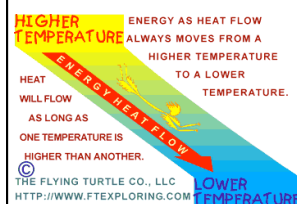


Overview: Follow the Energy

Energy flows downhill from hot to cold
 Earth's energy budget
 Definitions: Weather vs Climate
 Predictability

If Energy is Conserved ... then why do we need to "conserve energy?"

- Total energy is conserved (First Law), but not its **usefulness!**
- **Second Law of Thermodynamics:**
 Energy flows "downhill" from highly concentrated (hot) forms to very dilute (cold) forms



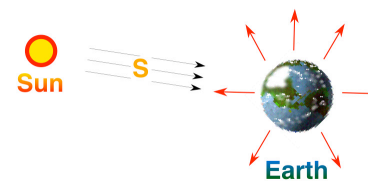
- Gasoline burned in your car (hot) makes it move
- Turbulence and friction of tires on road dissipated as heat
- Heat radiated to space (cold)

It all starts with the Sun

- Nuclear fusion in the Sun powers all changes on the Earth!
- Solar energy heats the air, lifts it, blows it around, evaporates water, makes snowstorms
- Conversion of solar energy and downhill dissipation as heat energy drive all weather and climate phenomena
- Energy comes in hot, and goes out cold, at 342 W m^{-2}



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

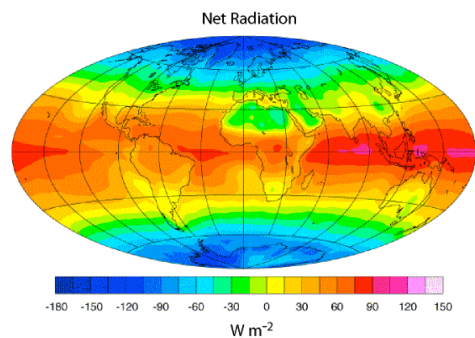
What's Missing from the O-D energy balance model?

- **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 Long's Peak, the figure is 40%
 - You are closer to outer space than you are to Colorado Springs!
- Changes in atmospheric temperature with height are responsible for the "**Greenhouse Effect**," which keeps us from freezing to death

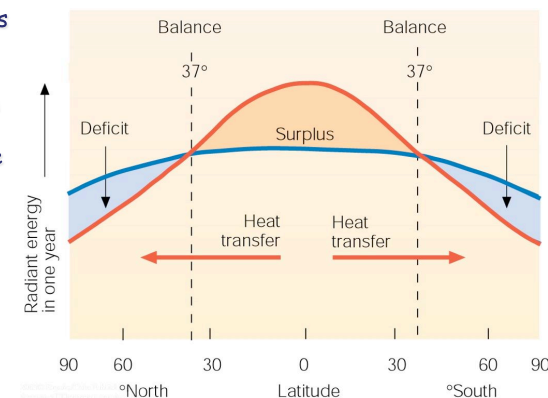
Net Accumulation of Energy

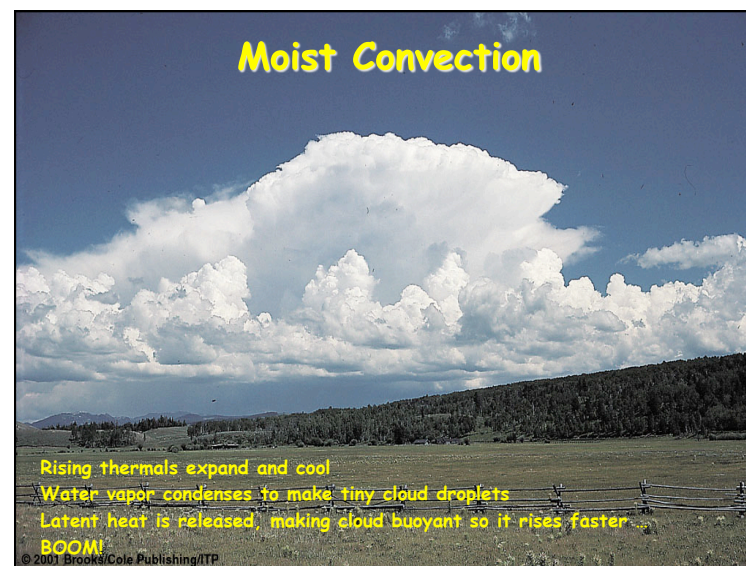
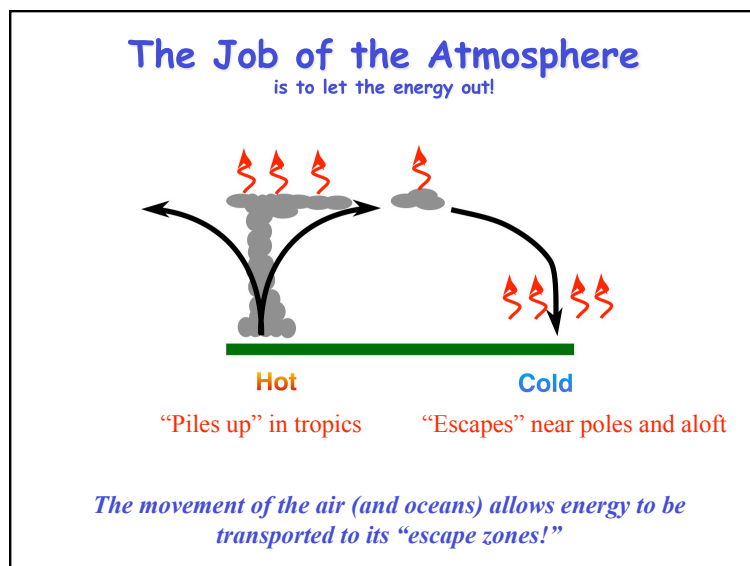


