Climate Prediction Challenges

Basics of Climate Physics (Lecture 1)

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STAT GR5243 / GU4243

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Learning Goals

- Earth receives Radiation from Sun; returns this energy to Space
- Climate in 1 dimension: The Greenhouse Effect
- Climate in 2 dimensions: Equator to Pole Heat Transport
  - Unequal solar radiation distribution creates the potential energy gradients that support winds and currents
  - These winds and currents move heat energy from Equator to Pole, rebalancing the energy distribution
- Climate in 3 dimensions: Earth's rotation strongly impacts flow
  - In the middle and high latitudes, "Weather" is how the atmosphere accomplishes energy transport
  - "Climate" is the long-term average of the turbulence that is "Weahter"

Radiation

What is Radiation?

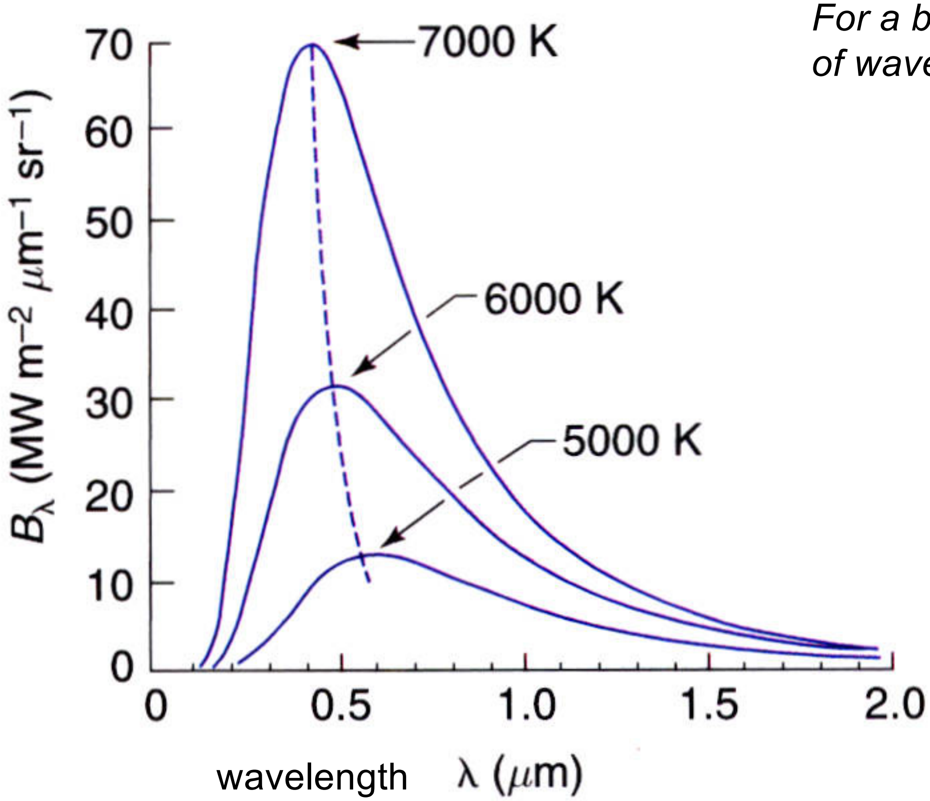
Blackbodies and σT^4

Blackbodies

- A ***blackbody*** is a chunk of matter that interacts with light at all possible frequencies
  - Analogy is a piano with all the strings – it can play all notes

- The light emitted by a blackbody is ***blackbody radiation***
- Units of energy are Watts = Joules/s

Blackbody emission curves, for matter of different temperatures



Planck Formula

For a blackbody of temperature T, there is a range of wavelengths emitted. This is plotted at left.

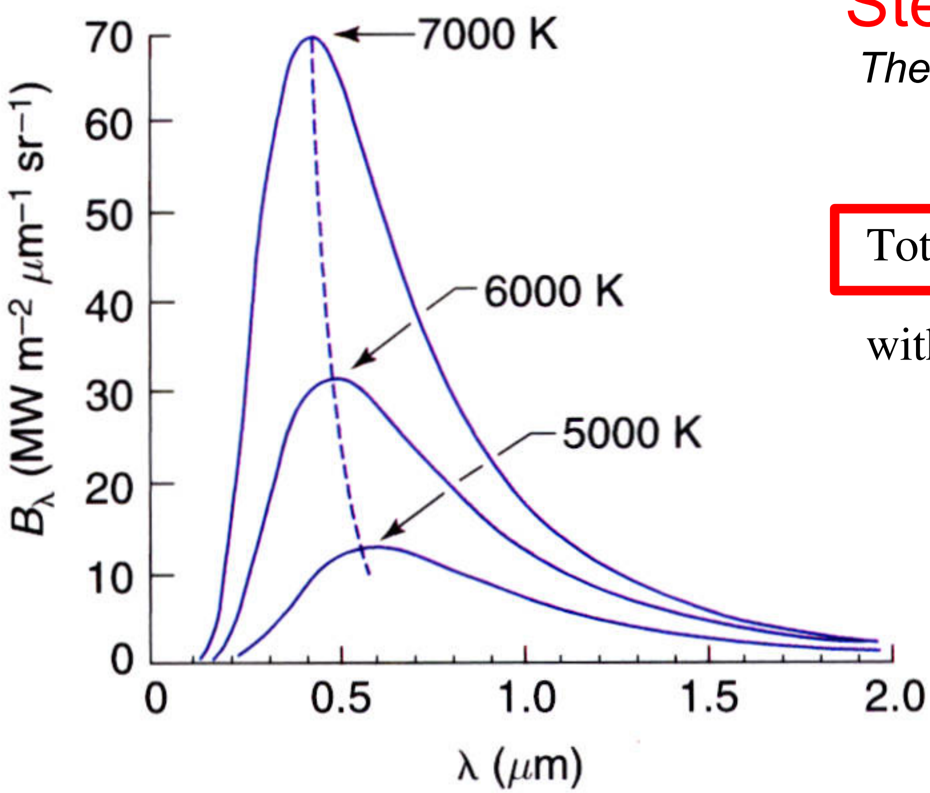
$$B_\lambda(\mathrm{T}) = \frac{2hc^2}{\lambda^5[\exp(\frac{\mathrm{hc}}{\lambda kT}) - 1]}$$

Wein Displacement Law

Tells us that the maximum wavelength is an inverse function of temperature

$$\lambda_{\max} = \frac{2.898x10^3}{T}$$

Integrate B_λ over all wavelengths and all directions



Stefan – Boltzmann Law

The integral across all wavelengths of the previous two

$$\boxed{\text{Total Energy Emitted (W/m}^2\text{)} = \sigma T^4}$$

with $\sigma = 5.67x10^{-8}\ \dfrac{W}{m^2 K^4}$

Kirchoff's Law (the two way street) tells us that if some matter is not a perfect blackbody (like some of the piano strings missing), then it will both absorb and emit imperfectly

This imperfection is quantified by the

Emissivity *(ε)* = **Absorptivity (a)**

which has a value between 0 and 1

Thus, the intensity of emitted radiation (W/m^2)

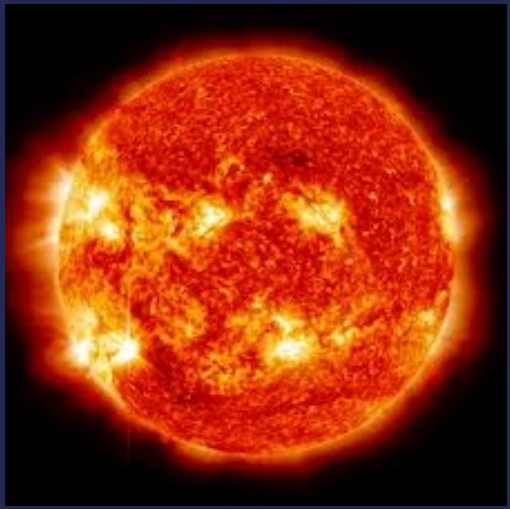
$$I = \varepsilon\sigma T^4$$

LAYER MODEL

First Law of Thermodynamics

$$dQ = dU - dW$$

"Heat added (dQ) to a system is equal to the change in internal energy (dU) minus the work extracted (dW)"



Earth receives ~350 W/m^2 of solar energy

Enough energy, at all times, on every m^2, for 3+ 100W lightbulbs!



First Law of Thermodynamics

$$dQ = dU - dW$$

"Heat added (dQ) to a system is equal to the change in internal energy (dU) minus the work extracted (dW)"

In the context of this massive flow of energy into the Earth, and its quite stable temperature for millions of years, to first order

<u>dU = 0 (Earth's internal energy is not changing)</u>

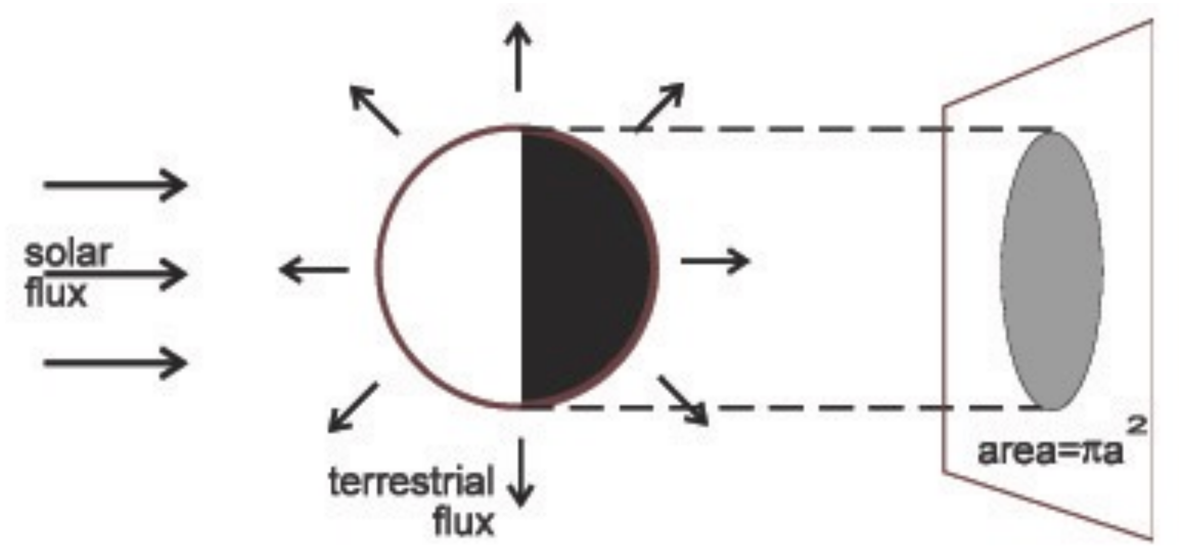
<u>dQ = - dW</u>

In other words, the Earth returns to space all energy received from the Sun!

