


What is Climate, and How Does it Work?


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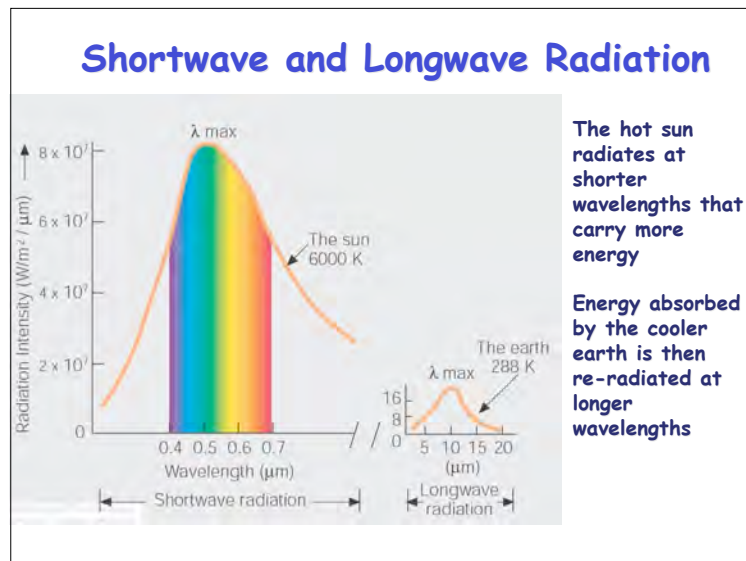
<http://www.cmmmap.org>



Outline

1. **How does the Earth's climate work?**
 - "Follow the energy"
 - Energy balance of the planet
 - Energy at the Earth's surface
 - The hydrologic cycle
 - Ocean circulation
 - Why the wind blows (and where, and how)

2. **How is weather different from climate?**
 - Climate is "average" weather
 - Weather prediction vs climate prediction



Planetary Energy Balance

Energy In = Energy Out

$$S(1 - \alpha)\pi R^2 = 4\pi R^2 \sigma T^4$$

$$T \approx -18^\circ\text{C}$$

But the observed T_s is about 15°C

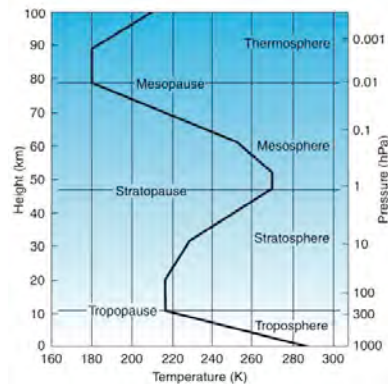
What's Missing from the O-D energy balance model?

- **Vertical structure**
The "greenhouse effect"
- **Energy storage and transport**
The "general circulation" of the atmosphere and oceans

Vertical Structure is Crucial

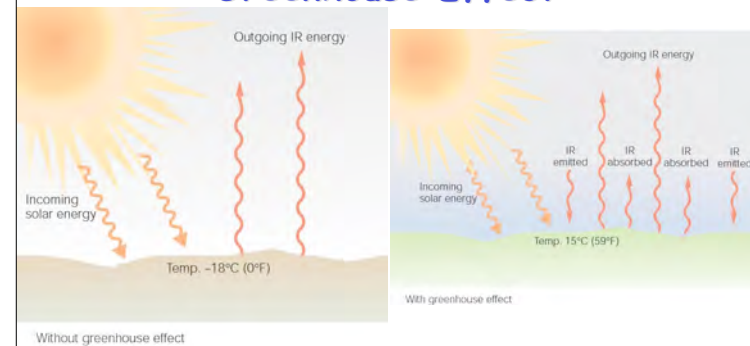
- The world is a big place, but the **atmosphere is very thin**, and most of it is close to the ground
 - About **15% of the atmosphere is below our feet**
 - At the top of Pike's Peak, the figure is 40%
 - You are closer to outer space than you are to Pueblo!
- Changes in atmospheric temperature with height are responsible for the "**Greenhouse Effect**," which keeps us from freezing to death

Vertical Thermal Structure



- Heated from below by the warm surface
- Heated in stratosphere by ozone absorption

Greenhouse Effect



Without greenhouse gases absorbing and emitting longwave radiation the surface temperature would be about 0°F!
Energy from the Sun gets "recycled" between the surface and the atmosphere. Avg surface temp ~ 59°F

Sun Doesn't Warm Earth Evenly

A sunlight beam that strikes at an angle is spread across a greater surface area, and is a less intense heat source than a beam impinging directly.

