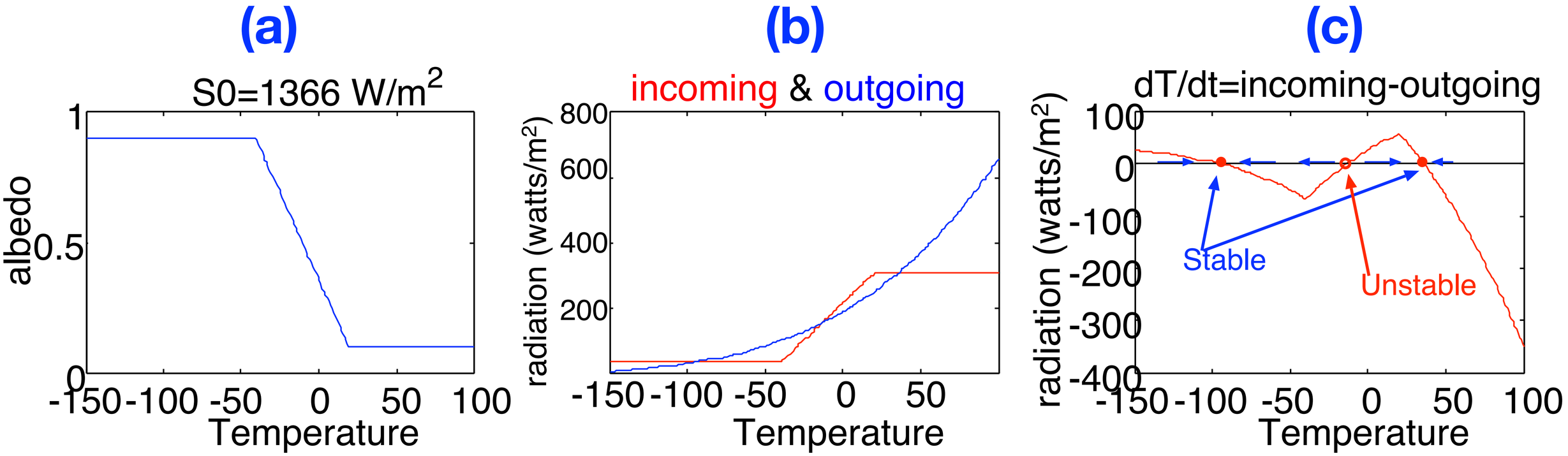
Energy balance & greenhouse

notes

A zero-dimensional version of the “Budyko-Sellers” energy-balance model for Earth’s temperature

(use the next two slides)

snowball bifurcation results



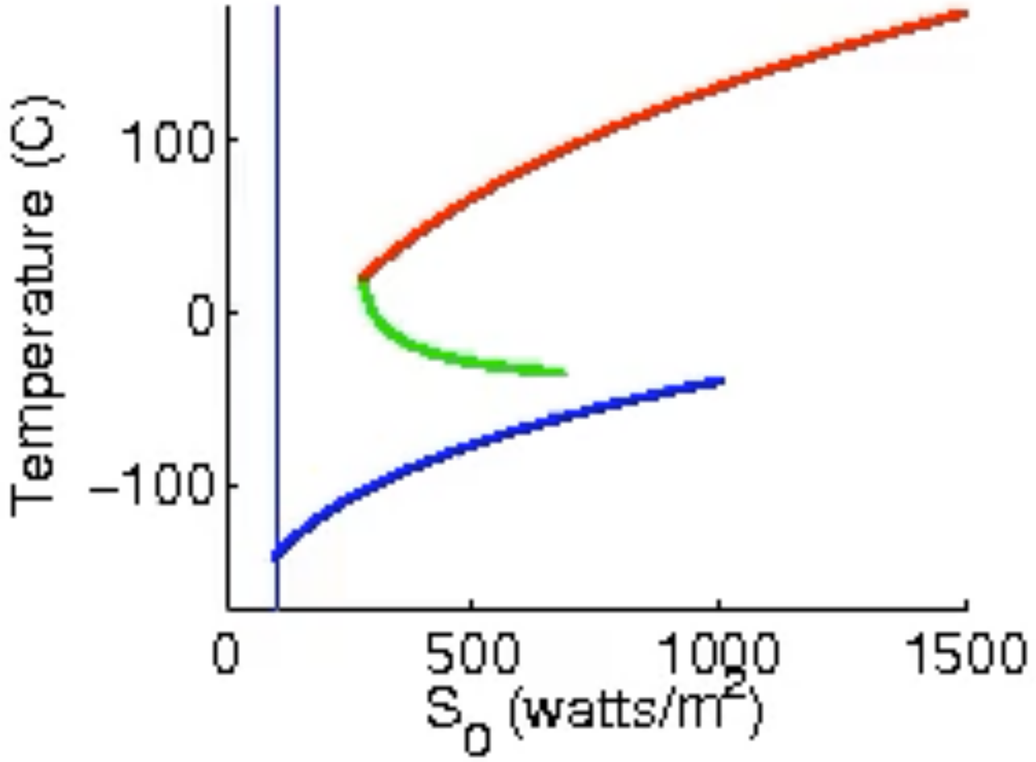
(a) albedo prescribed as a function of temperature.

(b) incoming & outgoing radiation terms in the energy balance model.

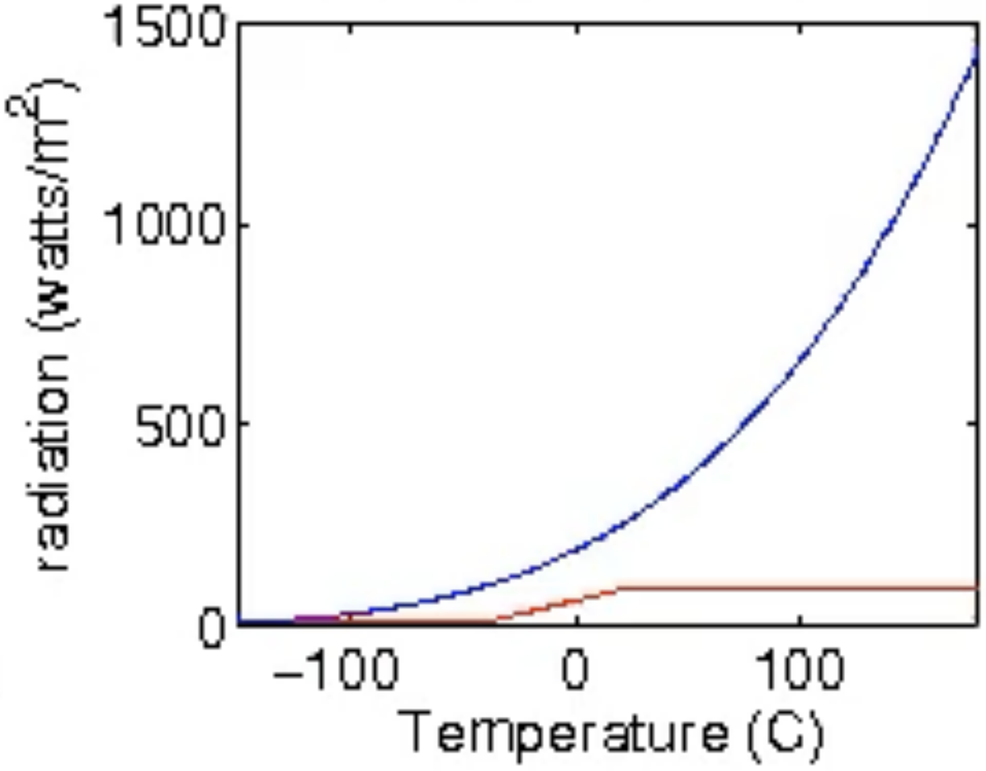
(c) The right-hand side of the heat balance equation, corresponding to incoming minus outgoing radiation as a function of temperature.

