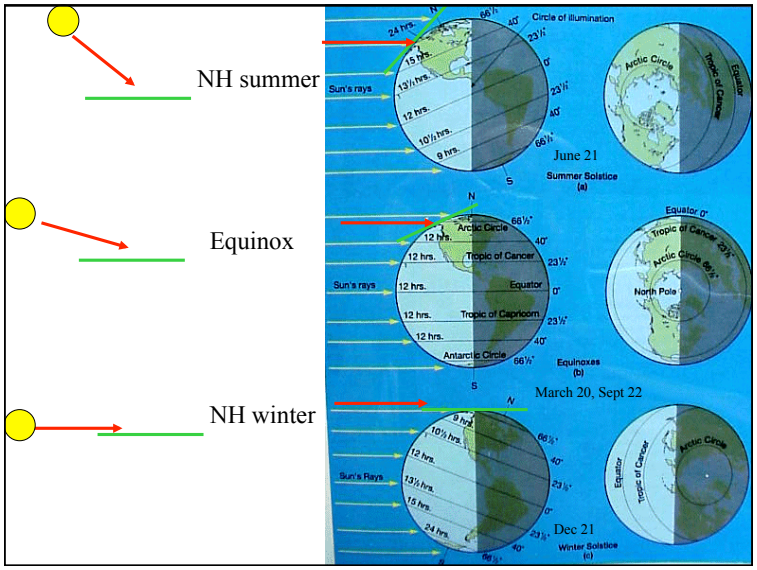
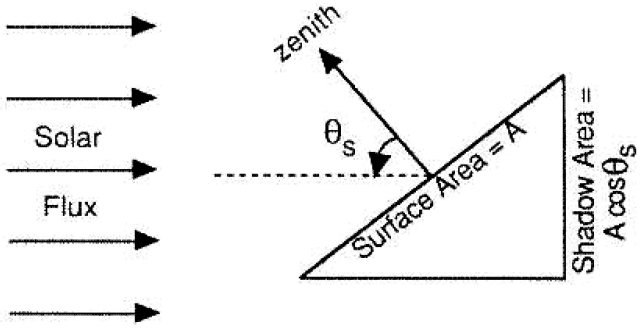
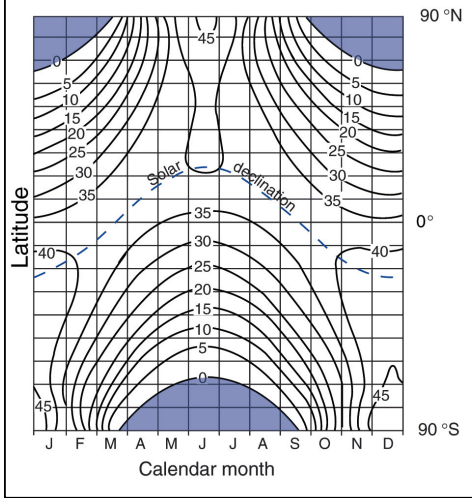


Geometry of Solar Absorption



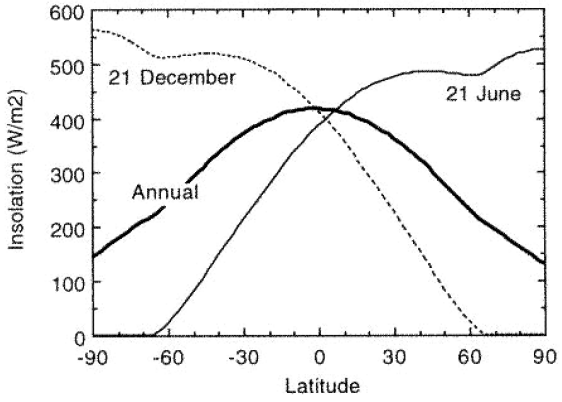
Think about geometry of sunlight striking our tilted spherical Earth: changes with latitude and seasons

Daily Insolation at Top of Atmosphere



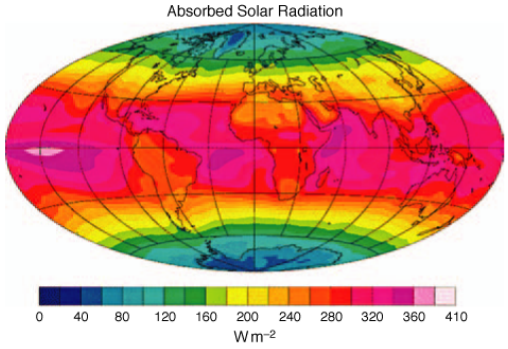
- 75° N in June gets more sun than the Equator
- Compare meridional gradient of insolation by seasons
- Very little tropical seasonality

