

## Overview: Follow the Energy

What is Energy?

Conservation of Energy

Energy flows downhill from hot to cold

Earth's energy budget

Definitions: Weather vs Climate

Predictability

## Defining Energy is Hard!

- "Energy is the capacity to perform work"
  - (but physicists have a special definition for "work," too!)
- Part of the trouble is that scientists have "appropriated" common English words and given them special meanings
- But part of the trouble is that the concept of energy is absolutely central to understanding the physical world, yet is very hard to define precisely

## "Energy Changes Make Things Happen"

Dave Watson, <http://www.ftexploring.com>

- Energy is a property or characteristic of matter that makes things happen, or, in the case of stored or potential energy, has the "potential" to make things happen.
- Without energy, nothing would ever change, nothing would ever happen. You might say energy is the ultimate agent of change, the mother of all change agents.

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## Conservation of Energy

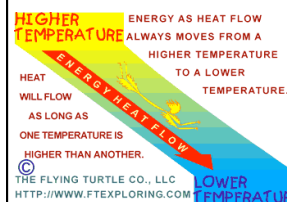
- Energy can be stored
- Energy can move from one piece of matter to another piece of matter
- Energy can be transformed from one type of energy to another type of energy
- **The First Law of Thermodynamics:**
  - During all this moving and transforming the total amount of energy never changes.

### Kinds of Energy

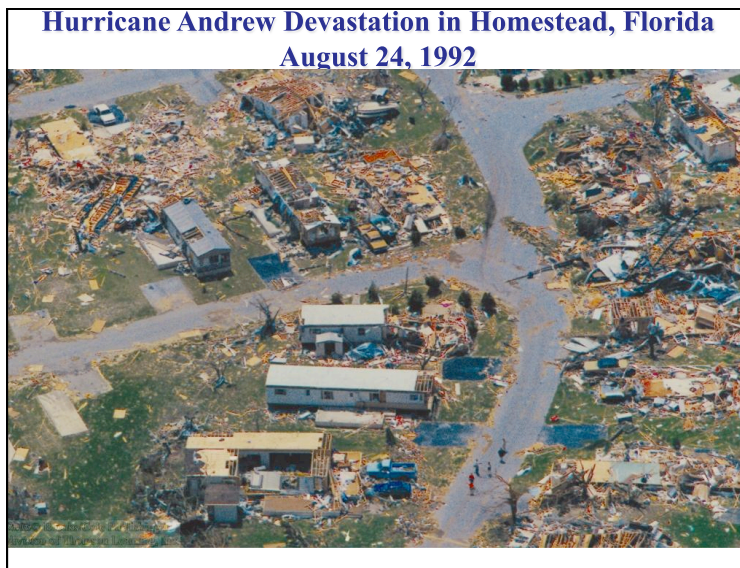
- Radiant Energy -- light
- Kinetic Energy -- motion
- Gravitational Potential Energy -- height
- "Internal Energy"
  - Temperature, Pressure -- hot air
  - Chemical energy
  - Nuclear energy
- **Conversions among different kinds of energy power all that happens in the weather and climate!**

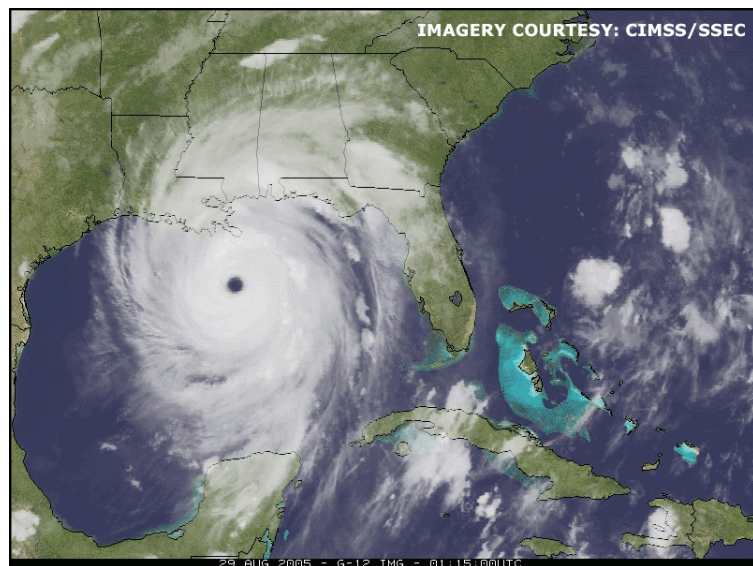
### If Energy is Conserved ... then why do we need to "conserve energy?"

