Climate vs Weather

Question 1: How can we predict Climate (50 yrs)
if we can't predict Weather (10 days)?

NCAR

What is Climate?

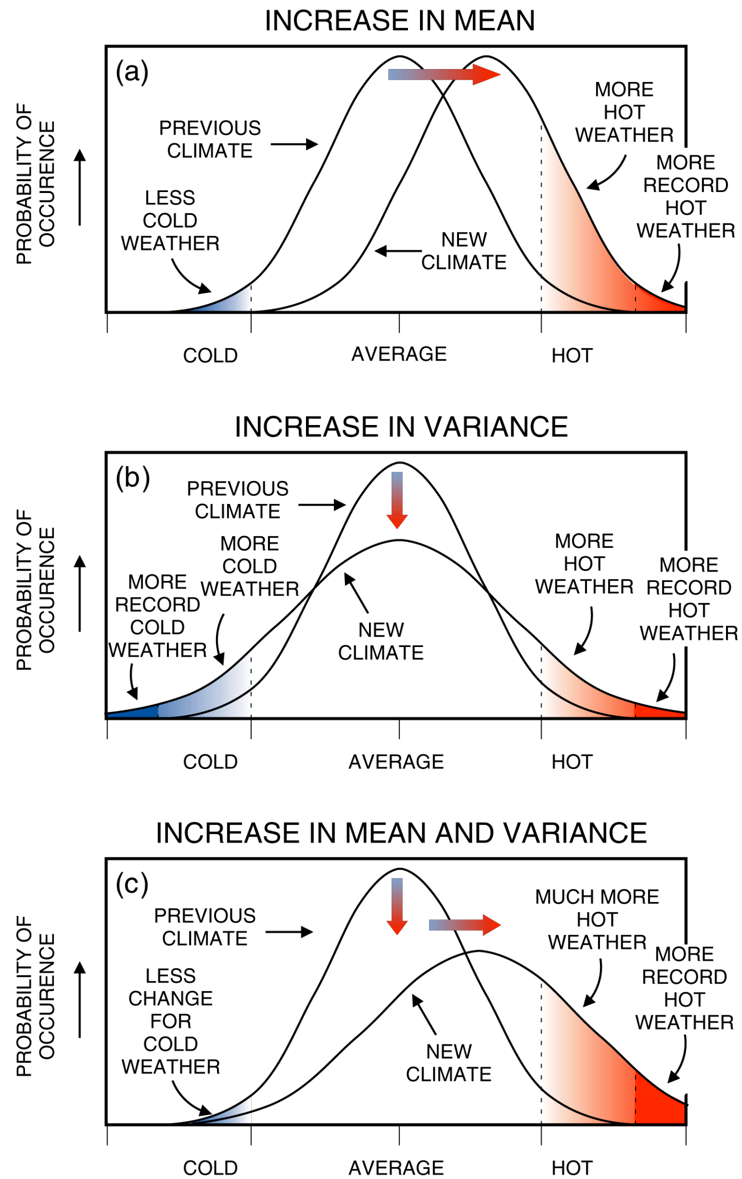
Question 1: How can we predict Climate (50 yrs) if we can't predict Weather (10 days)?

Question 2: What is Climate?

A. Average Weather
B. Record high and low temperatures
C. The temperature range
D. Distribution of possible weather
E. Extreme events

Characterizing Climate

Climate change and its manifestation in terms of weather (climate extremes)



J. J. Hack/A. Gettelman: June 2005

NCAR

Climate vs Weather

Question 1: How can we predict Climate (50 yrs)
if we can’t predict Weather (10 days)?

Question 3: Why can’t we predict weather?
- Weather is an inherently chaotic system
- Classic example: the Lorenz system

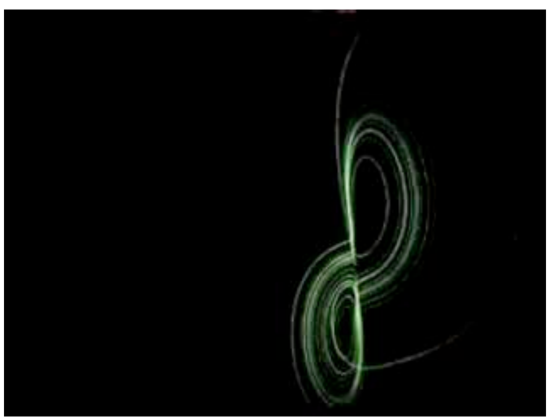
Characterizing Climate

The chaos is the weather

Even in 3-dimensional systems, nearby initial conditions in a dynamical system can have VERY different destinies.

Lorenz Attractor

The attractor is the climate

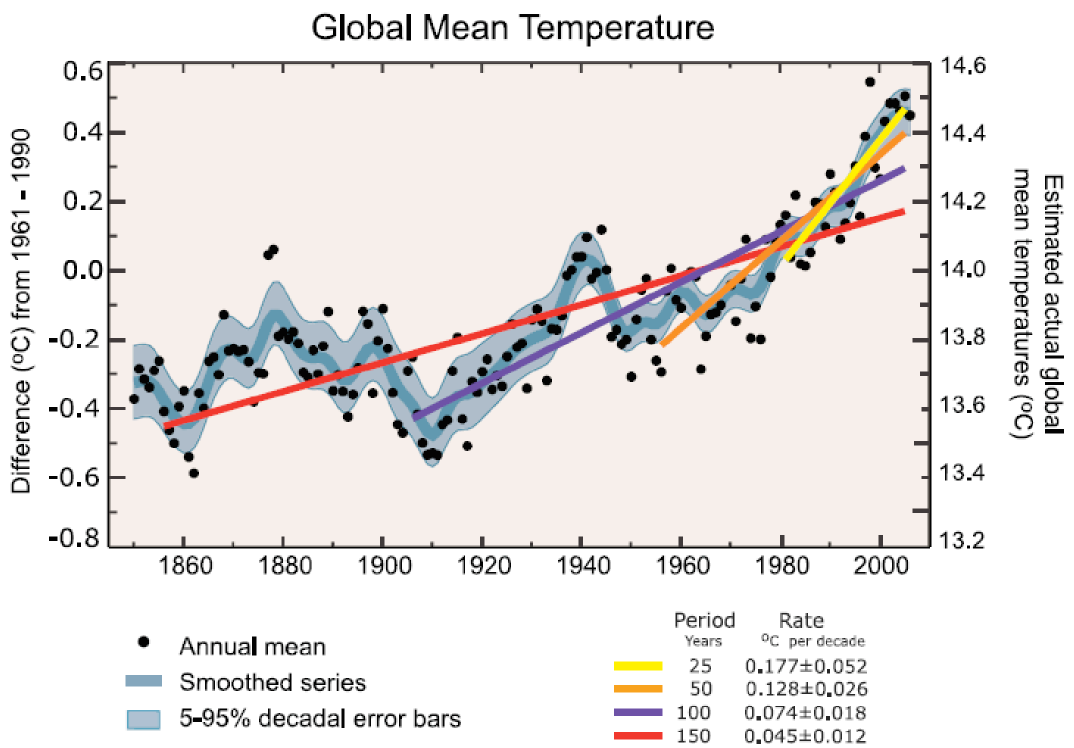


The attractor itself enjoys structure and it is the parameters of the attractor we are after in predicting the climate

Jones

Evidence of a Changing Climate

Intergovernmental Panel on Climate Change (IPCC):
Warming is "unequivocal"



Pandora's Box

Observations:

FACTS

carbon in atmosphere

EVIDENCE

rising temperatures

Theory:

PHYSICS

greenhouse effect

PREDICTION

mathematical models

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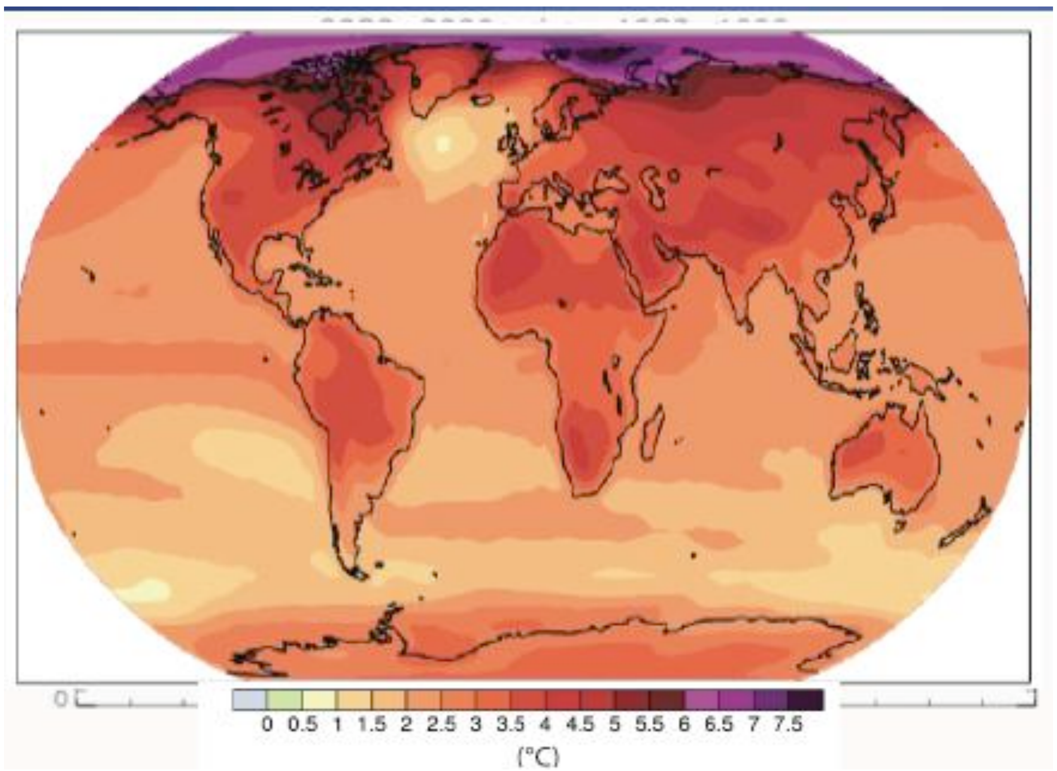
Why do we try to predict?



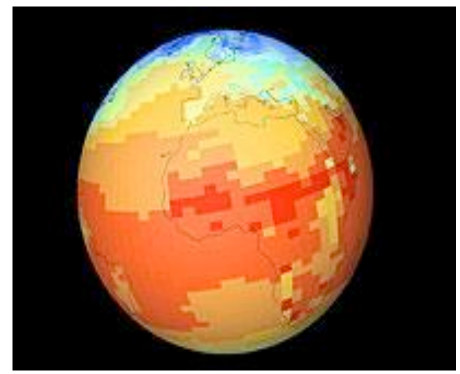
Warming is NOT uniform

Jones

Why use computational models?

1

many

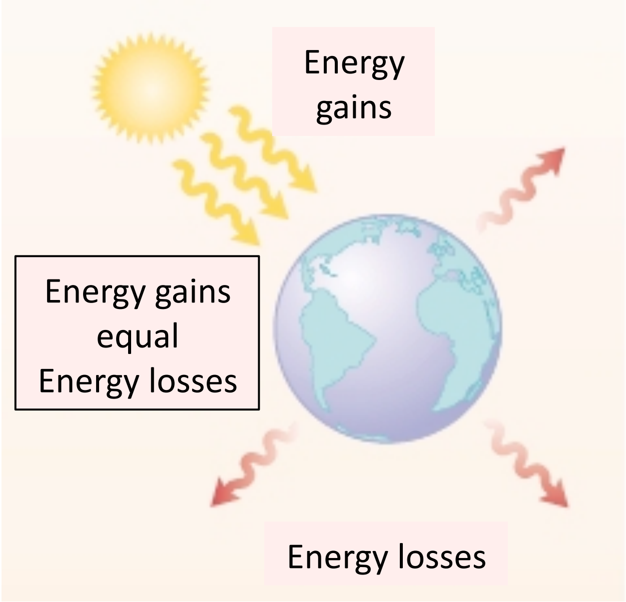


Friday: Natalie Mahowald will talk about full climate models

Today: Intro to most basic concepts of energy balance models

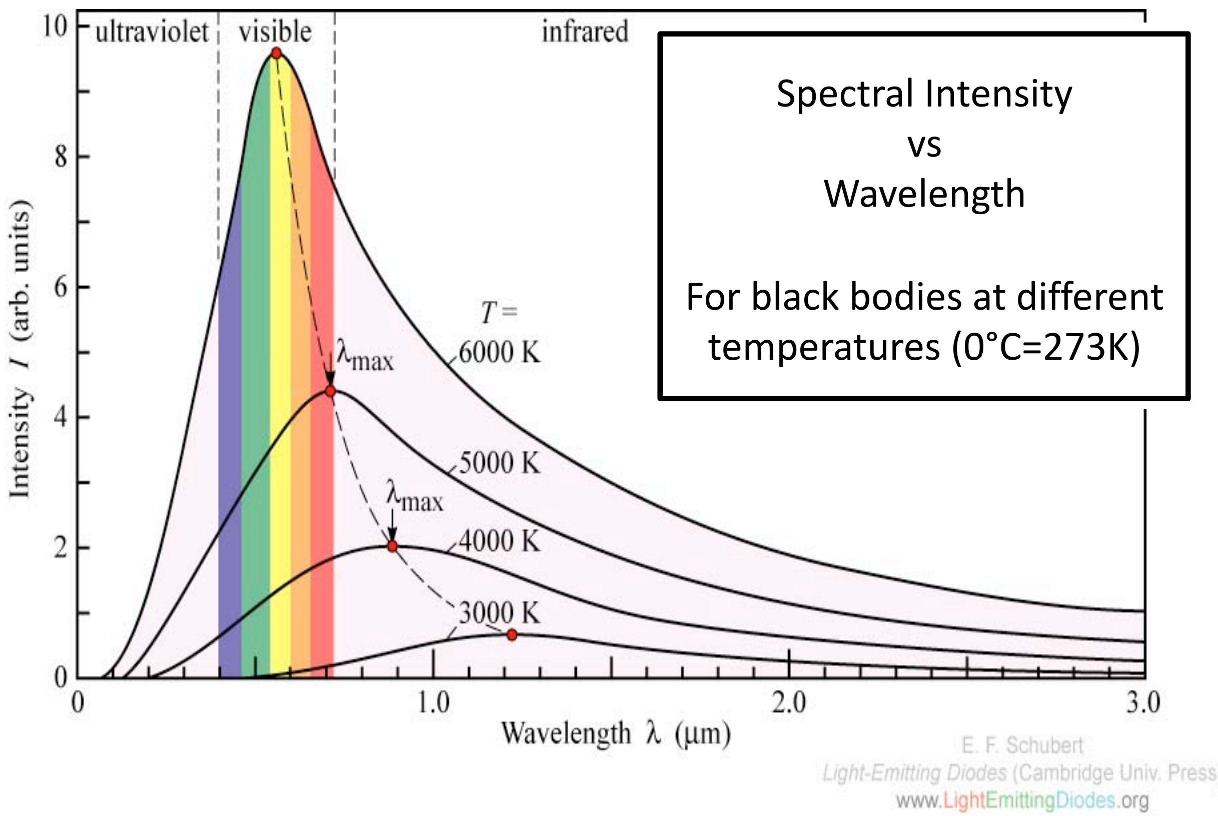
Jones

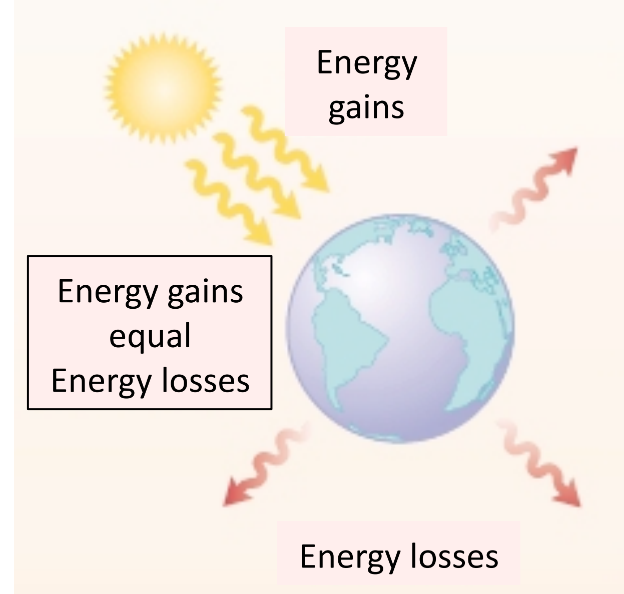
Simplest Energy Balance Models



Simplest Energy Balance Models

Black Body Radiation - Planck





Sun: ~6000K, emits mainly in visible spectrum (shortwave)
Earth: ~300K, emits mainly in IR (longwave)

Integrate over wavelength for temp T to get total emission flux σT^4 -- Stefan-Boltzmann

Energy Balance, No Atmosphere

Hypothesis: Earth's temperature is a consequence of

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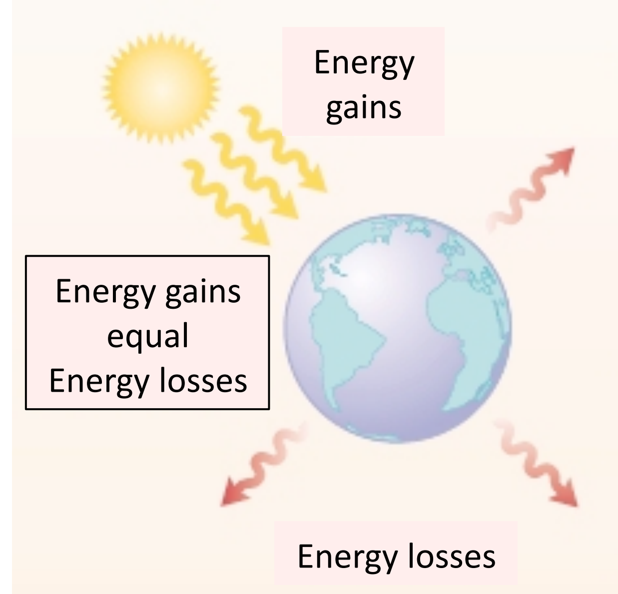
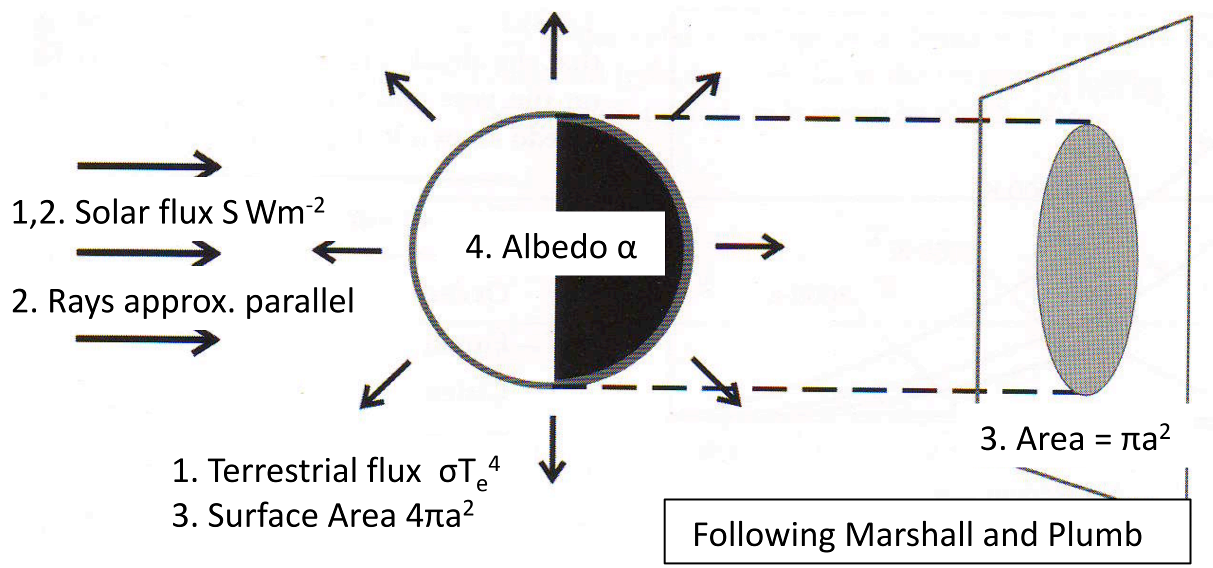
2. Distance from Sun
3. Size
4. Albedo (reflectivity)