TOA Daily Insolation
(zonal integral)



- Nearly flat in summer hemisphere
- Steep gradient from summer tropics to winter pole

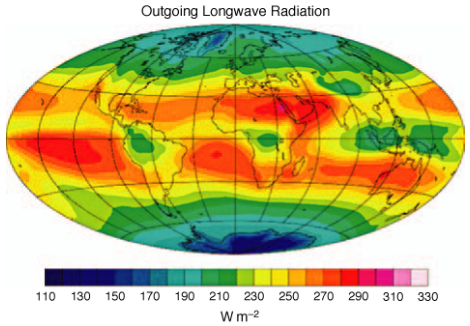
Absorbed Solar Radiation



Annual Mean

- Meridional gradient
- Land-sea contrast
- Ice and snow
- Deserts vs forests

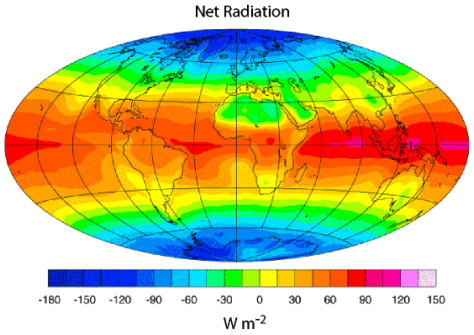
TOA Outgoing Longwave Radiation



Annual Mean

- Given by esT^4 (which T?)
- Combined surface and atmosphere effects
- Decreases with latitude
- Maxima over subtropical highs (clear air neither absorbs or emits much)
- Minima over tropical continents (cold high clouds)
- Very strong maxima over deserts (hot surface, clear atmosphere)

Top of Atmosphere Annual Mean

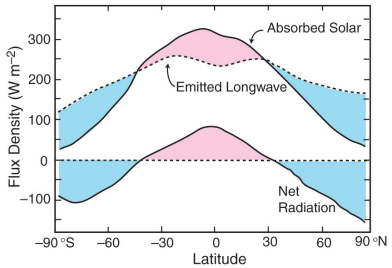


- Tropics are always positive, poles always negative
- Western Pacific is a huge source of energy (warm ocean, cold cloud tops)

- Saharan atmosphere loses energy in the annual mean!
- TOA net radiation must be compensated by lateral energy transport by oceans and atmosphere

Energy Surplus and Deficit

Annual Mean Zonal Mean TOA Fluxes

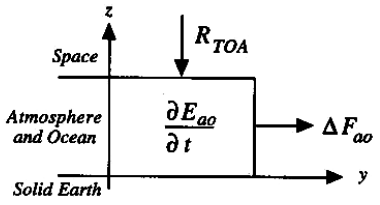


Adapted from Dennis L. Hartmann, *Global Physical Climatology*, p. 31 (Copyright 1994), with permission from Elsevier.

- Absorbed solar more strongly "peaked" than the emitted longwave
- OLR depression at Equator due to high clouds along ITCZ
- Subtropical maxima in OLR associated with clear air over deserts and subtropical highs

TOA net radiation surplus in tropics and deficits at high latitudes must be compensated by horizontal energy transports in oceans and atmosphere

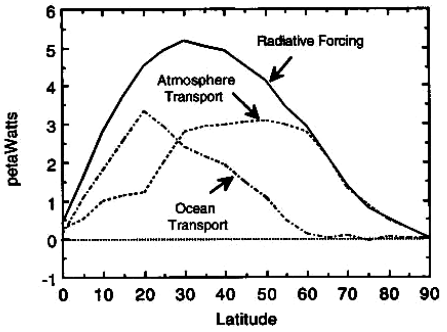
Energy Budget Cross-Section



$$\frac{\partial E_{ao}}{\partial t} = R_{TOA} - \Delta F_{ao}$$

- Excess or deficit of TOA net radiation can be expressed as a trend in the total energy of the underlying atmosphere+ocean+land surface, or as a divergence of the horizontal flux of energy in the atmosphere + ocean
- Can't have a trend for too long. Transport or R_{TOA} will eventually adjust to balance trends.