Earth’s Climate in 1 dimension

The Layer Model

Incoming Radiation

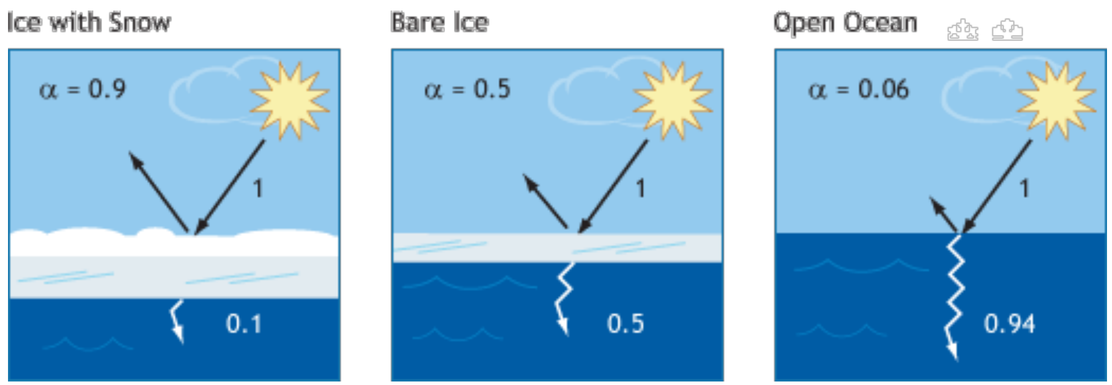


Average Solar Flux = I_{solar} = 1350 W/m^2

Energy Received in Shadow: Area = πa^2
a = Earth radius

Figure: Marshall and Plumb, 2003

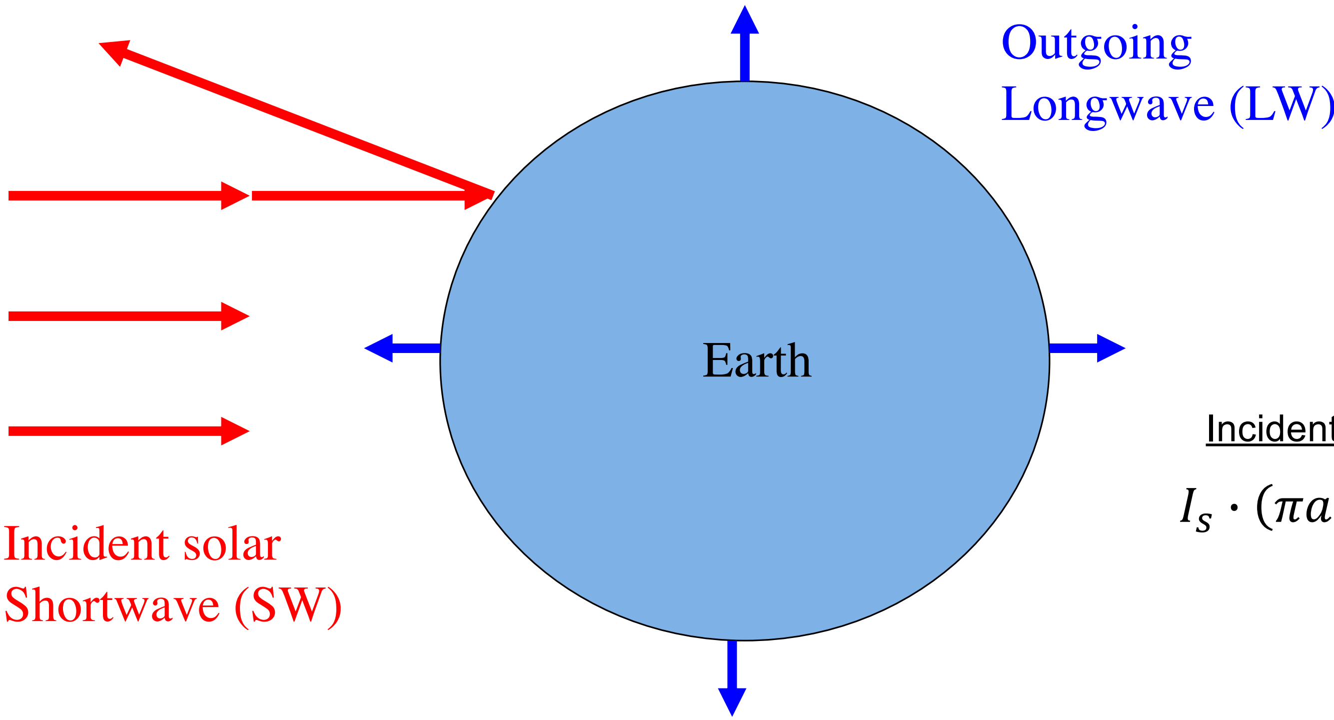
Albedo (α) – different surfaces on earth have different reflectivities to shortwave solar radiation. Clouds can also be quite reflective.



Averaging over the planet, Earth reflects 30% of the solar shortwave radiation.
Thus, $\boldsymbol{\alpha = 0.3}$

**This energy is not absorbed and reemitted – it reflects back in the direction from which it came **

Assume Earth is a perfect blackbody, at what temperature does it emit?



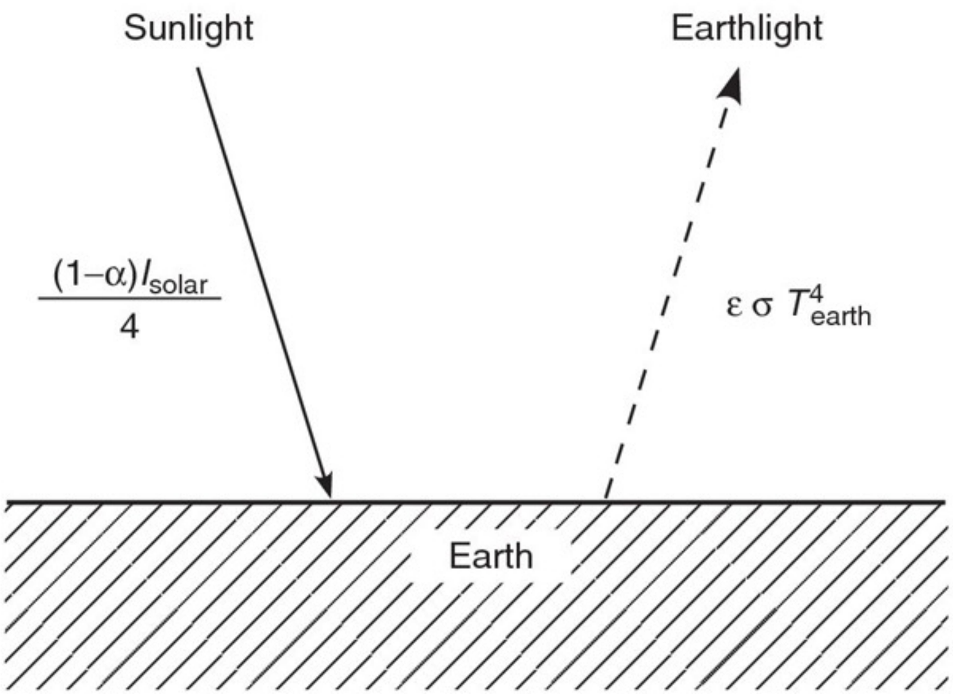
Energy Emitted over Sphere: Area = $4\pi a^2$

Incident absorbed SW = outgoing LW

$$I_s \cdot (\pi a^2) \cdot (1 - \alpha) = \varepsilon \sigma T^4 \cdot (4\pi a^2)$$

$$T = \sqrt[4]{\frac{I_s(1 - \alpha)}{4\varepsilon\sigma}}$$

Energy Balance for 'Bare Rock' from Archer.
1D schematic, same interpretation as previous.



Archer Figure 3-3

$$T = \sqrt[4]{\frac{I_s(1-\alpha)}{4\varepsilon\sigma}} = 254\text{K}$$

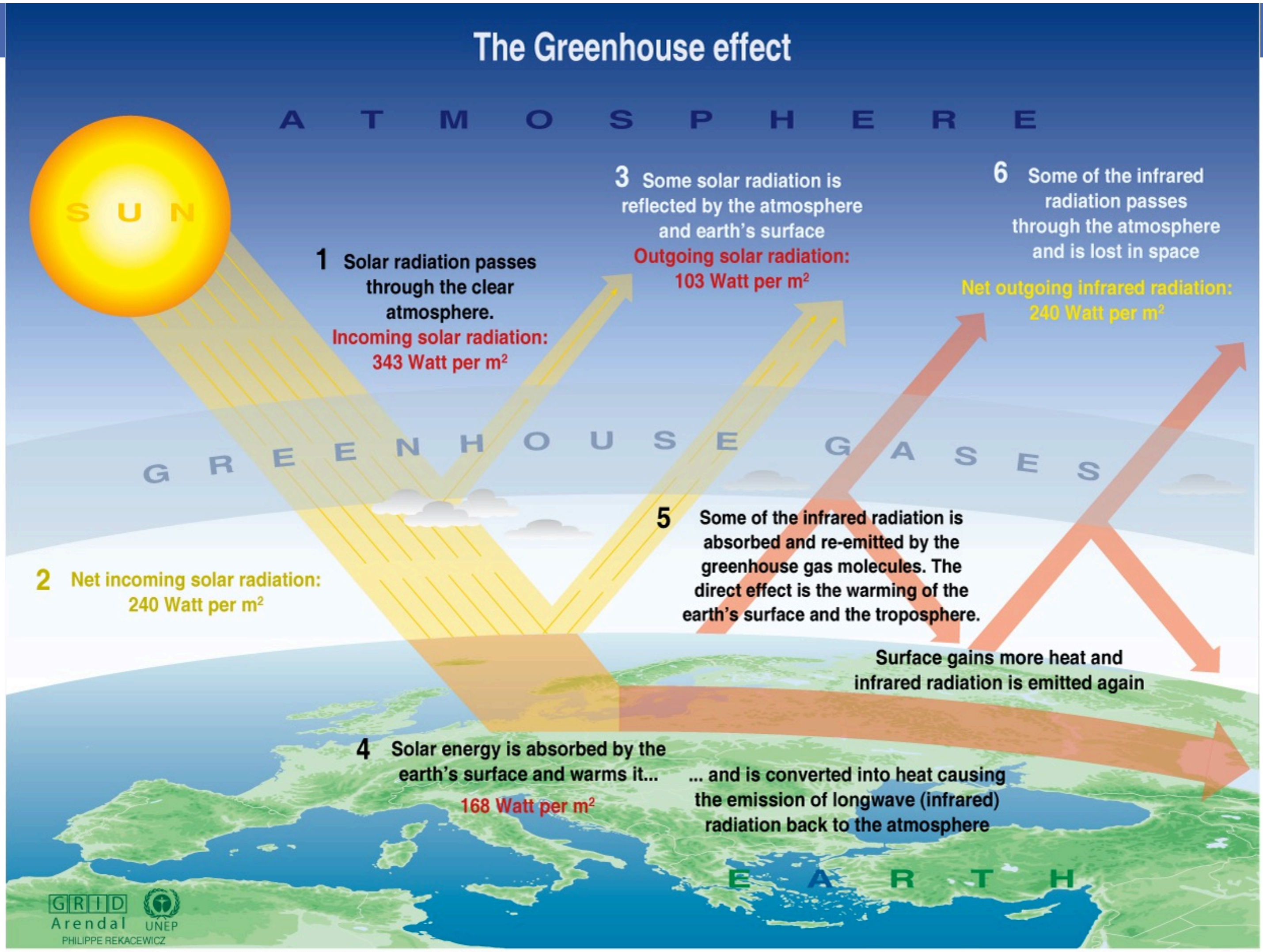
Input values used throughout:
I_s = 1350W/m^2
albedo = 30%

SURFACE TEMPERATURE = 254K (-19^{O}C)

Far too cold, actual ~288K (15^{o}C)

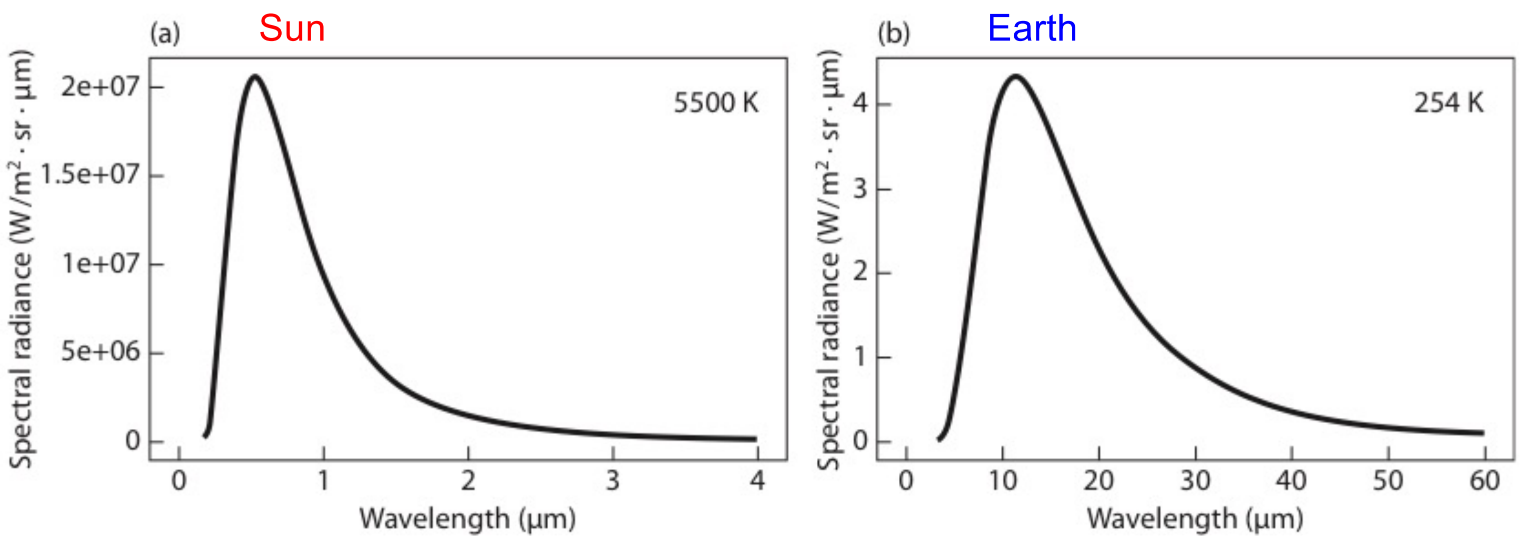
Why?

We’ve left off the atmosphere



Sources: Okanagan university college in Canada, Department of geography, University of Oxford, school of geography; United States Environmental Protection Agency (EPA), Washington; Climate change 1995, The science of climate change, contribution of working group 1 to the second assessment report of the intergovernmental panel on climate change, UNEP and WMO, Cambridge university press, 1996.