- 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



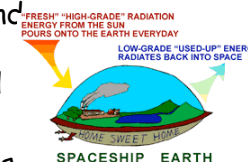
- Gasoline burned in your car (hot) makes it move
- Turbulence and friction of tires on road dissipated as heat
- Heat radiated to space (cold)



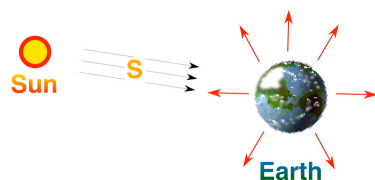


## It all starts with the Sun

- 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  $342 \text{ W m}^{-2}$



## 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  $15^\circ \text{C}$*

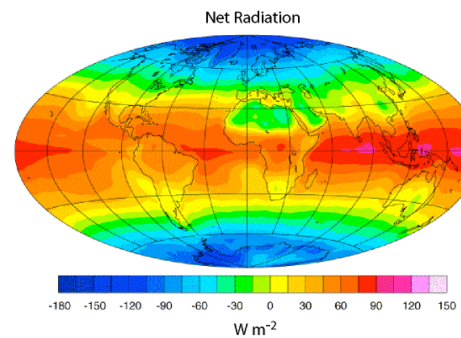
## What's Missing from the 0-D energy balance model?

- **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

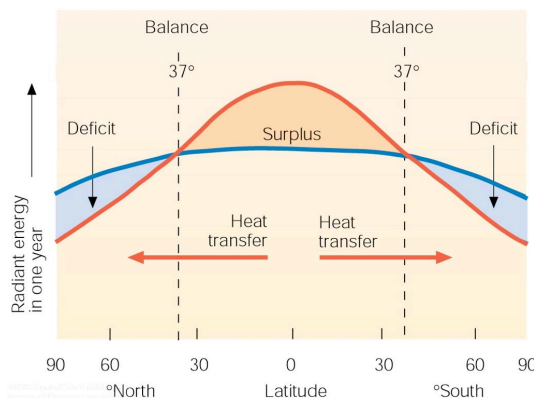
### Net Accumulation of Energy



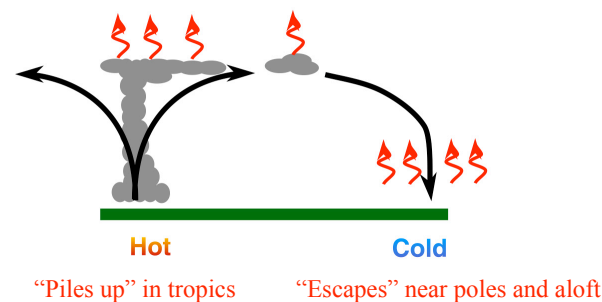
- Incoming (solar) minus outgoing energy
- Must be balanced by horizontal transport of energy by atmosphere and oceans!

### Earth's Energy Balance

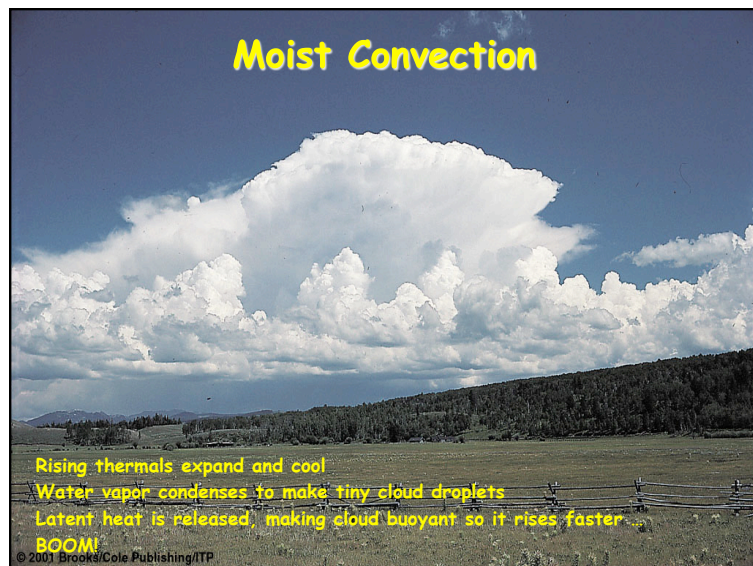
A global balance is maintained by transferring excess heat from the equatorial region toward the poles