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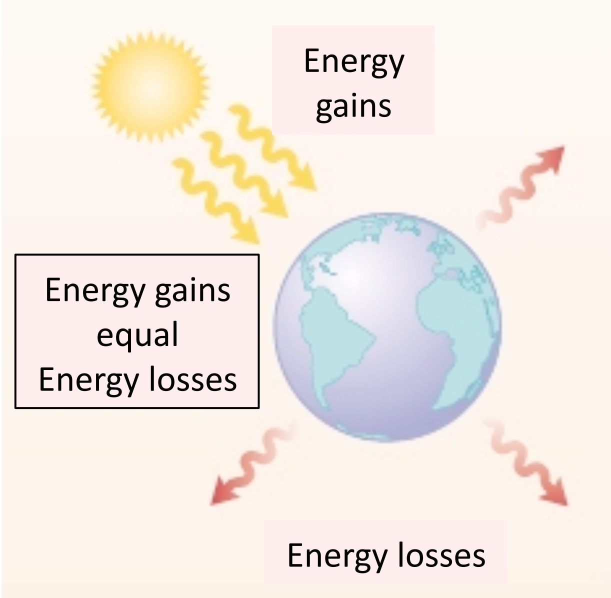
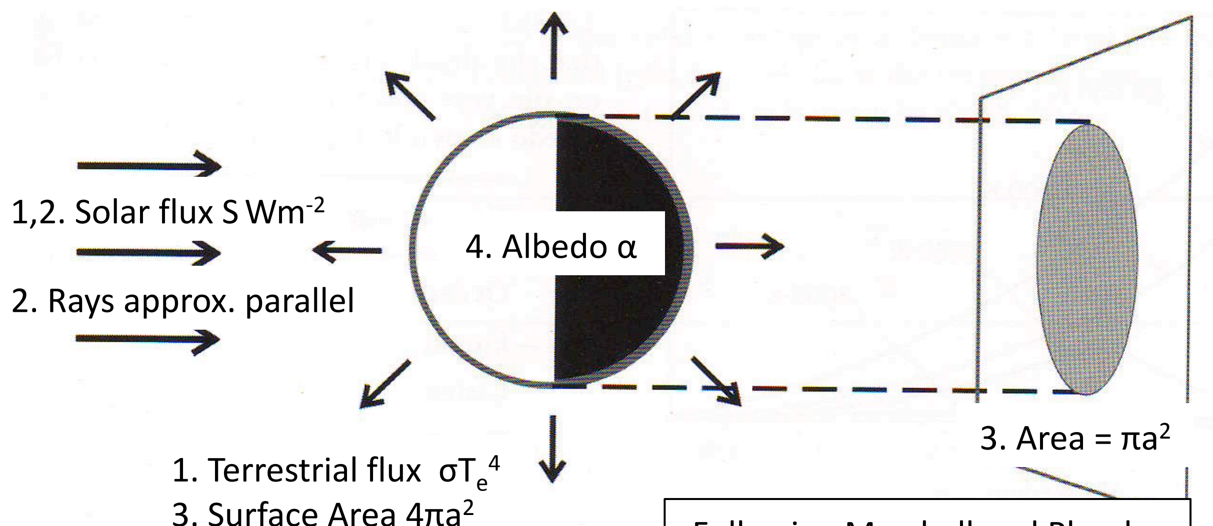


Energy Gain

Solar flux * cross-sect area = $S\pi a^2$ W



Following Marshall and Plumb

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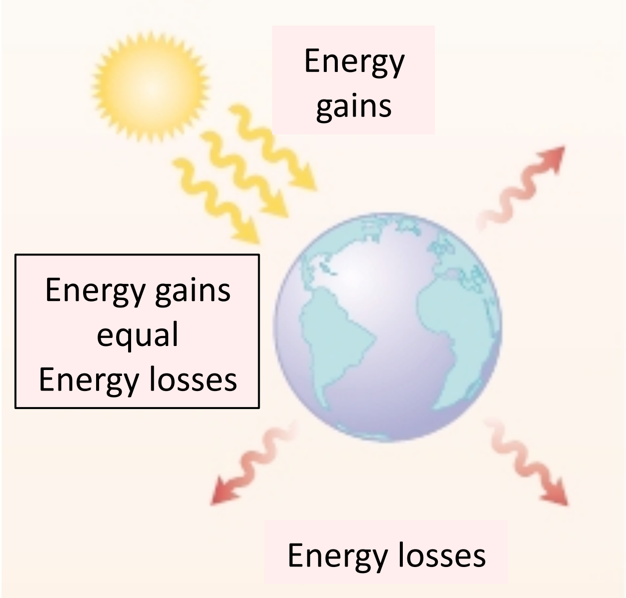

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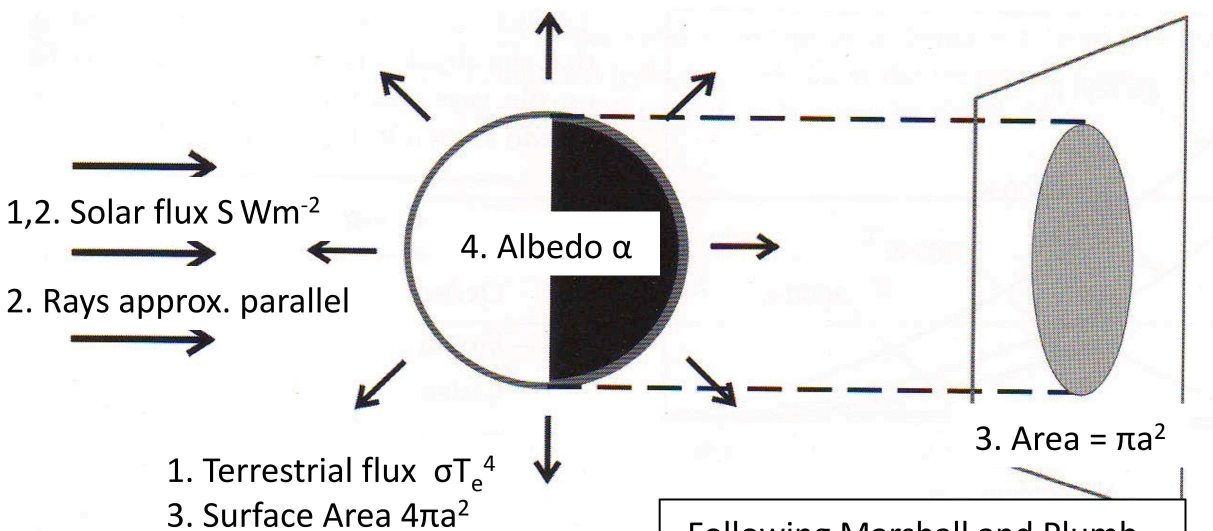
Energy loss by Terrestrial Radiation

Terrestrial flux * surface area = $\sigma T_e^4 \, 4\pi a^2$



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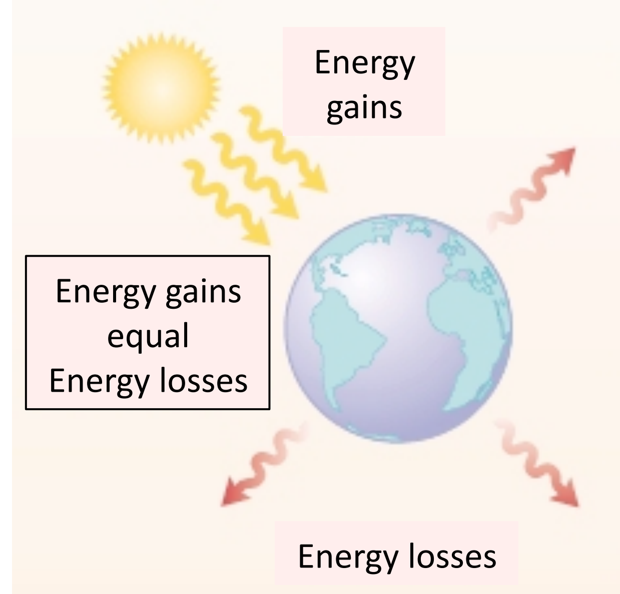

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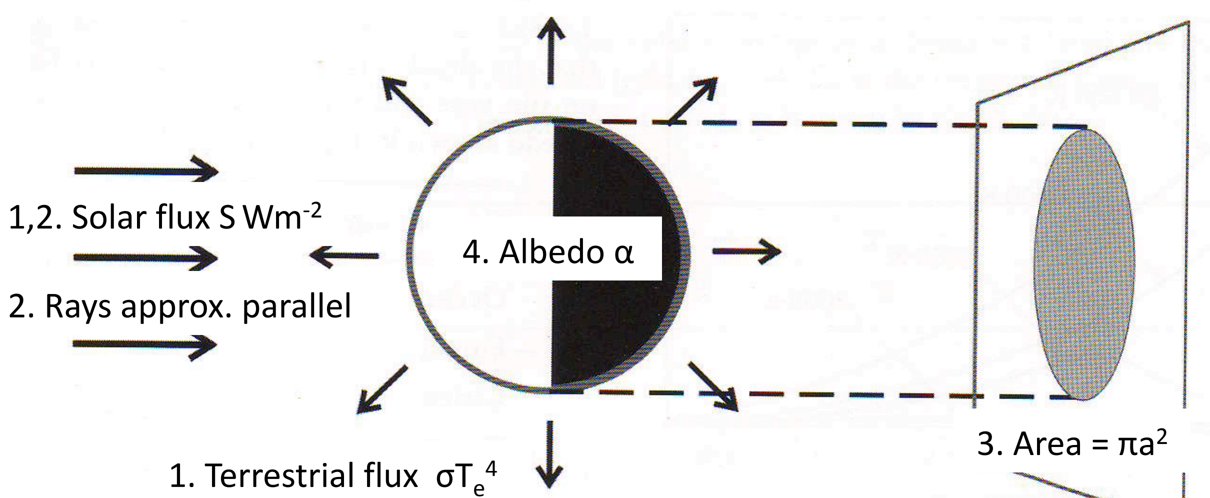

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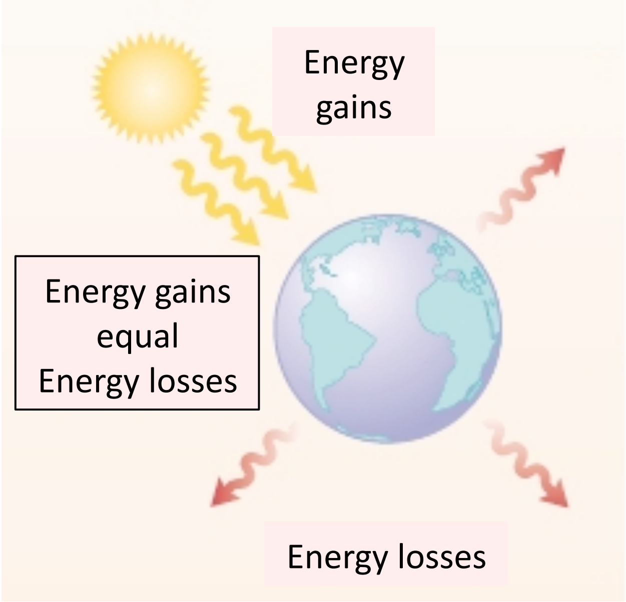

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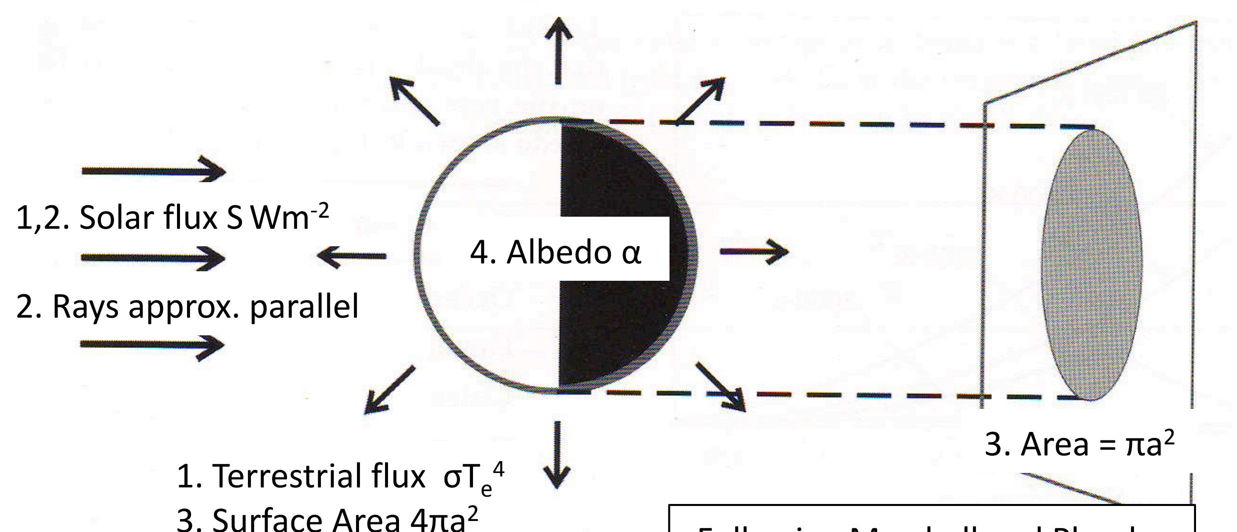
Balance

$S\pi a^2 = \alpha S\pi a^2 + \sigma T_e^4 \, 4\pi a^2$

➔ $(1-\alpha)S = 4\sigma T_e^4$

➔ $T_e = 255K = -18°C$



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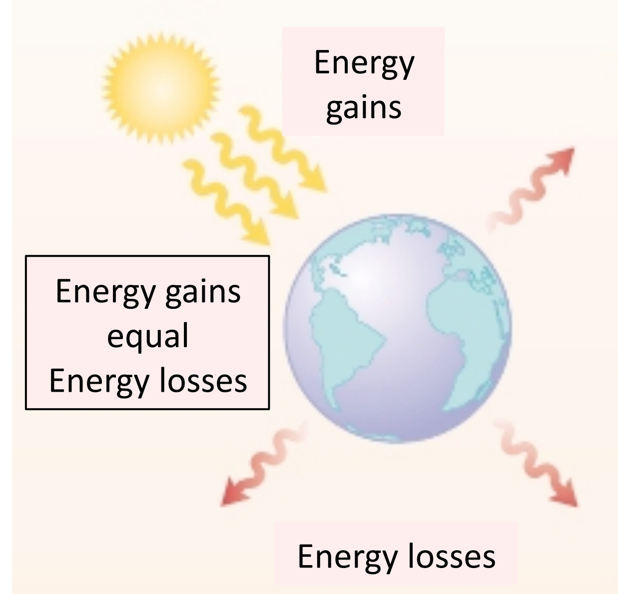

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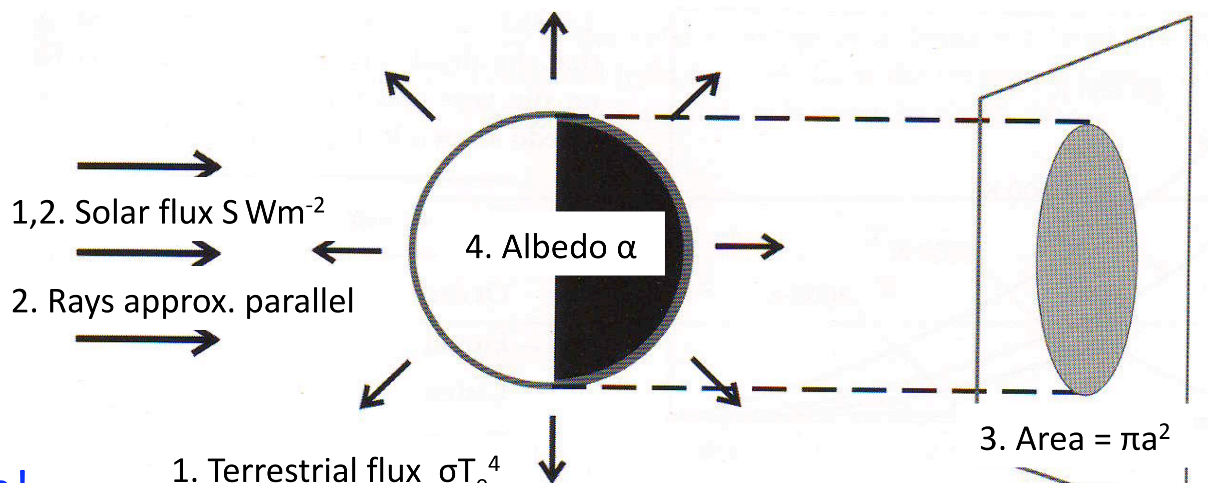
Too Cold – Snowball Earth!