Solstice & Equinox

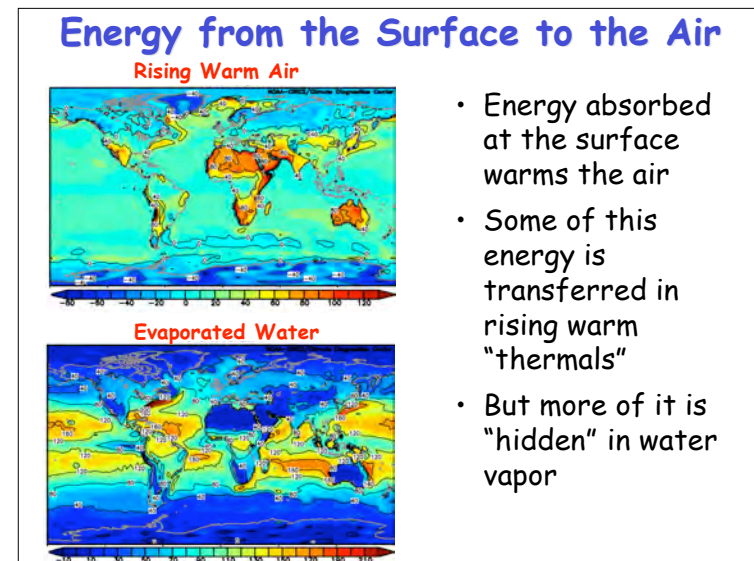
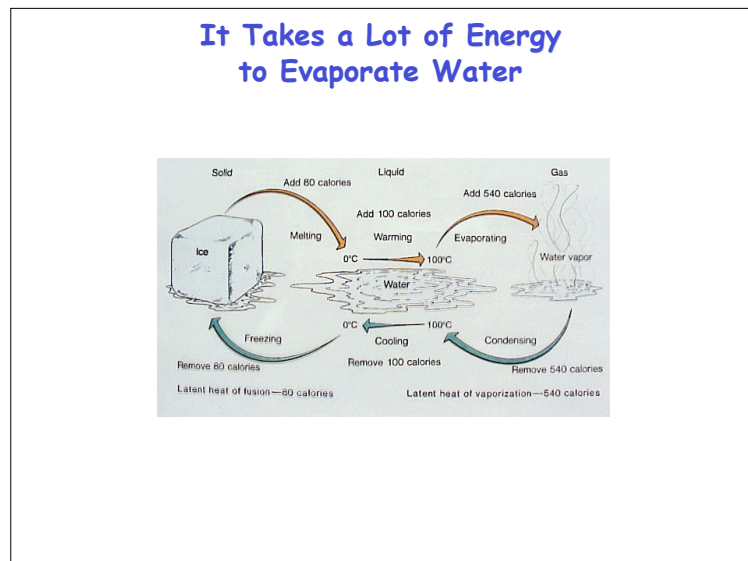
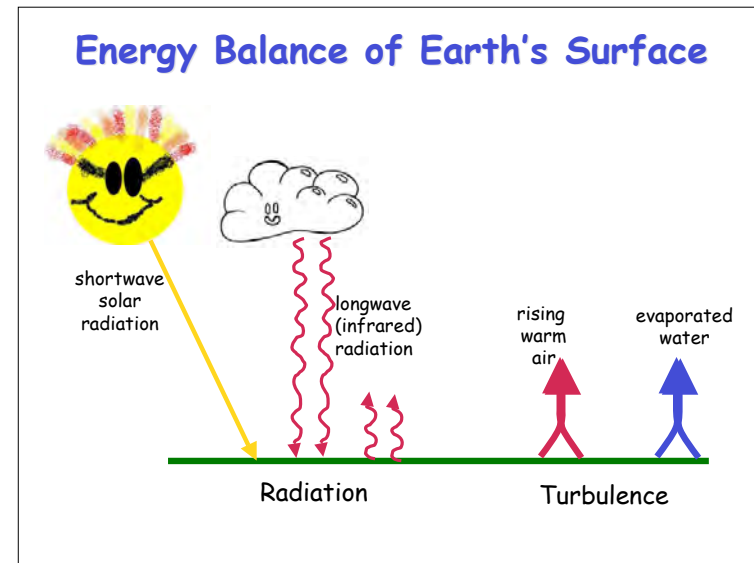
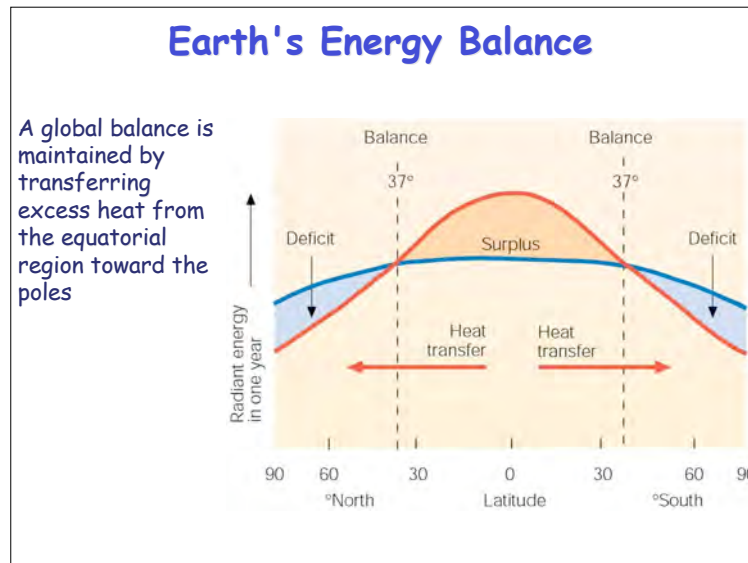
- Earth's tilt of 23.5° and revolution around the sun creates seasonal solar exposure and heating patterns
- At **solstice**, tilt keeps a polar region with **either 24 hours of light or darkness**
- At **equinox**, tilt provides exactly **12 hours of night and 12 hours of day** everywhere