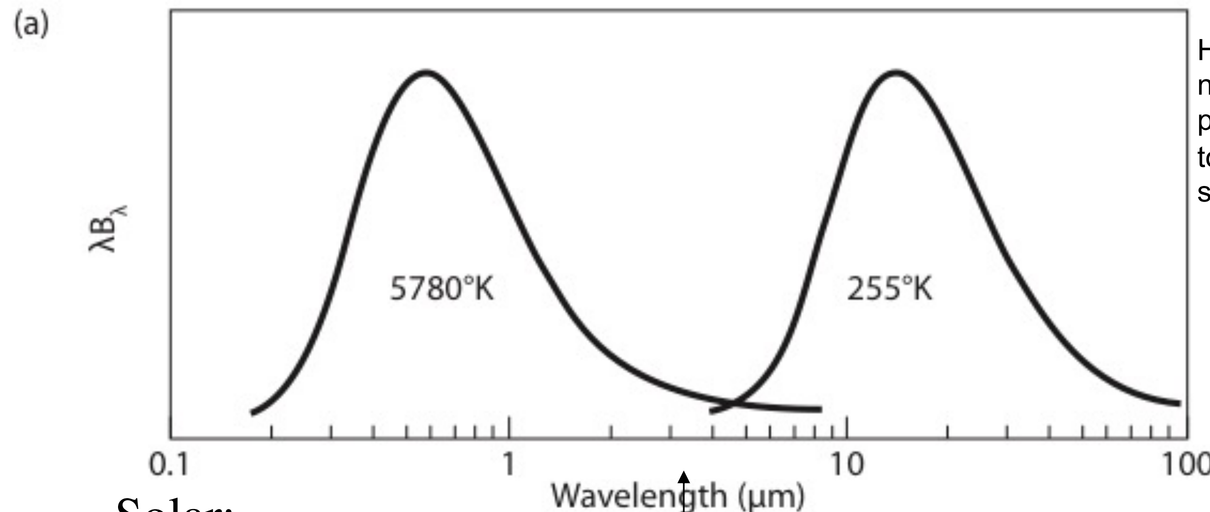
Compare Planck Curves for Sun and Earth



Note the magnitude of the vertical axis! Radiance is 7 orders of magnitude larger from the sun! And it occurs at shorter wavelength.

Cook Fig 4.3

Earth maintains balance through radiation



Here, the vertical axis is normalized for the purpose of presentation. This allows you to see the two curves on the same plot.

Solar:

99% Visible and near IR

1% UV

Earth:

Thermal IR

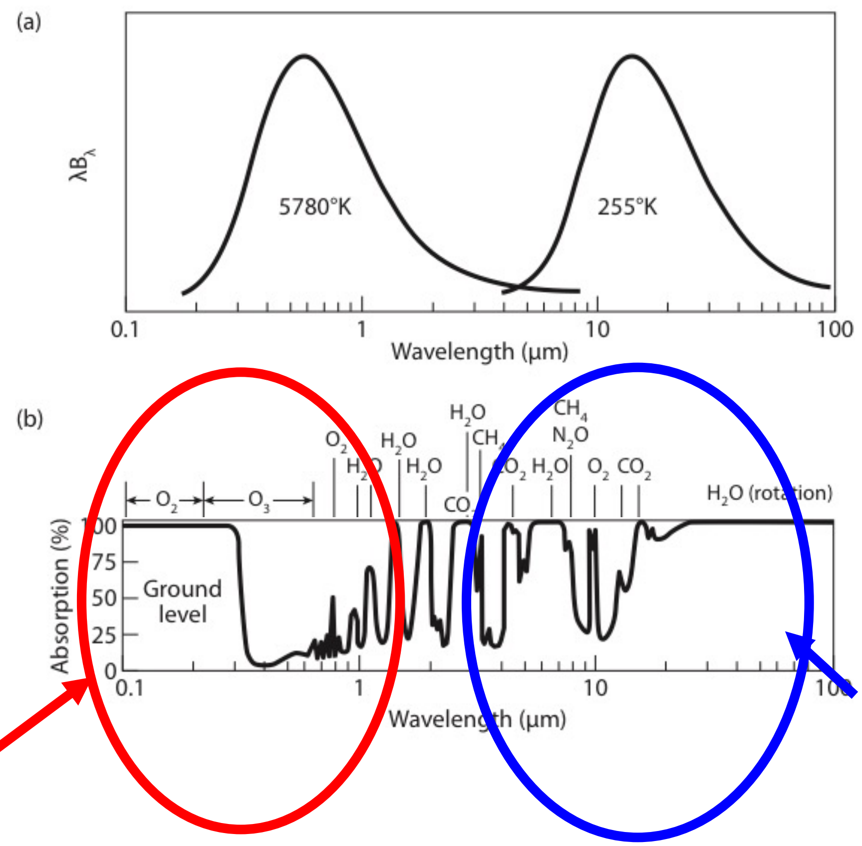
Note distinct separation. Thus, the atmosphere can be considered both "transparent" to solar radition and "opaque" to terrestrial radiation.

Figure from Hartmann, Global Physical Climatology

Combined absorption spectra and relation to emission

Energy emission of Sun (left) and Earth (right) at different wavelengths

% absorption by the atmosphere at different wavelengths



Relatively Transparent in Shortwave

Relatively Opaque in Longwave

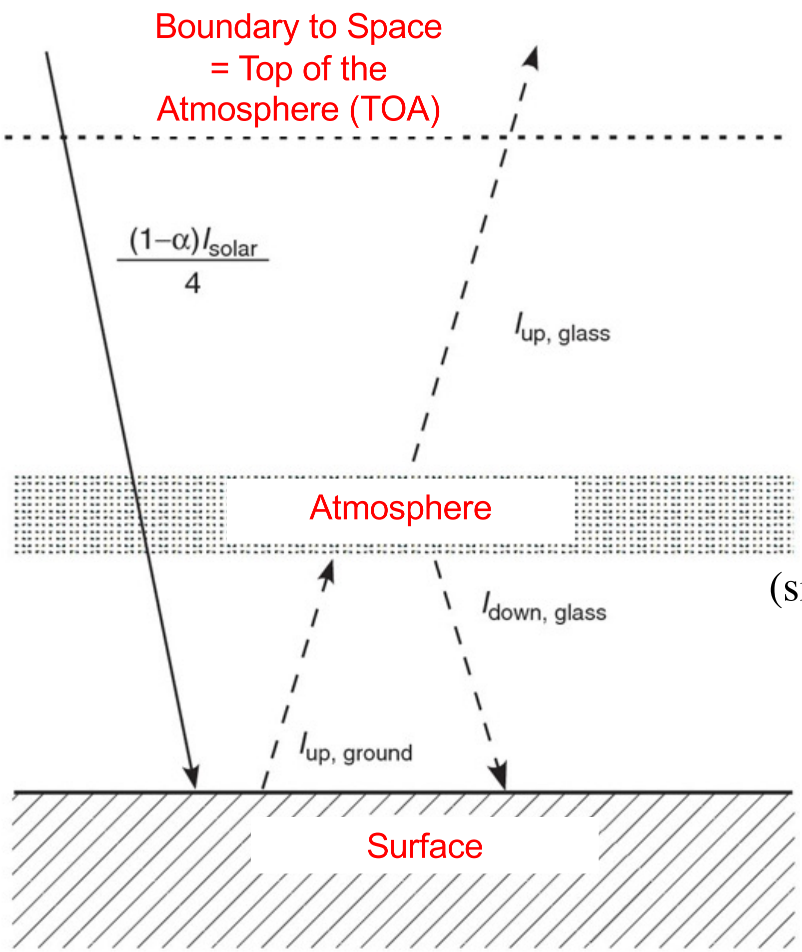
Figure from Hartmann, Global Physical Climatology

To get a better estimate of the surface temperature, must account for the atmosphere

- Atmosphere is relatively transparent to shortwave solar radiation
  - Simplest is to use $\varepsilon_{\text{Atm, SW}} = 0$ for shortwave from Sun
- And relatively opaque to longwave heat radiation
  - Again, start simple, so use $\varepsilon_{\text{Atm, LW}} = \varepsilon_A = 1$ for longwave from Earth

- For surface, $\varepsilon = 1$ always

'One layer' energy-balance model



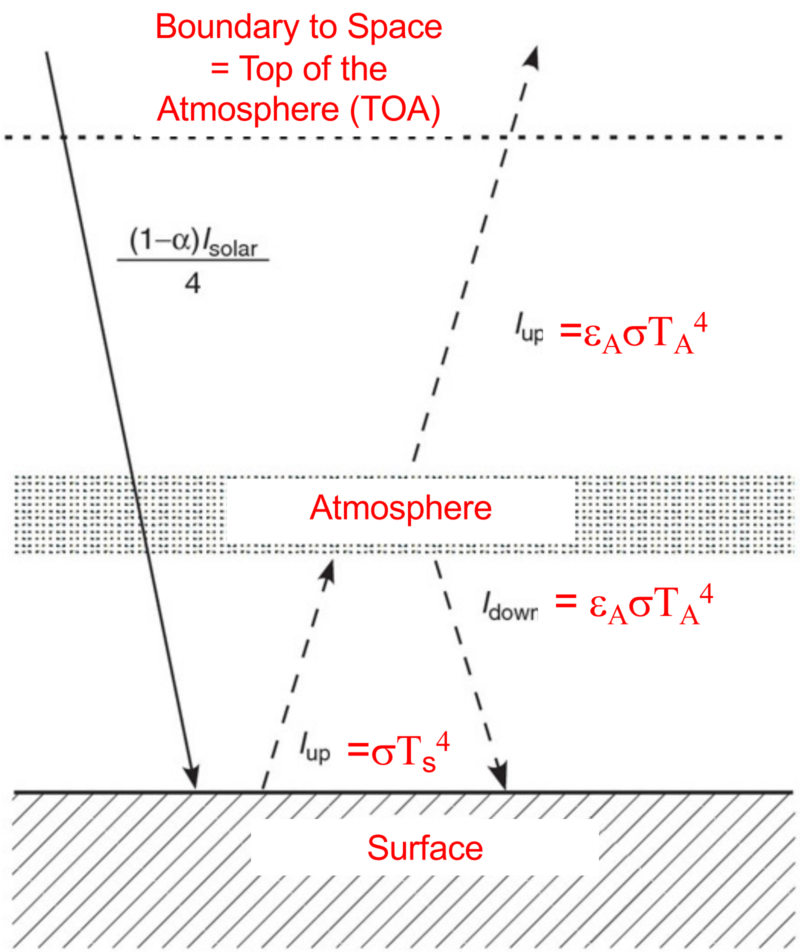
$\varepsilon_{Atm,LW} = \varepsilon_A = 1.0$

(simplest case, a starting point)

$\varepsilon_{ground} = 1.0$ (always)

Archer Figure 3-4

'One layer' energy-balance model, equations



$$T_A = \sqrt[4]{\frac{I_S(1-\alpha)}{4\varepsilon_A \sigma}}$$

$$T_S = \sqrt[4]{2}\, T_A = 302K$$

Archer Figure 3-4

SURFACE TEMPERATURE = 302K (29^{O}C)

Better, but still too warm, actual value 288K (15^{o}C)

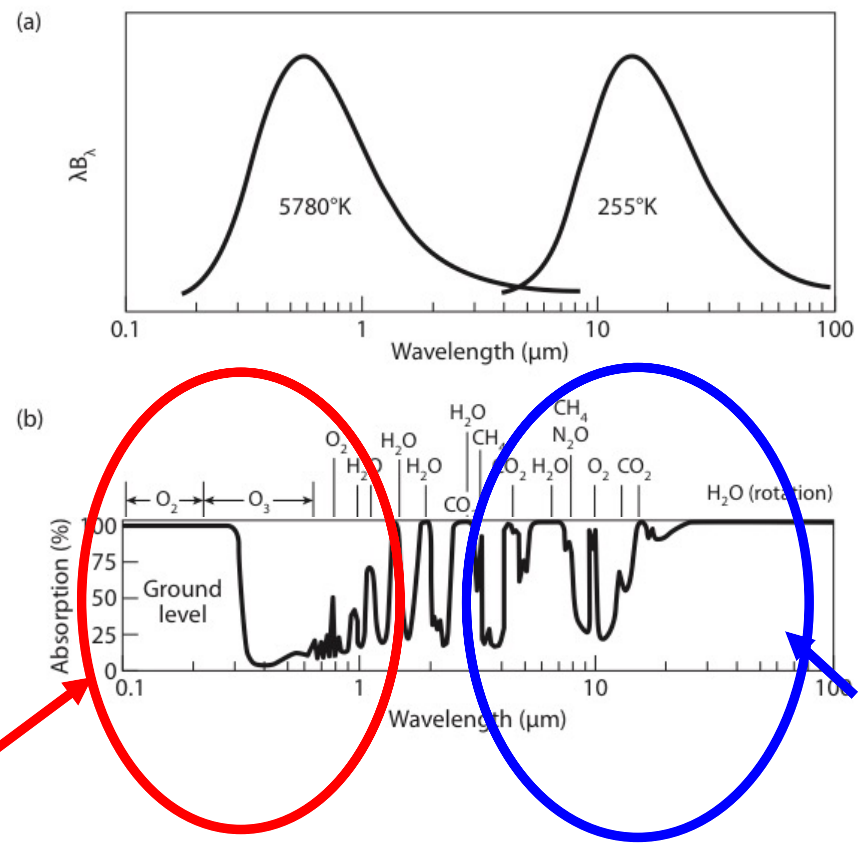
Why is it too warm?