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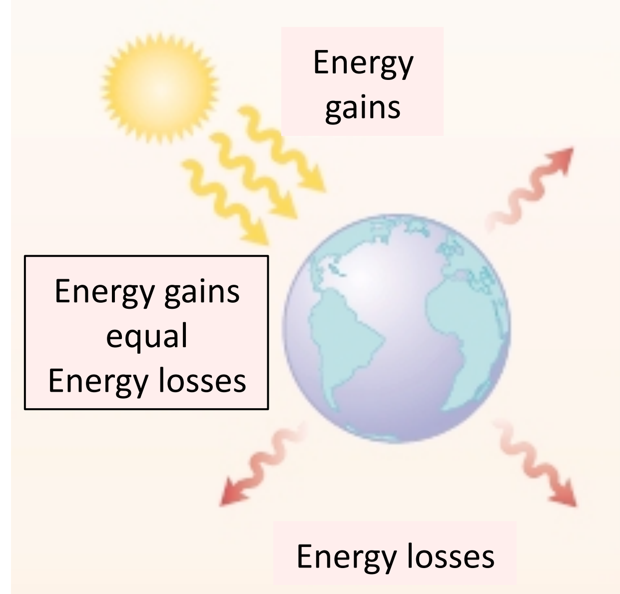

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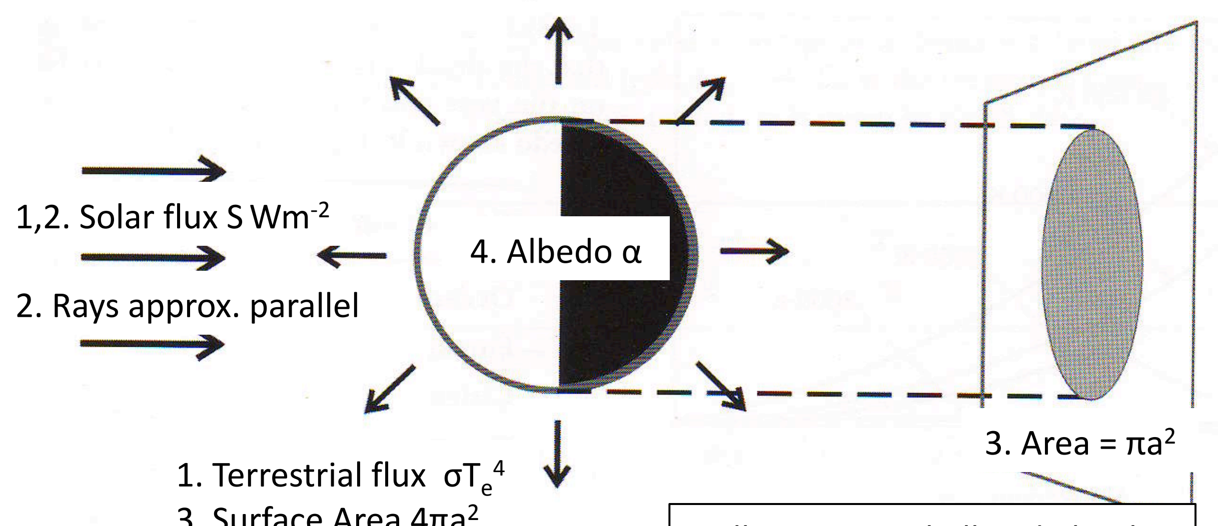
Observed global average surface temp $T_s = 288K = 15°C$



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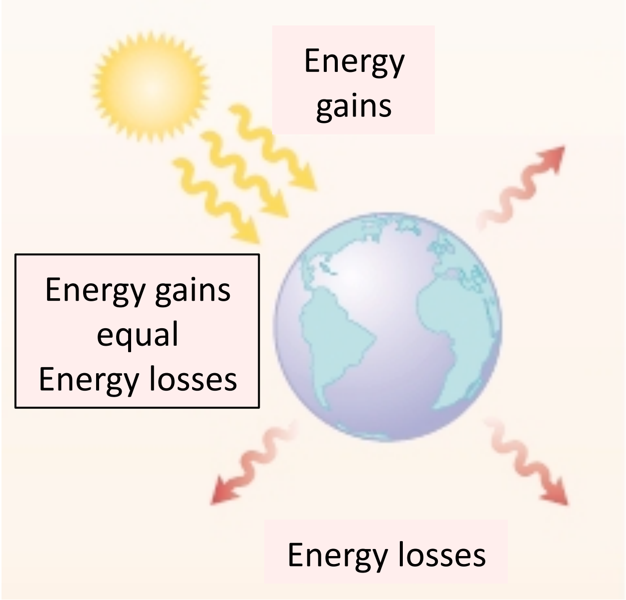
With these hypotheses, surface temp is 33°C too low
We need to include atmosphere to correct this

255K is a good estimate for the top of the atmosphere.
Which does satisfy the hypotheses more closely.



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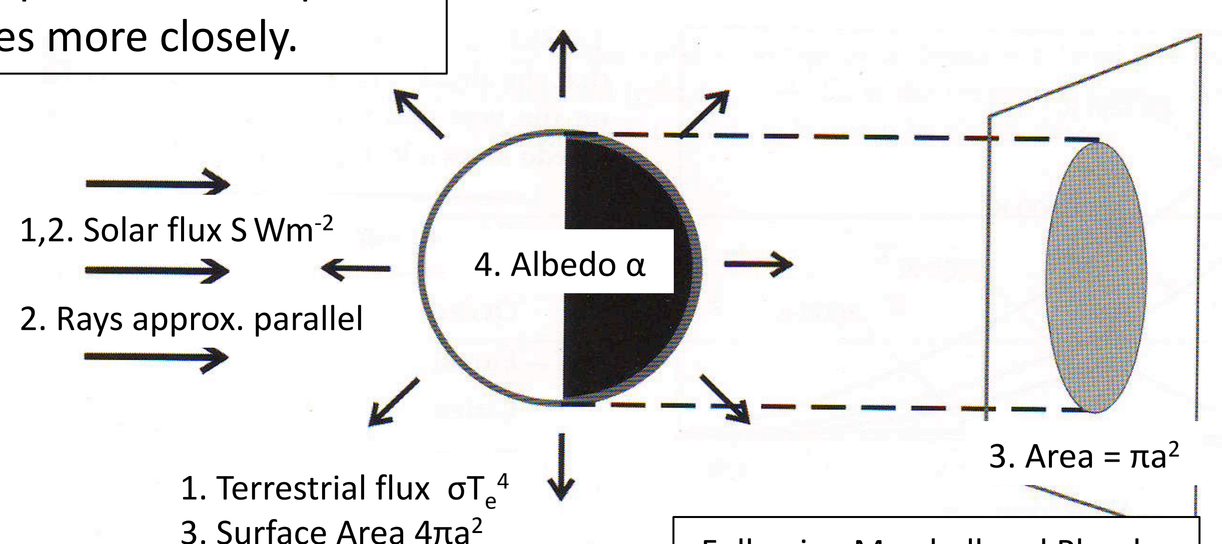

Following Marshall and Plumb

Aside: DE Viewpoint

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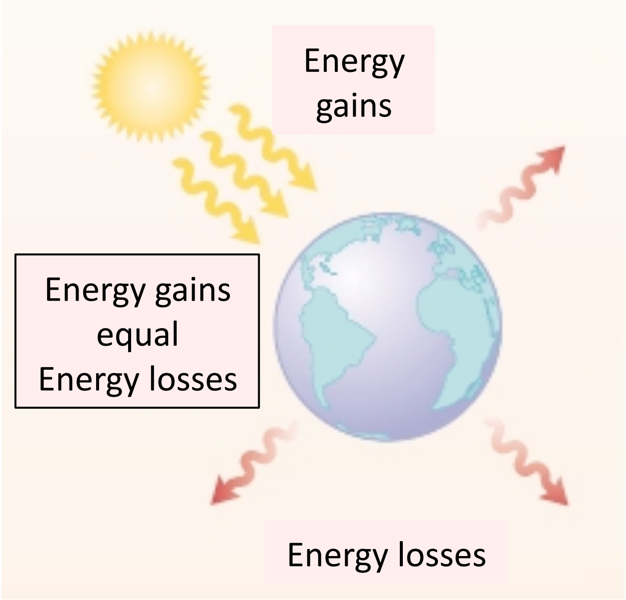

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Aside: as a differential equation for temp T_e

Sign(dT_e/dt) = energy gain – energy loss

$= ((1-\alpha)S - \sigma T_e^4)\,\pi a^2$

- when $T_e = 255K$, $dT_e/dt = 0$
- when $T_e > 255K$, $dT_e/dt < 0$
- when $T_e < 255K$, $dT_e/dt > 0$

Energy balance corresponds to attracting equilibrium.

Energy Balance, No Atmosphere

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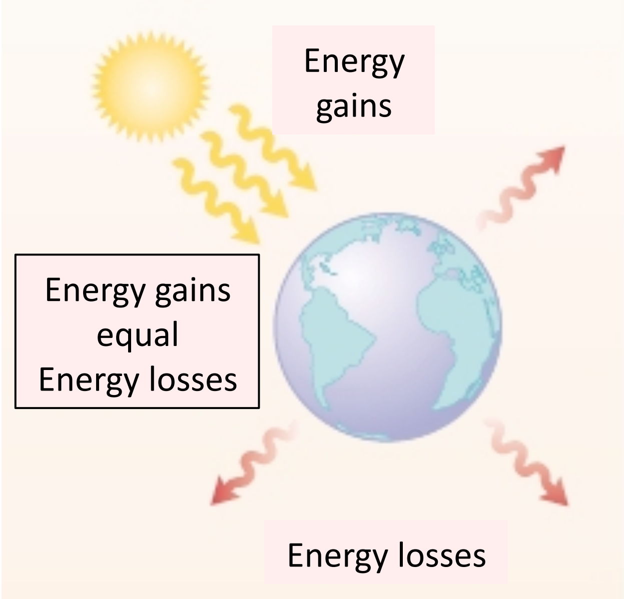

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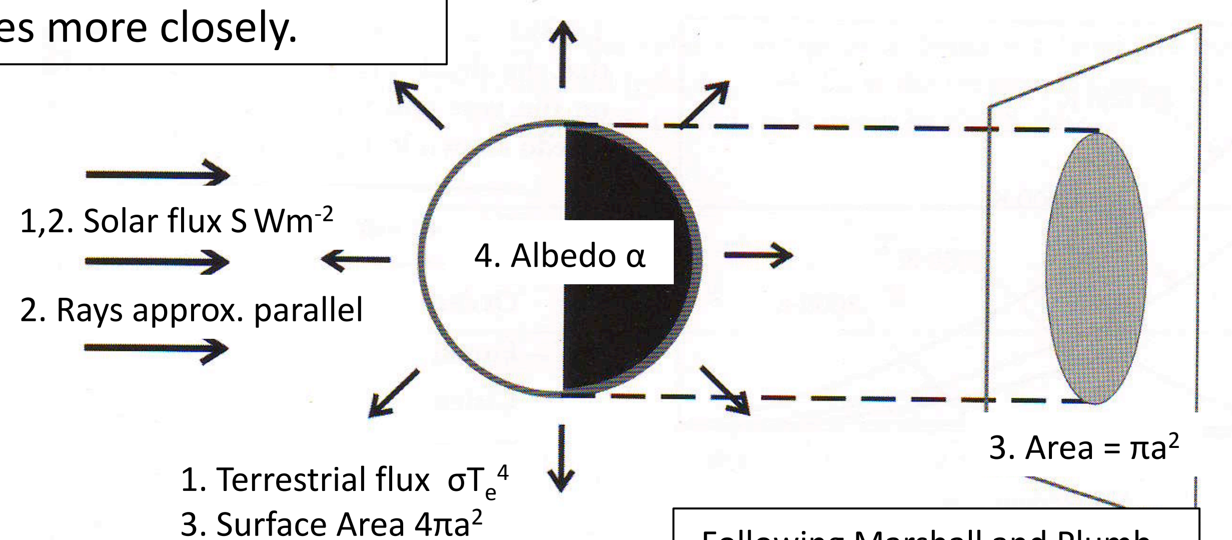

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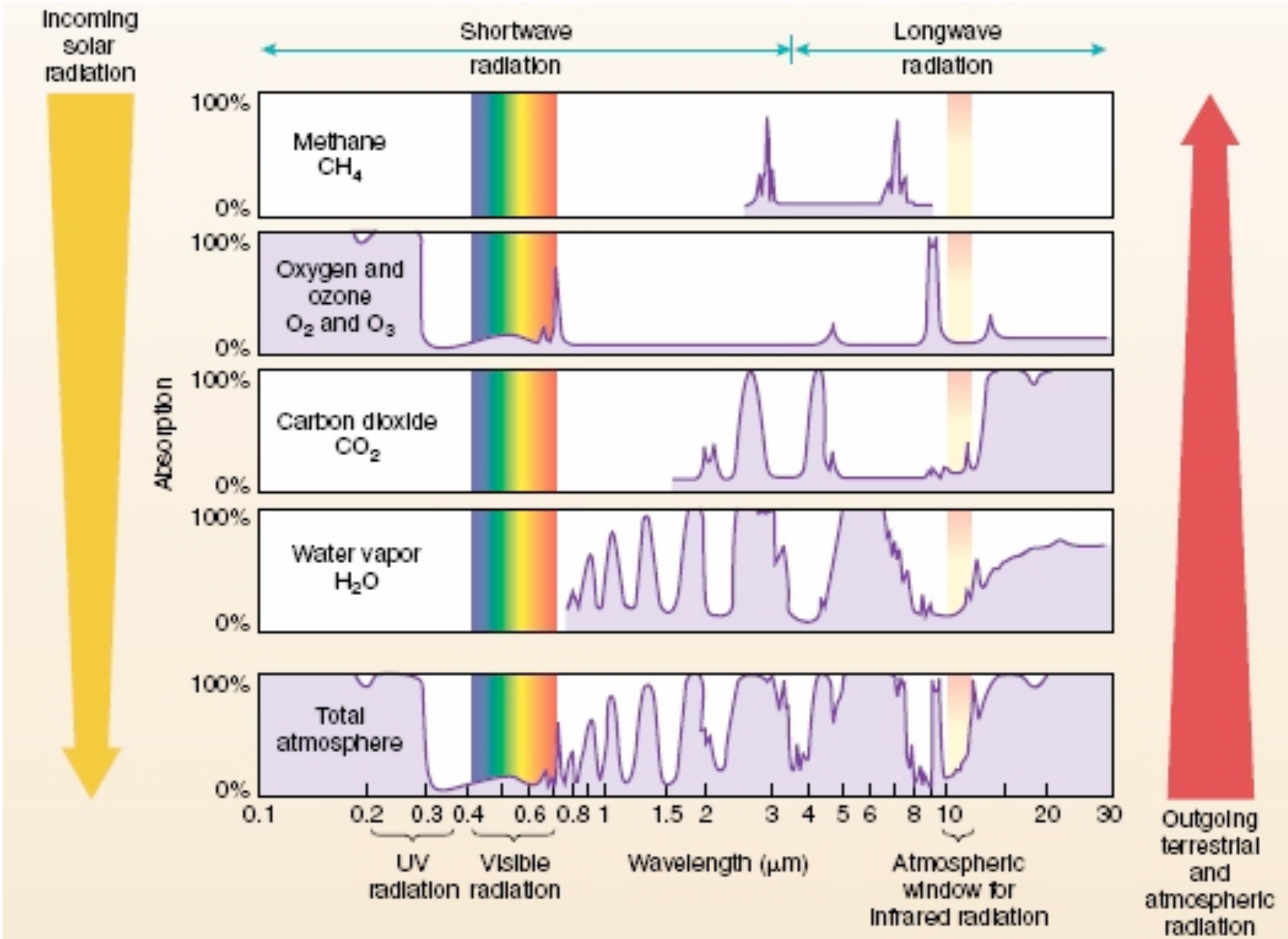
Atmospheric Absorption Spectrum



CIMSS/ U Wisc

Energy Balance, 1-Layer Atmosphere

Hypotheses: Earth's temperature is a consequence of

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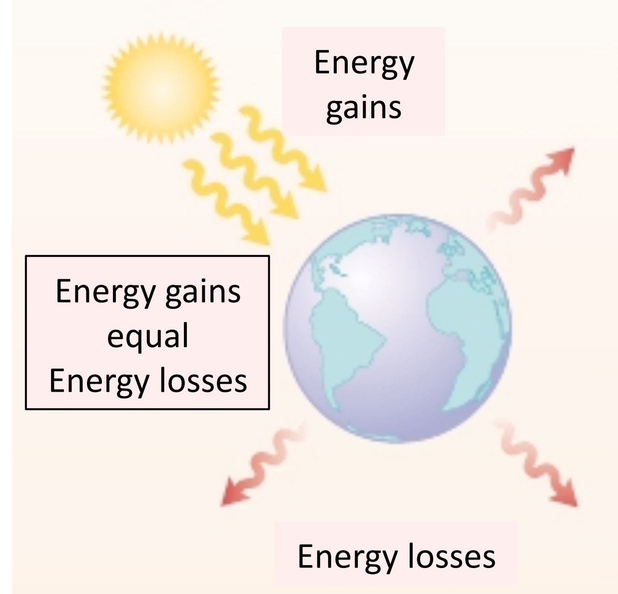
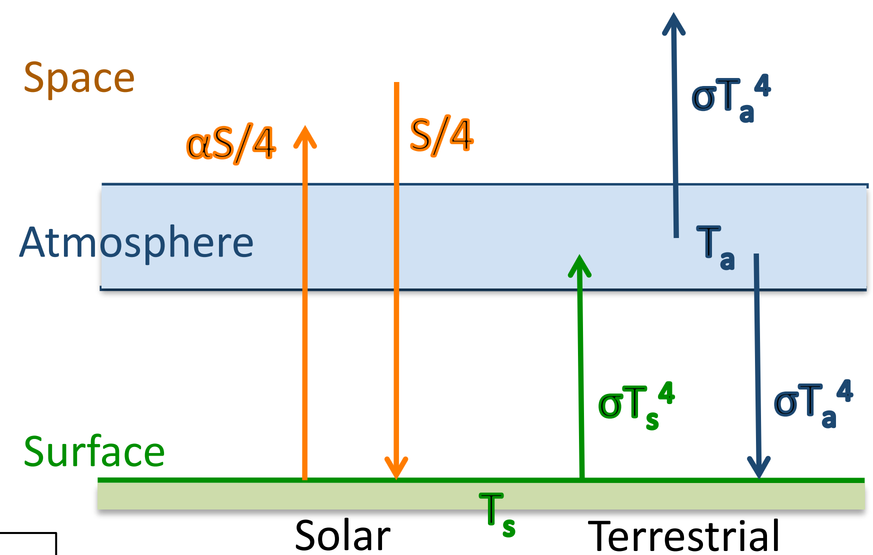