Snowball bifurcation results

Bifurcation diagram (green=unstable)



Red: incoming, blue: outgoing



Snowball bifurcation results

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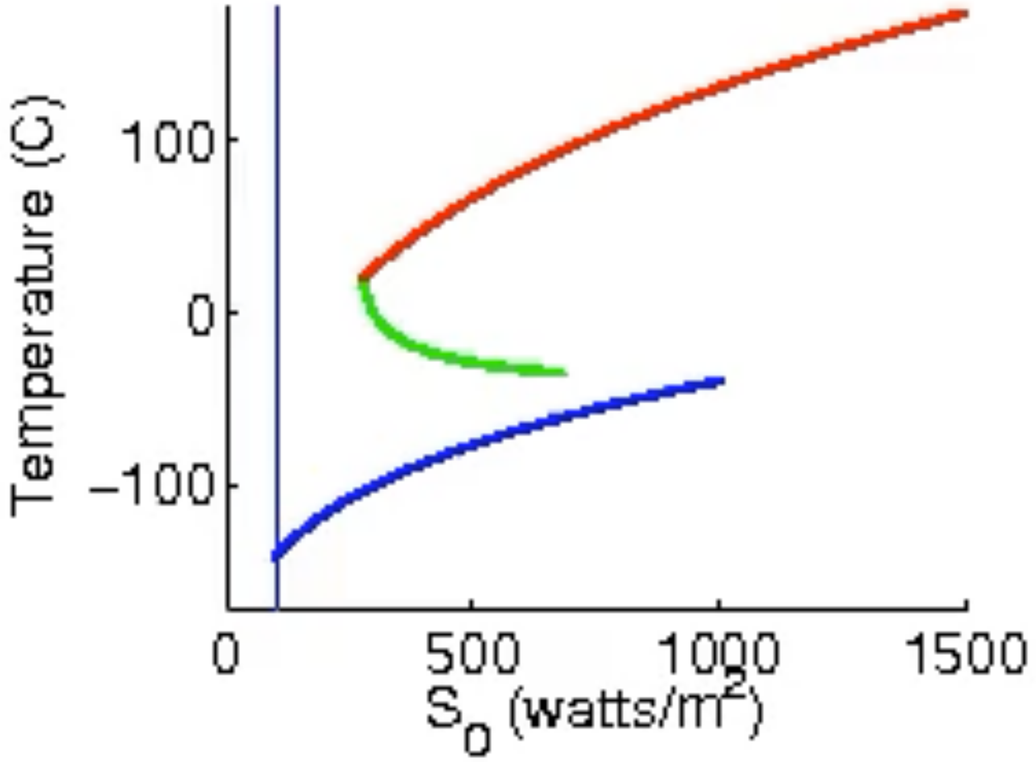
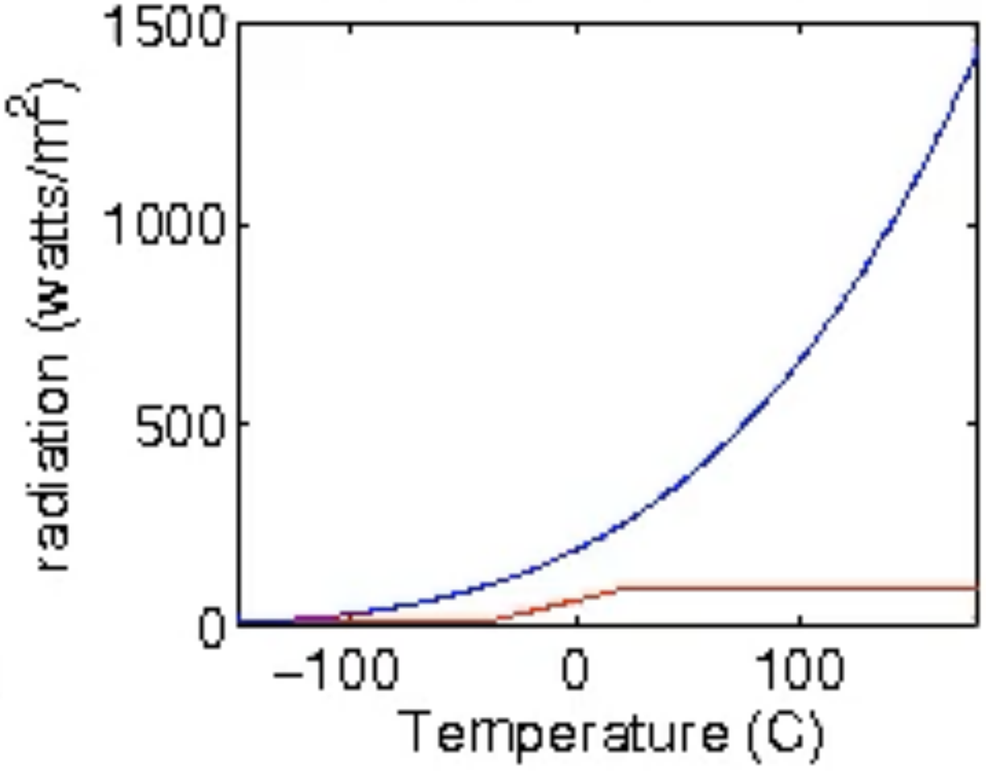


Red: incoming, blue: outgoing



Snowball bifurcation results

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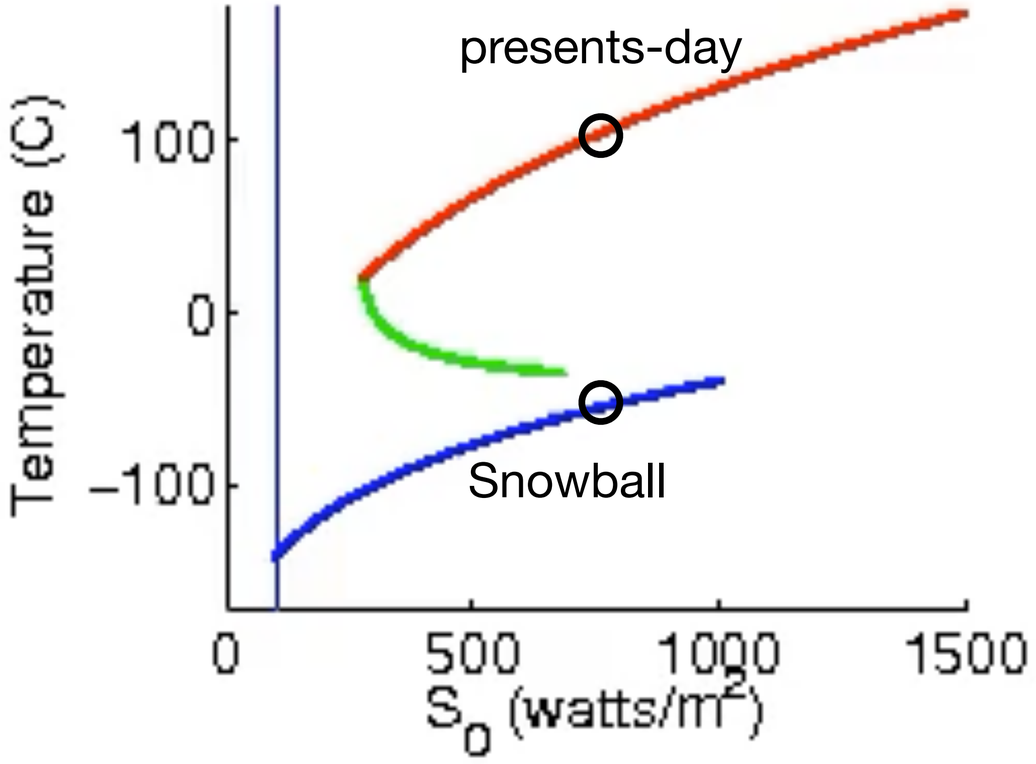