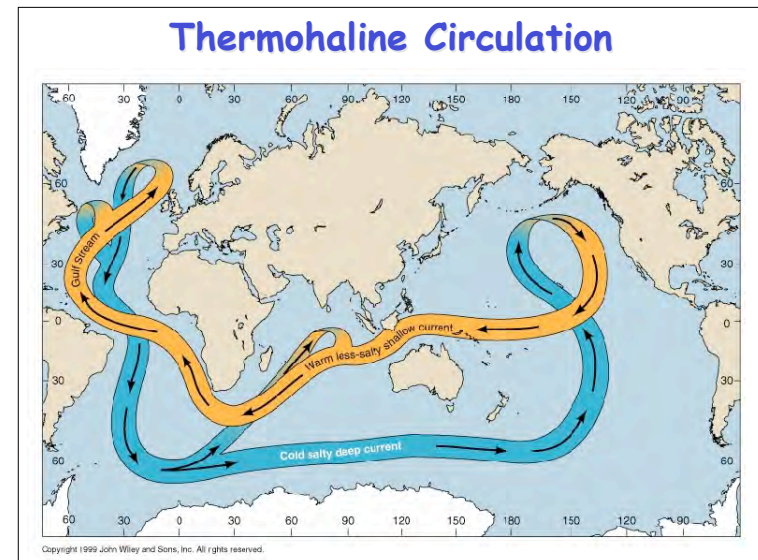
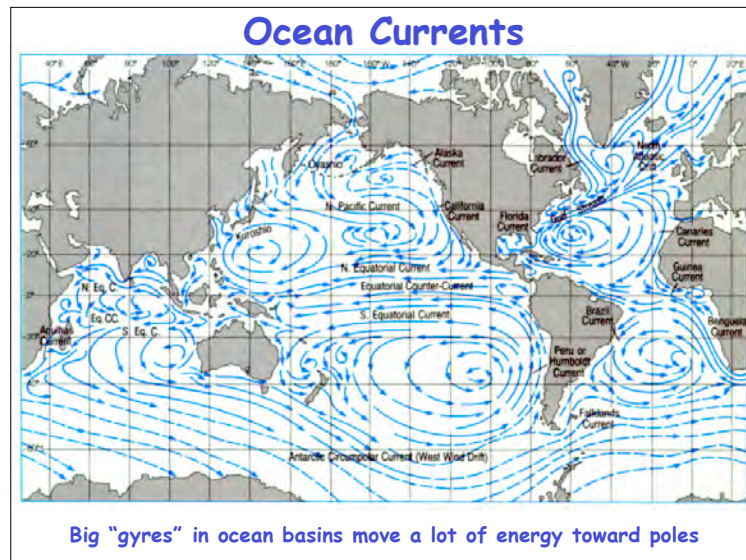
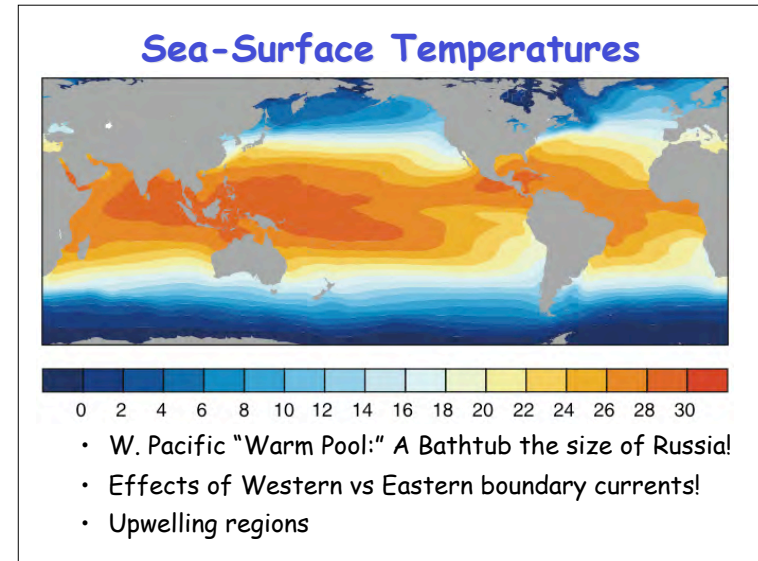
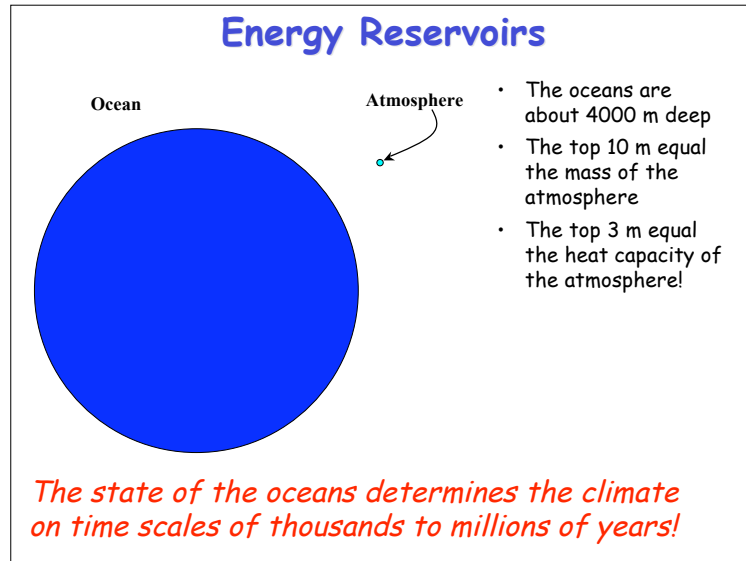
Energy In, Energy Out