- The atmosphere is actually not 100% absorbing to longwave radiation
- Need to use $\varepsilon_A < 1$ to improve our estimate

Combined absorption spectra and relation to emission

Energy emission of Sun (left) and Earth (right) at different wavelengths

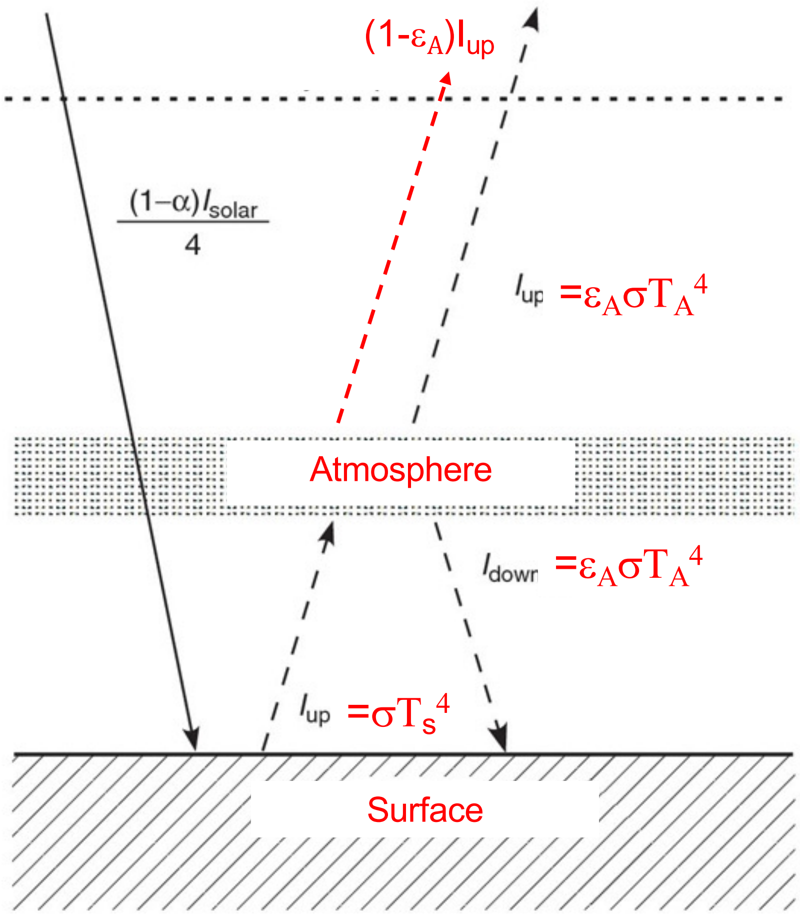
% absorption by the atmosphere at different wavelengths



Relatively Transparent in Shortwave

Relatively Opaque in Longwave

Add atmospheric absorptivity (ε_A) for outgoing IR. Now some terrestrial radiation is not absorbed in the atmosphere, instead escapes to space.



To solve, must revise equations.

Note: A fraction of I_{up} is absorbed in the atmosphere; the remaining fraction passes through; this must be accounted for in equations.

If $\varepsilon_A = 0.7$, Ts = 283K

Sufficiently close to observed 288K

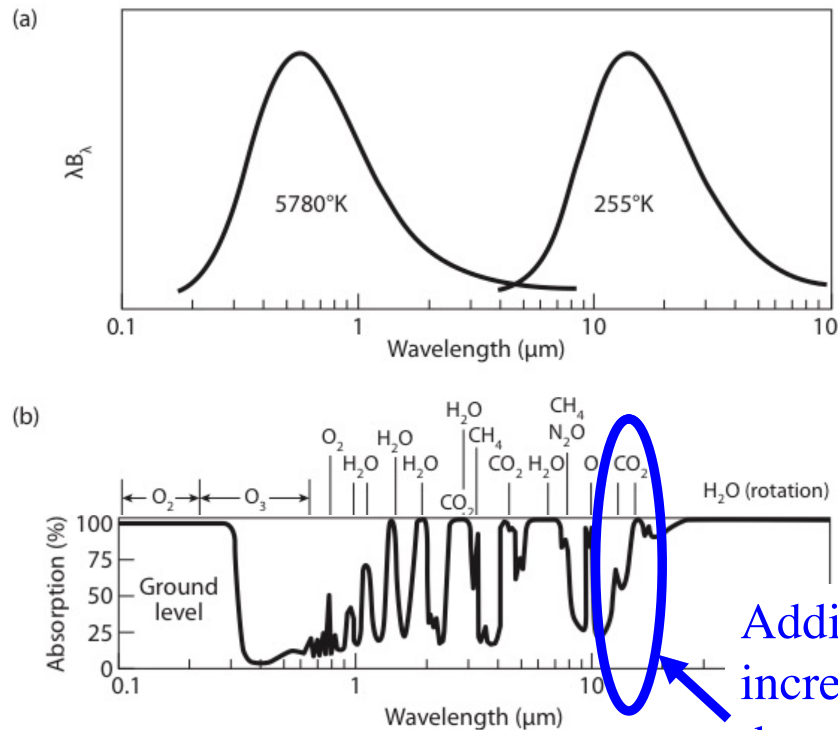
with I_s = 1350W/m^2, α = 0.3

Archer Figure 3-4

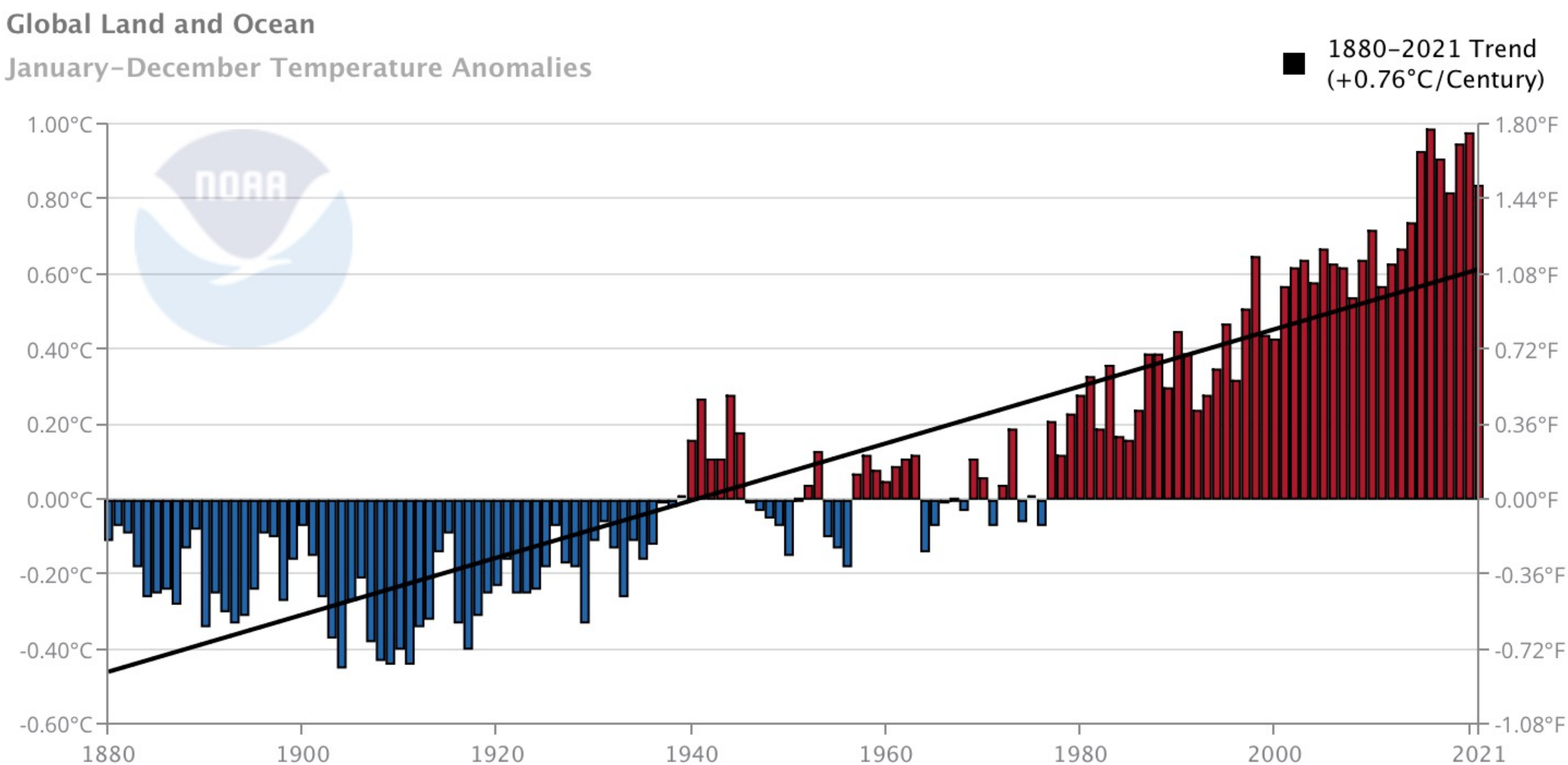
Combined absorption spectra and relation to emission

Energy emission of Sun (left) and Earth (right) at different wavelengths

% absorption by the atmosphere at different wavelengths



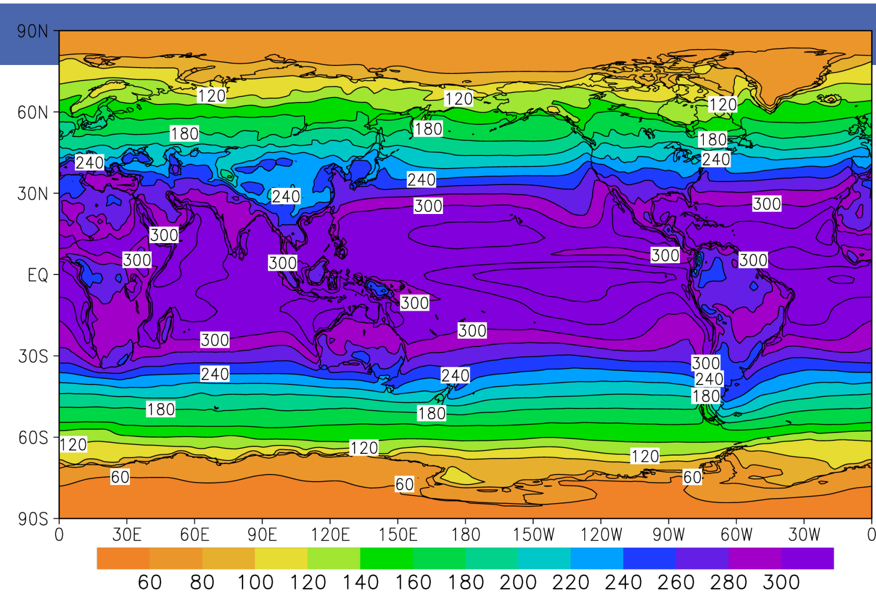
Adding CO_2 to atmosphere increases LW absorption in these wavelengths. This raises ε_A, thus increases T_s

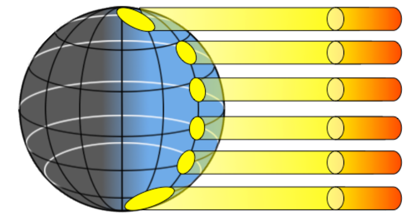

Global Land and Ocean
January–December Temperature Anomalies
1880–2021 Trend
(+0.76°C/Century)
1.00°C
0.80°C
0.60°C
0.40°C
0.20°C
0.00°C
-0.20°C
-0.40°C
-0.60°C
1.80°F
1.44°F
1.08°F
0.72°F
0.36°F
0.00°F
-0.36°F
-0.72°F
-1.08°F
1880
1900
1920
1940
1960
1980
2000
2021

Earth’s Climate in 2 dimensions

Heat is transported from the equator to the poles

Absorbed Solar Radiation
= Incident radiation*(1-albedo)