Following Marshall and Plumb

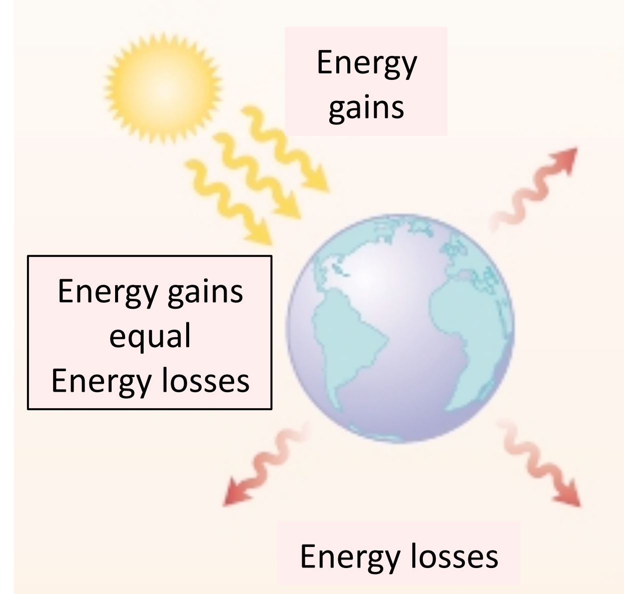
Solar Flux

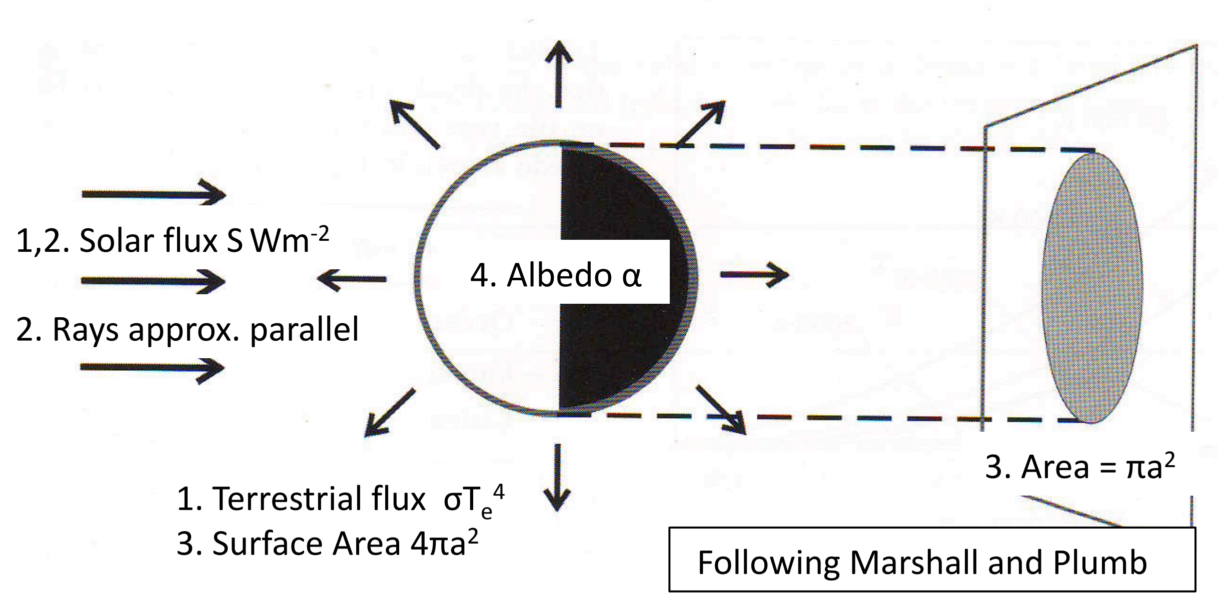
Recall total solar radiation (W)

Solar flux * cross-sect area = $S\pi a^2$

Solar flux (W/m^2):

Total solar in / surface area = $S\pi a^2 / 4\pi a^2 = S/4$





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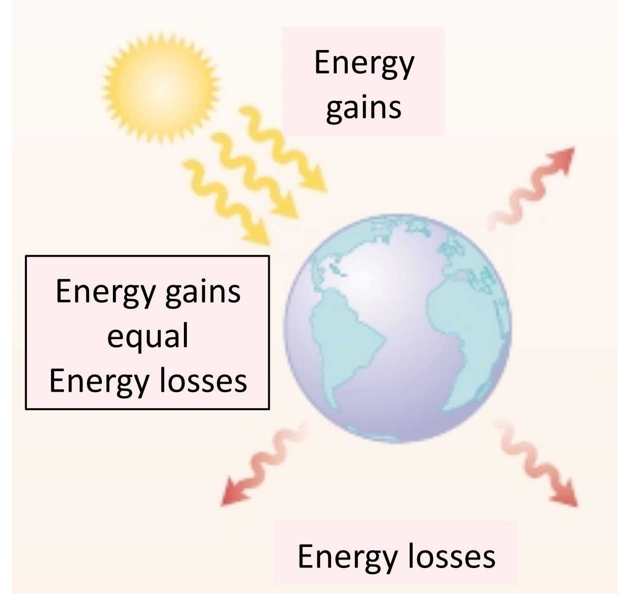

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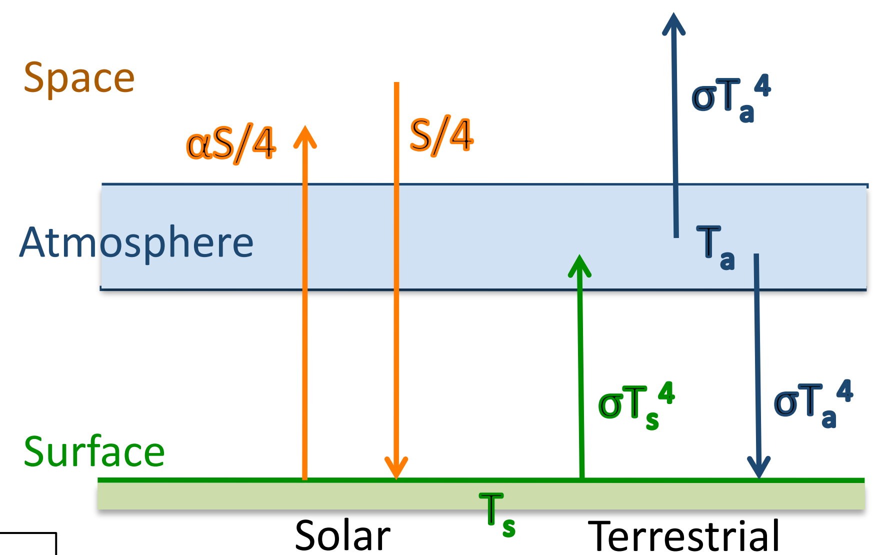

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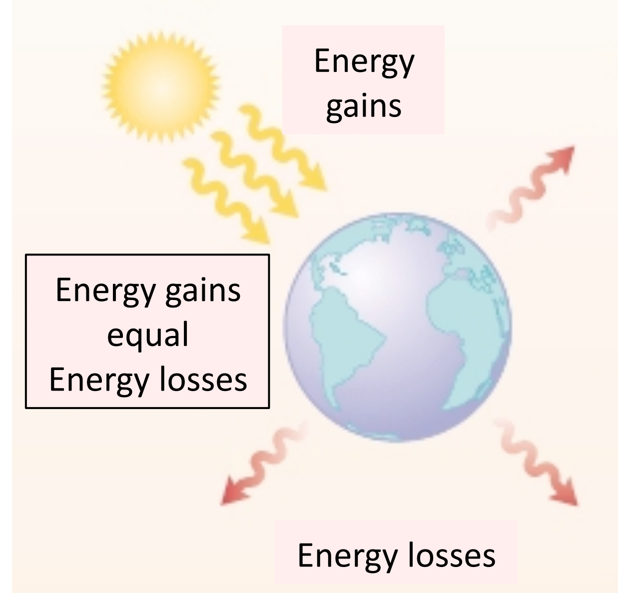

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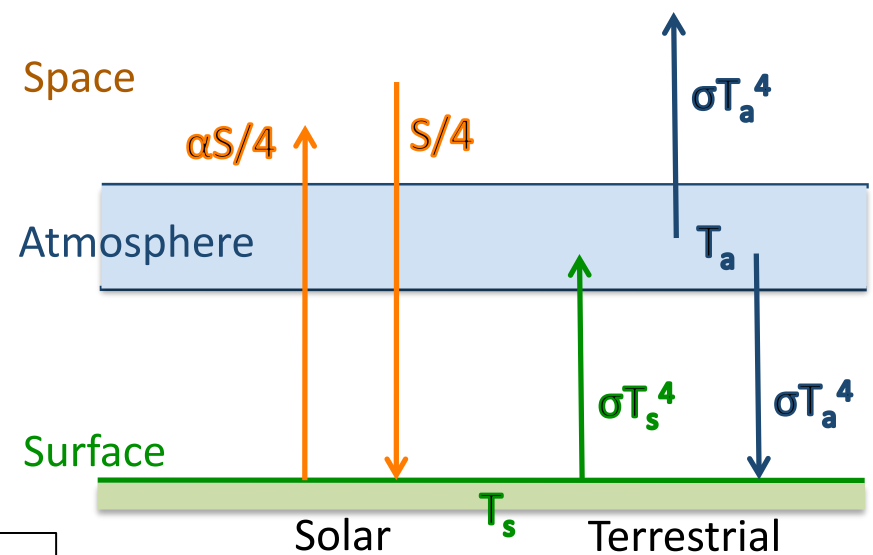

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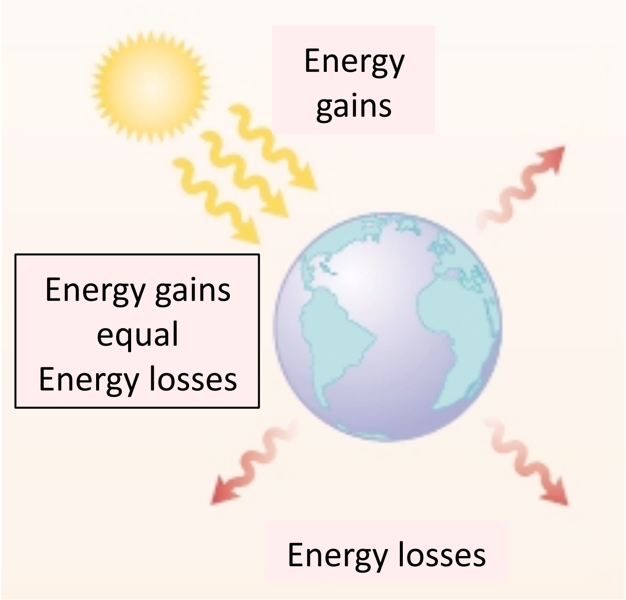

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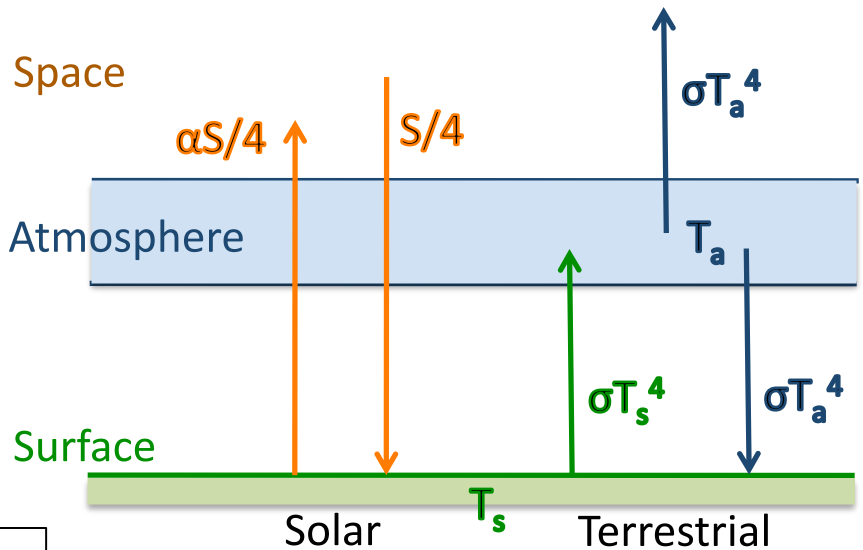

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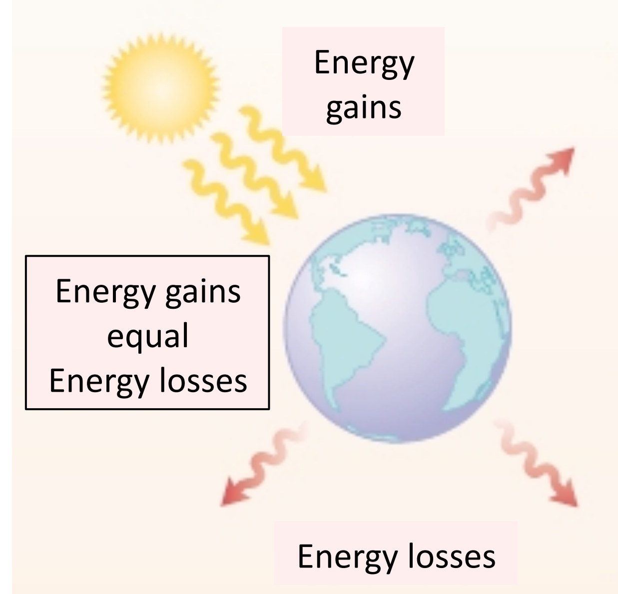

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Energy balance at surface:

$S/4 + \sigma T_a^4 = \alpha S/4 + \sigma T_s^4$

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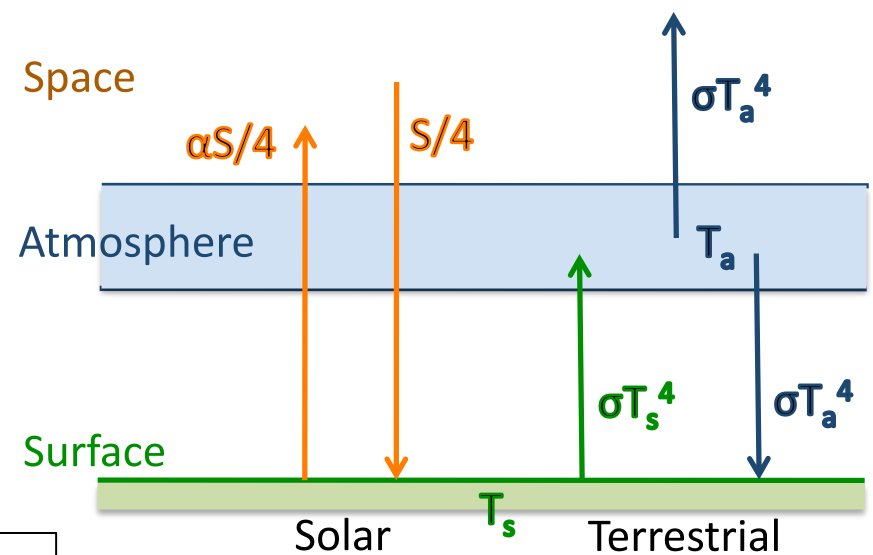

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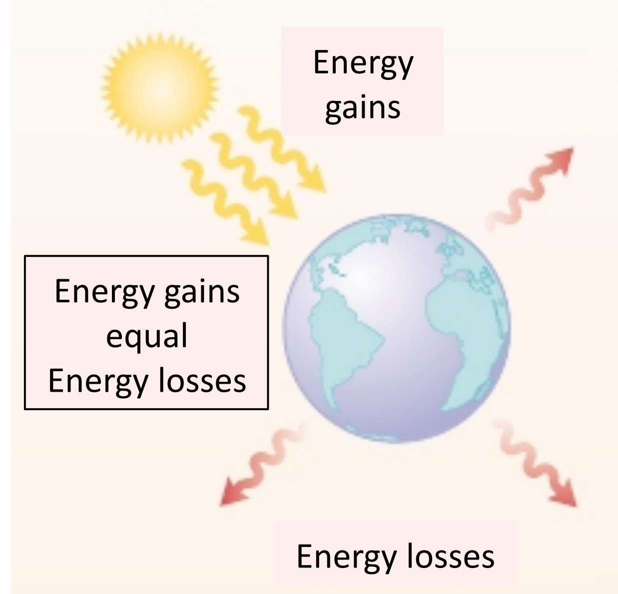

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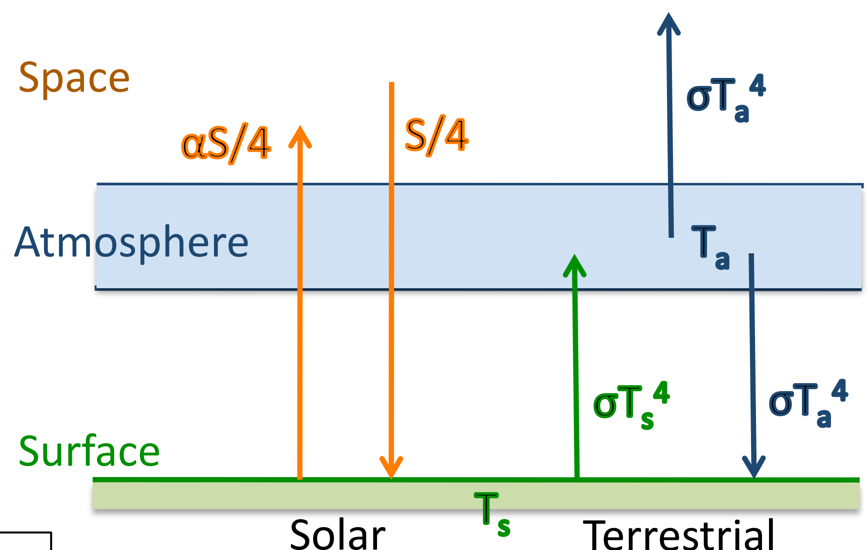
$= 2\sigma T_a^4$



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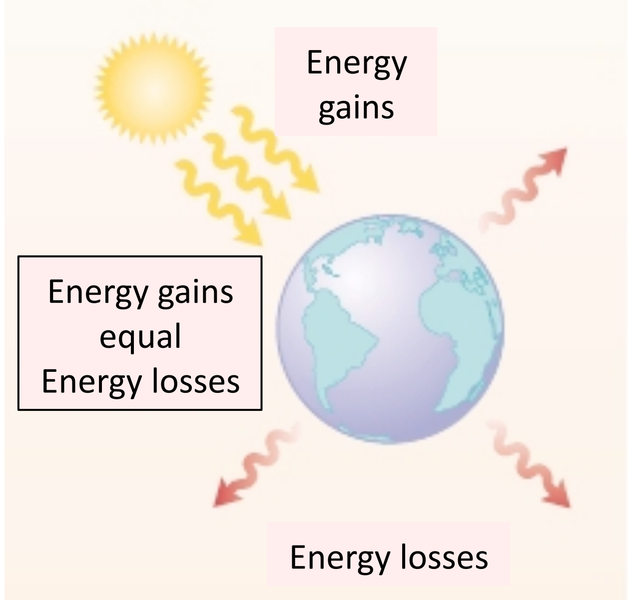

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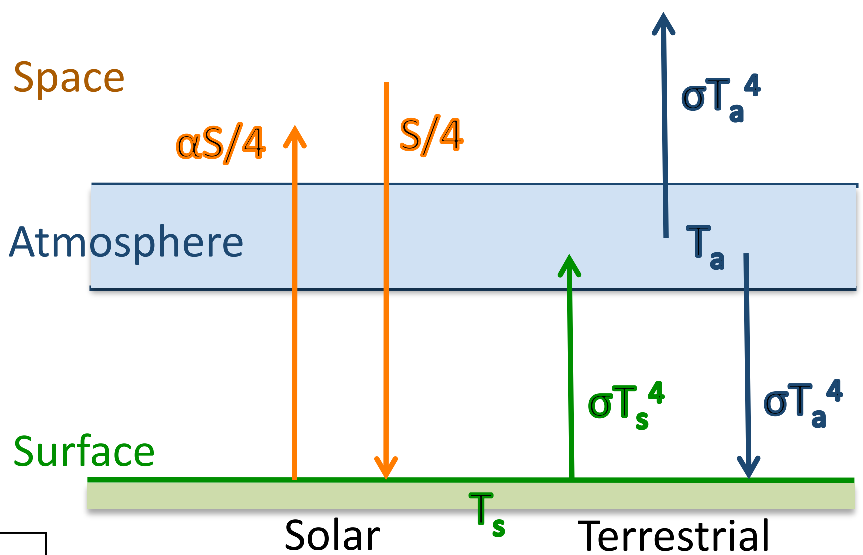
$\sigma T_s^4 = (1-\alpha)S/4 + \sigma T_a^4$