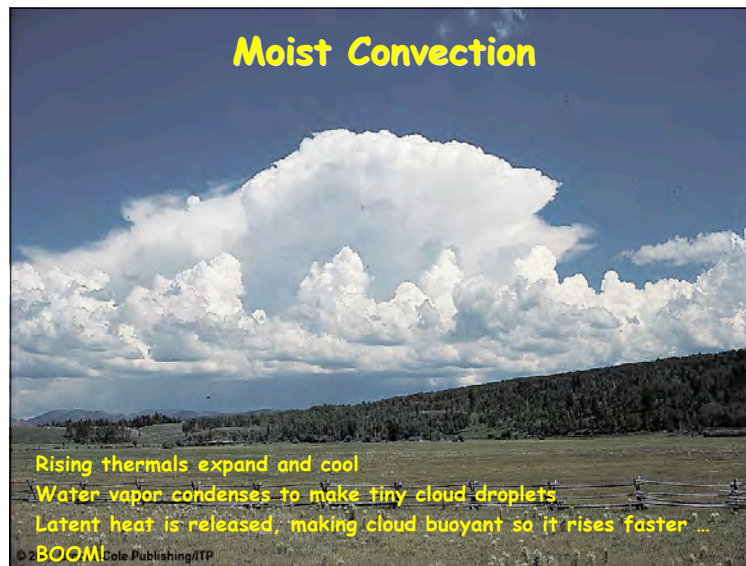
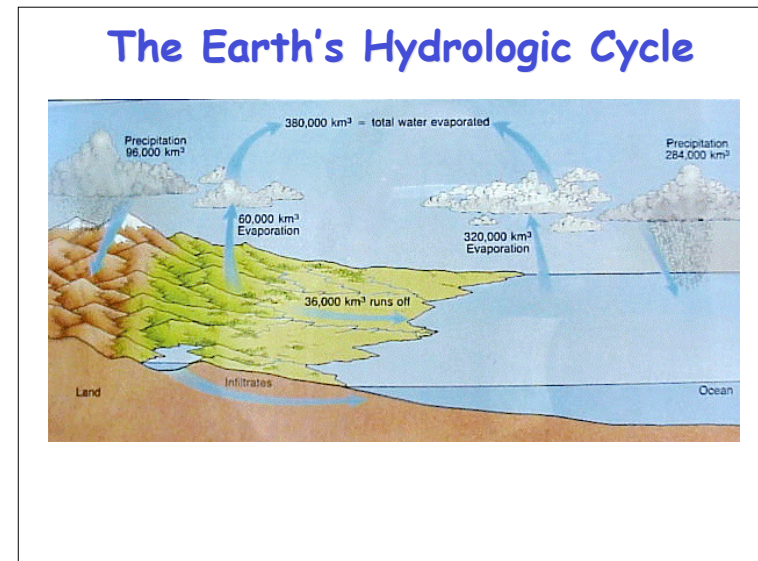
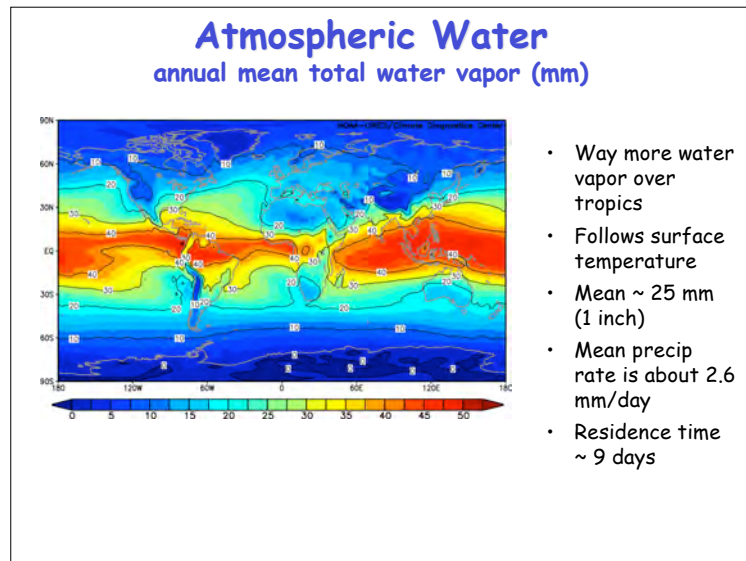
- Incoming and outgoing energy must balance on average
- But there are huge differences from place to place
- Way more solar heating in tropics
- Some places (deserts) emit much more than others (high cold clouds over rainforests)