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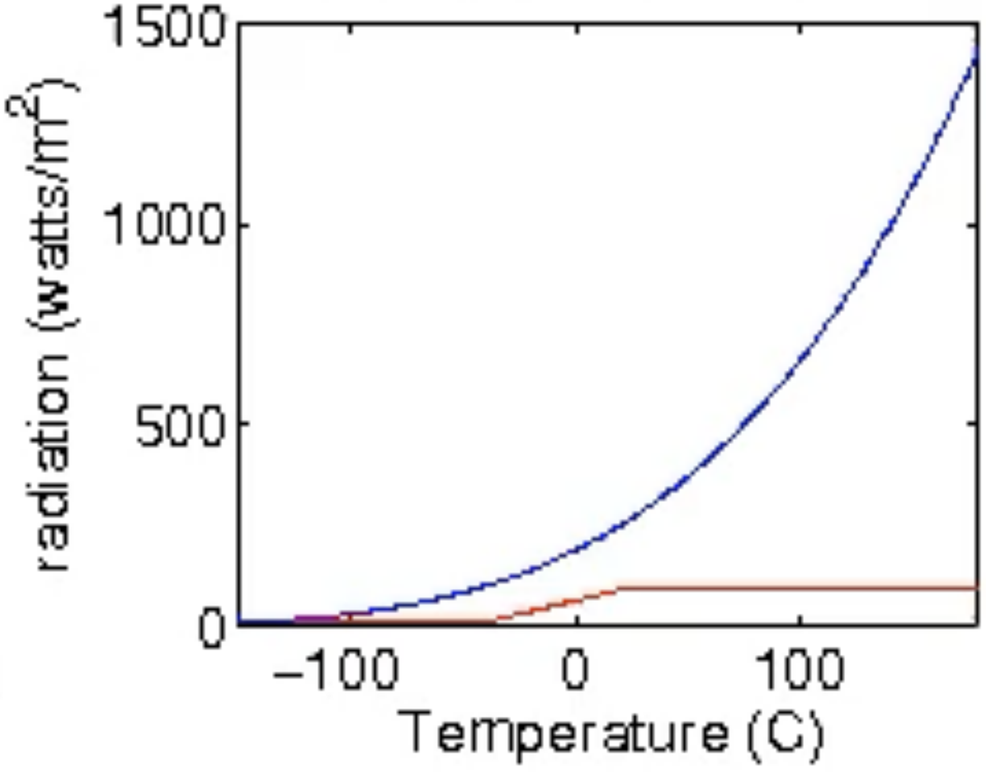
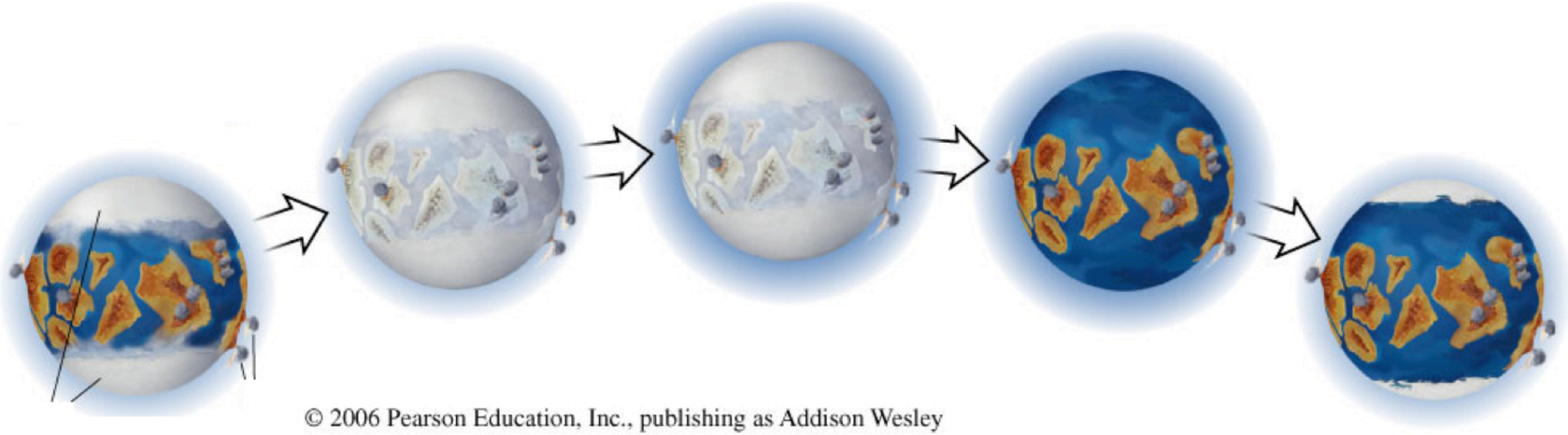