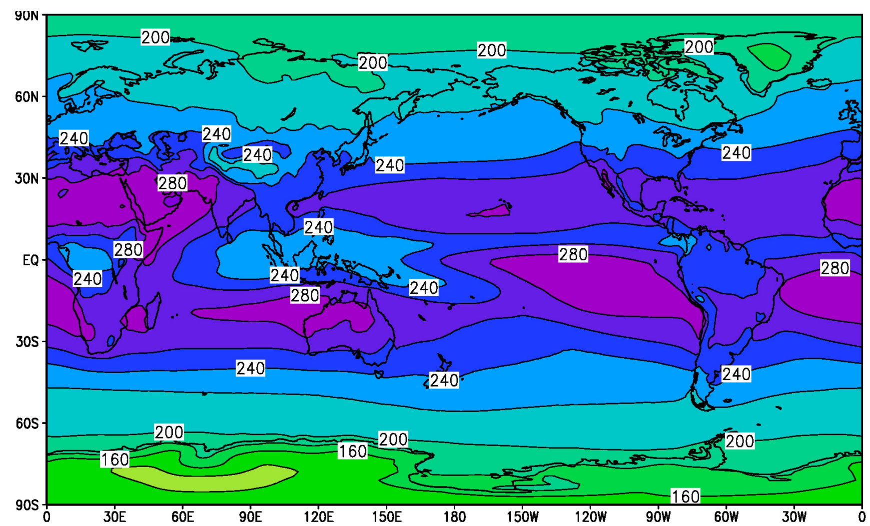




Sun’s rays

W/m², both panels

Outgoing Longwave Radiation (OLR)

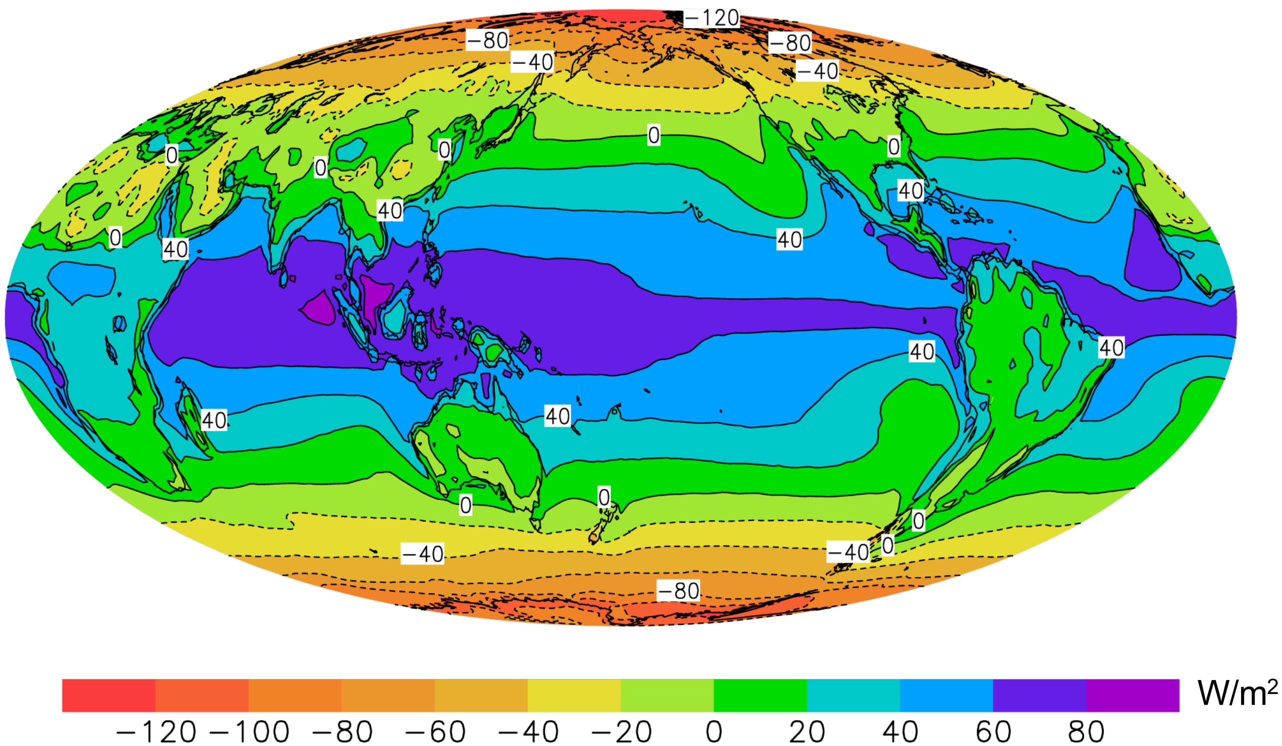


Cook Fig 5.5

Cook Fig 5.8

Net Radiation = Incident SW – OLR

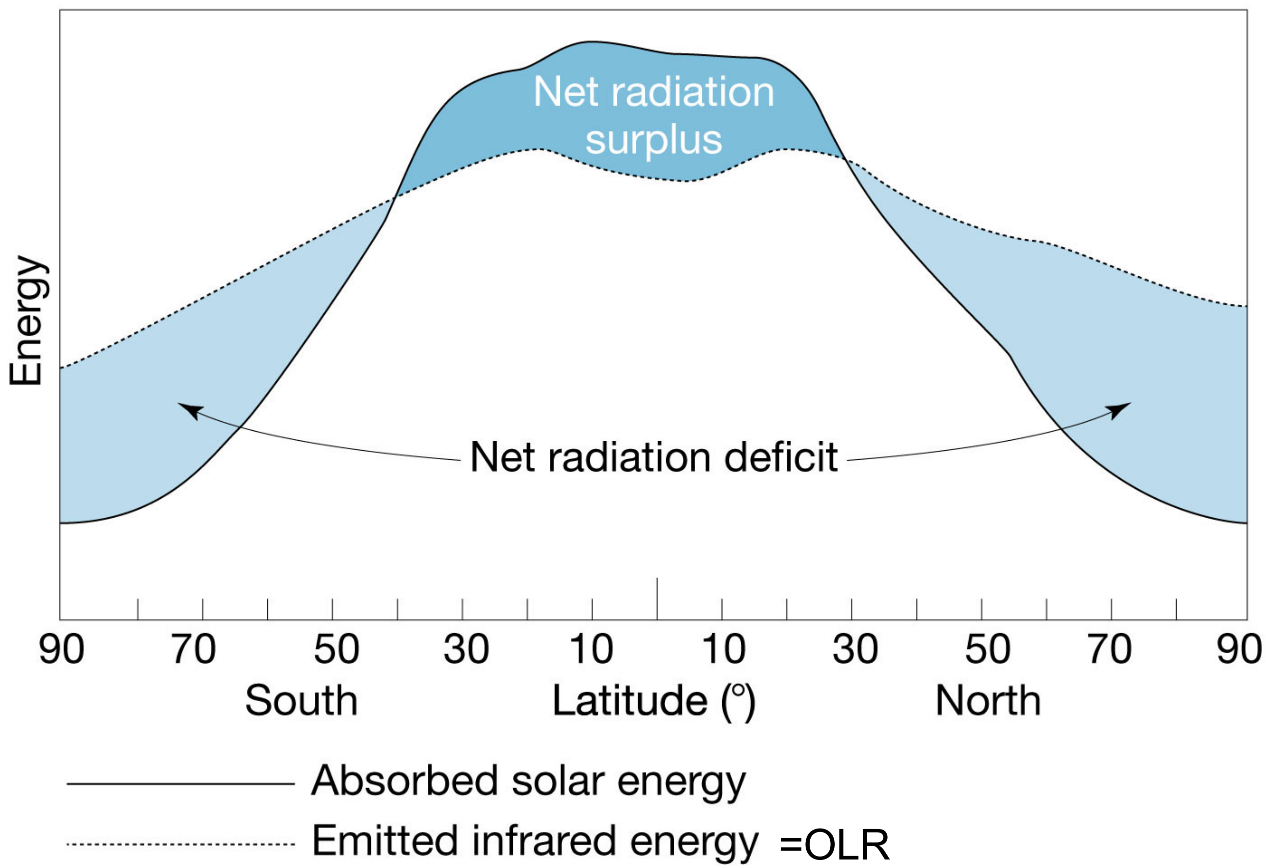
Note the excess at equator, deficit at pole



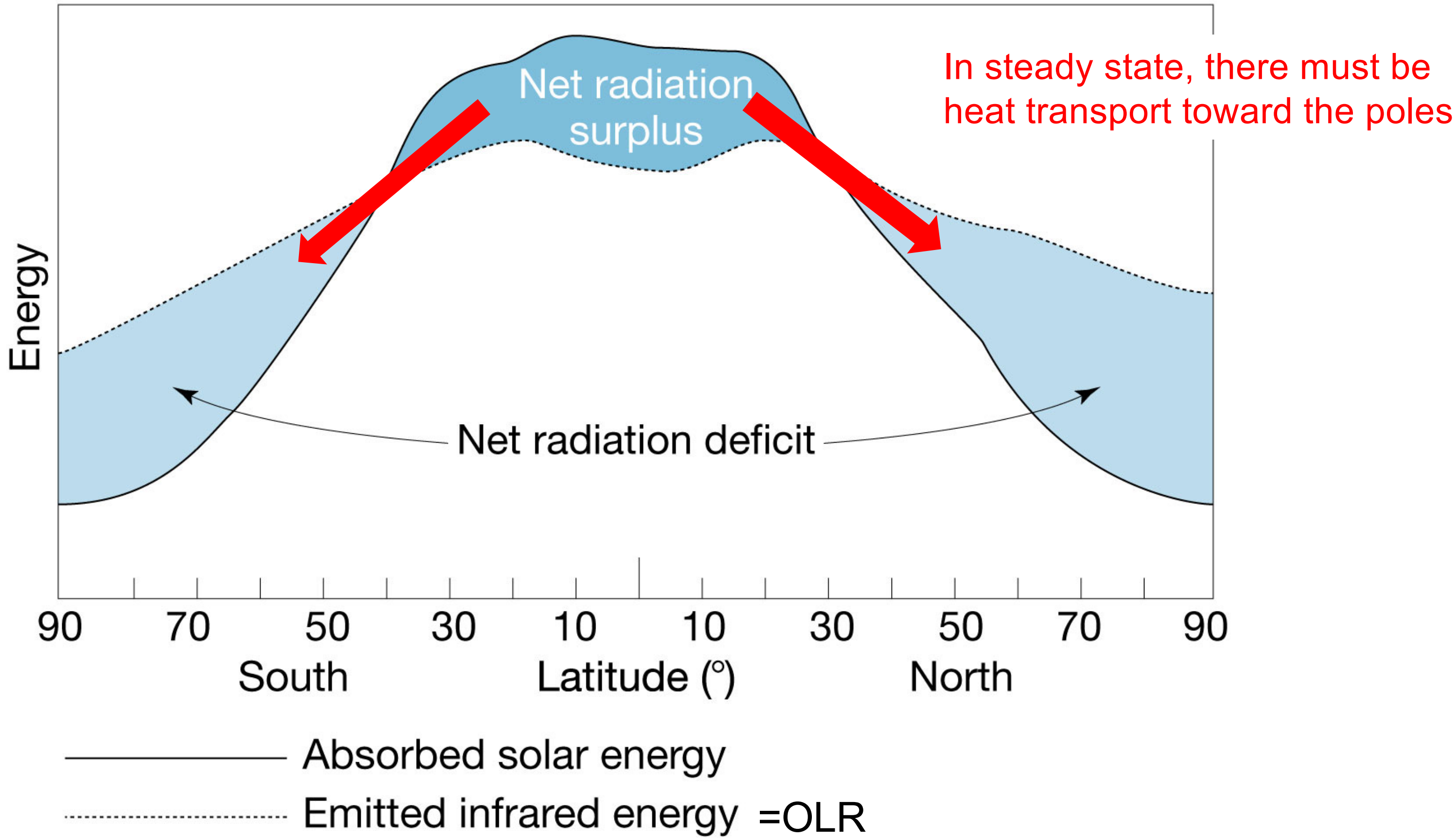
Cook Fig 5.9

W/m²

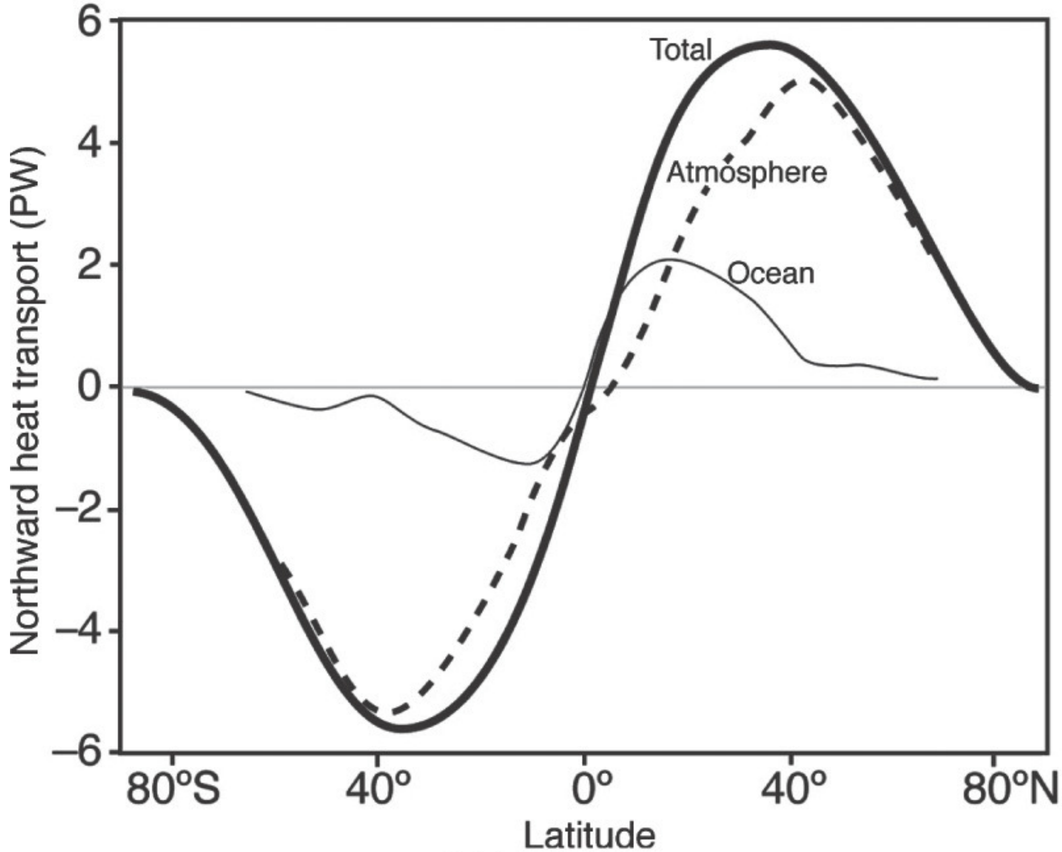
Average along longitudes



Average along longitudes



Poleward Heat Transport occurs in the atmosphere and ocean



(From Trenberth and Caron (2001).)