### The Job of the Atmosphere is to let the energy out!

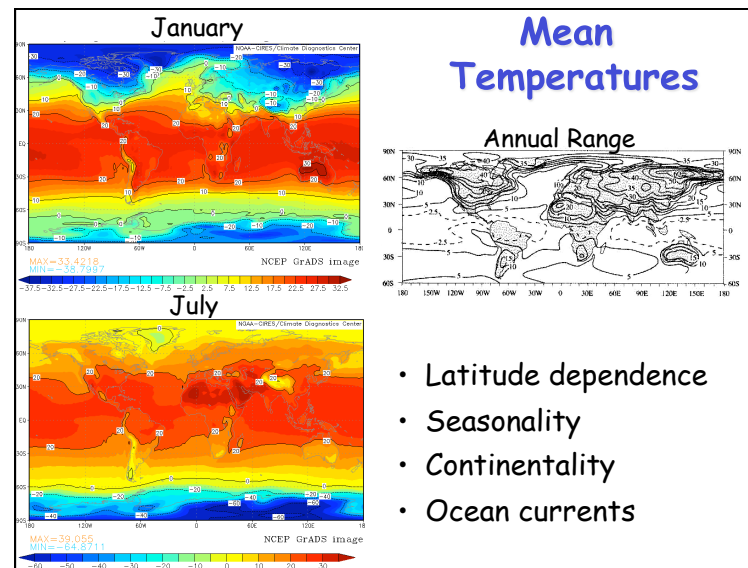


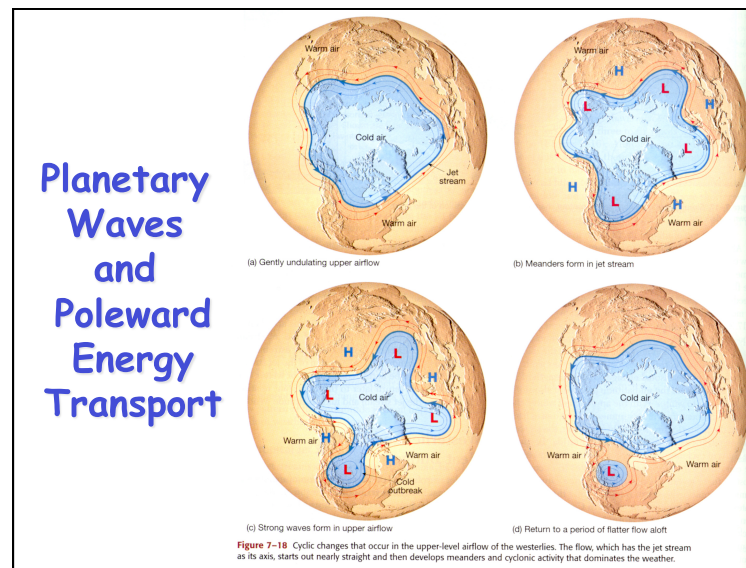
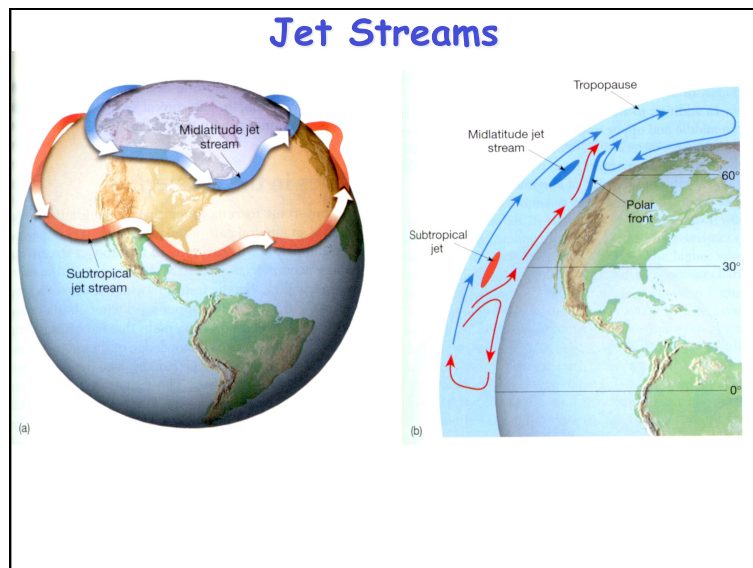
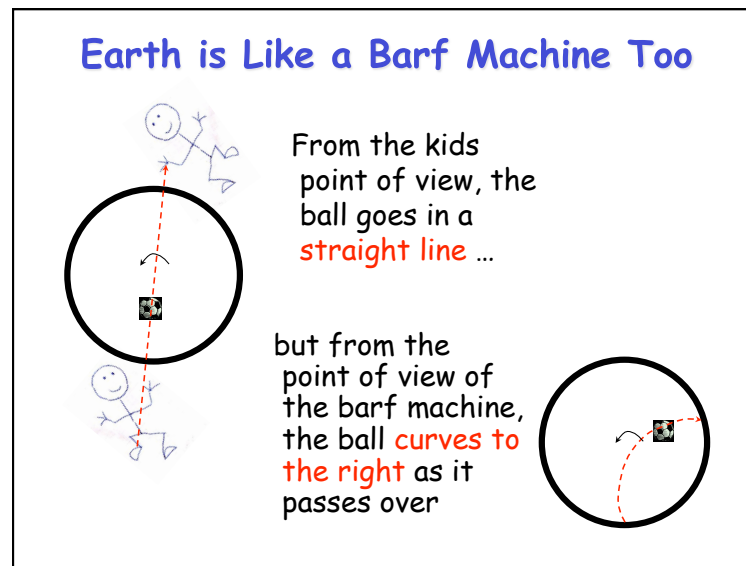
*The movement of the air (and oceans) allows energy to be transported to its "escape zones!"*