Snowball observations



Snowball observations

Late Proterozoic Low-Latitude Global Glaciation: the Snowball Earth

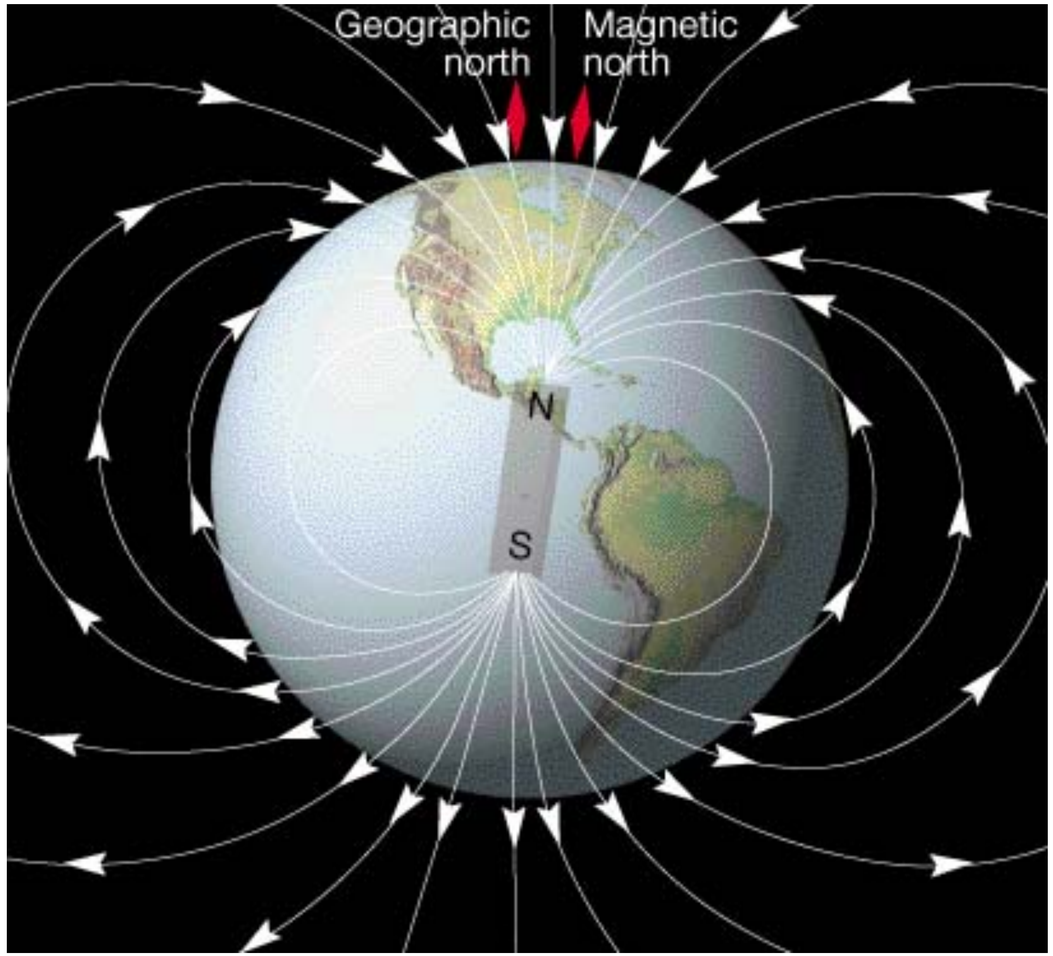
JOSEPH L. KIRSCHIVINK

- Neoproterozoic, 1000–542 Myr
- Two or more major glaciations, some probably global
- Sun ~7% weaker [Kirschvink, 1992]
- Dropstones, paleomagnetism

Dropstones in Namibia

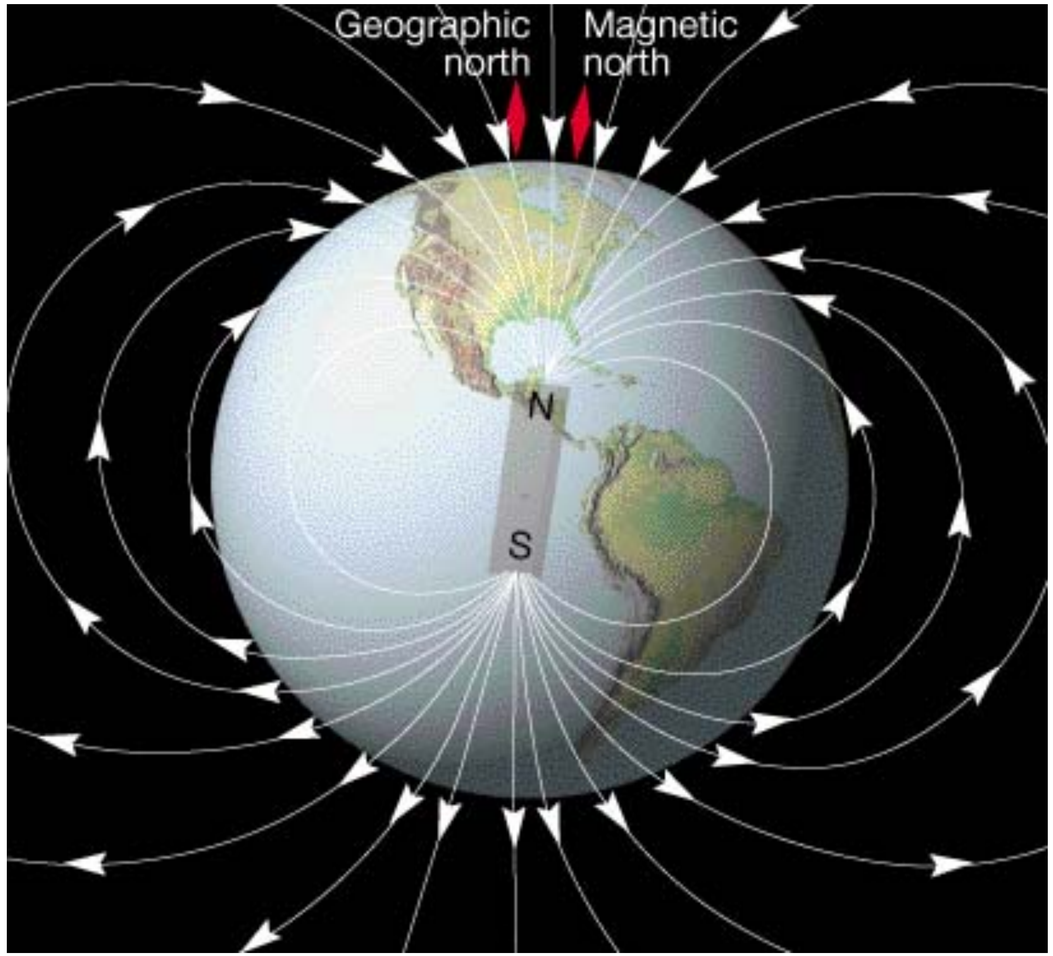
www.snowballearth.org

Paleo-latitudes from magnetic measurements



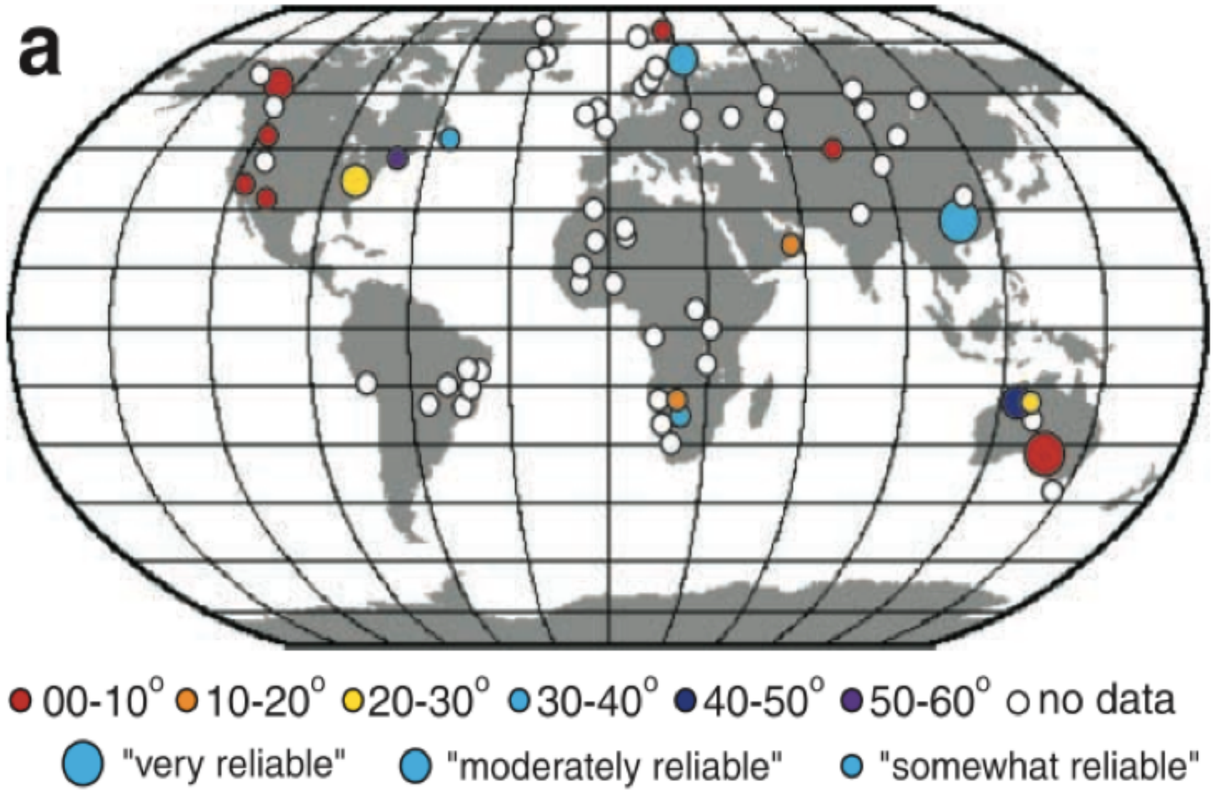
http://www.viewzone.com/magnetic.weather.html

