Climate Dynamics (PCC 587): Energy Transports

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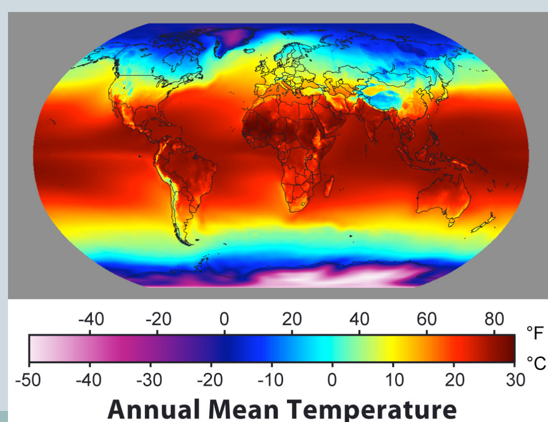
DAY 3: 10-8-09

Today

- We'll address what determines the north-south temperature gradients

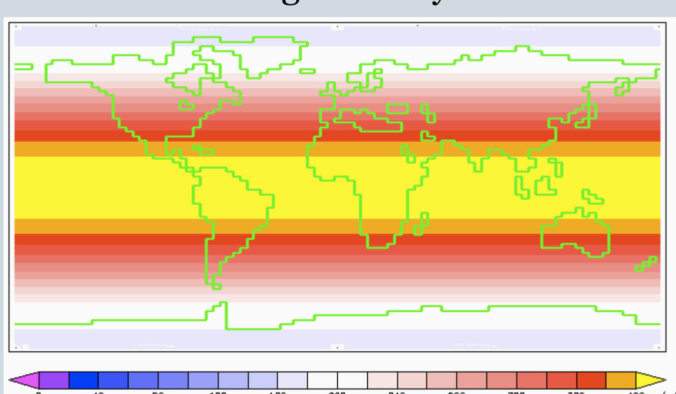


Outline

- Solar radiation as a function of latitude
  - Seasonal cycle
- A 1-D model (in *latitude*) for temperature and energy transports
  - "Energy balance model" used in project 1
- Justification of energy balance model
  - Using simple turbulence arguments
- Observed energy fluxes
  - Role of moisture

Solar Radiation

- Equator is heated strongly by the sun
- Pole receives significantly less radiation

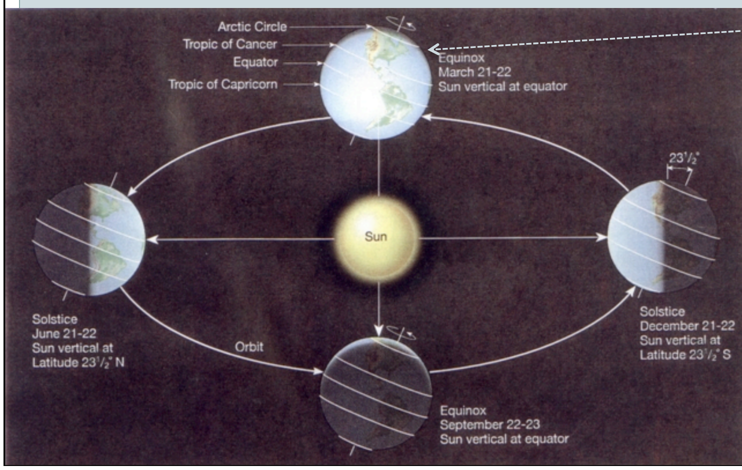


Annually averaged incoming solar radiation at the top of atmosphere

What determines this?

Solar Radiation

- Obliquity (tilt of Earth) is key to determining this
  - 23.5 degree tilt b/w axis of rotation and perpendicular to orbit

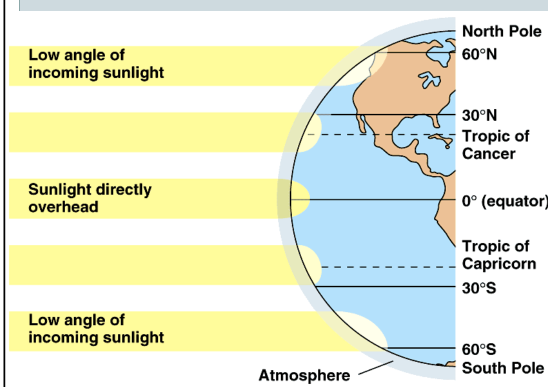


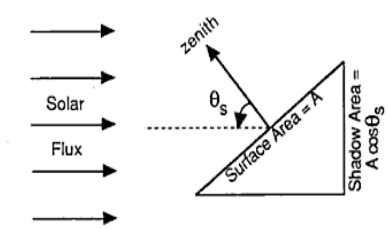
Equinox: sun directly above equator (March/ September)