$= 2\sigma T_a^4$

So, $T_s = 2^{1/4} T_a \approx 1.19\, T_a$ = 303K = 30°C

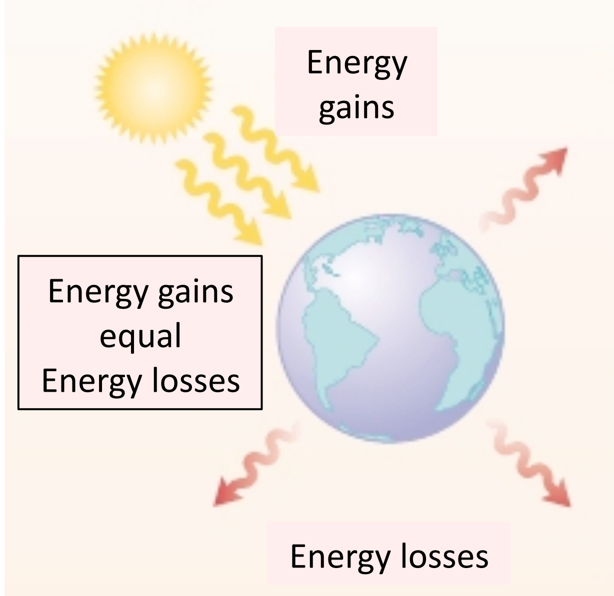


Following Marshall and Plumb

Energy Balance, 1-Layer Atmosphere

Hypotheses: Earth's temperature is a consequence of

1. Radiation, distance from sun, size, albedo
2. Single layer, uniform atmosphere
3. Atmosphere transparent to solar radiation
4. Atmosphere opaque to terrestrial radiation



Solar flux (W/m²):

Total solar in / surface area = $S\pi a^2 / 4\pi a^2 = S/4$

Energy balance of total system:

$S/4 = \alpha S/4 + \sigma T_a^4$

$(1-\alpha)S/4 = \sigma T_a^4$

So, as before, T_a=255K

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$= 2\sigma T_a^4$

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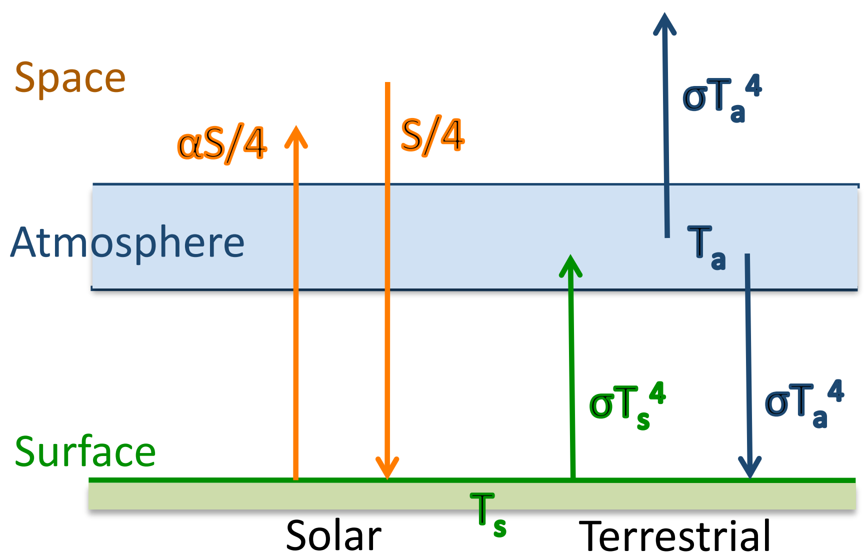
Surface is 15°C warmer than observed.



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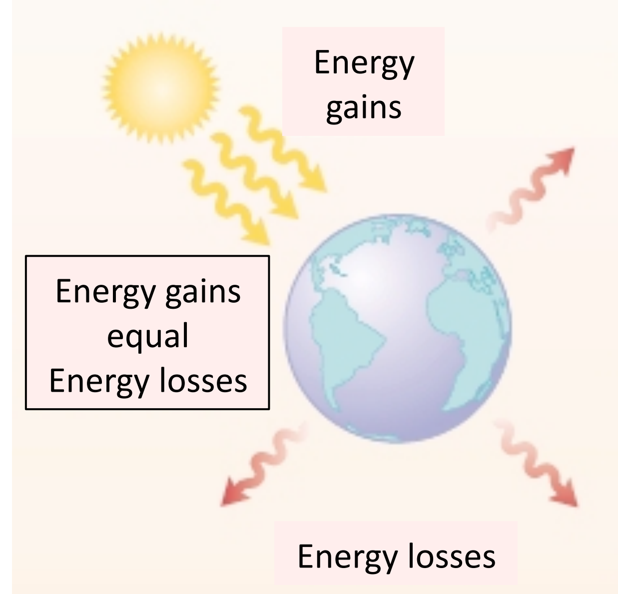

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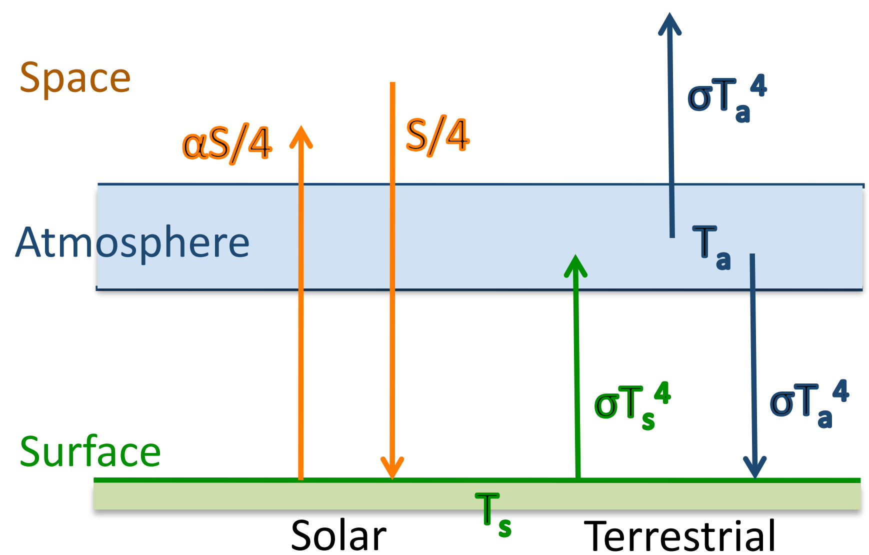
$= 2\sigma T_a^4$

So, $T_s = 2^{1/4} T_a \approx 1.19\ T_a = 303K = 30°C$

Note: downwelling from atmosphere is at magnitude of solar flux.



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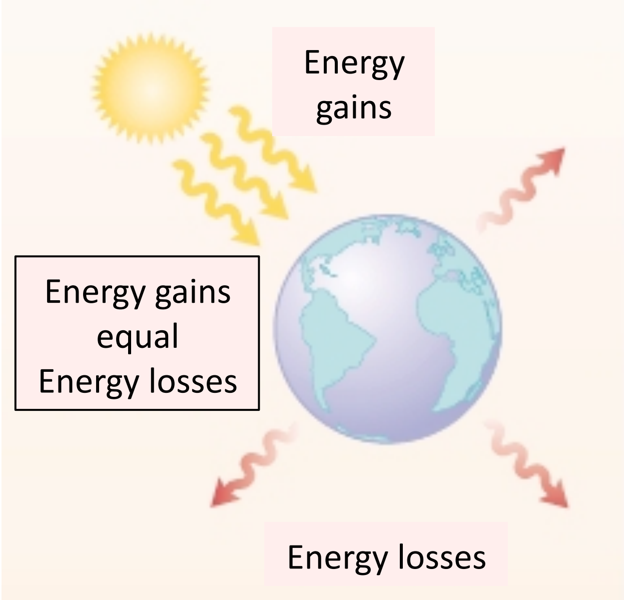

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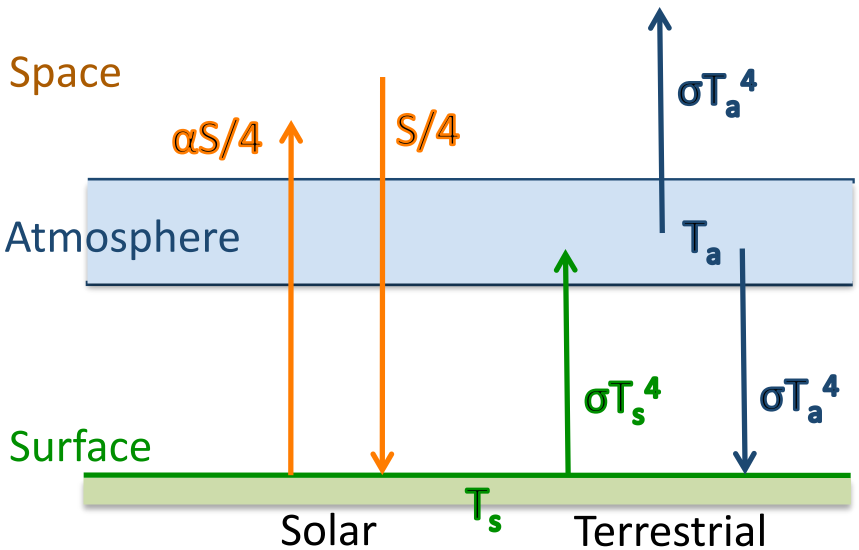

Note: Atmosphere is cooler than the surface.

Energy Balance, 1-Layer Atmosphere

Hypotheses: Earth's temperature is a consequence of

1. Radiation, distance from sun, size, albedo
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3. Atmosphere transparent to solar radiation
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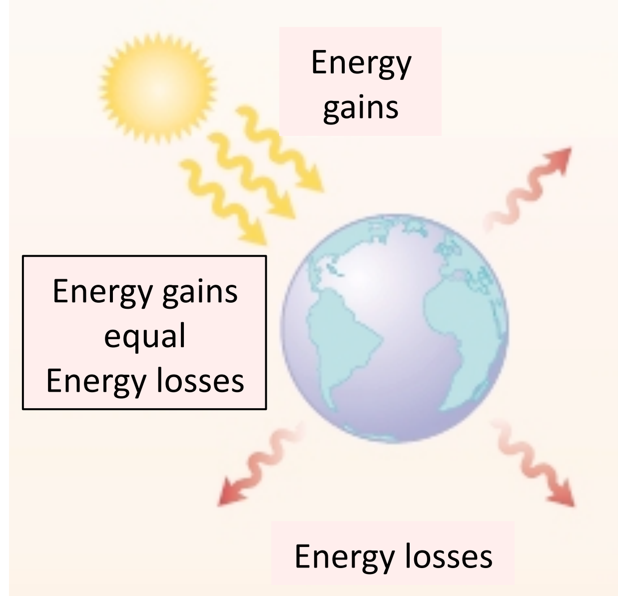
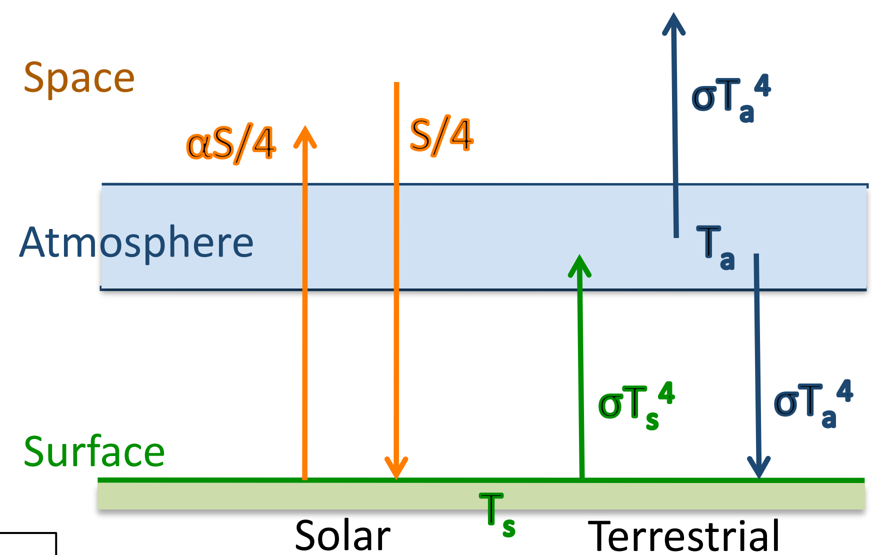
Conclusions: With these hypotheses

- Top of atmosphere is 255K (observed 250K)
- Surface temp is 15°C too high
- Atmosphere is cooler than surface





Following Marshall and Plumb

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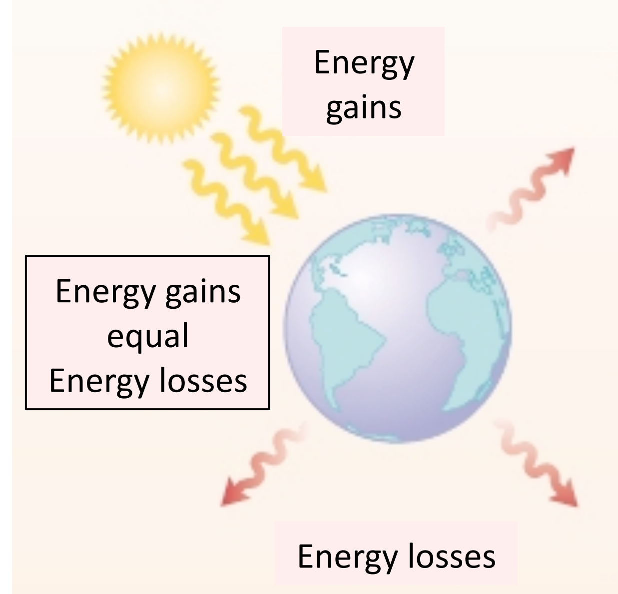

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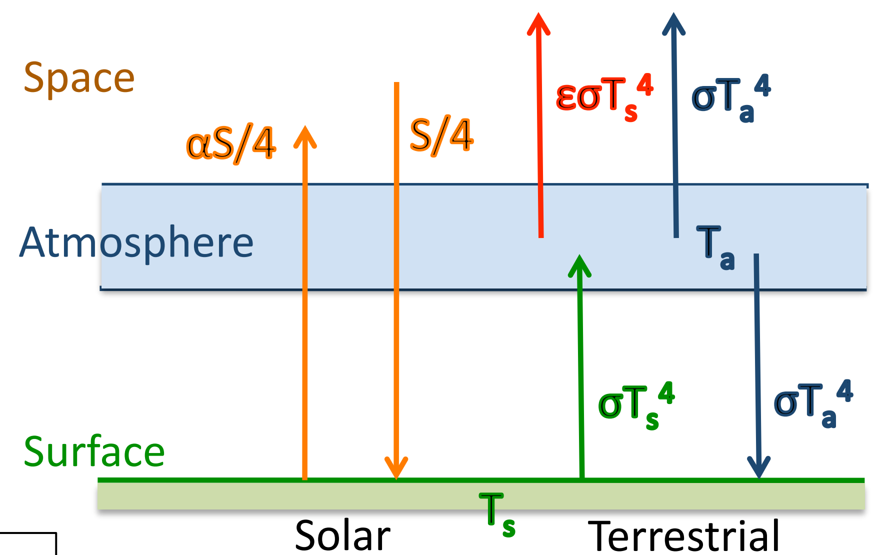
New Hypotheses:

- Atmosphere partially opaque to terrestrial IR

Conclusion: With realistic ε, surface temp is still too high



Following Marshall and Plumb

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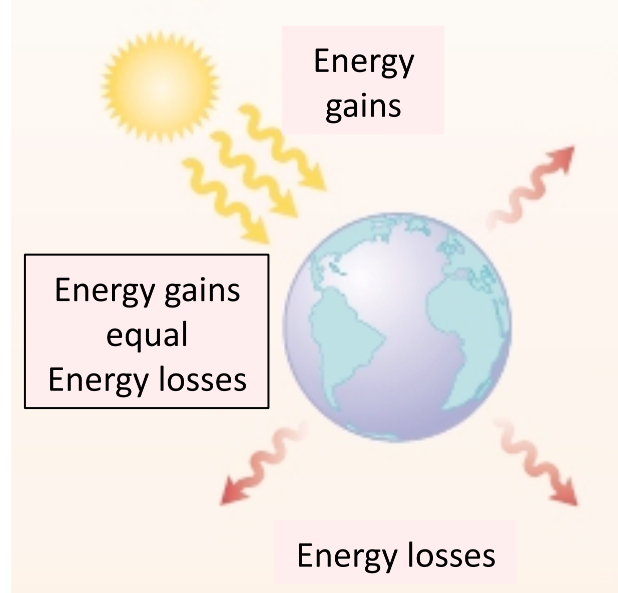

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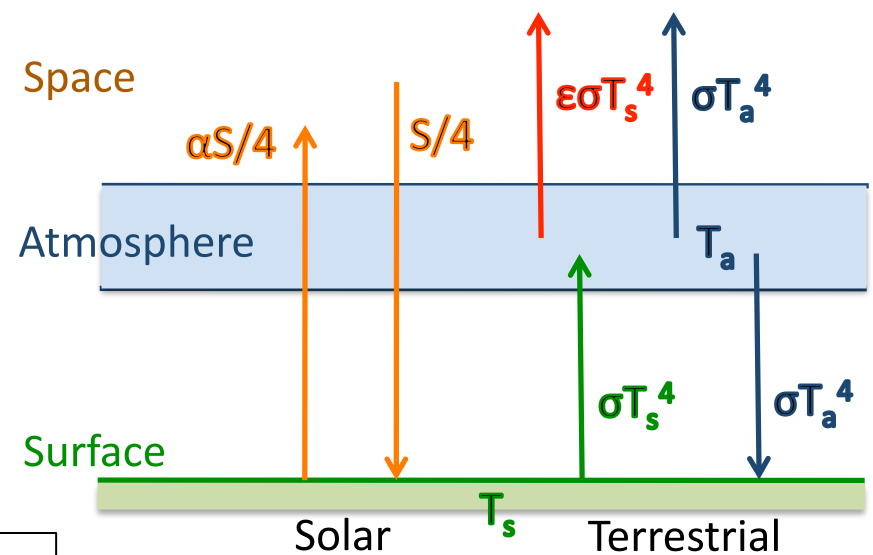
- Atmosphere partially opaque to terrestrial IR
- Many layers of atmosphere
- Accurate ε for each layer
- Accurate ε for each wavelength



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1. Radiation, distance from sun, size, albedo
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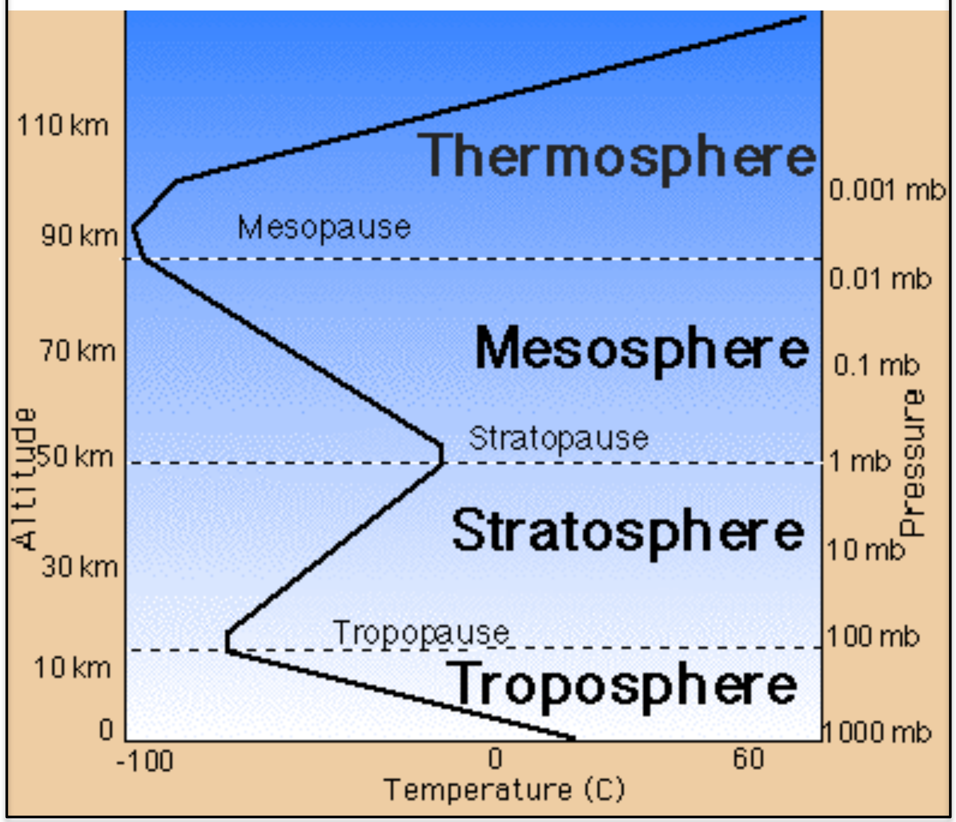
Do get qualitative reproduction of temperature distribution in atmosphere.