Energy Transports in the Ocean and Atmosphere

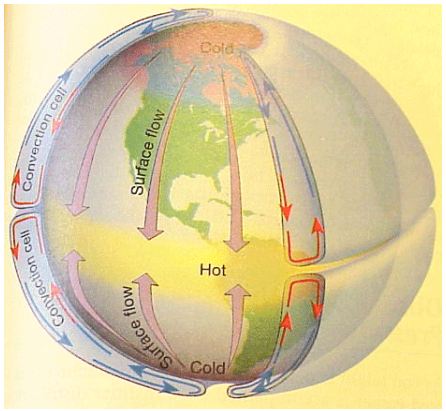


- Northward energy transports in petawatts (10^{15} W)
- "Radiative forcing" is cumulative integral of R_{TOA} starting at zero at the pole
- Slope of forcing curve is excess or deficit of R_{TOA}
- Ocean transport dominates in subtropics
- Atmospheric transport dominates in middle and high latitudes

- *How are these numbers determined?*
- *How well are they known?*

What a single cell convection model would look like for a *non-rotating* earth

- Thermal convection leads to formation of convection cell in each hemisphere
- Energy transported from equator toward poles
- What would prevailing wind direction be at the surface over N. America with this flow pattern on a rotating earth?

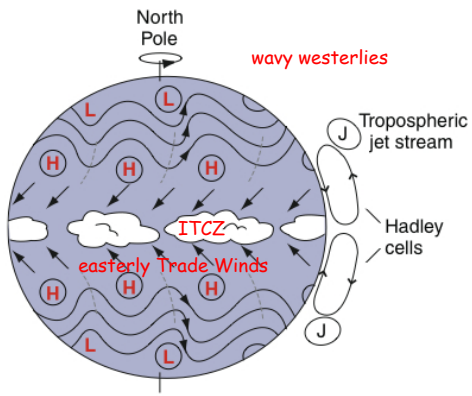


The Coriolis Barf Machine

Remember these things?

Coriolis Movies

Wind patterns on a rotating earth

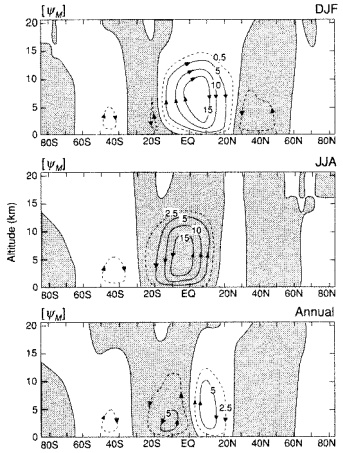


- Deep thermally direct convective cells confined to tropics
- Condensation heating in rising branch of Hadley Cell lifts the center of mass of the atmosphere (converts latent to potential energy)
- Downhill slope toward winter pole produces jet streams in middle latitudes
- Jet is unstable to small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

Atmospheric Circulation
in a nutshell

- Hot air rises (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

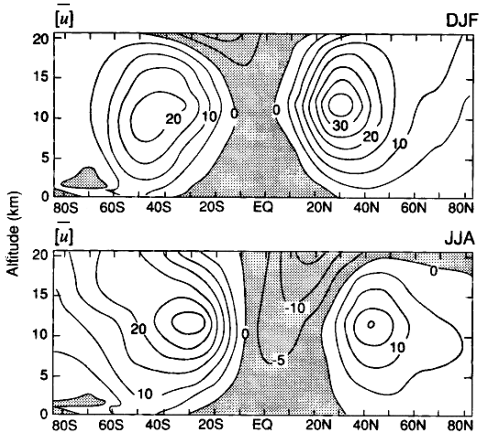
Mean Meridional Circulation



Mean meridional mass streamfunction (10^{10} kg s^{-1})

- Strongest feature is the Hadley Cell
  - Rising air in tropics
  - Poleward flow aloft into winter hemisphere
  - Sinking air in winter subtropics
  - Surface flow equatorward
  - Rising branch slightly displaced into summer hemisphere
- Much weaker Ferrel Cells in middle latitudes
  - "Thermally indirect"
  - A byproduct of much stronger eddy fluxes

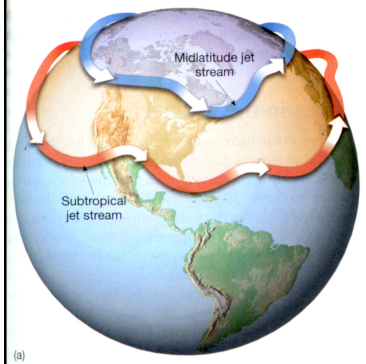
Mean Zonal Wind

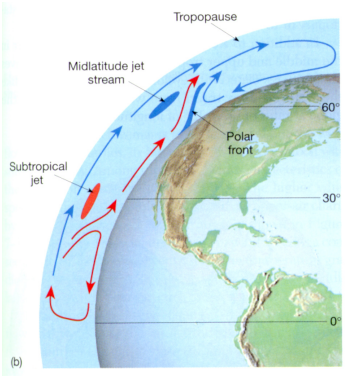


- Midlatitude westerly winds
- Deep tropical easterlies
- Well-defined winter wind max ~ 30° lat at ~ 12 km ("jet stream")
- Summer jet is weaker and further poleward