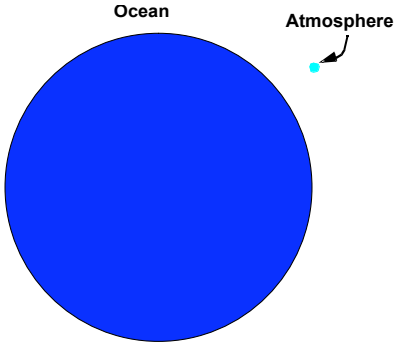
### Atmospheric Circulation in a nutshell

- 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





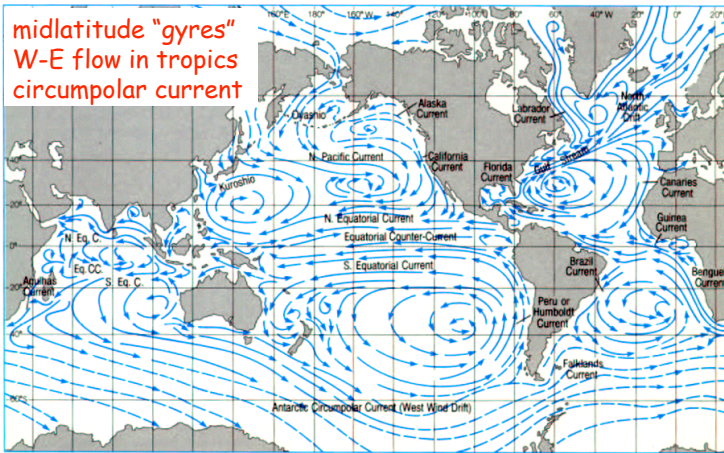
### Energy Reservoirs



- The oceans are about 4000 m deep
- The top 10 m equal the mass of the atmosphere
- The top 3 m equal the heat capacity of the atmosphere!

*The state of the oceans determines the climate on time scales of thousands to millions of years!*

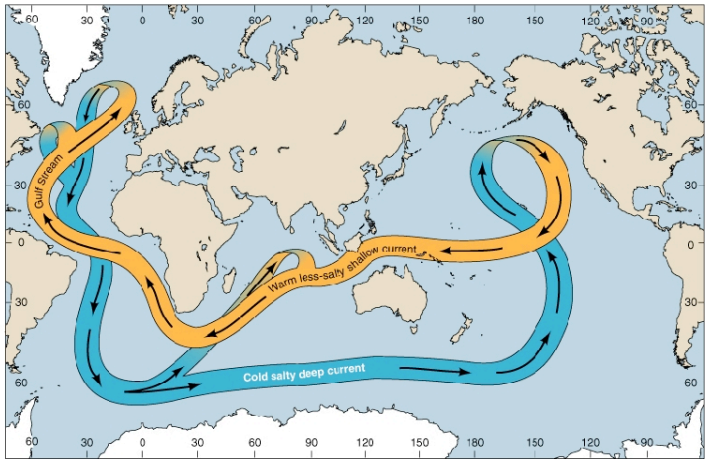
### Ocean Currents



midlatitude "gyres"  
W-E flow in tropics  
circumpolar current

How are these known?    Effects on poleward energy transport?

### Thermohaline Circulation



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### 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