- Incoming (solar) minus outgoing energy
- Must be balanced by horizontal transport of energy by atmosphere and oceans!

Earth's Energy Balance

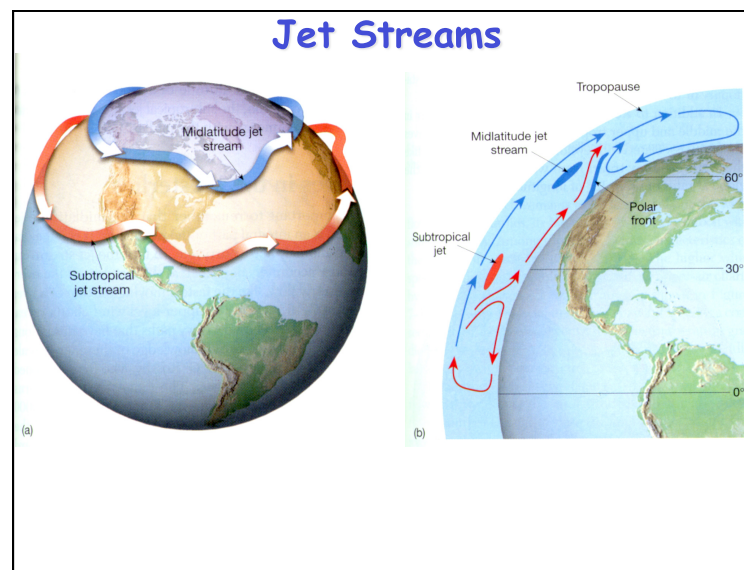
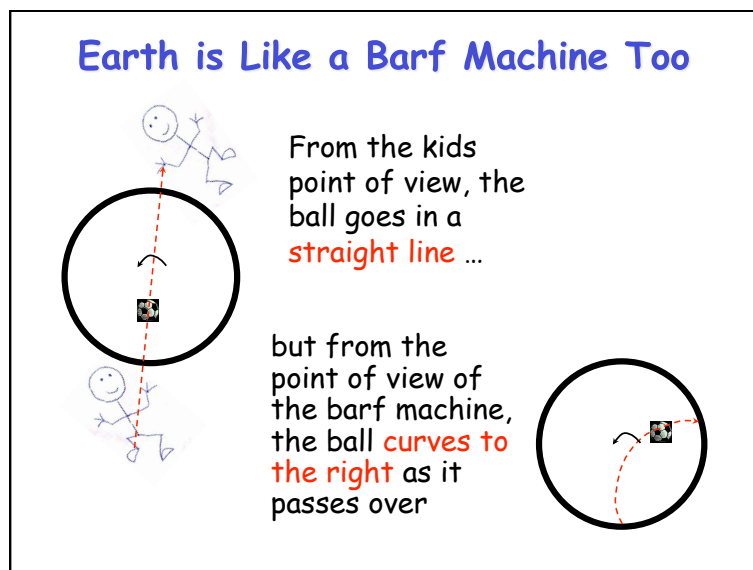
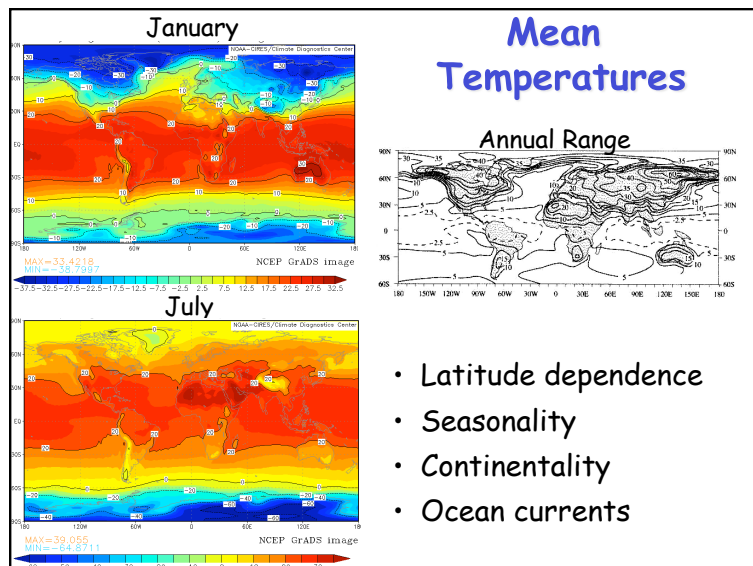
A global balance is maintained by transferring excess heat from the equatorial region toward the poles