New Hypotheses:

- Atmosphere partially opaque to IR
- Many layers of atmosphere
- Accurate ε for each layer
- Accurate ε for each wavelength

Conclusion: With realistic atmosphere, surface temp is still too high

Atmospheric temperature with height



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Radiative energy balance is NOT enough to explain surface temperature.

New Hypotheses:
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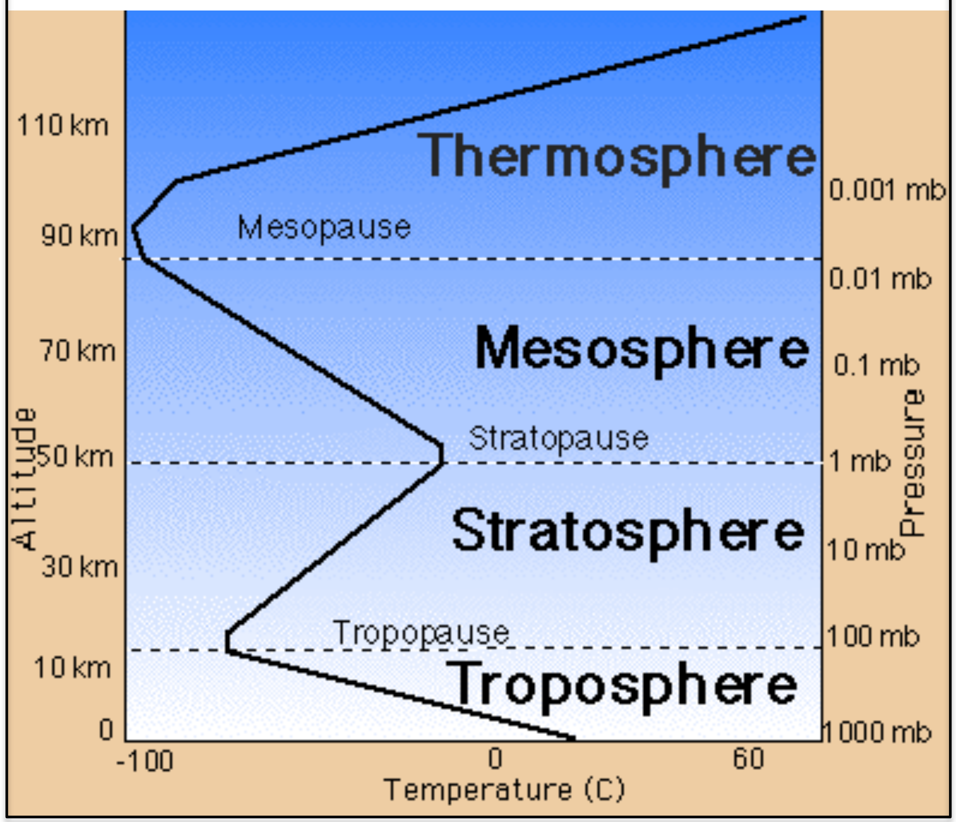
Atmospheric temperature with height



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2. Single layer, uniform atmosphere
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4. Atmosphere opaque to terrestrial radiation

Why? Cold fluid above hot fluid is an unstable equilibrium, so convection sets in… fluid dynamics and weather in troposphere

New Hypotheses:

- Atmosphere partially opaque to IR
- Many layers of atmosphere
- Accurate ε for each layer
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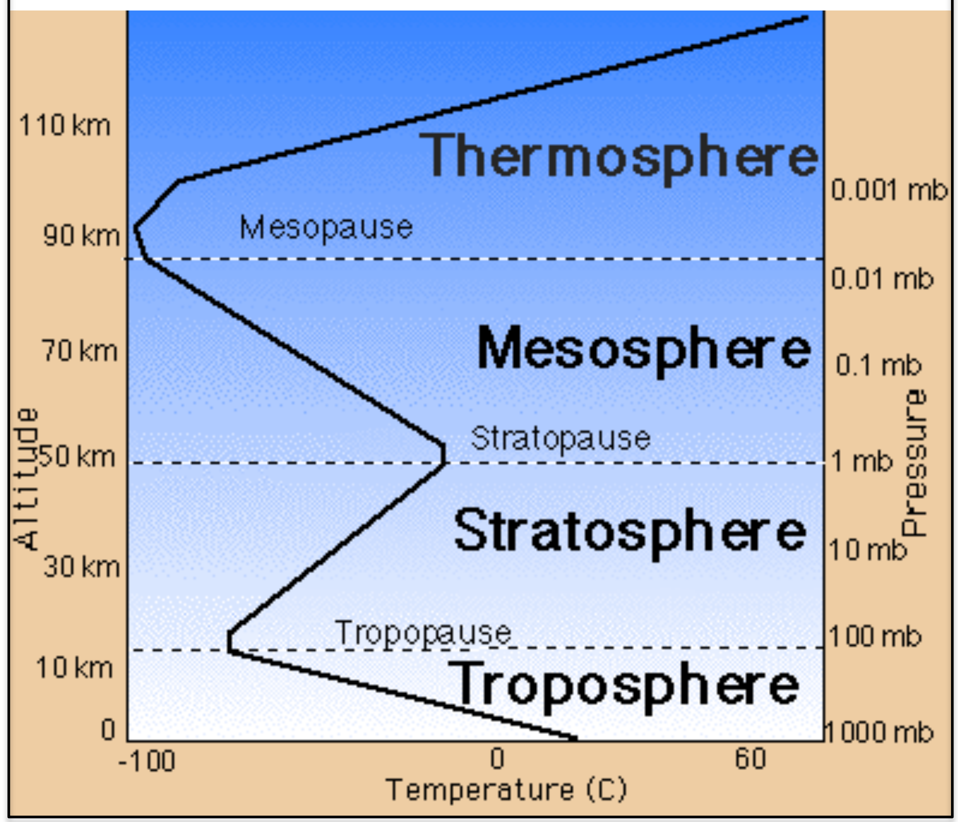
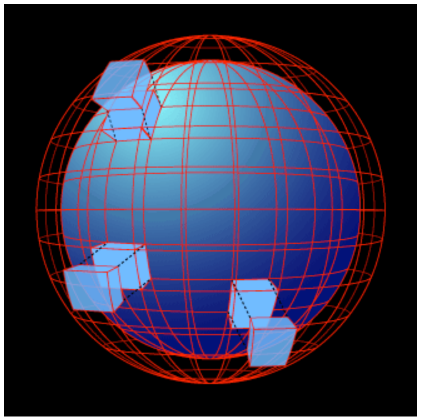
Atmospheric temperature with height



Numerical Climate Model

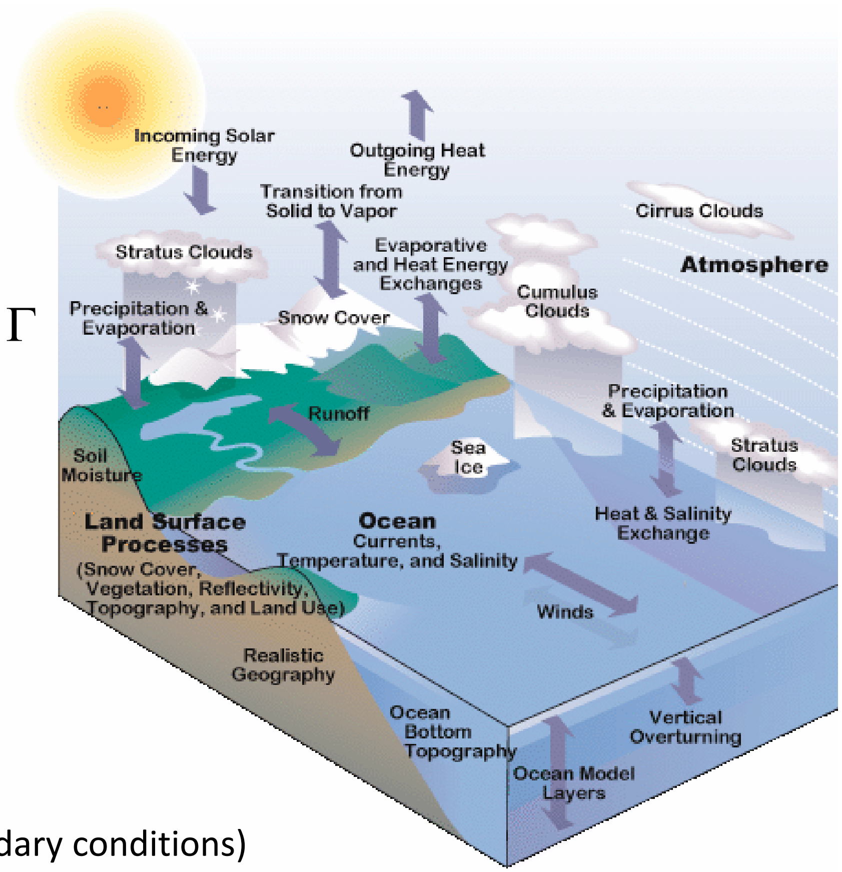


$$\rho \frac{D\vec{u}}{Dt} = -\rho\left(2\Omega \times \vec{u}\right) - \nabla p + \rho g\vec{k} + \Gamma$$

$$+$$

- conservation of mass
- water vapor (atmosphere)
- salinity (ocean)
- conservation of energy

  brings in all other processes



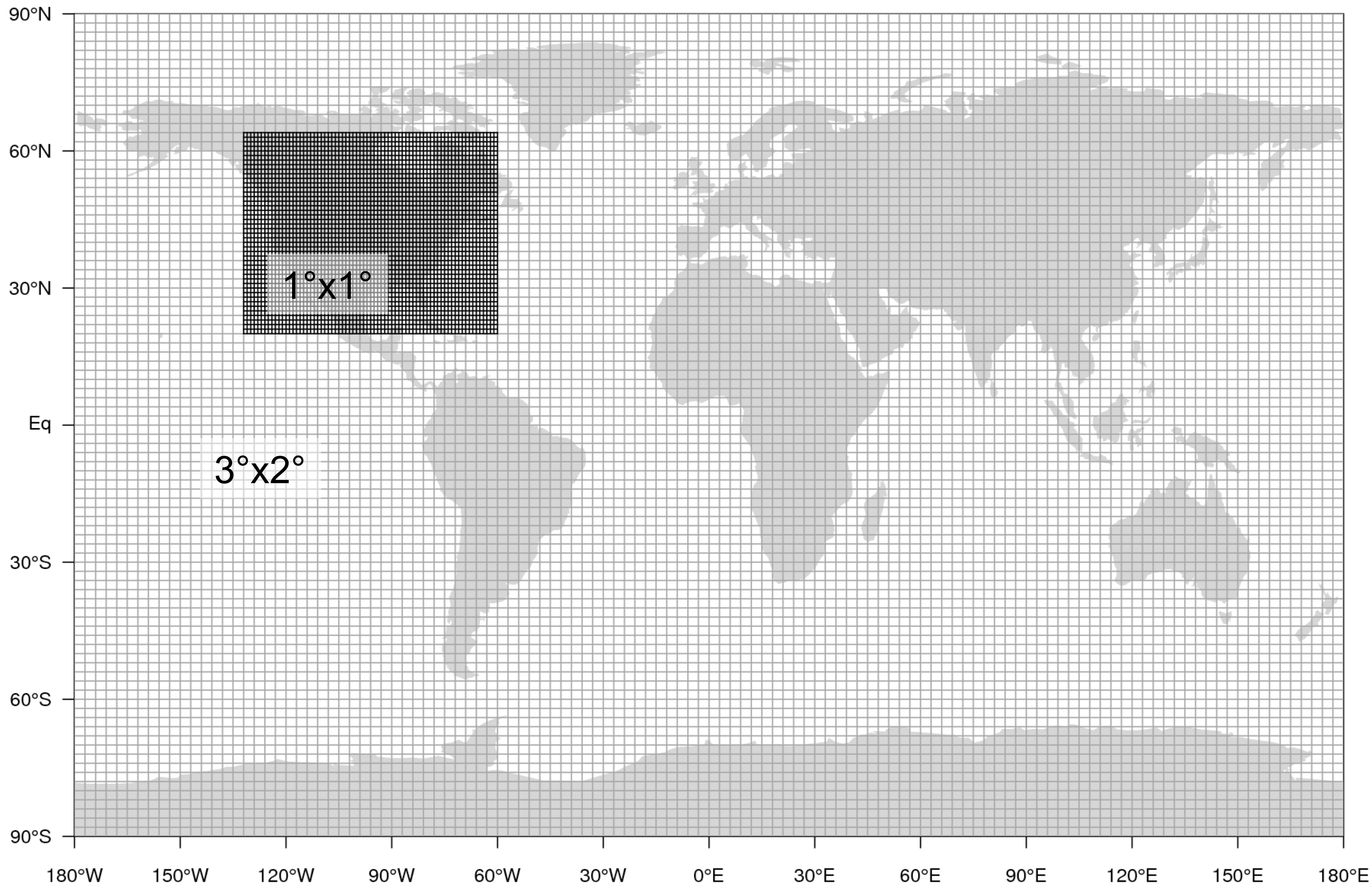
Discretize (put on grid)

→ connect pieces of model (boundary conditions)