Time mean zonal mean zonal wind component (m/s)

Jet Streams





- Subtropical Jet is zonal mean response to poleward flow in upper branch of Hadley Cell
- Polar front jet is response to meridional temperature gradients

Planetary Waves and Poleward Energy Transport

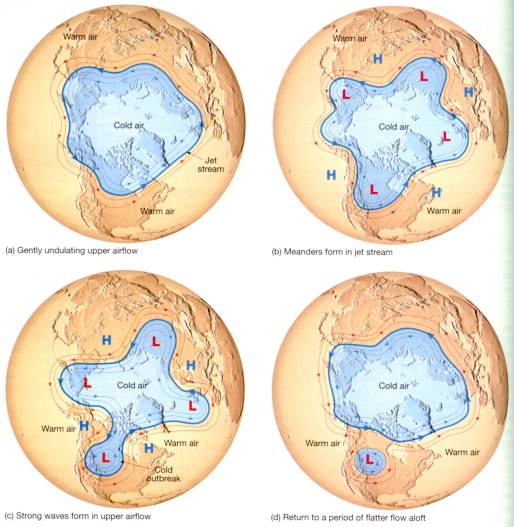
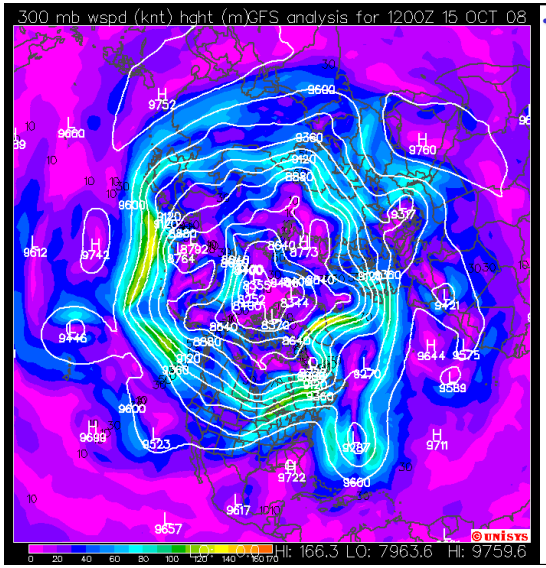


Figure 7–18 Cyclic changes that occur in the upper-level airflow of the westerlies. The flow, which has the jet stream as its axis, starts out nearly straight and then develops meanders and cyclonic activity that dominates the weather.



Today @ 300 mb

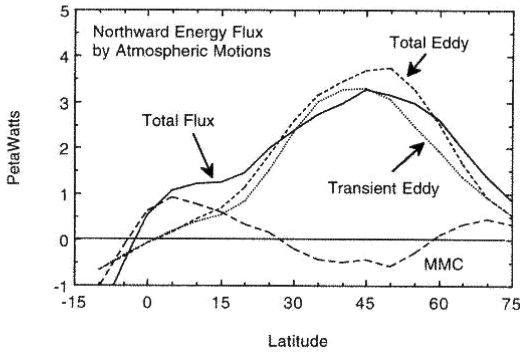
- "Bowl-shaped" height contours
- Waves
- Cutoff over North Atlantic
- Jet streak over North Pacific

Circulation Movie

link to file or download from

http://www.ssec.wisc.edu/data/globe/cldspin.html

Poleward Energy Transport



- MMC carries energy out of tropics (as gz)
- Eddy motions carry it the rest of the way (mostly as transients)
- Consider d/dj of energy flux (divergence)
- Thermally indirect MMC in midlats is response to strong eddy flux divergences

Global Energy Cascade

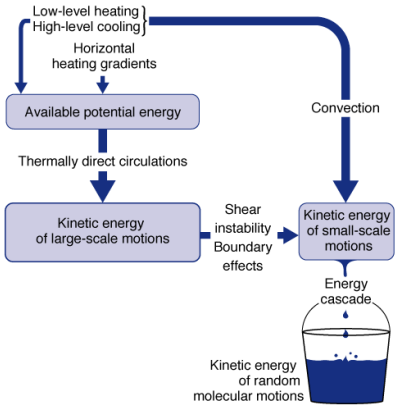
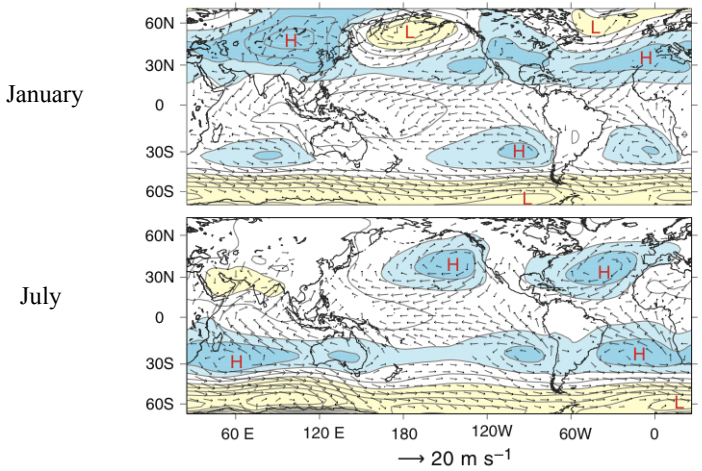