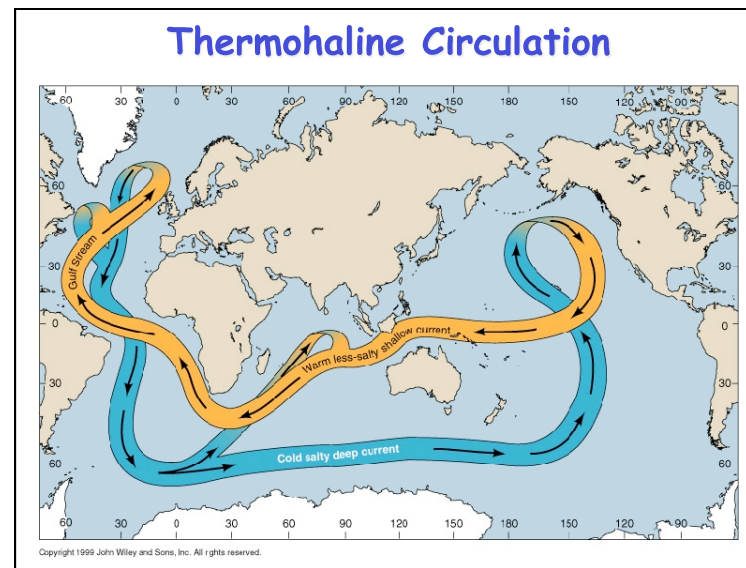
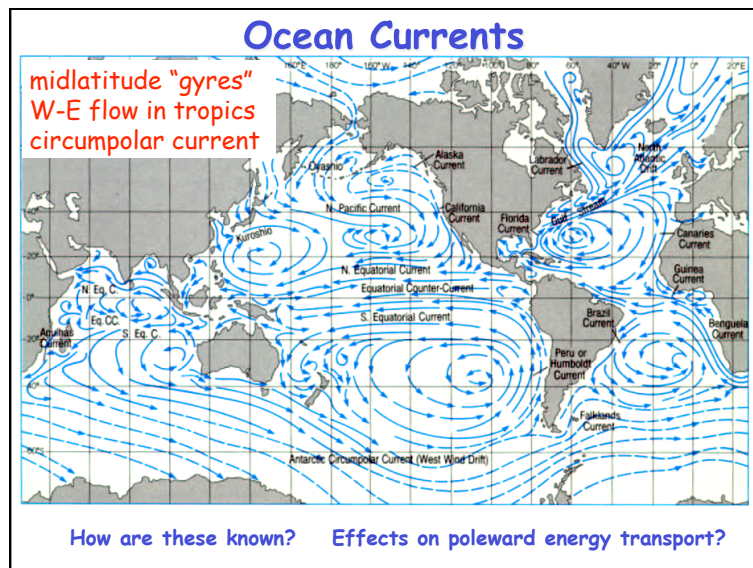
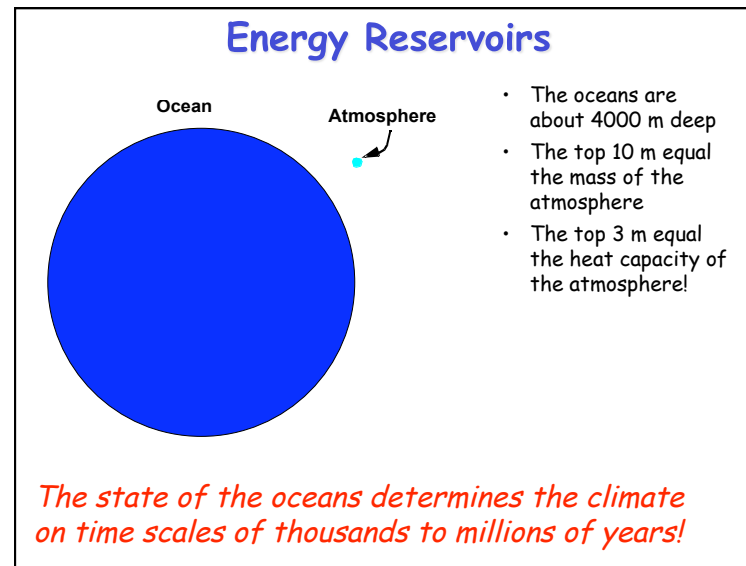
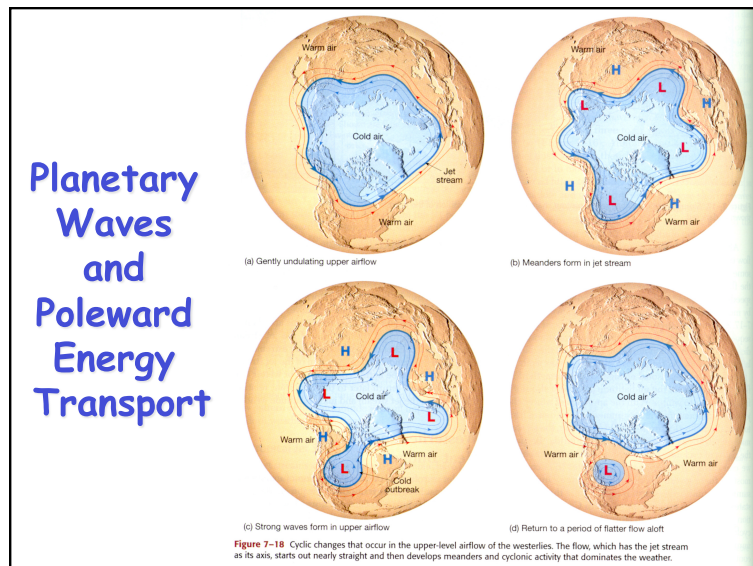