Net Accumulation of Energy

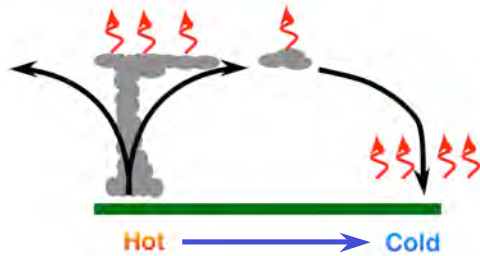
- Incoming solar minus outgoing longwave
- Must be balanced by horizontal transport of energy by atmosphere and oceans!







How is Energy Transported to its "escape zones?"



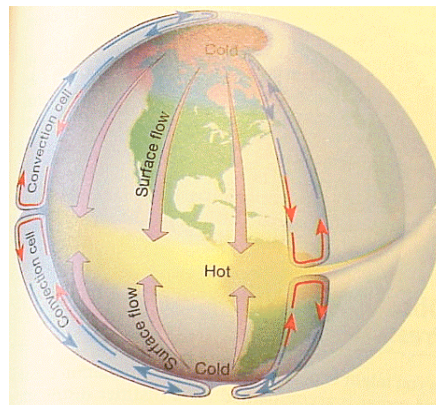
- Both **atmospheric and ocean** transport are crucial
- Buoyancy-driven **convection** drives vertical transport
- **Latent heat** is more important than sensible heat

Why Does the Wind Blow?