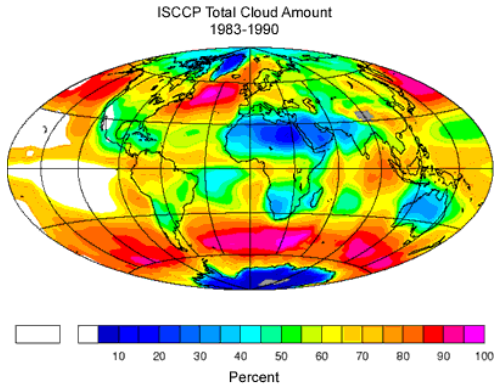
Fig. 7.24 Schematic flow diagram for the kinetic energy cycle in the atmospheric general circulation.

- Heterogeneous heating creates available potential energy (APE)
- Thermally-direct MMC converts APE to zonal mean KE
- Baroclinic instability converts zonal mean KE to eddy KE
- Eddies shed eddies "and so on to viscosity"
- Dissipation of KE converts energy back to heat

Surface Winds and Pressure



Atmospheric Cloudiness



- Persistent clouds over ITCZ
- Cloudiest areas are over mid- to high-latitude oceans
- Clearest areas are subtropical highs

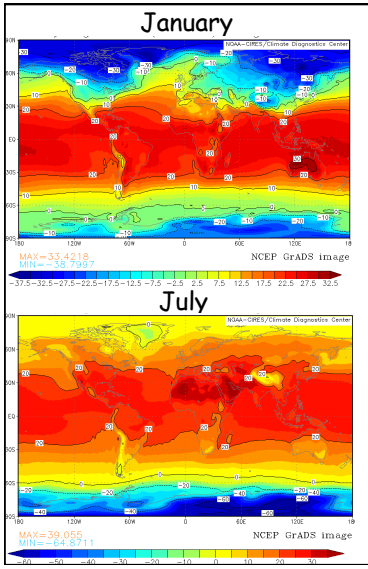
Climates of the World

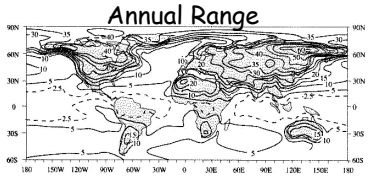
- **Deep Tropics**: hot and wet, with little seasonal variation
- **Seasonal tropics**: hot, with "summer" rain and "winter" dry (monsoon)
- **Subtropics**: dry and sunny, deserts and savannas, often with a well-defined rainy season (summer *or* winter)
- **Midlatitude temperate zone**: warm summers, cold winters, moisture varies by location but often comes in episodes throughout the year
- **Polar regions**: very cold, generally very dry, dark in the winter

Other Influences:

Ocean currents, "continentality," vegetation, mountain ranges (altitude and orographic precipitation)