Atmospheric Circulation
in a nutshell

- Hot air rises (it rains a lot) in the **tropics**
- Air cools and sinks in the **subtropics** (deserts)
- Poleward-flow is deflected by the *Coriolis* force into westerly jet streams in the **temperate** zone
- *Jet streams* are unstable to small perturbations, leading to huge eddies (**storms and fronts**) that finish the job





Definitions

- **Weather:**
the state of the atmosphere at a place and time as regards heat, cloudiness, dryness, sunshine, wind, rain, etc.
- **Climate:**
the weather conditions prevailing in an area in general or over a long period of time

Elements of Weather & Climate

- Temperature
- Humidity
- Precipitation (Rain, Snow, Hail, Sleet, etc)
- Wind (speed, direction, "gustiness")
- Clouds and Sunshine
- Drought
- Tornado, Hurricane, Blizzard
- Heat "wave," cold "snap"
- El Nino

Climate vs. Weather

"Climate is what you expect ... weather is what you get!"


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

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) 

Airplane analogy

- The flow around an **airplane wing is governed by the same physics** that govern the atmosphere
- For the same reasons we will never forecast the weather a month in advance, **we can never predict the details of the flow around the wing**
- But given boundary values and parameters, we can **predict with confidence the statistics** of this flow, or flight would be impossible!

Long-term Forecasting

- Can't **forecast the weather in Fort Collins on Thanksgiving** (Snow? Sunshine? -30 C? +20 C?)
- Can "forecast" with complete confidence that $-100\text{ C} < T_{\text{max}} < +100\text{ C}$, or even that it will be **colder than it is today**
- Why?
- **Boundary conditions!**
 - Brightness of the Sun
 - Atmospheric composition
 - Tilt of Earth's axis, Fort Collins latitude, etc

Slow vs. Fast Climate Components

- Some parts of the Earth system are **slower to respond to changes than the atmosphere** (e.g., ocean temperatures, soil moisture)
- Such slow processes give the climate **"memory"**
- If processes that control these "slow" processes are known, they may be **predicted**
- The **statistics of the weather respond in systematic and predictable ways** to changes in boundary forcing

Seasonal Forecasting

- In the past 10 years, we've learned a lot about the processes that control tropical Pacific sea-surface temperatures (El Niño and La Niña)
- Once these processes get started, we can predict their evolution with some skill
- Weather anomalies associated with these events are then forecast several months in advance
- Works much better in some places than others (not too reliable in Colorado)

Things to Remember

- Earth's weather and climate are "driven" by the flow of energy from warm places (tropics) to cold places (poles)
- Weather changes from day to day, and depends mostly on recent conditions nearby
- Climate is the average weather, and is determined mostly by the properties of the Earth and Sun
- Weather is unpredictable, but predictable changes in Earth properties may change climate in predictable ways