→ initialize

→ solve computationally

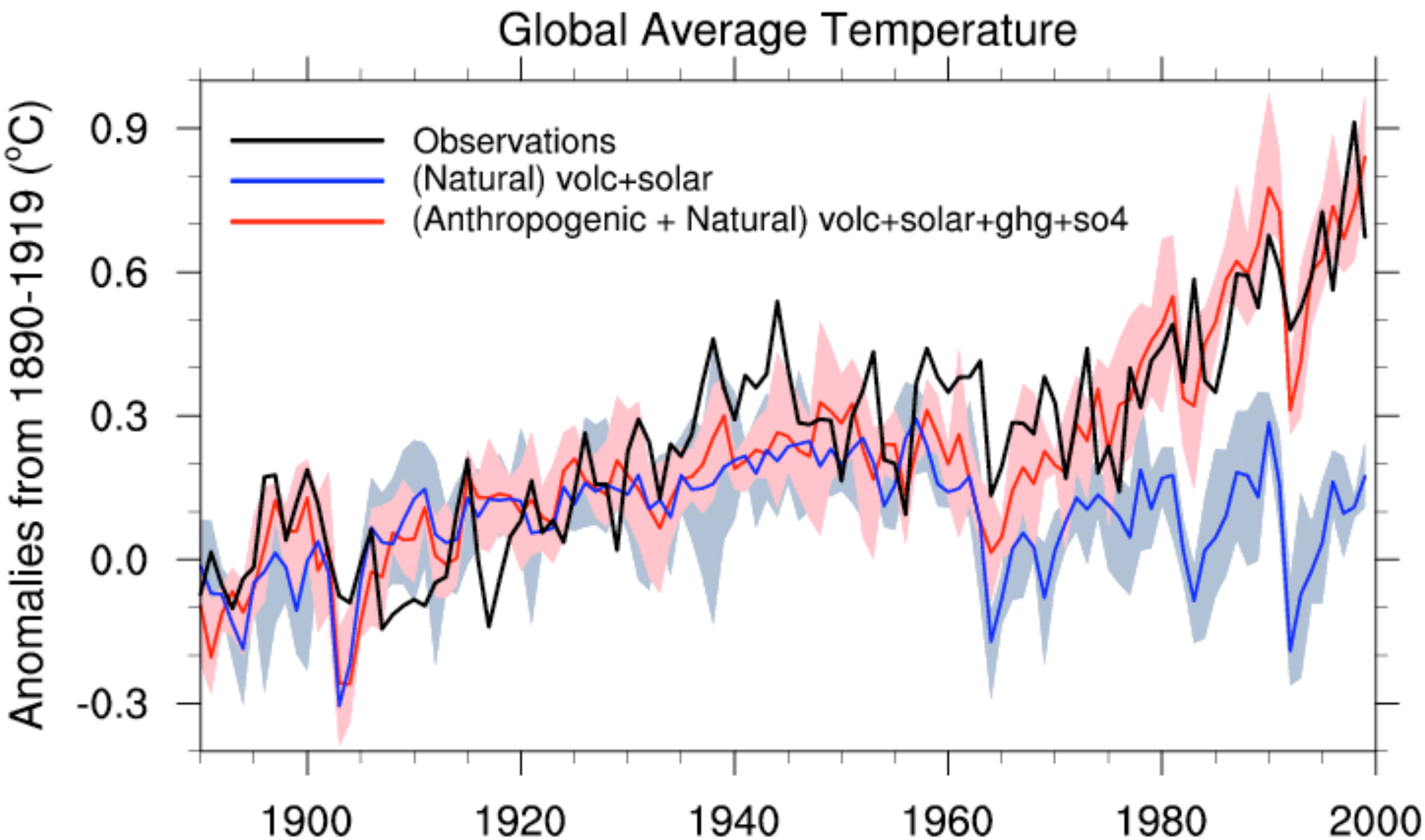
Climate Model Grid Size



Jacobson

Hypothesis Testing

Model Solutions with Human Forcing



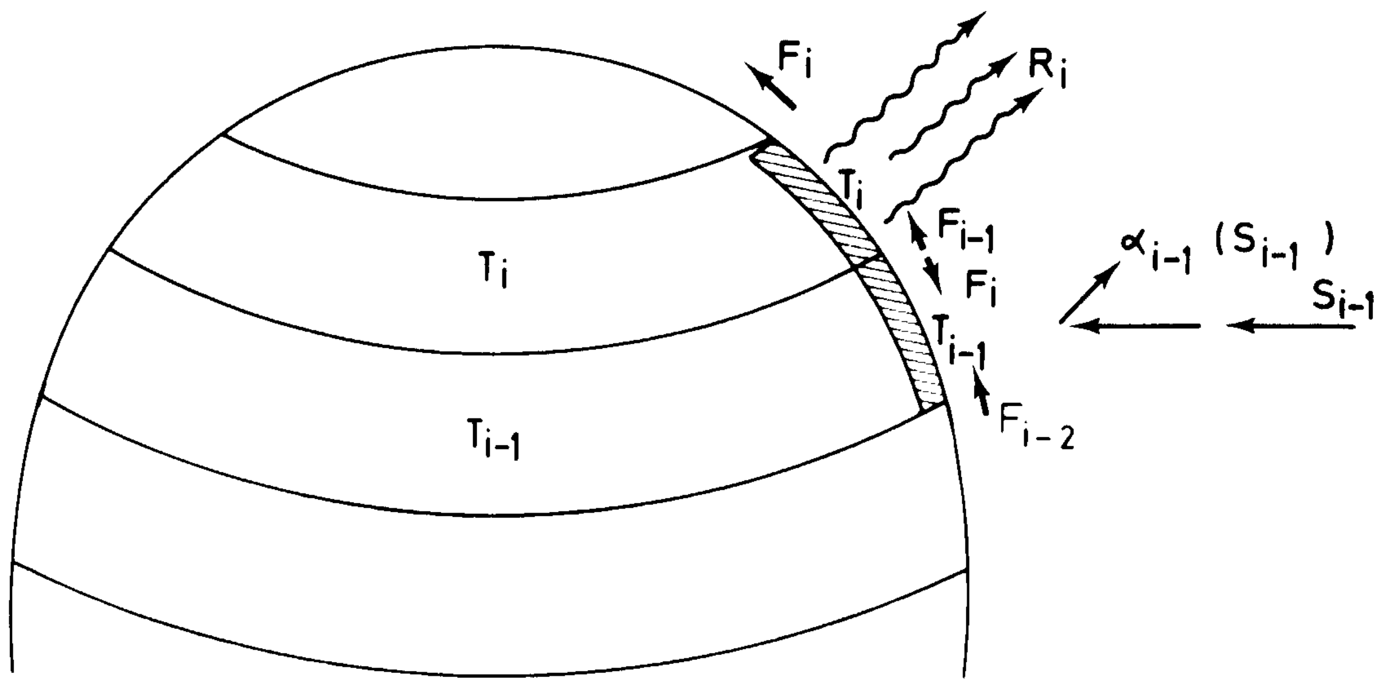
NCAR

J. J. Hack/A. Gettelman: June 2005

1-Dimensional Energy Balance

Budyko-Sellers-North. Hypotheses:

1. Rotational symmetry of earth
2. Energy balance calculated for each latitude x_i, with temp T_i
3. Atmospheric dynamics provide heat transport between layers
4. Albedo depends on T_i (ice or not) – captures ice-albedo feedback



Solve equations for T_i profile, and for location of ice line

1-D Energy Balance Equations

Latitude *x*, temperature *T*

Solar Radiation

Atmospheric and oceanic heat transport.

$$\frac{Q}{4}S(x)(1-\alpha(x)) = A + BT(x) + \nabla \cdot \vec{F}.$$

Albedo: reflected light increases if T(x) drops below freezing!

Linearization of Outgoing Terrestrial Radiation

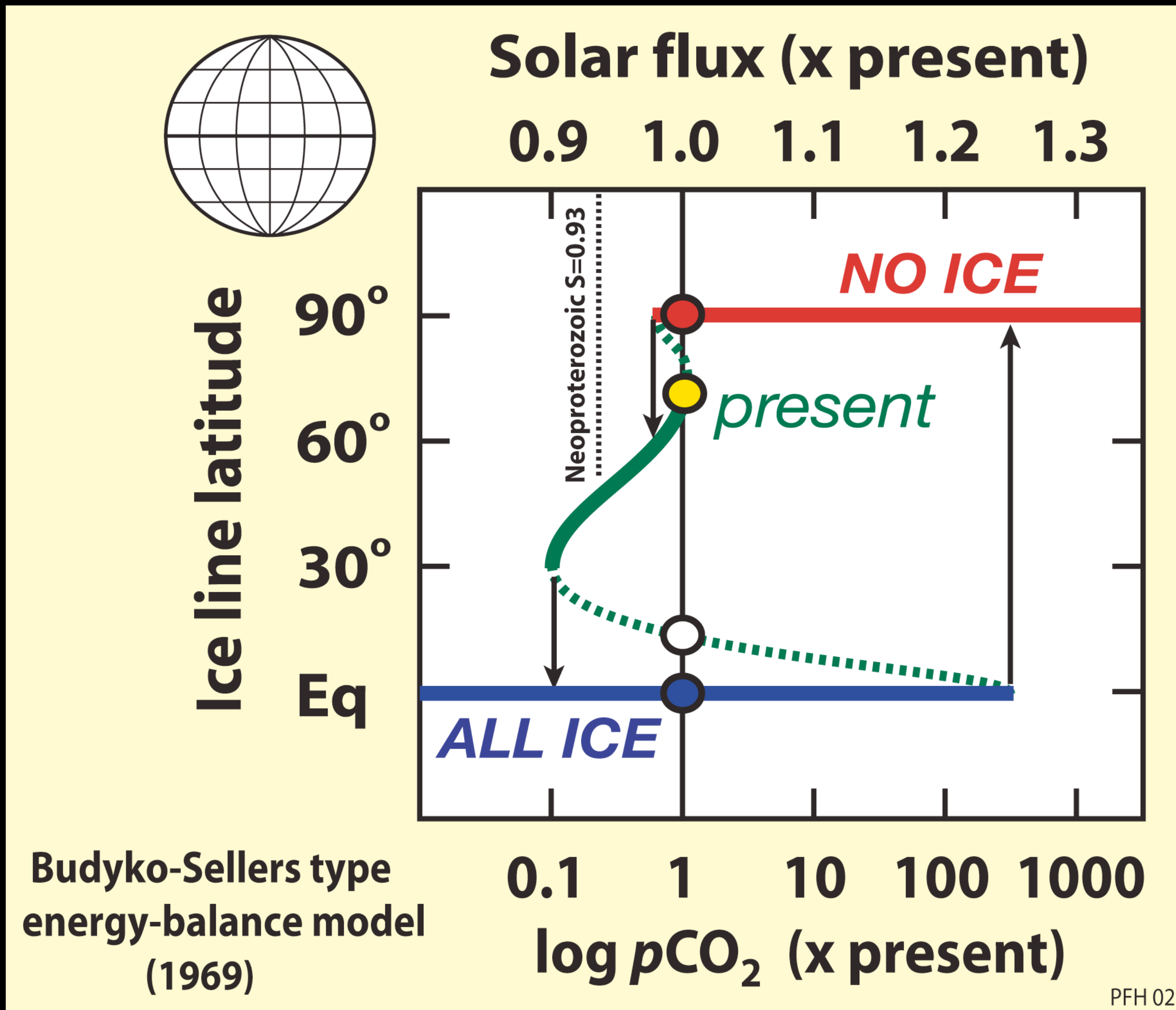
Assume that atmospheric and oceanic movements smooth the temperature profile

$$\nabla \cdot \vec{F} = C(T - \overline{T}),$$

$$\nabla \cdot \vec{F} = -D\frac{d}{dx}(1-x^2)\frac{dT}{dx}.$$

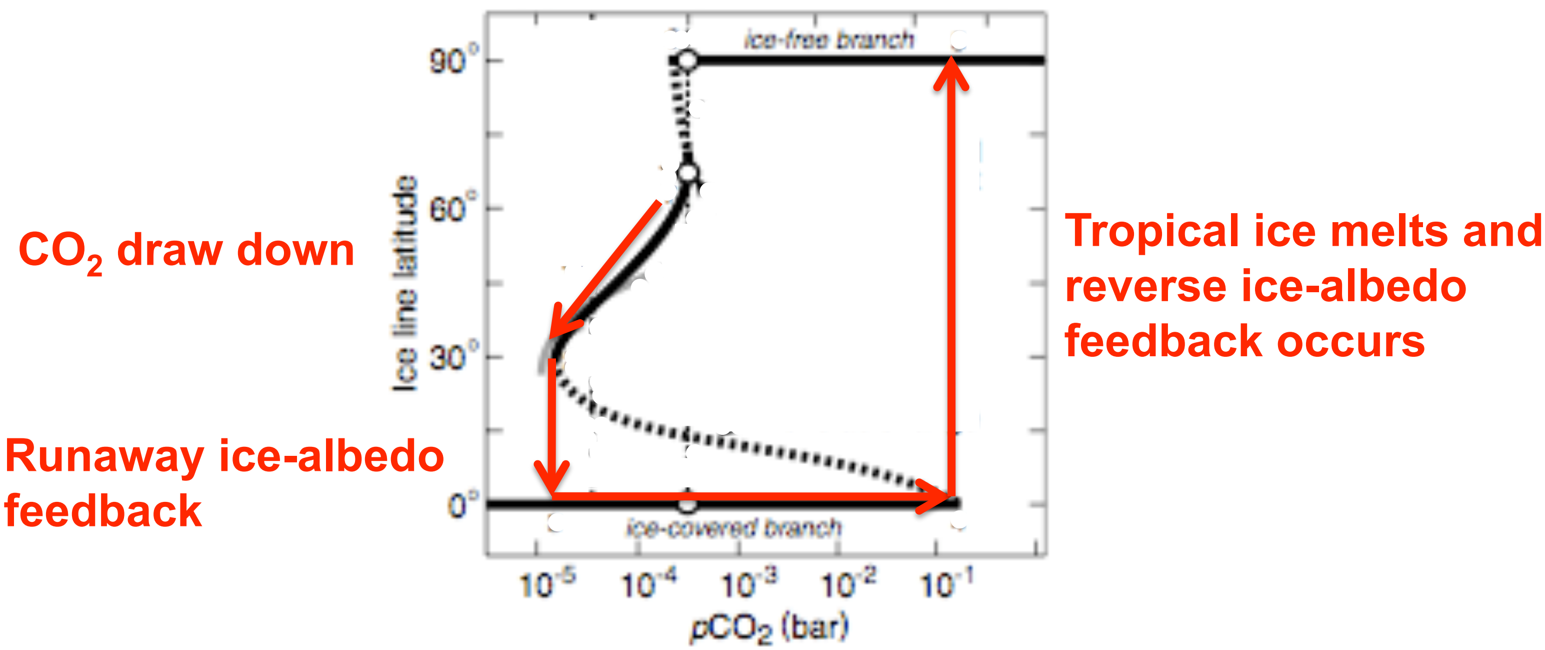
Abbot

Budyko-Sellers Model Predictions



Snowball Earth: 700M yrs ago

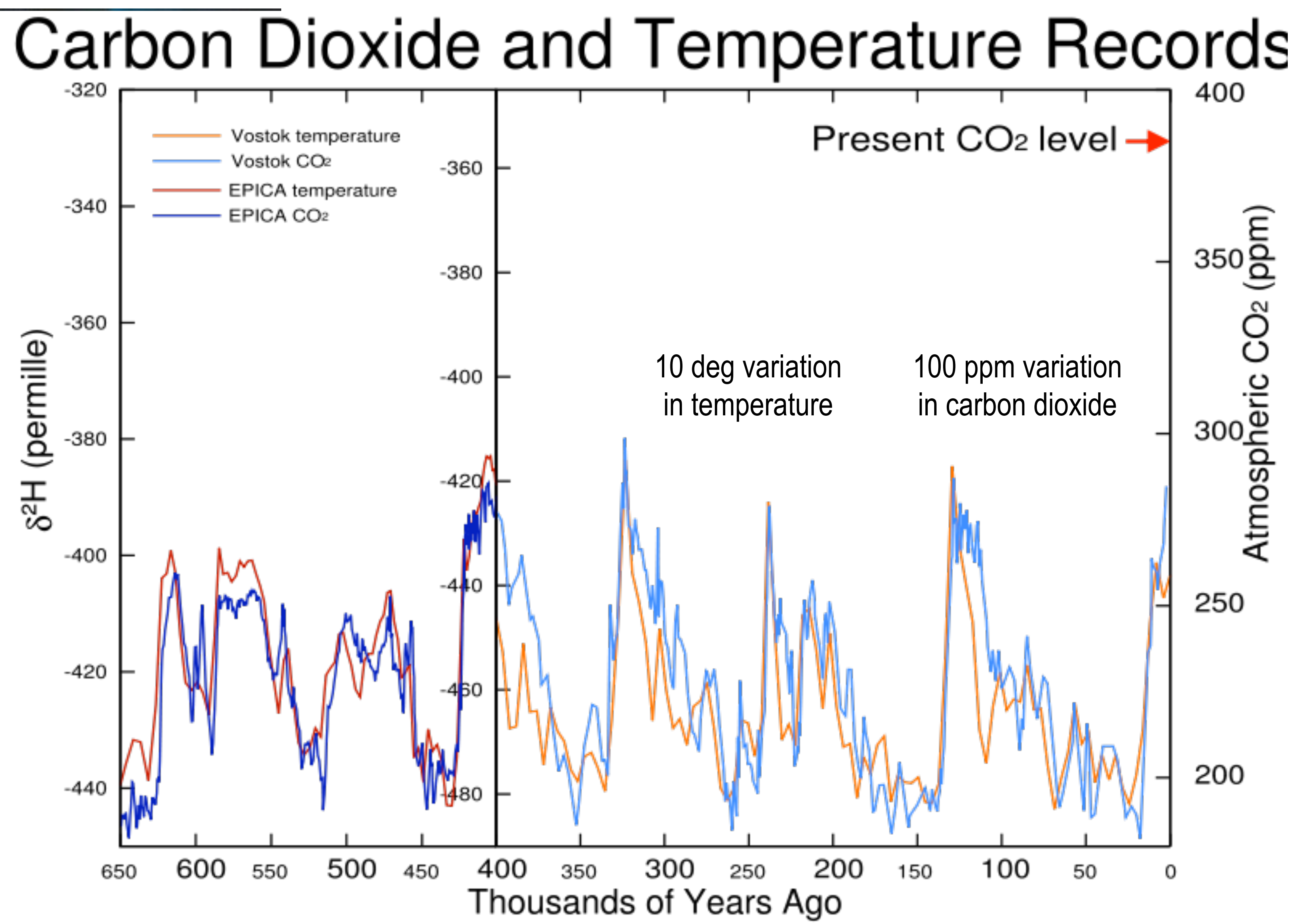
Energy Balance Models produces a bifurcation diagram that might explain the geological observations.



Very low weathering allows CO_2 to build up to ~10% of atmosphere over 1-10 million years

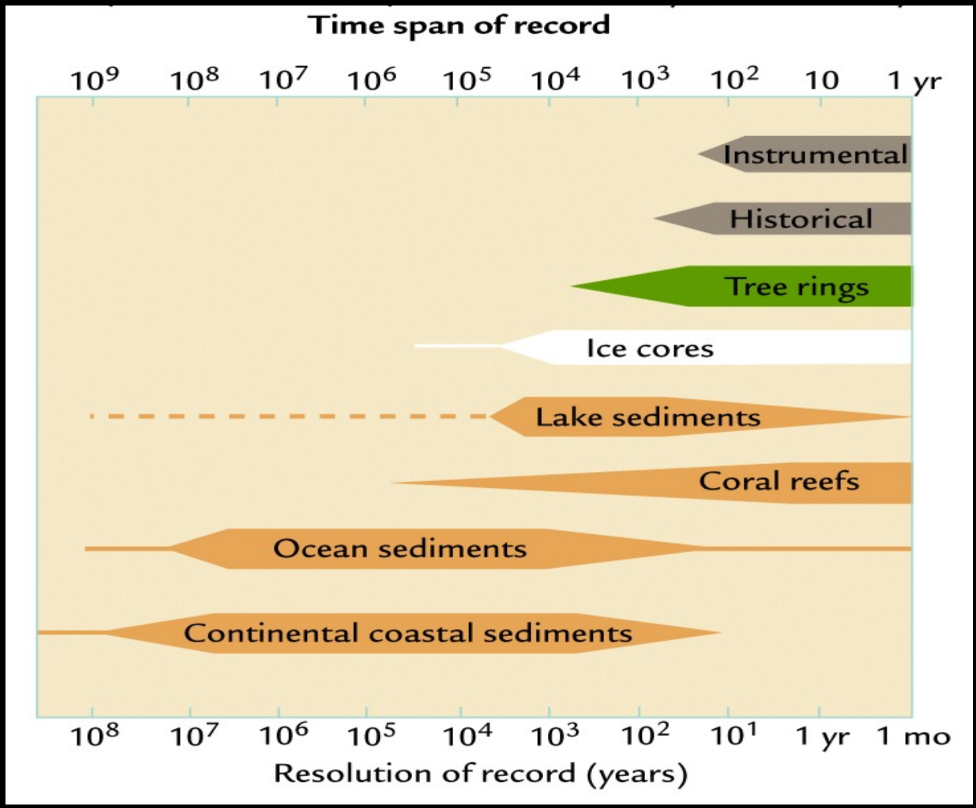
Abbot

More recent: last 600K yrs



Martin

Climate archives: what information do we have?