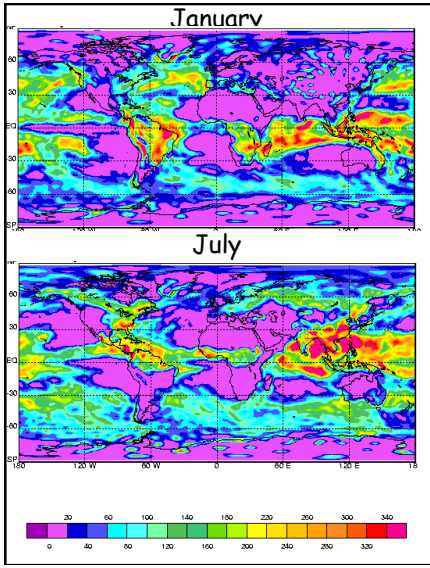
Mean Temperatures





- Latitude dependence
- Seasonality
- Continentality
- Ocean currents

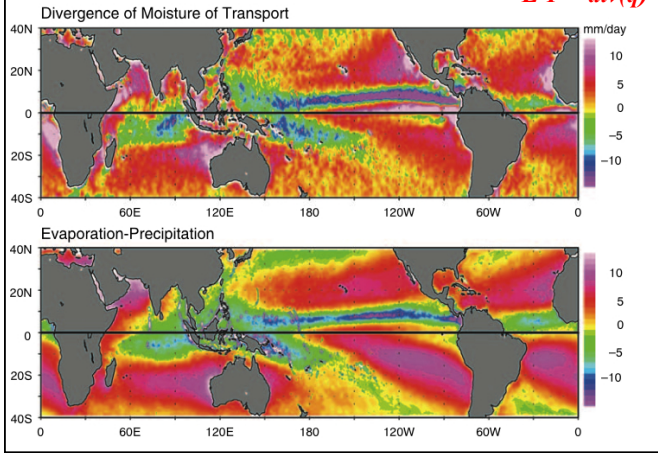
Precipitation (mm/month)



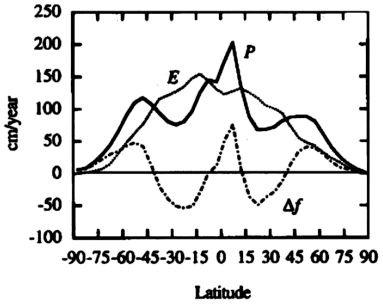
- Very wet over tropics
- Seasonal shift (N/S)
- Monsoon regions
- Extremely dry subtropical highs
- Midlatitudes get more summer rain
- July rainfall looks like a map of forest cover

Vapor, Winds, and Rainfall

E-P ~ div(q)



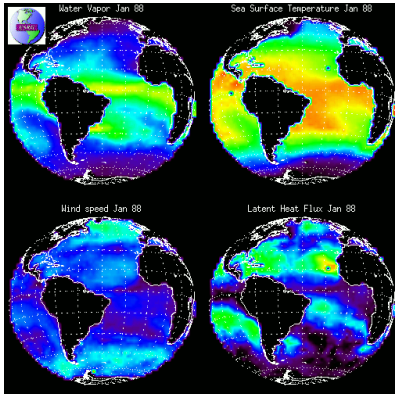
Atmospheric Water Balance



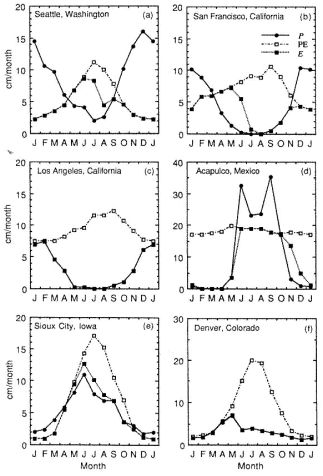
- P-E = Df = f_{in} - f_{out}
  - Net water import by atmosphere
- Water vapor is imported into the tropics and midlatitudes
- Water vapor is exported from the subtropics

Sources of Atmospheric Water

- Water vapor is concentrated in the tropics (Clausius-Clapeyron Eqn)
- Evaporation from the sea surface depends on R_{net}, T, u, and RH
- The greatest water source is in the *subtropics*, with near zero LE in the ITCZ

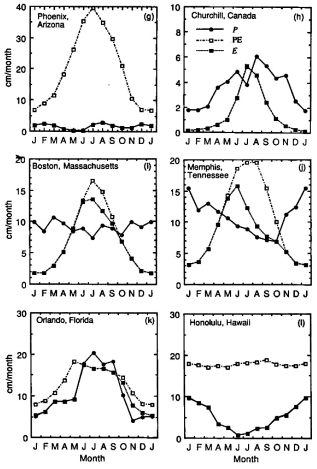


Seasonal Hydrology



- "Potential evap" tracks temp and radiation
- Winter rain/summer dry climates on the US West Coast
- Summer rain climates in tropics

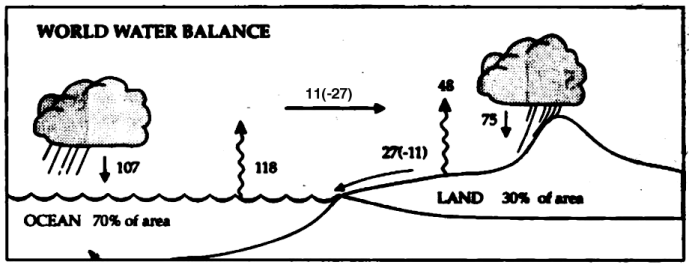
Seasonal Hydrology (cont' d)