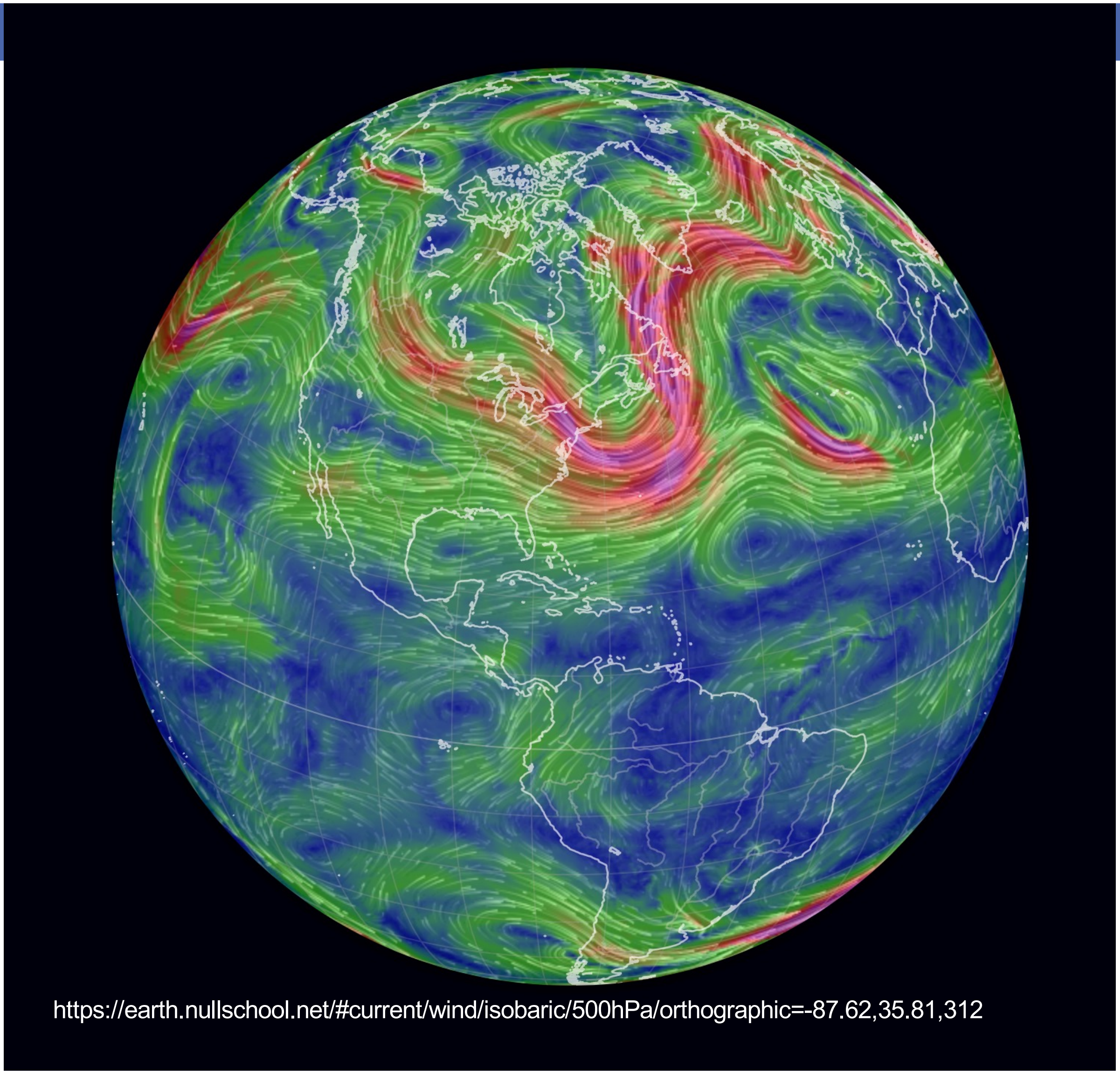
Marshall & Plumb 8.13

Positive to North; so toward pole in both hemispheres

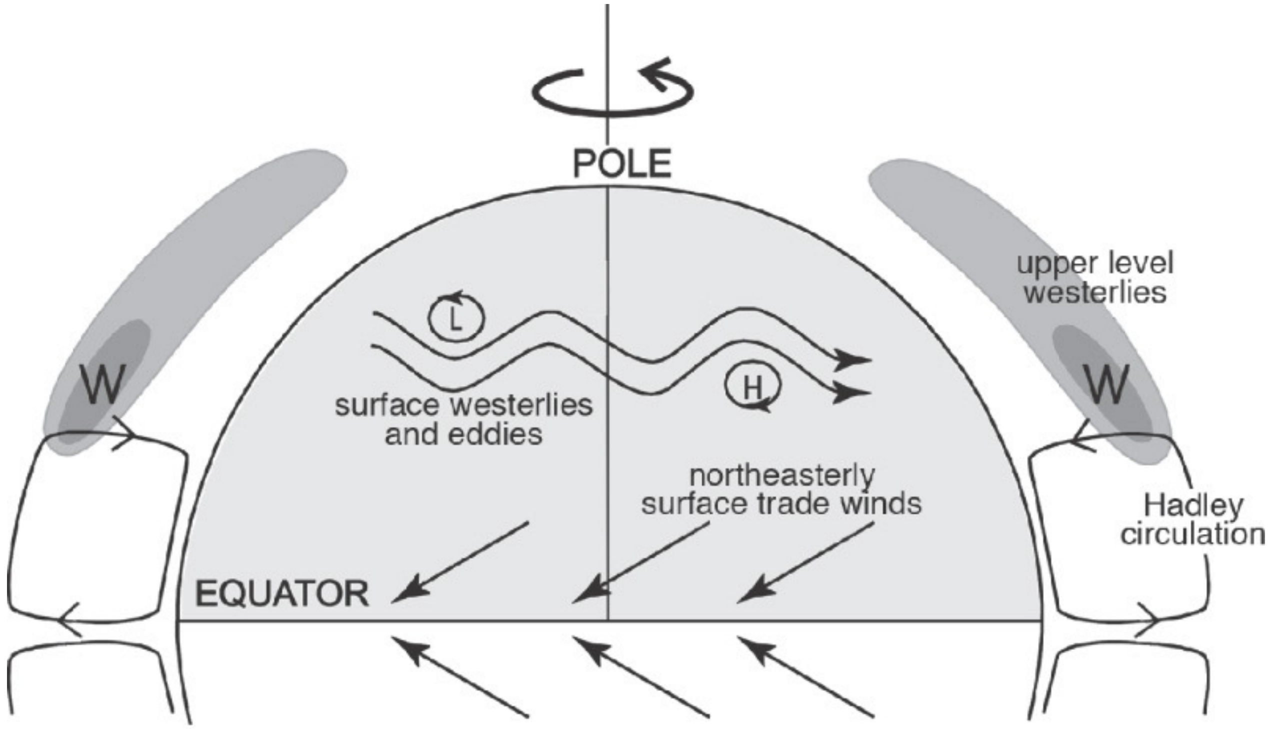
Earth's Climate in 3 dimensions

Heat transport from equator to the pole has a complex structure that is strongly influenced by Earth's rotation

Atmosphere (and ocean) motions occur in 3D



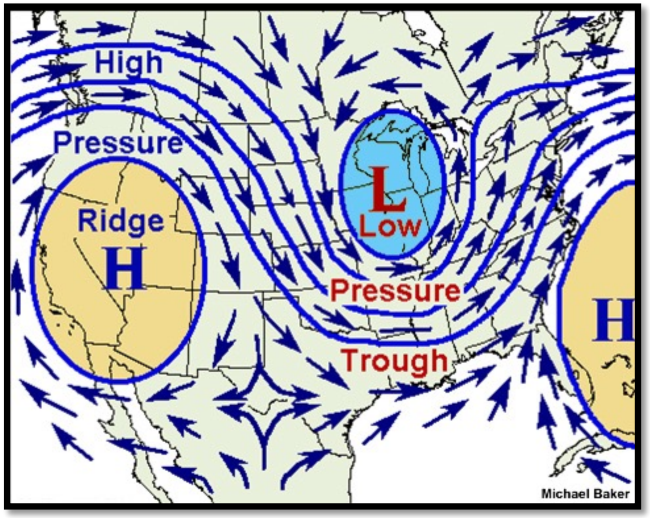
Schematic of atmospheric circulation



Figures: Marshall and Plumb 2006, 8.2

Why the swirls?

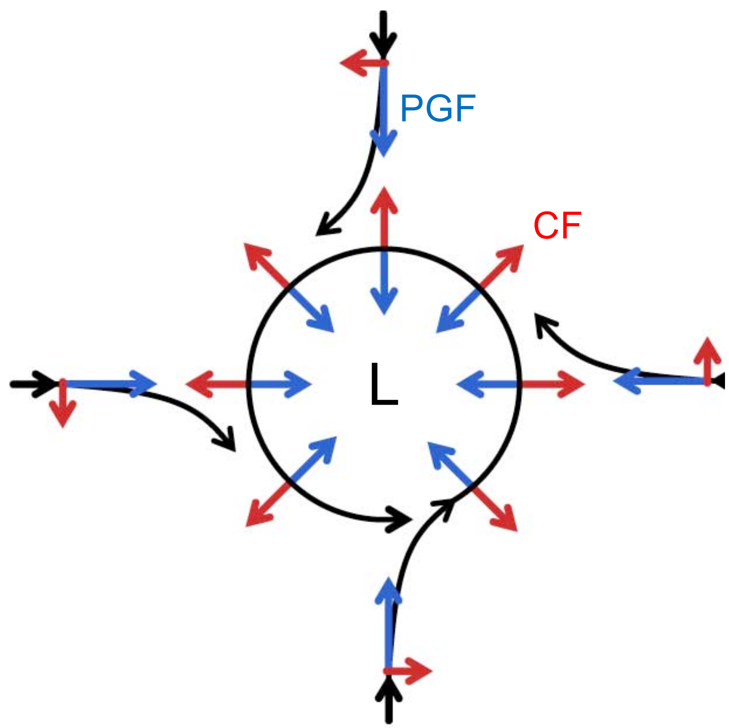
Figure: NASA Earth Observatory: Hurricane Sandy



Geostrophic Balance,
Coriolis Force = Pressure Gradient Force
Flow “Around the Valley” (if low center); ”Around the Hill” (if high center)

Inward flow (black straight arrows) due to PGF toward Low (blue force arrows) is turned to right by CF (red arrows); When PGF and CF come to balance, a steady geostrophic flow (black arrow circle)

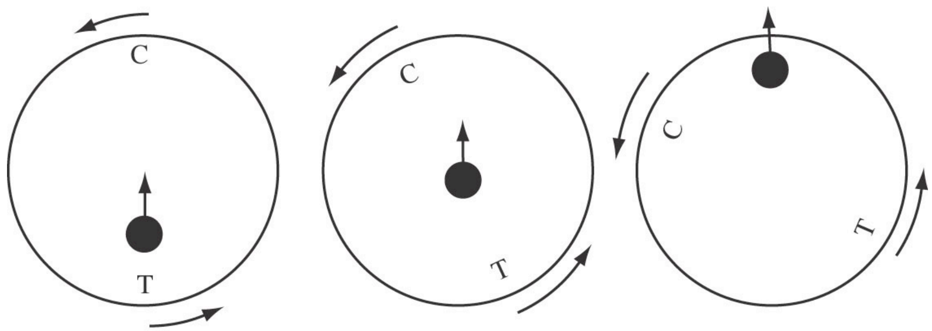
This is a cyclonic system, around a pressure low (“Low”) in N. Hemisphere



Coriolis “Force”

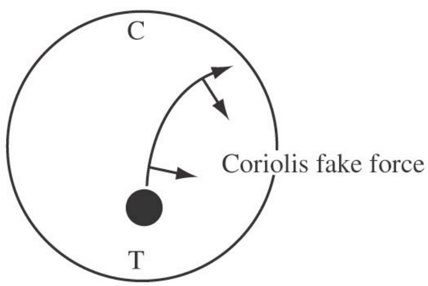
Not a true force -- an apparent force due to the rotating frame.