Solstice: sun above 23.5 N (June) or 23.5 S (December)

Equinox Insolation

- Equinox case first
  - Symmetric between NH and SH, and tilt doesn't matter
  - Insolation just depends on *latitude* and *time of day*





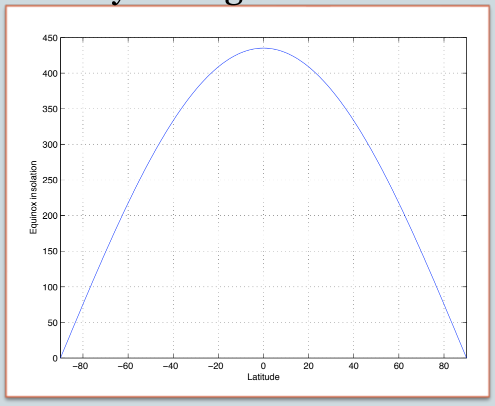
Depends on cosine of zenith angle

$$max(S_0 \cdot cos(h) \cdot cos(\phi), 0)$$

h = hour, phi = latitude

Equinox Insolation

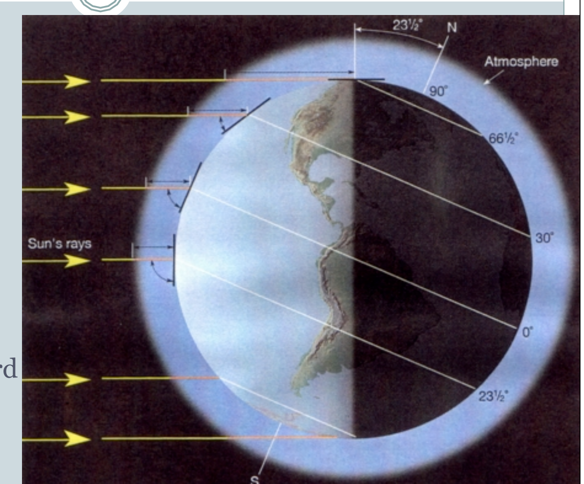
- Daily averaged insolation is $0.318 \cdot S_0 \cdot cos(\phi)$



Zero at the poles!

Solstice

- During solstice, sun is directly overhead 23.5°
  - More direct sunlight in summer hemisphere
- Length of day is very different b/w hemispheres
  - Perpetual night poleward of 66.5° in winter hem.
  - Perpetual day poleward of 66.5° in summer hem.



Solstice and Annual Average Insolation

- Length of day effect wins during solstice
  - Maximum insolation at poles!

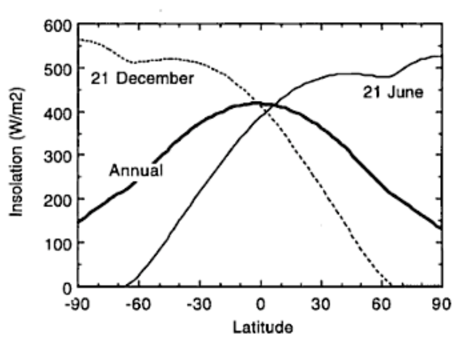


Fig. 2.7 Annual-mean and solstice insolation as functions of latitude.

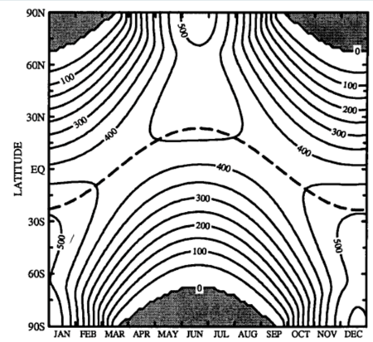
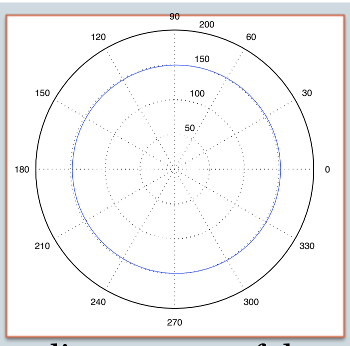


Fig. 2.6 Contour graph of the daily average insolation at the top of the atmosphere as a function of season and latitude. The contour interval is 50 W m^{-2}. The heavy dashed line indicates the latitude of the subsolar point at noon.