Paleo-latitudes from magnetic measurements



http://www.viewzone.com/magnetic.weather.html

Glacial deposits at low paleo-latitude



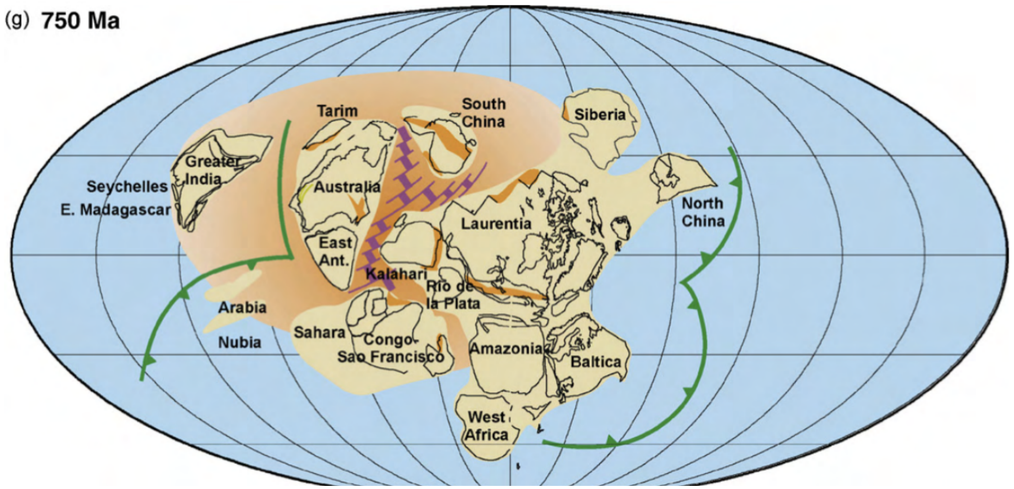
http://www.snowballearth.org/images/figure_1.gif

More snowball observations

http://www.snowballearth.org/slides/Ch3-5.jpg

Dropstone in Banded Iron Formations
(➔ anoxic Ocean, ➔ complete ice cover)

[Lee et al 2008]



Low-latitude continents

Snowball termination

➢Volcanoes keep emitting CO_2

https://images.csmonitor.com/csm/2016/03/973176_1_volcano_standard.jpg?alias=standard_900x600

Snowball termination

- Volcanoes keep emitting CO_2
- Natural CO_2 sink due to silicate weathering deactivated: no rain, no exposed rocks

https://images.csmonitor.com/csm/2016/03/973176_1_volcano_standard.jpg?alias=standard_900x600

Snowball termination

- Volcanoes keep emitting CO_2
- Natural CO_2 sink due to silicate weathering deactivated: no rain, no exposed rocks
- Atmospheric CO_2 concentration increases within millions of years to ~30% atmosphere -- as opposed to 400 ppm (0.04%) now, 280 pre-industrial.

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Snowball termination

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- Greenhouse effect melts ice
- An important role for the greenhouse effect of clouds (Abbot)

https://images.csmonitor.com/csm/2016/03/973176_1_volcano_standard.jpg?alias=standard_900x600

Why paleo letter

~/tex/Presentations/Misc/why-paleo-…

notes

saddle node bifurcation

2 saddle nodes & hysteresis

Energy balance: black body

Planck's law of black-body radiation:

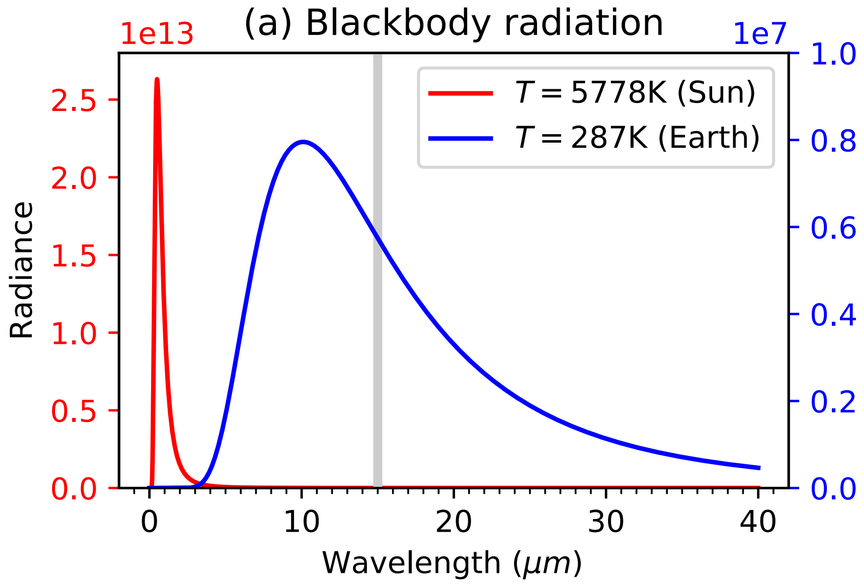
$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}.$$

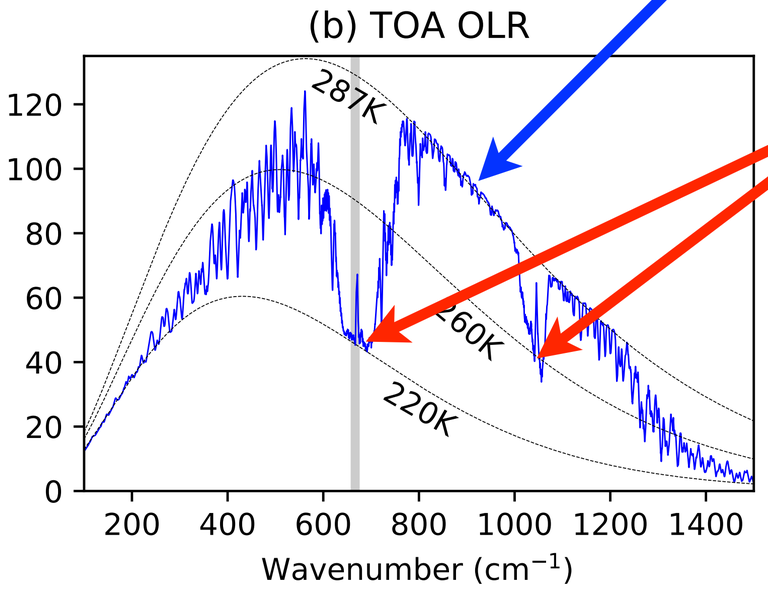
B(λ)dλ is the energy per area/ time/ angle emitted between wavelengths λ & λ+dλ;

T=temperature; h=Planck's const; c=speed of light; k=Boltzmann's const.