- Actual E is strongly limited by water availability in many places (E ~ P rather than PE)
- Some midlatitude locations (e.g., Boston) have little seasonality in P, but strongly seasonal E

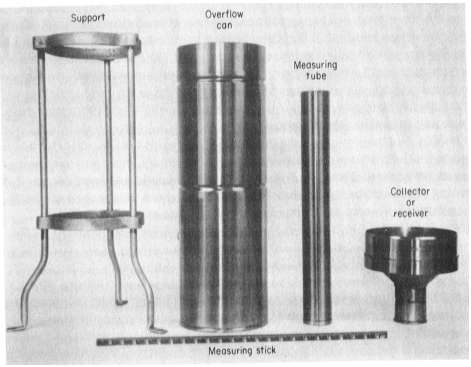
Land-Ocean Transfers

fluxes in cm/yr (adjusted for area of land and ocean)



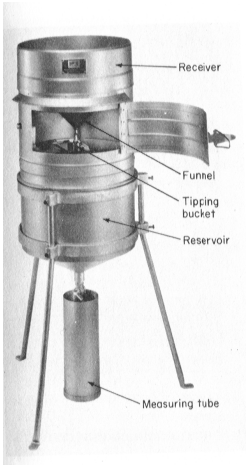
- Ocean transfers water to land in atmosphere
- Land returns this water in rivers
- Most precip over land (48/75=64%) is "recycled" water

Precipitation Measurement



Primary data on precipitation is a can with a stick

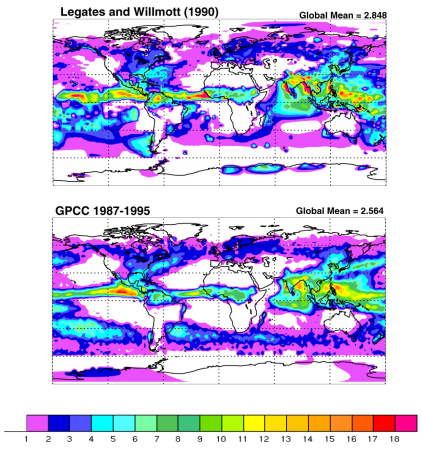
Precipitation Measurement



- These gauges can work well without supervision in remote areas
- What about snow?
- Wind shielding: Alter or Nipher shields
- Gauge catch is abysmal
- These are the "ground truth" by which radar and satellite products are judged!

Precipitation Climatologies

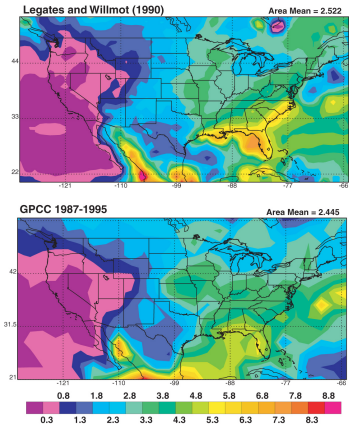
July Precipitation (mm per day)



- L&W (1990) used spherical interpolation to estimate 0.5° precipitation from about 20,000 gauge stations
- GPCC merges gauges with two kinds of satellite imagery to estimate precip on a 2.5 ° grid

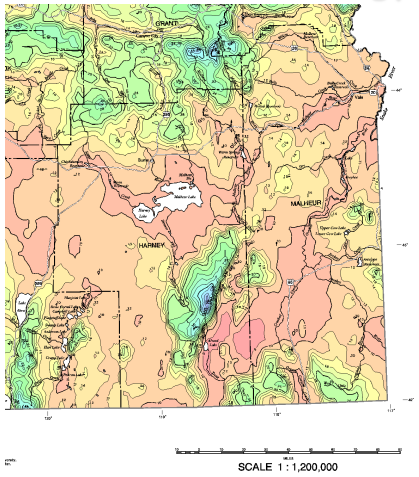
Precipitation Climatologies (cont' d)

July Precipitation



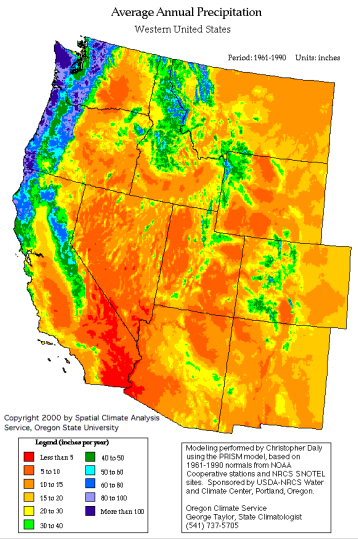
- Two climatologies agree that west is drier than east
- Many details are different
- Effects of resolution
- Where are the gauges?
  - Land vs ocean
  - Valleys vs mountains

