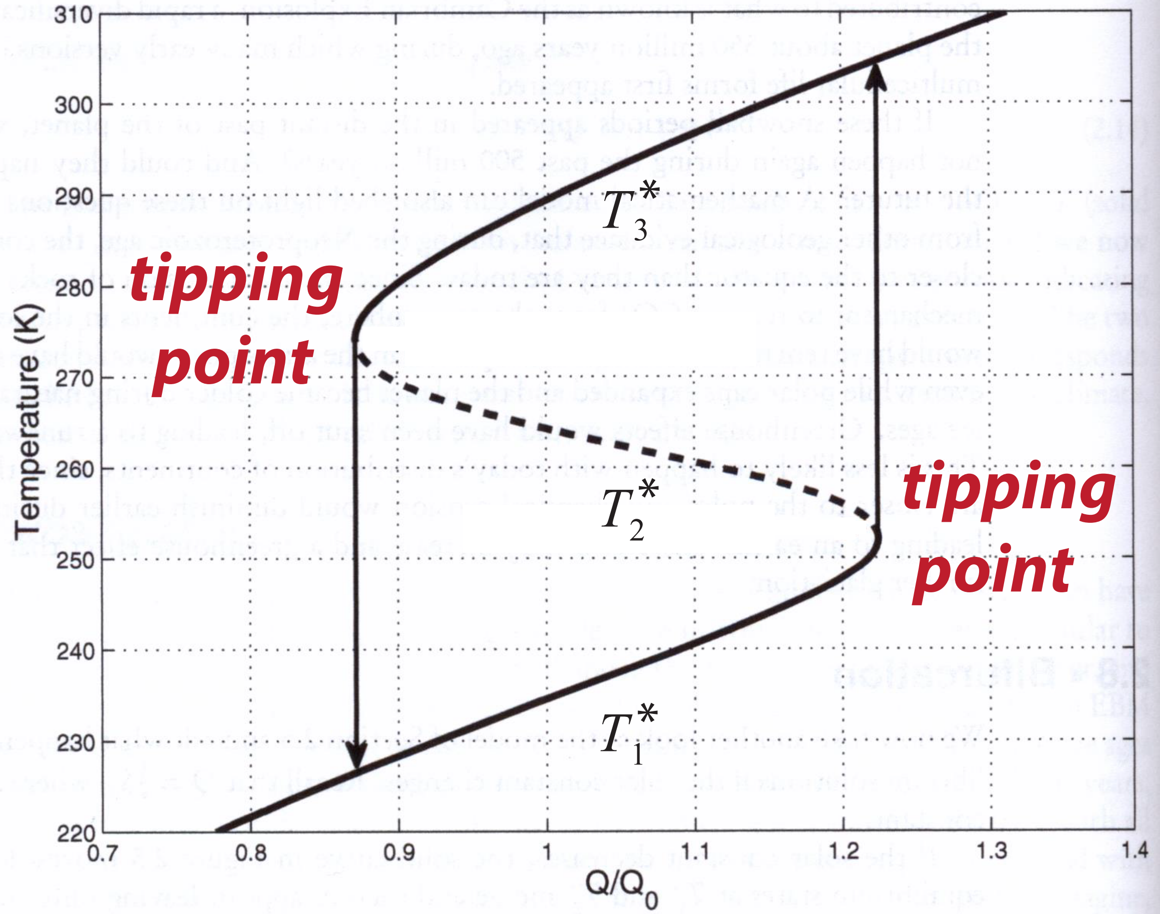
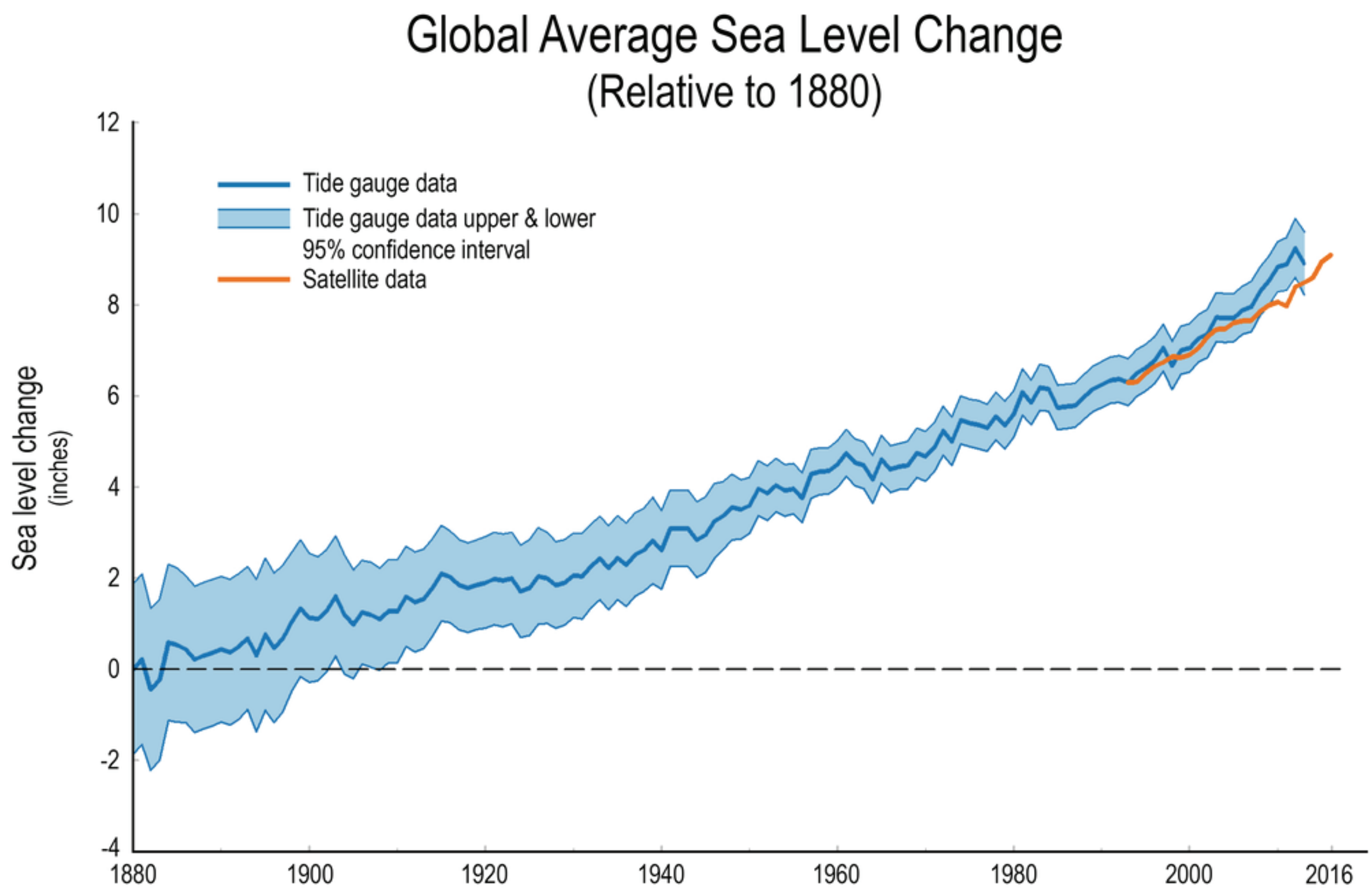
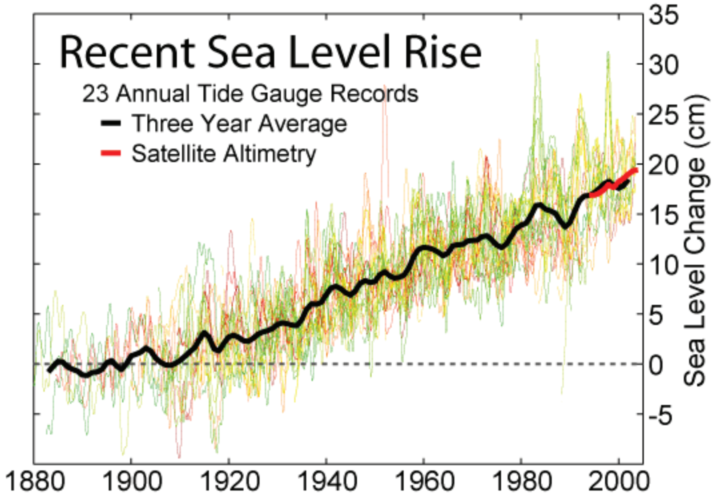