Total emitted radiation per area/ time: σT^4

Stefan–Boltzmann constant: $\sigma = 5.670367 \times 10^{-8}$ W·m^{-2}·K^{-4}





emitted by surface

emitted from high elevations

Energy balance: Albedo, greenhouse

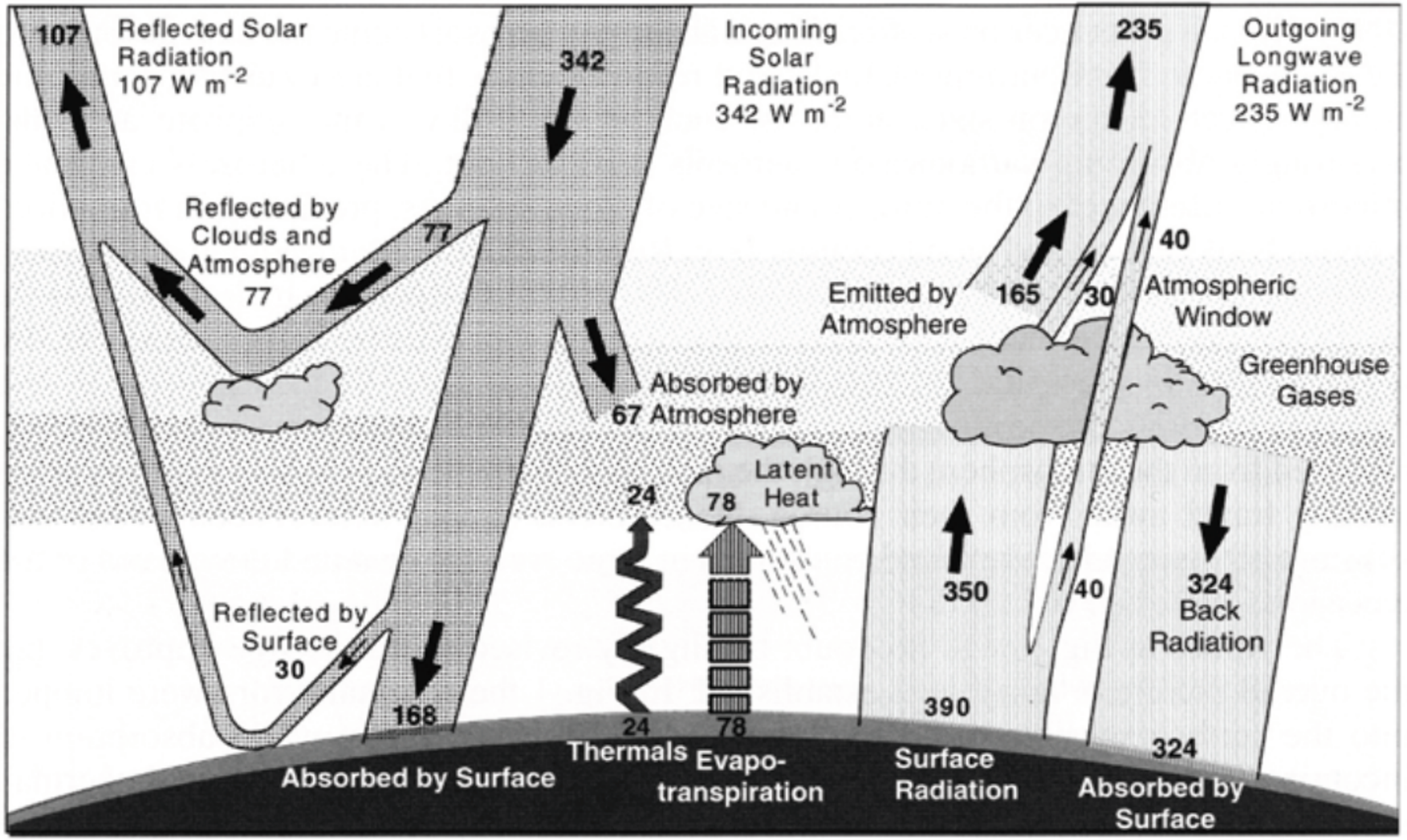


FIGURE 9.4. Earth's energy balance (from Trenberth, K.E., and D.P. Stepaniak, 2004: The flow of energy through the Earth's climate system. **Q.J.R.Meteorol.Soc., 130**, 2677-2701).

notes

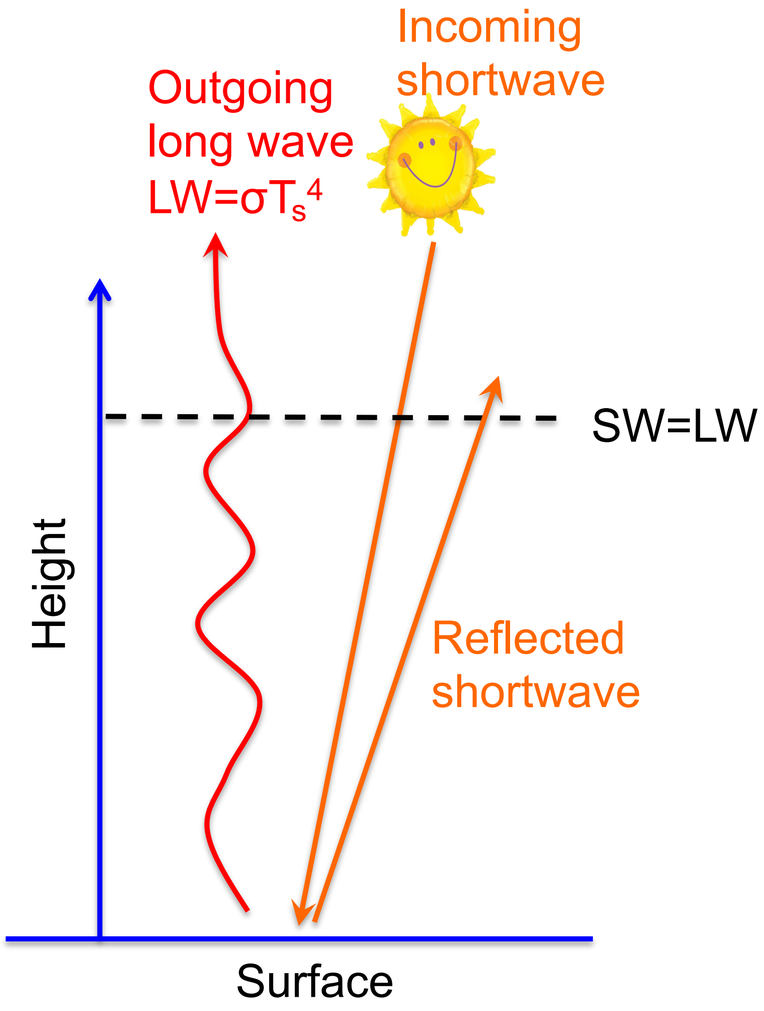
2-level greenhouse model

lapse rate, emission level, & the greenhouse effect

(Use the next 3 slides)

Energy balance of the Earth

Step 1: no atmosphere!!



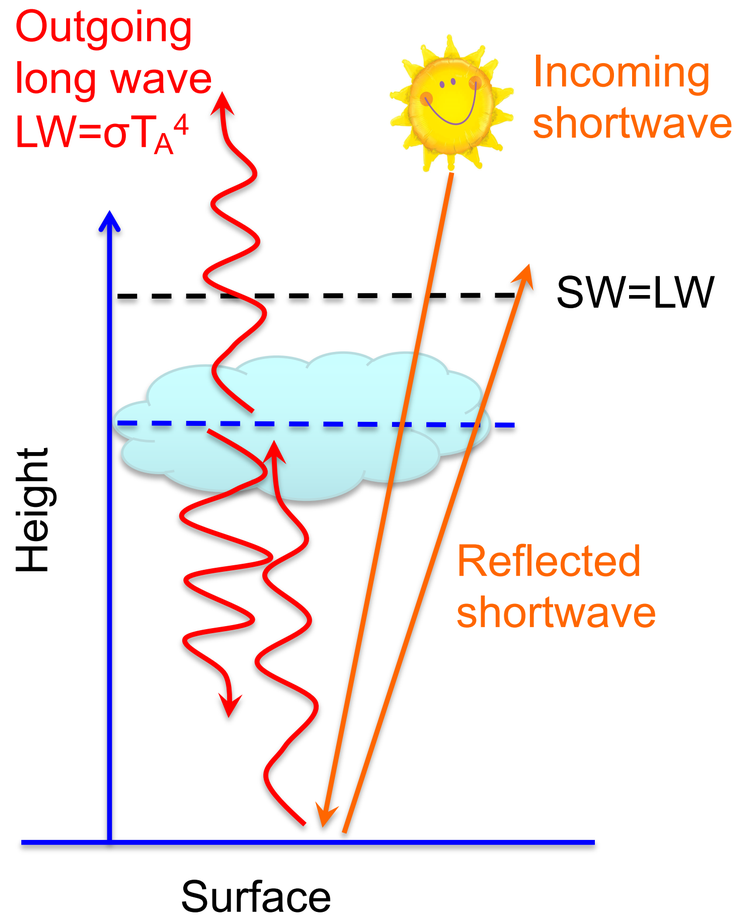
- Energy conservation: incoming **SW** radiation to Earth = outgoing **LW** radiation to space
- Incoming **SW** $= \frac{S_o}{4}(1-\alpha)$
- α = albedo = proportion SW reflected
- Outgoing **LW** $= \sigma T^4$
- Set incoming = outgoing ➡ solve for *T*:

$$T = \left(\frac{(S_0/4)(1-\alpha)}{\sigma} \right)^{1/4} = 255\text{K} = -18\text{C} \equiv T_0$$

The Greenhouse Effect

Step 2: add a 1-layer atmosphere

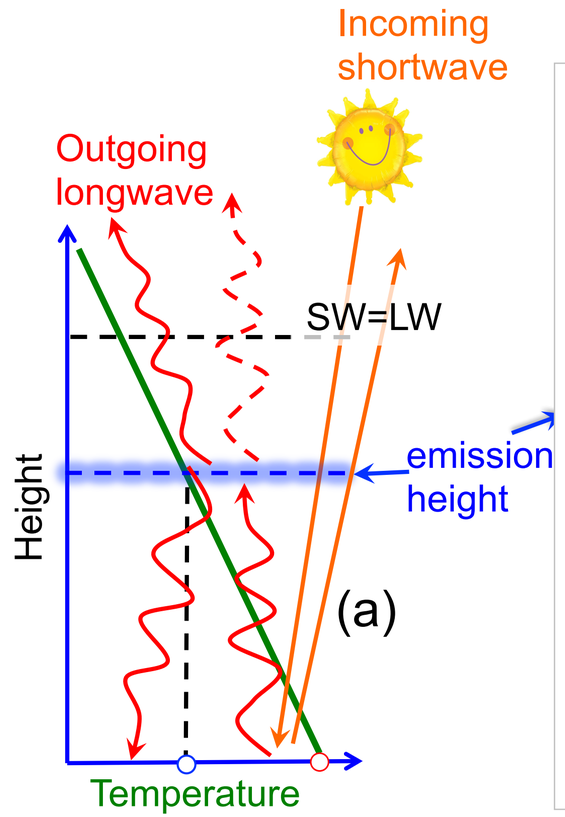
- Add an atmospheric layer (because gases in the real atmosphere absorb radiation): transparent to SW, absorbs/emits LW
- LW radiation emitted from surface is “trapped” (absorbed and re-emitted) by atmosphere
- Two unknowns: surface temperature *T* and (mid) atmospheric temperature T_a. Two equations (energy balance at surface, and at mid-atmosphere)
- Do the calculations (see notes) and result: surface temperature increases!
- This is the “greenhouse effect”



$$T = \left(\frac{(S_0/4)(1-\alpha)}{\sigma(1-\varepsilon/2)} \right)^{1/4} = T_0(1-\varepsilon/2)^{-1/4} = 284\text{K} = 13^\circ\text{C}$$

The Greenhouse Effect

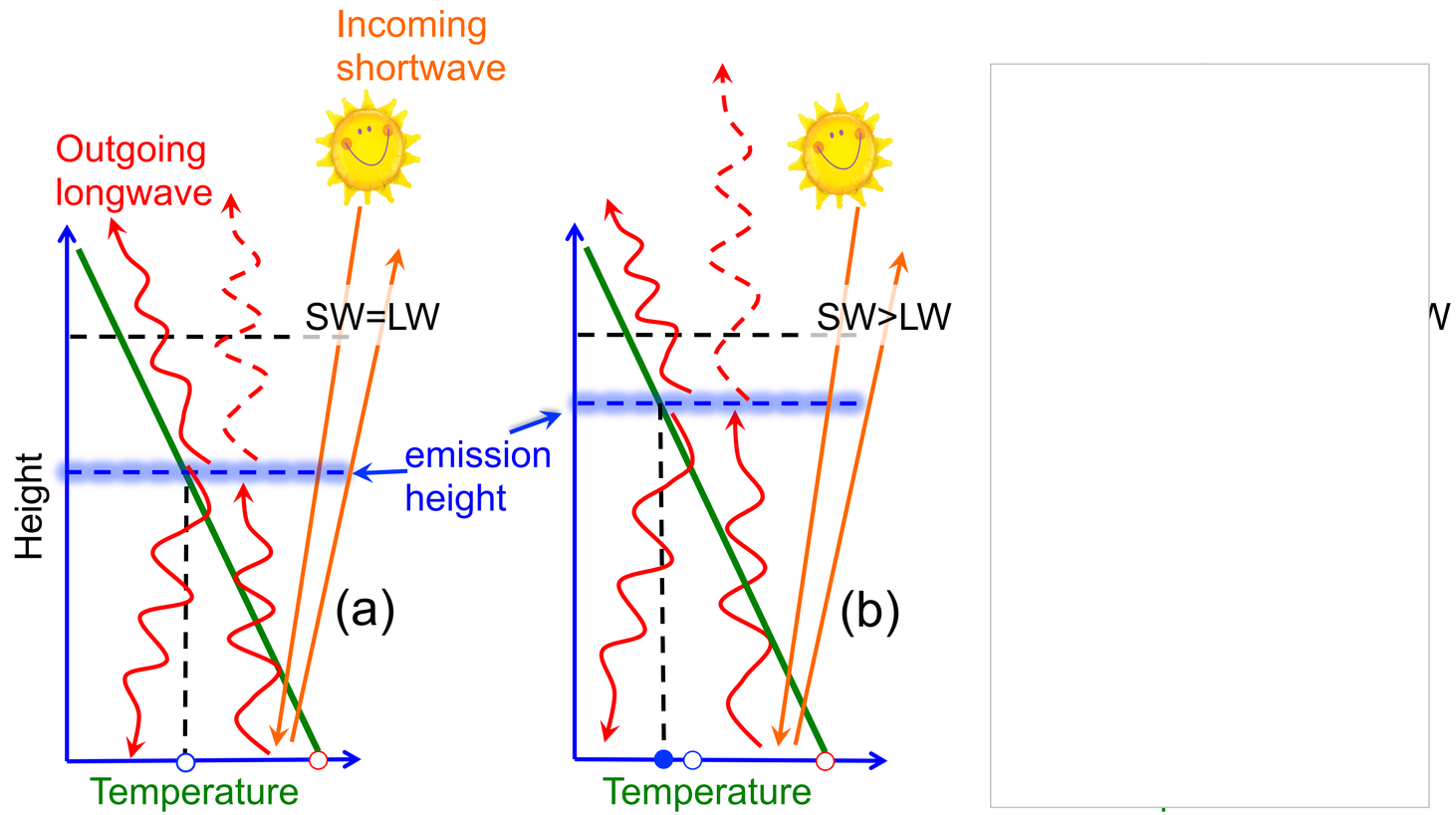
Step 3: add a continuous atmospheric temperature profile