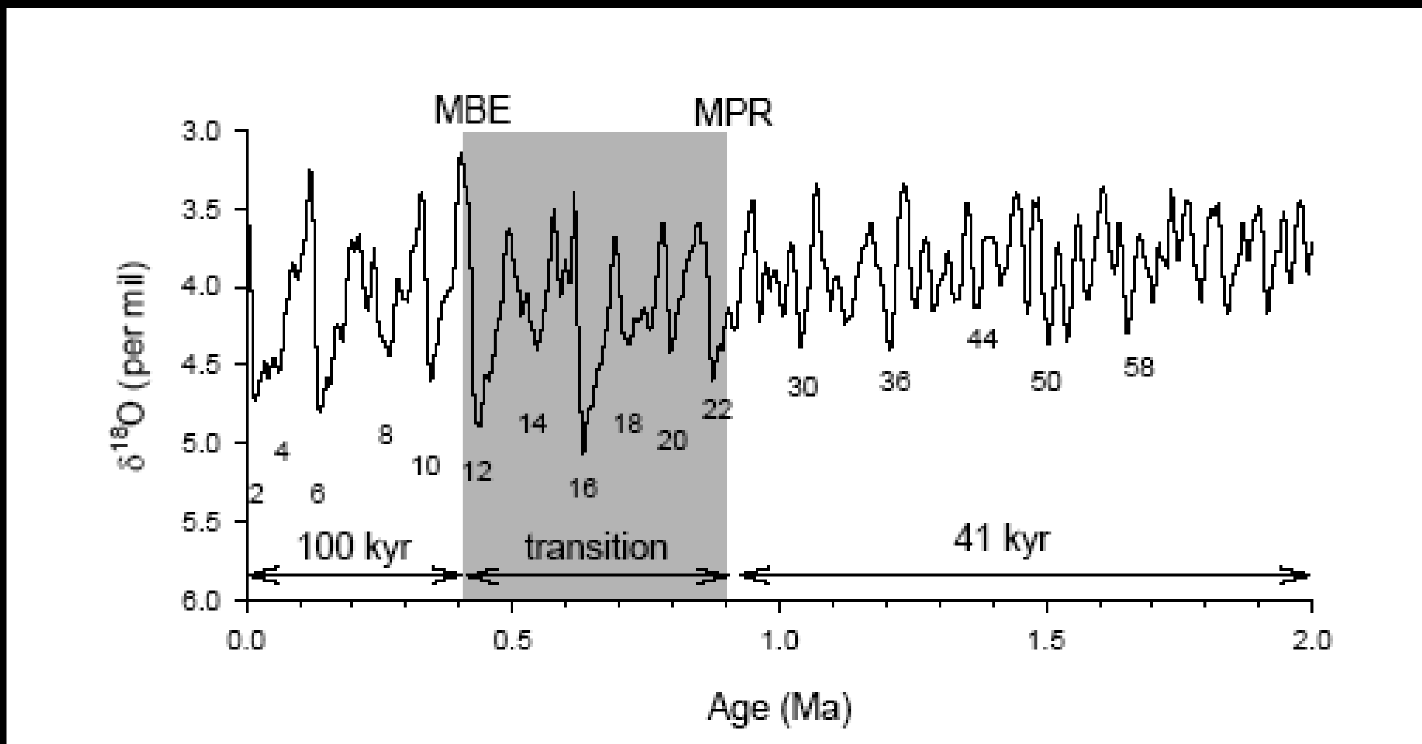


Ruddiman, W. F., 2008. Earth's Climate: past and future

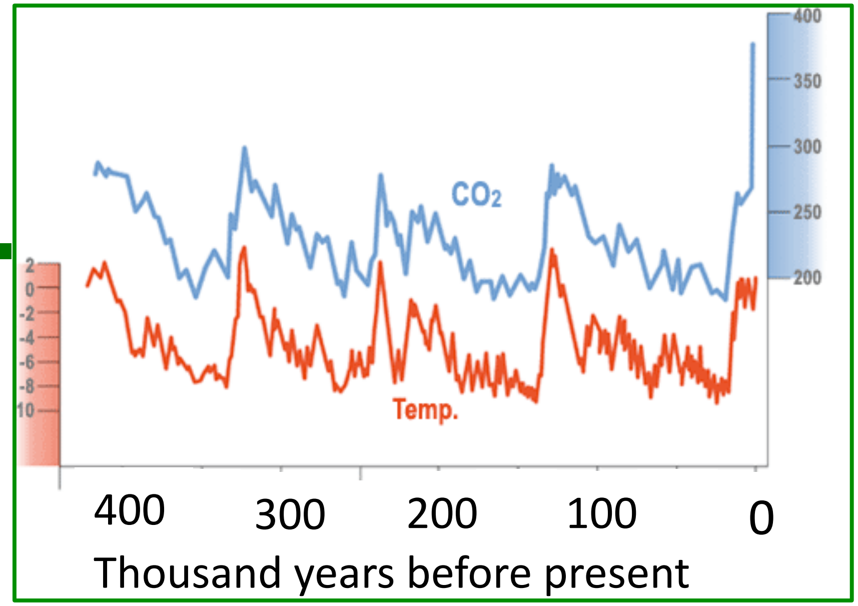
Martin

Temperature Record - 2M yrs

Glacial-interglacial cycles

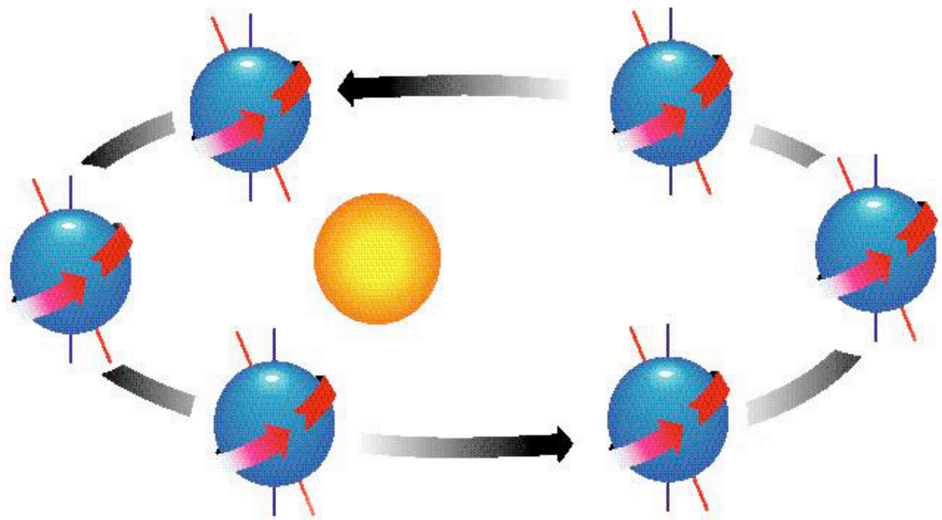


Sun



Milankovich cycles:
Variation in orbit & axis,
20K, 40K and 100K years

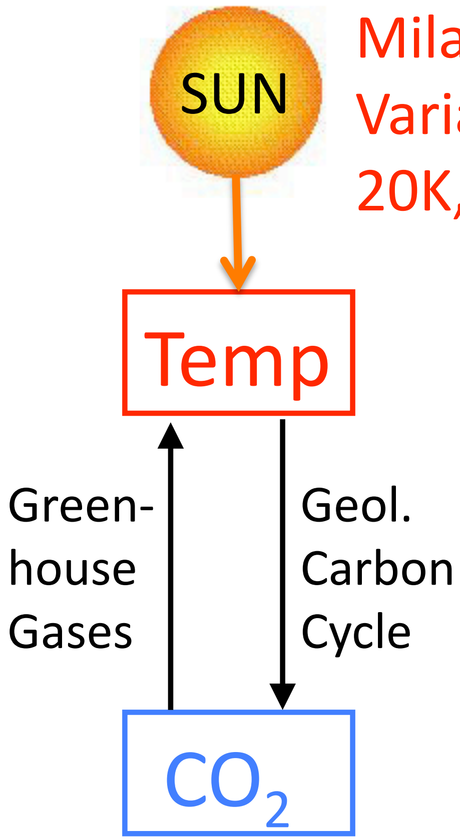
Combine Budyko model with Milankovich cycles



As orbit changes slightly, amount of solar radiation received changes.

- Can explain *timing* of end of ice ages
- Cannot explain speed or amplitude of rise

Sun



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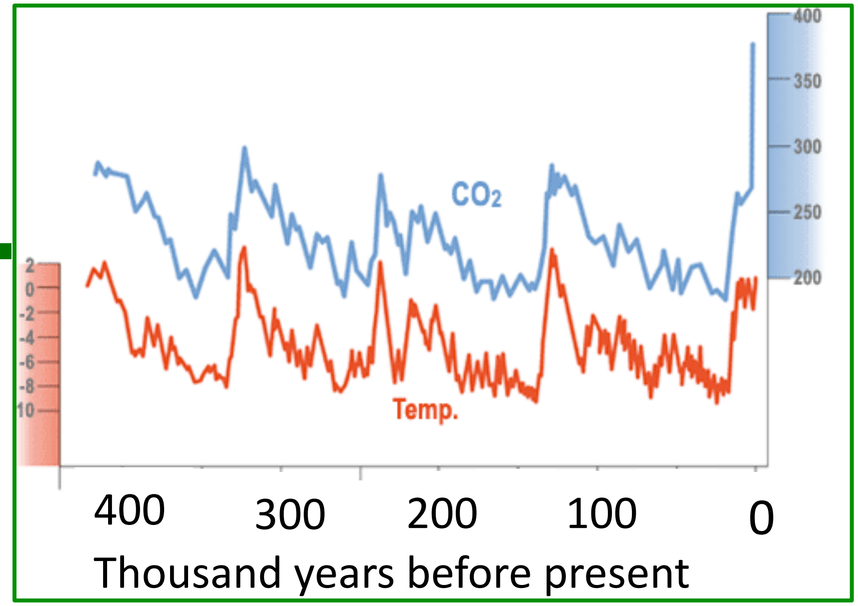
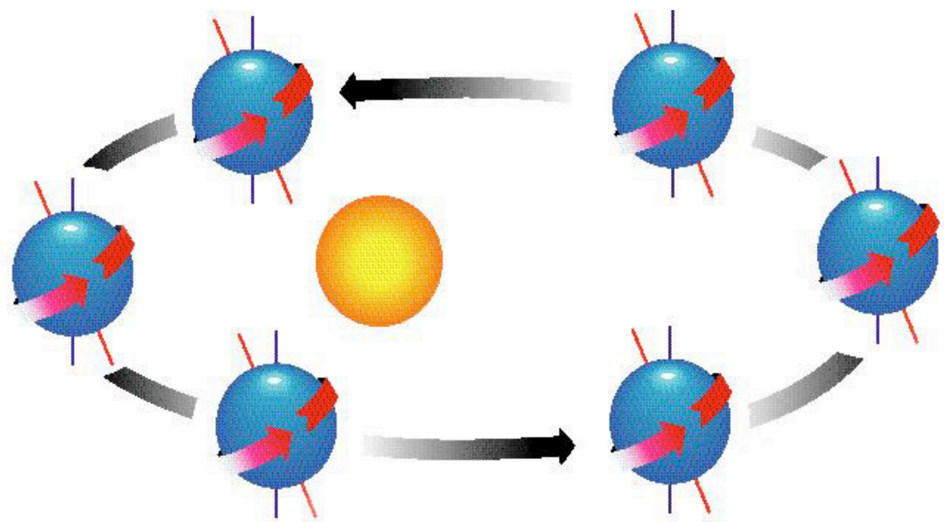
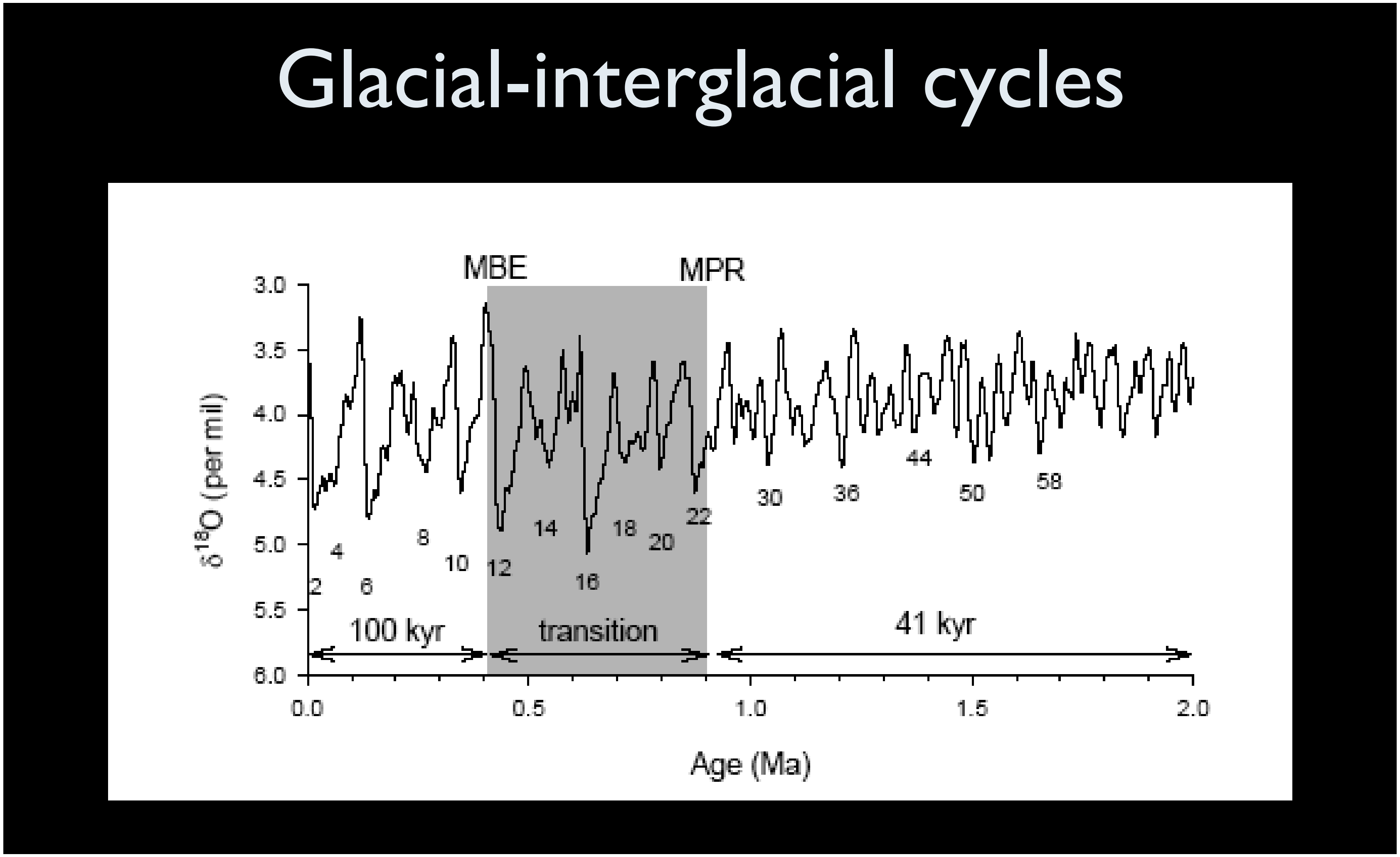


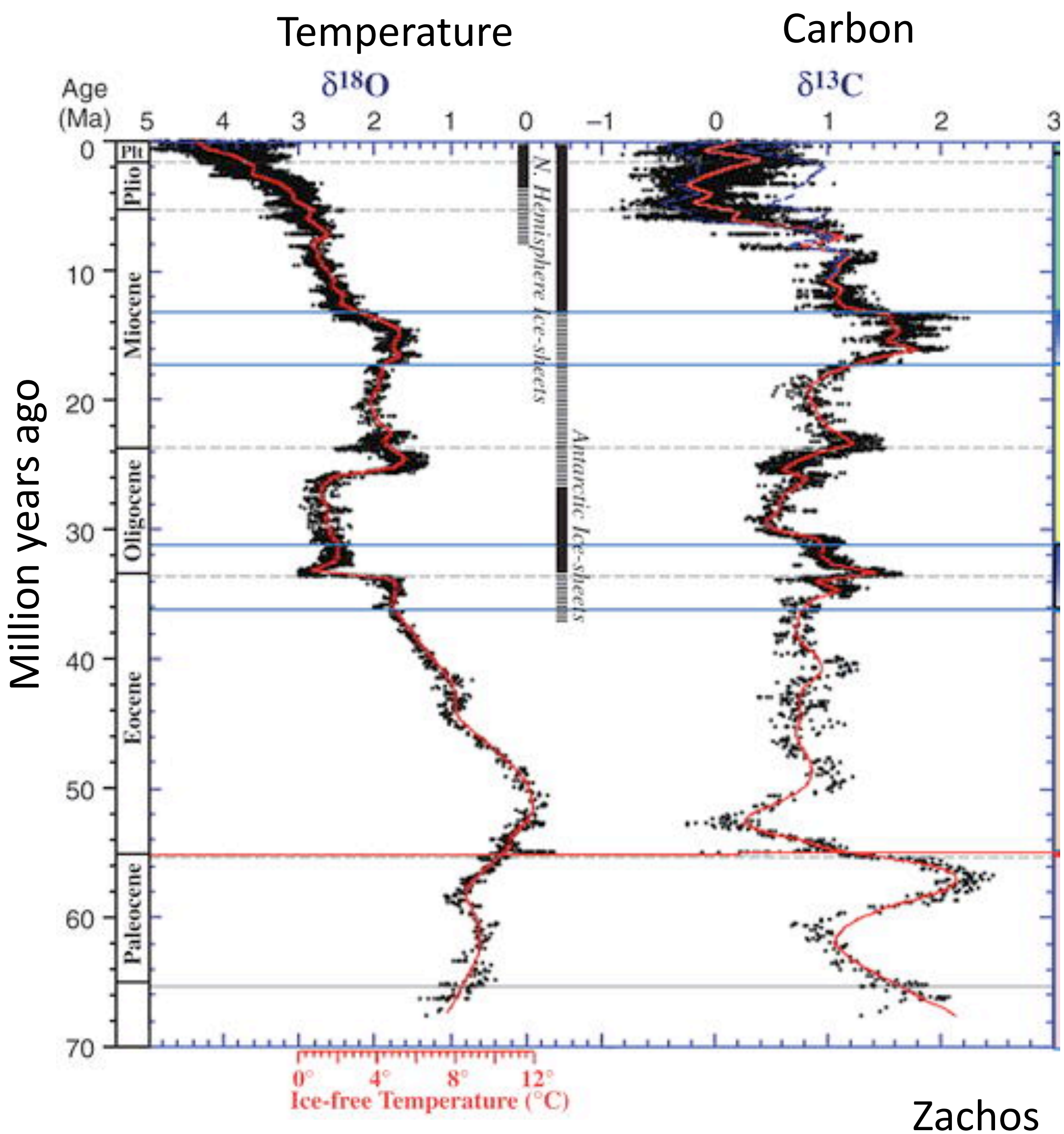


Include Temp-CO_2 feedback from geological carbon cycle to help understand speed and amplitude of rise.

Temperature Record - 2M yrs



PaleoClimate Record – 70M years



What models capture this behavior?

Especially abrupt changes.

Instructive to develop a hierarchy of models of increasing complexity.

When do robust behaviors of simple models persist as we increase complexity?

Use different levels of model hierarchy to give insight into feedback interactions between climate processes.