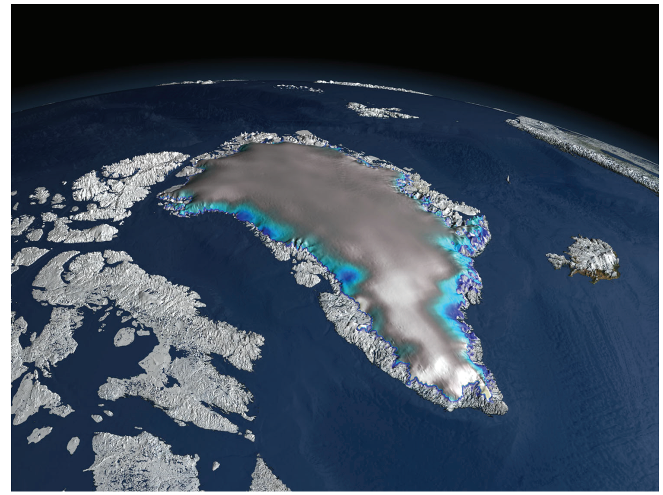
Figure 2.6. *Mean surface temperatures at equilibrium as a function of the solar constant (in units of its present value).*

Why is sea level rising?



As Earth's climate warms, why does sea level rise?





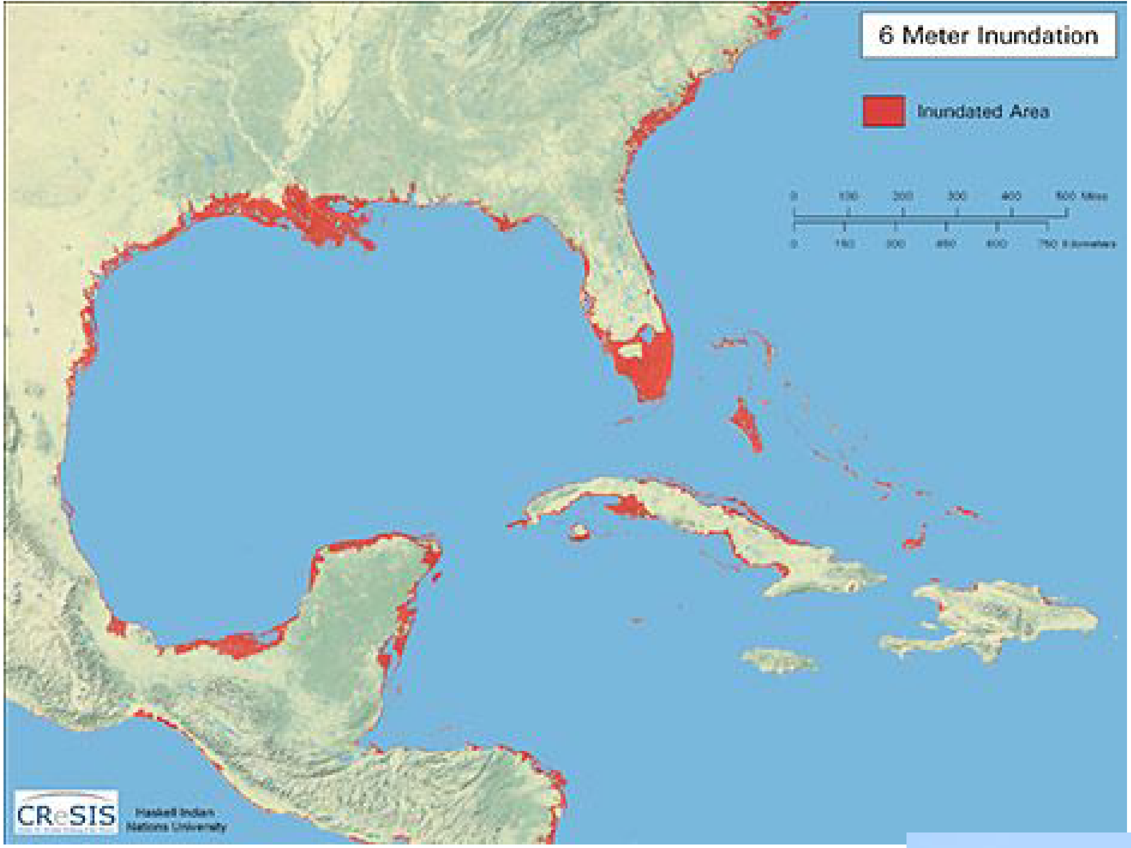
- ***melting land ice: Antarctica, Greenland, mountain glaciers***
  (if all melted : 70 m or ~230 ft of sea level rise)
- ***thermal expansion of warming ocean***

  accounts for about 25% of rise in last half of 20th century, rate ~ tripled in 21st century
- ***continental rebound***

  rise of land masses that were depressed by the huge weight of ice sheets

The interaction of warm waters with the periphery of the large ice sheets represents one of the most significant possibilities for abrupt change in the climate sysytem.

no coupling yet of ice sheets and ocean in climate models - no feedback effects


6 Meter Inundation
Inundated Area
CReSIS
Haskell Indian Nations University


EUROPE AT RISK FROM RISING SEA LEVELS
5 Meter Inundation
0 60 100 150 200 250 Miles
0 75 160 225 300 375 kilometers
Inundated area