PRISM Climatology (SW Oregon)



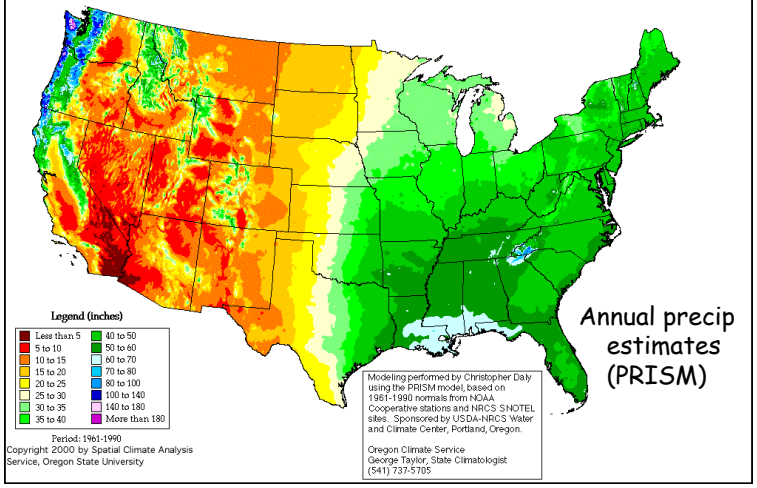
- Start with gauge data and a digital elevation model
- Divide the region into topographic "facets" by slope and aspect
- Develop regression relationships between gauge catch at each station and elevation, for each prism "facet"
- Apply statistics to each gauge to make a map of precipitation

Orographic Effects



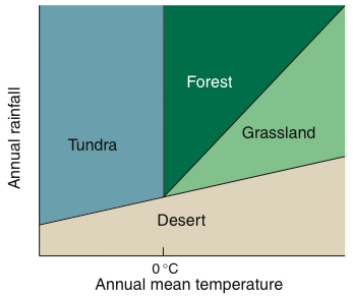
- Rain gauges are where the people are (flatlands and valleys)
- Most precip falls where the people aren' t!
- Precipitation rates in the west are dominated by orographic effects

PRISM Climatology

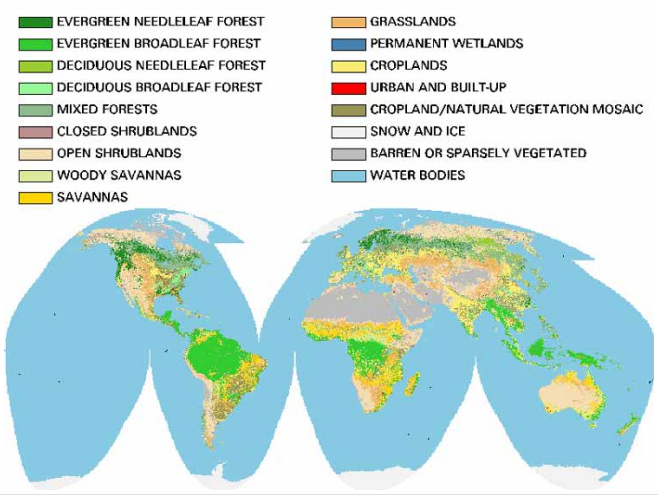


Annual precip estimates (PRISM)

Patterns of Climate and Vegetation



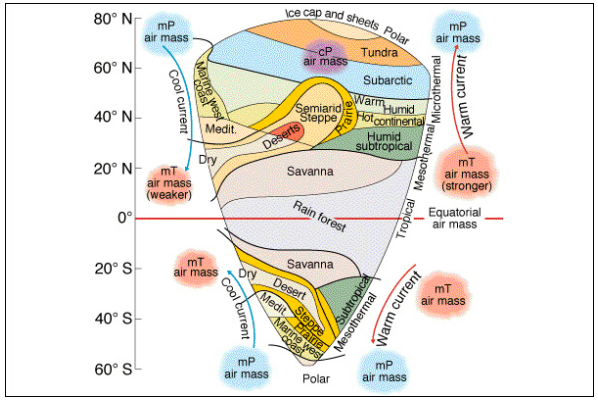
Classification of Land Vegetation



Land Use
(Percentage of Total Land Area)

Land use	Percent
Arable mixed farming and human areas	10–13
Grazing land	20–25
Extratropical forests (mostly conifer)	10–15
Tropical forests and woodlands	13–18
Deserts	25–30
Tundra, high latitude	6–9
Swamp and marshes, lakes and streams	2–3

Climate is Geography



an idealized continent