- Solar heating is greater than longwave cooling in the **tropics: energy accumulates** there, both in the atmosphere and the oceans
- Longwave cooling is greater than solar heating near the **poles: energy is lost** there, by thermal radiation to outer space
- The "job" of the **atmosphere and the oceans is to transport energy** from where it accumulates to where it can be lost (**poleward and upward**)
- This job is difficult because the Earth spins on its axis (the "**Coriolis force**")

If Earth Didn't Rotate ... the winds would be like a supermarket conveyor belt

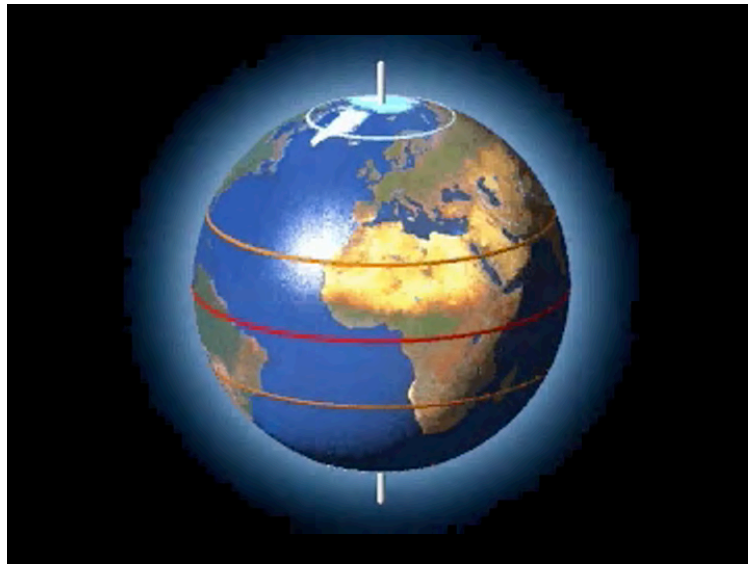
- Warm air would rise in the tropics, and flow poleward aloft...
- Cold air would sink at the poles and flow equatorward at the surface
- A cold wind would always blow in Colorado from the North!



The Coriolis Barf Machine



Remember these things?



Wind patterns on a rotating earth

- Deep thermally direct convective cells confined to tropics
- Condensation heating in rising branch of Hadley Cell lifts the center of mass of the atmosphere (converts latent to potential energy)
- Downhill slope toward winter pole produces jet streams in middle latitudes
- Jet is unstable to small perturbations, breaks down in waves

Jet Streams

(a)

(b)

Planetary Waves and Poleward Energy Transport

(a) Gently undulating upper airflow

(b) Meanders form in jet stream

(c) Strong waves form in upper airflow

(d) Return to a period of flatter flow aloft

Figure 7-18 Cyclic changes that occur in the upper-level airflow of the westerlies. The flow, which has the jet stream as its axis, starts out nearly straight and then develops meanders and cyclonic activity that dominates the weather.

Climate vs. Weather

*"Weather tells you what to wear today ...
climate tells you what clothes to buy!"*


- Climate is an "envelope of possibilities" within which the weather bounces around
- Weather depends very sensitively on the evolution of the system from one moment to the next ("initial conditions")
- Climate is determined by the properties of the Earth system itself (the "boundary conditions")

Predictability

"If they can't predict the weather, how can they possibly hope to predict the climate?"

- Weather forecasts are only useful for a few days, maybe a week at best
- Forecasting is limited by modeling skill and inadequate observations, but even if these were perfect, the limit of predictability would be about 2 weeks
- This limit is a property of the atmosphere itself, not a failure of our science!

Limits to Predictability

- The dynamical equations governing the motions of the atmosphere and oceans are strongly nonlinear
- This makes them very sensitively dependent on their initial conditions
- Errors in the initial conditions, no matter how trivial or on how small a spatial scale, quickly grow in magnitude and propagate to larger spatial scales
- Butterfly analogy of Lorenz (1963) 

Things to Remember

- Earth's climate is determined by
 - Exchange of radiant energy with the universe
 - Storage and transport of energy from warm places to cold places by the atmosphere, oceans
 - The water cycle is an important part of the energy cycle
 - Transport of energy from tropics to poles is hard because the Earth spins ... leads to storms
- Climate is the "average" of "weather"
 - Weather depends on what happened yesterday, just upwind from here. Tiny errors in "initial conditions" clobber weather forecasts in a week or so.
 - Climate depends on properties of the Earth itself: Brightness of sun, rate of spin, land/sea contrasts, etc. Can predict the average even though we can't predict every event ahead of time.