The motions that we wish to explain occur on rotating Earth.



Stationary observer

Coriolis Animation
http://en.wikipedia.org/wiki/File:Corioliskraftanimation.gif



Rotating observer

Figure: Archer 6-6

On Earth, Coriolis acts to the right of fluid flow in the Northern Hemisphere; to the left in the Southern.

Coriolis is zero at the equator and becomes stronger approaching the poles. This is due to the local vertical coming into greater alignment with Earth’s rotation axis toward pole.

Pressure Gradient Force
A true force. Fluids flow high to low pressure

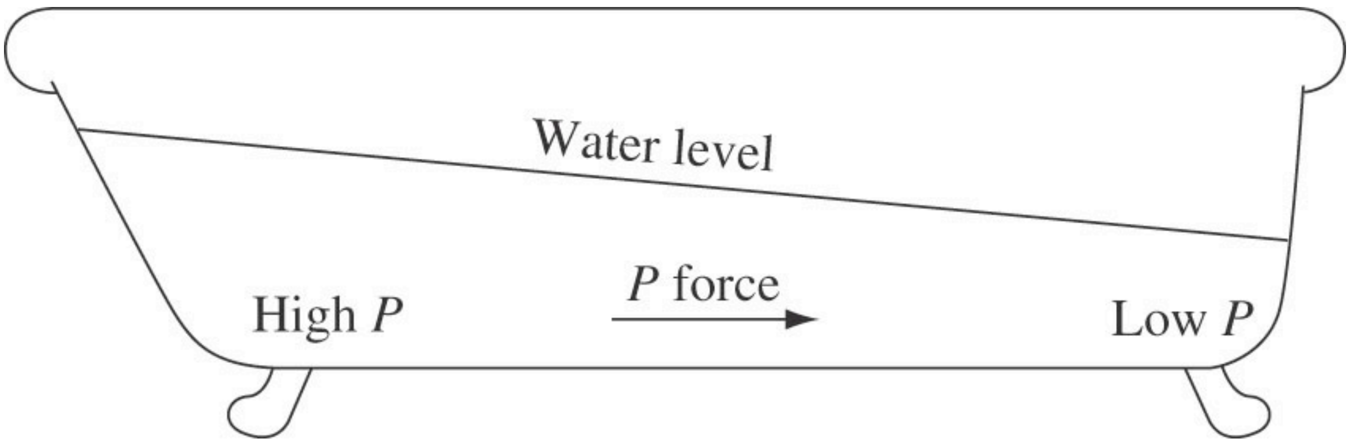


Figure: Archer 6-7

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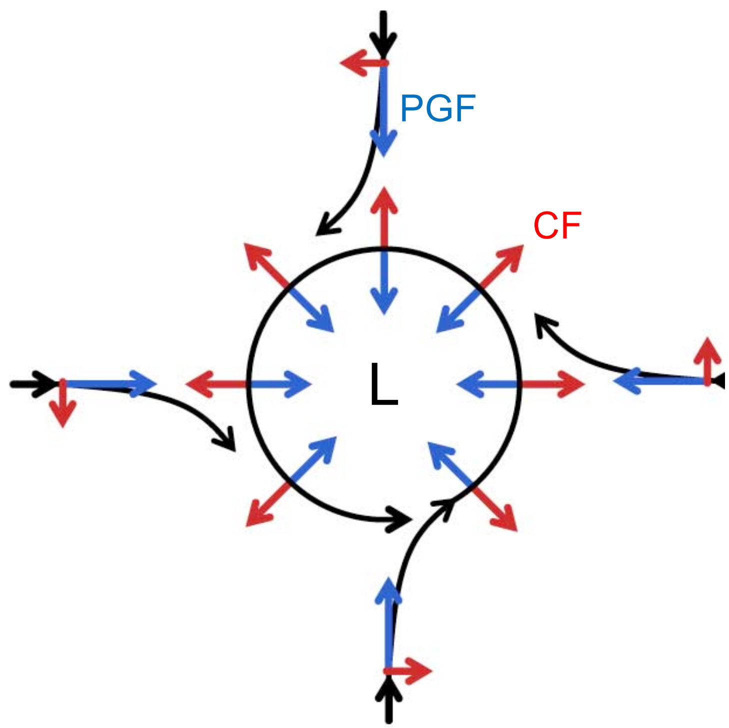


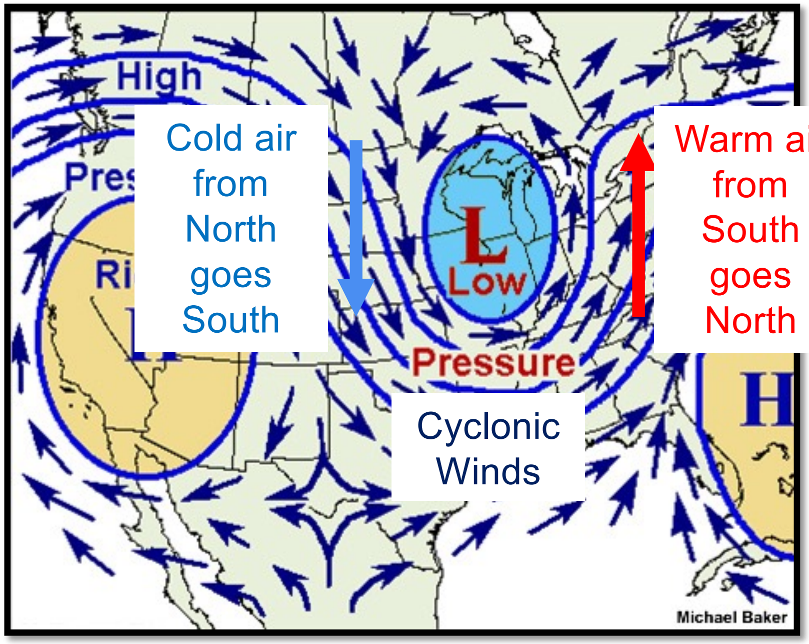
Geostrophy equations in cartesian coordinates

$$fv = \frac{1}{\rho}\frac{\partial p}{\partial x}$$

$$fu = -\frac{1}{\rho}\frac{\partial p}{\partial y}$$

$f = 2\Omega sin\phi$
$\Omega = Earth\ rotation\ rate$
ϕ= latitude

Impact of these Swirls on Heat Transport?

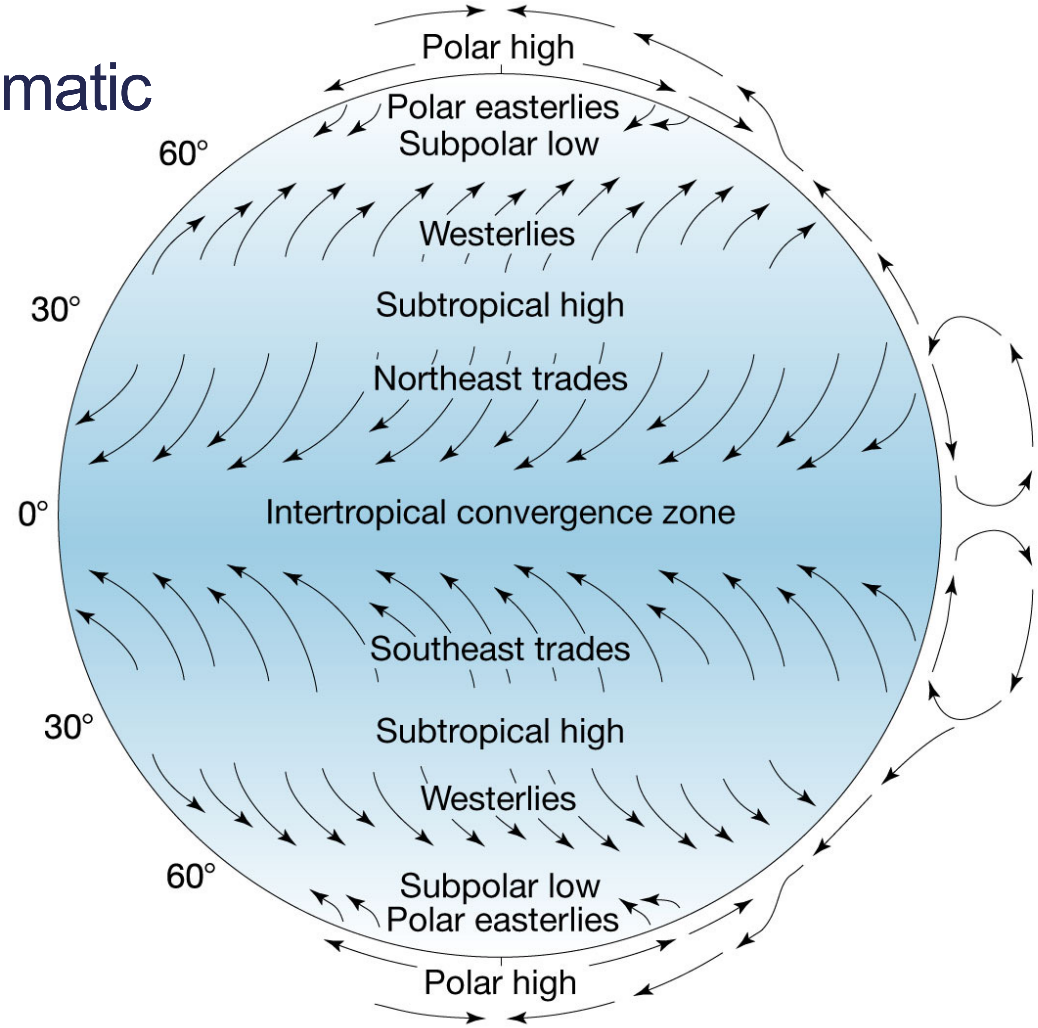


Global Winds, global schematic

Winds carry heat (latent and sensible) from equator to the pole

This energy warms the poles and allows them to radiate longwave in excess of their shortwave absorption.

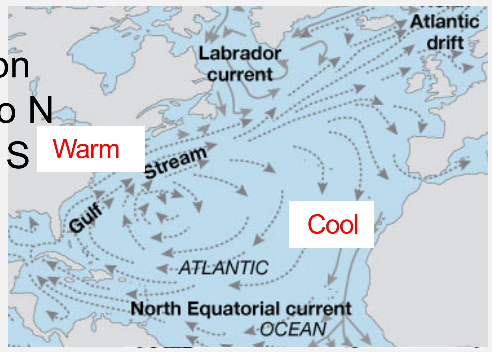
The ocean also carries heat to the poles



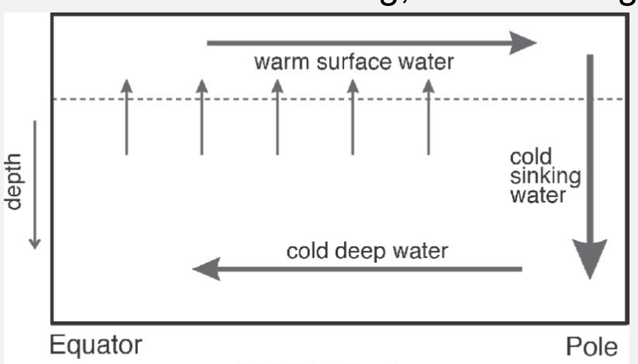
Poleward Heat Transport: the Ocean

Ocean does its part in two ways

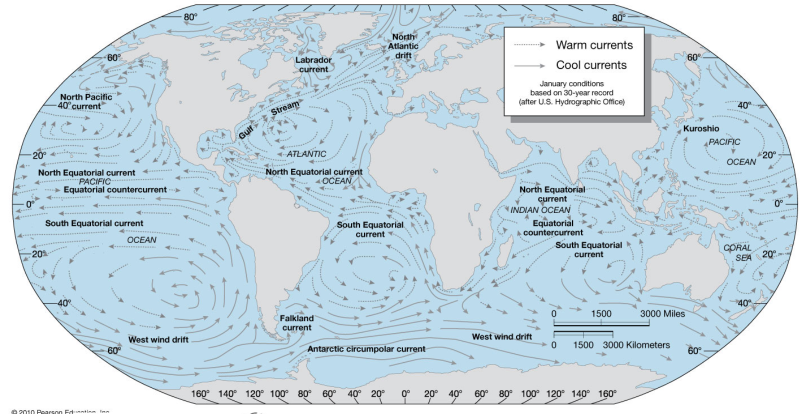
Surface Circulation
- Warm to N
- Cool to S