- Level of last absorption: where most of the radiation emitted upward escapes to space, without getting absorbed again
- Increasing greenhouse gas —> raising level of last absorption —> Earth radiates from a colder temperature —> Energy balance is broken: LW < SW —> temperature must adjust

The Greenhouse Effect

Step 3: add a continuous atmospheric temperature profile



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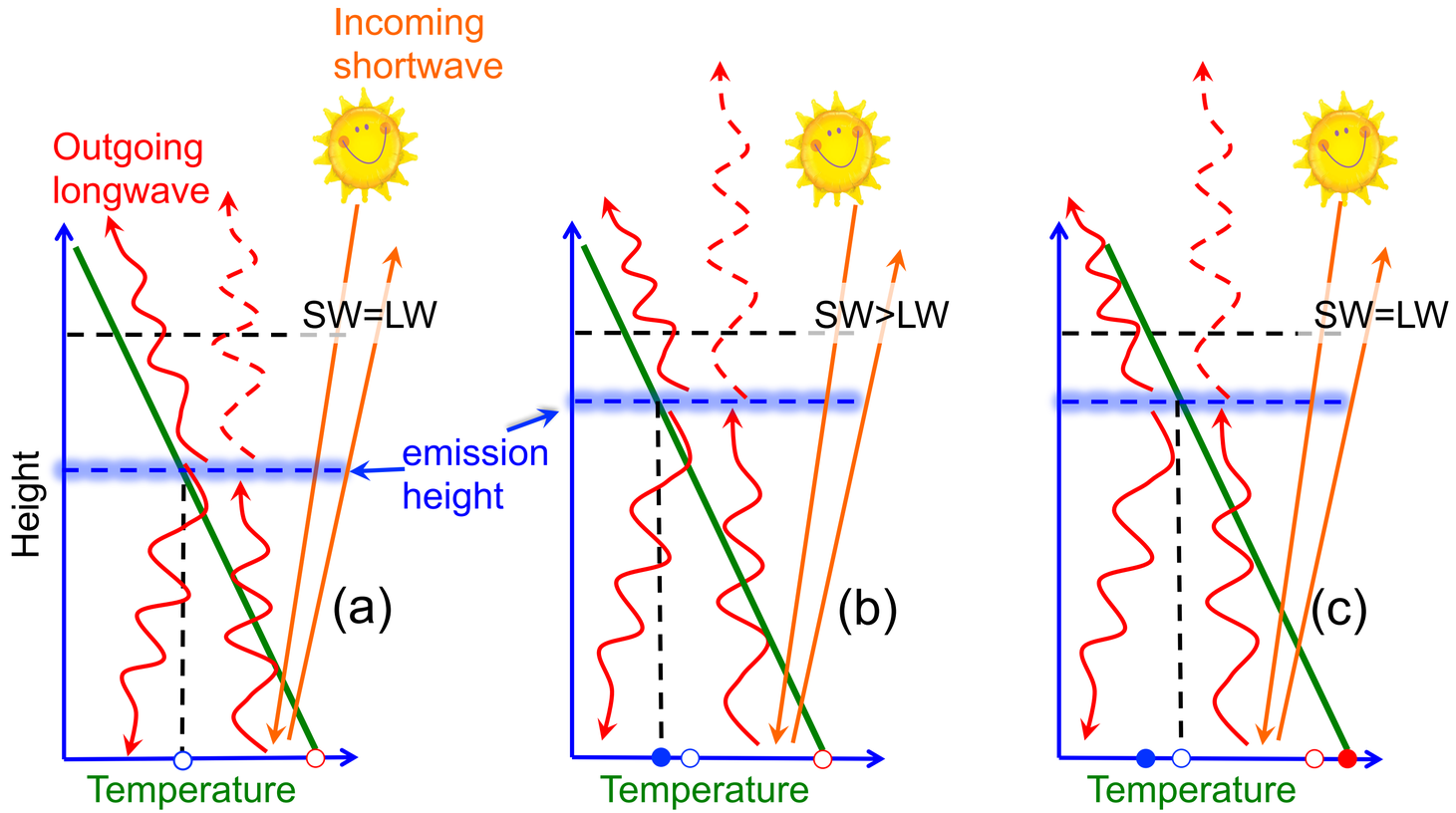

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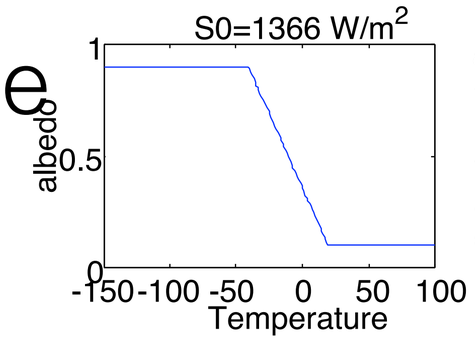
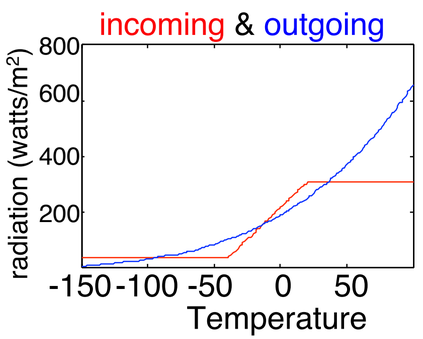
in-class workshop

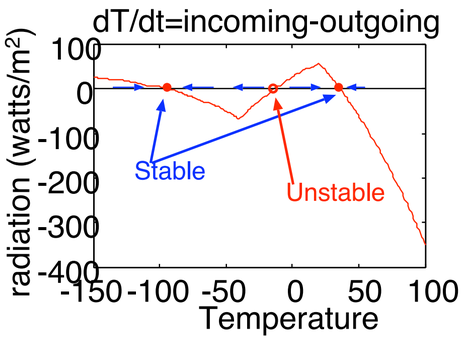
Calculate the change in emission height required to compensate for an increase in radiative forcing of 4 W/m^2

Energy balance and Greenhouse: Summary

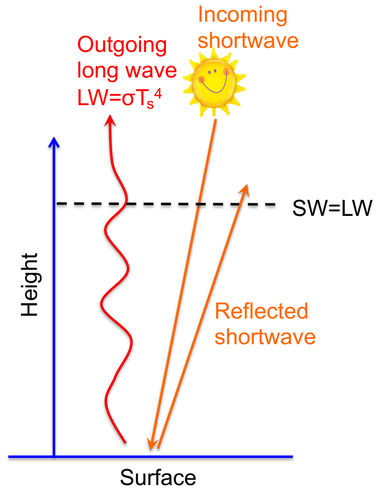
1. Energy balance of Earth, the Snowball bifurcation



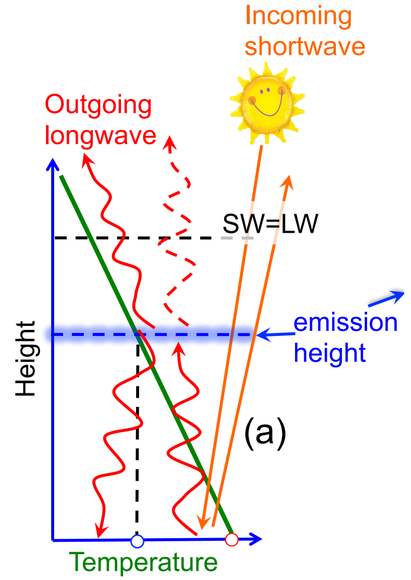




2. The greenhouse effect:
   A. Two-layer model of the natural greenhouse effect



   B. Lapse rate, emission height, & anthropogenic greenhouse



The End