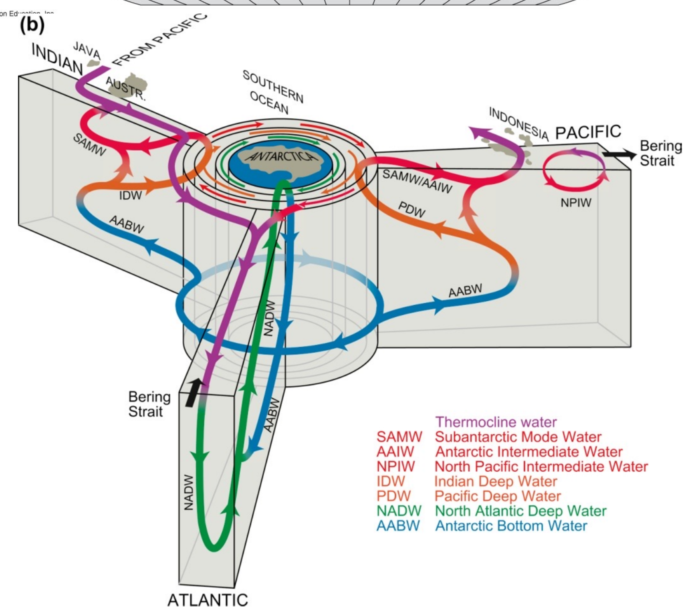
Thermohaline overturning, zonal average



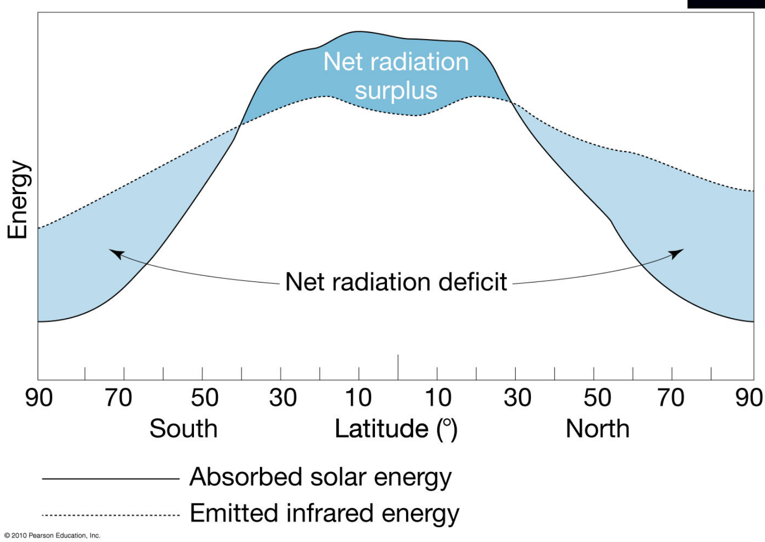
Surface currents

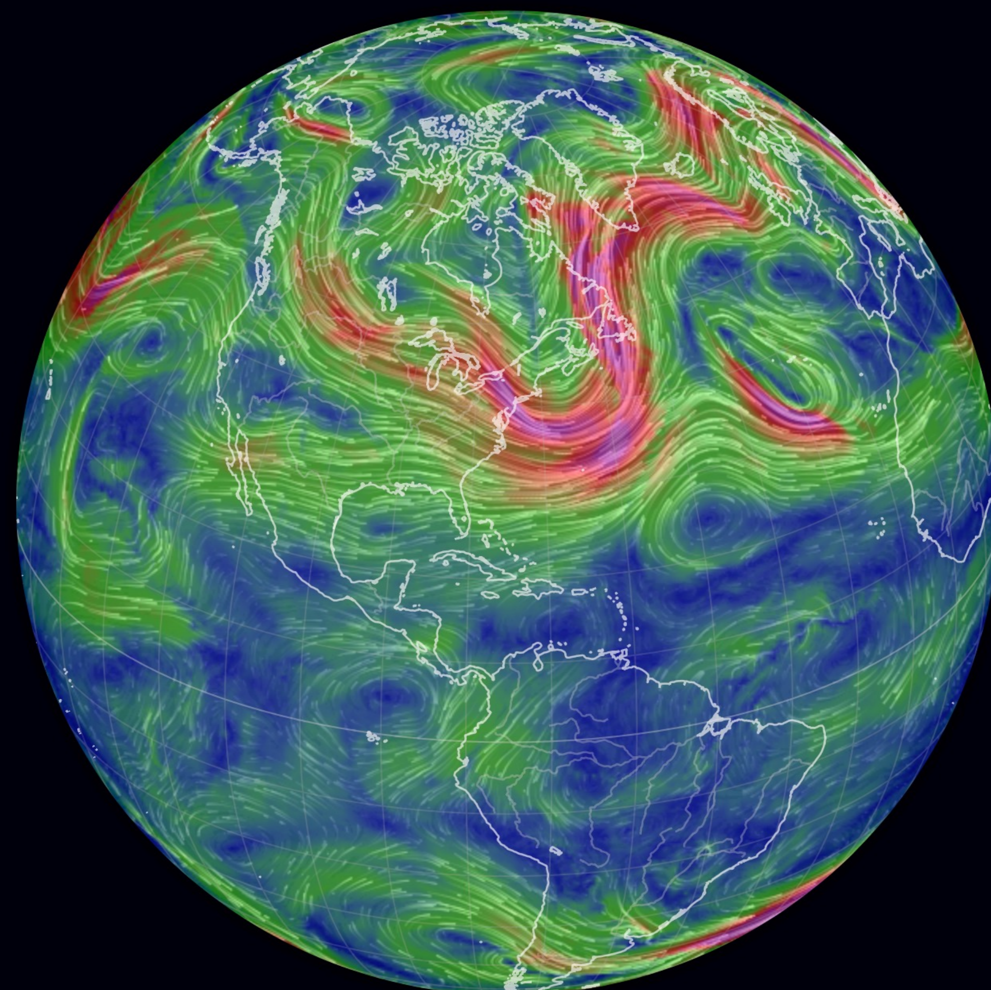


Thermohaline overturning



The atmosphere (and ocean) are constantly driving excess absorbed solar energy from equator to Pole

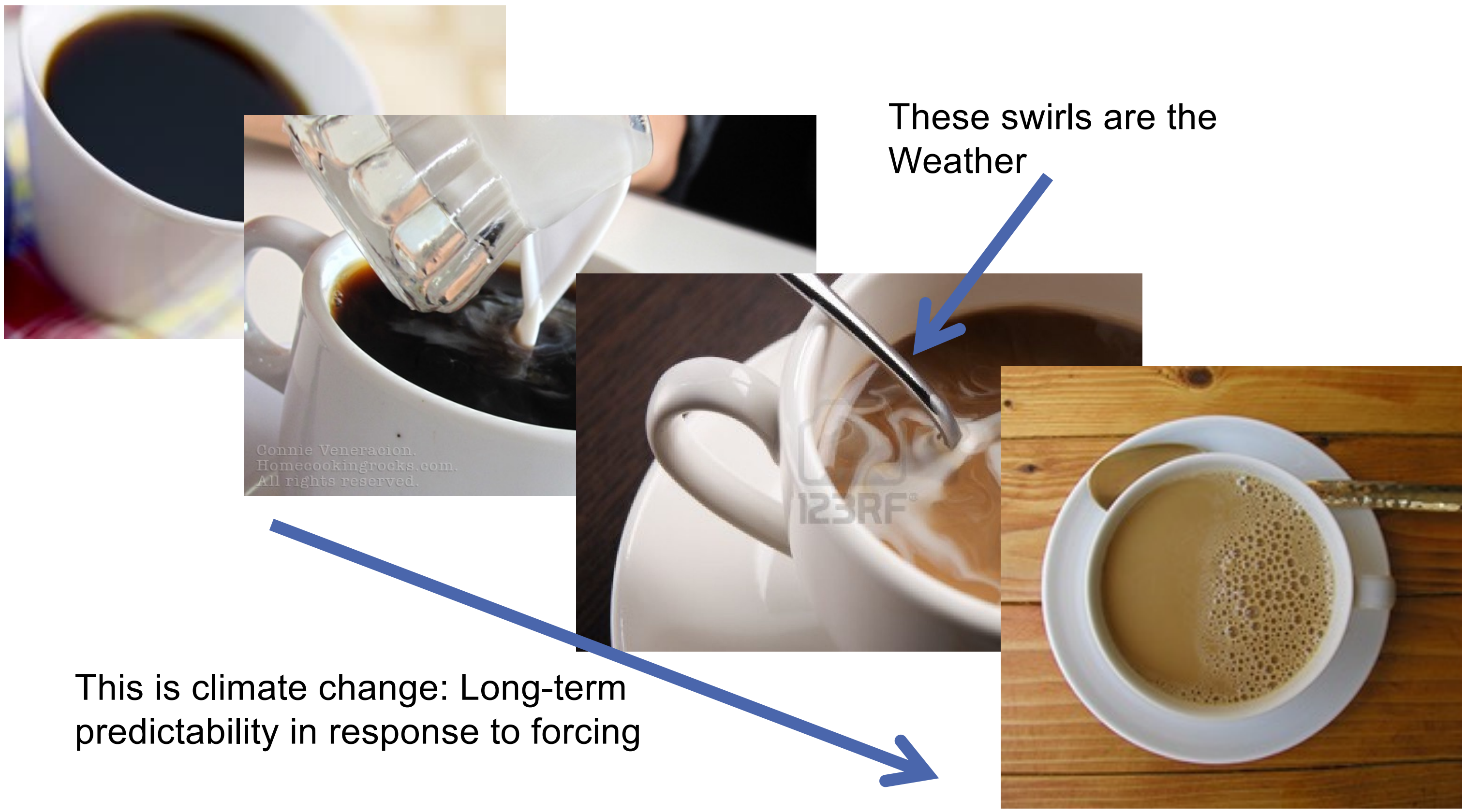




https://earth.nullschool.net/#current/wind/isobaric/500hPa/orthographic=-87.62,35.81,312

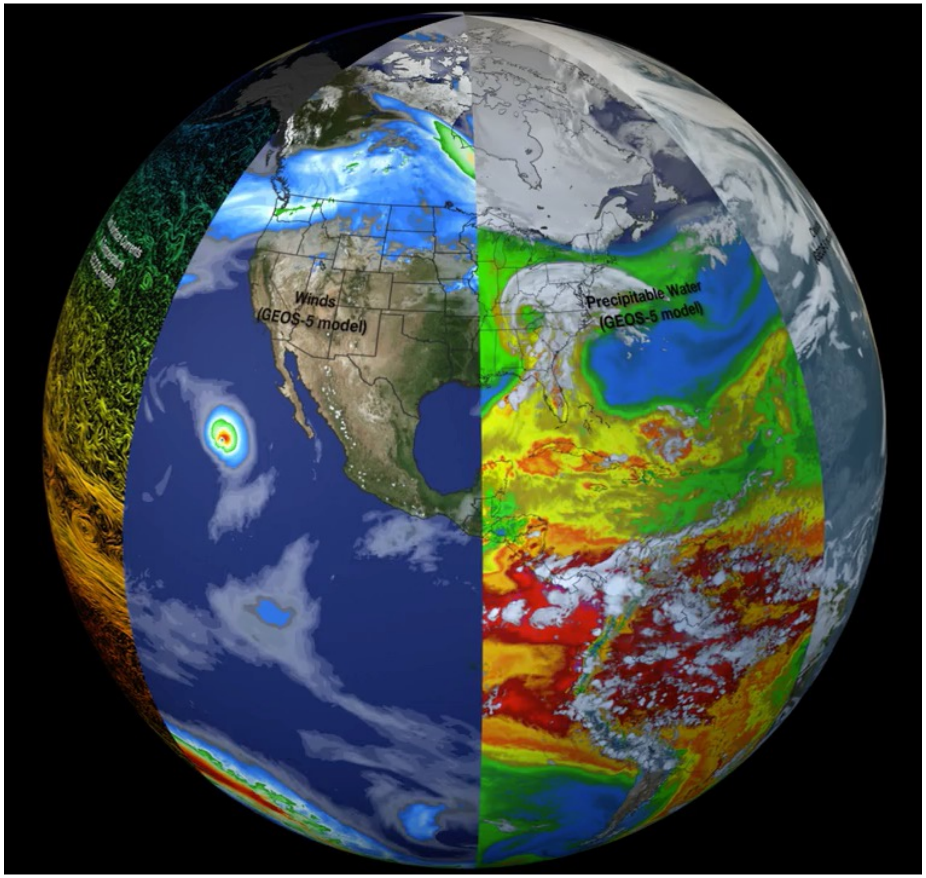
Do we need to know exactly where all the swirls will be to predict climate? .. i.e. the difference between Weather and Climate

These swirls are the Weather



This is climate change: Long-term predictability in response to forcing

Earth's climate system is the integrated effect of these physics, plus diverse chemistry, biology, and geology. It sustains all known life in the Universe.



This NASA animation illustrates a small subset of climate system components

QUESTIONS?

Professor Galen McKinley

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Office hours: by appointment