Hartmann

Elliptical Nature of Earth's Orbit

- The Earth's orbit is not perfectly circular
  - Eccentricity = 0.017 → → →
- We're closer to the Sun during SH summer
  - SH summers have more intense radiation (7% higher maximum insolation), but are also shorter



- We'll discuss this more in the paleoclimate parts of the course
  - Eccentricity, obliquity (tilt), and time of year when Earth is closest to the sun vary

Next: Back to Energy Balance

- Conservation of energy, globally averaged:

$$\frac{\partial E}{\partial t} = \boxed{Q_{solar}} - Q_{out}$$

Solar energy warms the Earth

The Energy Balance of the Climate System

- Conservation of energy, globally averaged:

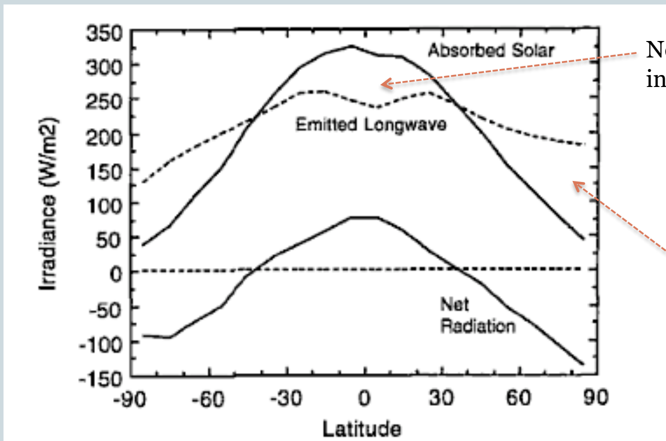
$$\frac{\partial E}{\partial t} = Q_{solar} - \boxed{Q_{out}}$$

Longwave radiation to space provides all the cooling

A function of temperature, water vapor, CO2, etc

Energetics as Function of Latitude

- Latitudinal profiles of shortwave in and OLR:



Net gain of radiation in tropics

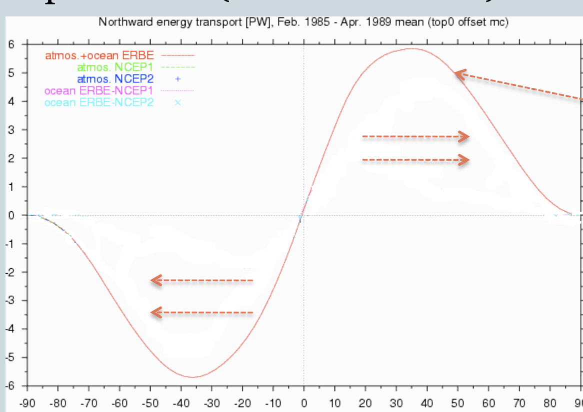
Net loss of radiation in high latitudes

How is this in equilibrium?

Hartmann

Energy Transports

- Climate system must be transporting energy polewards (from hot to cold)



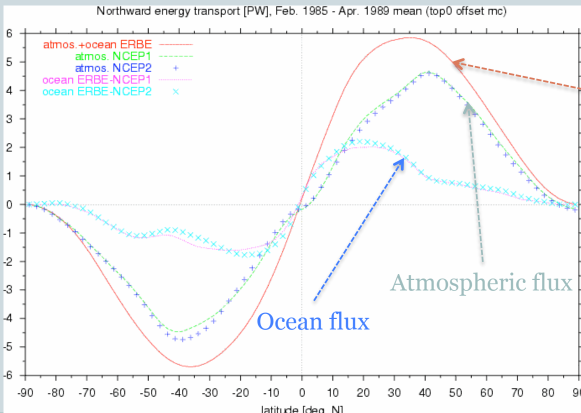
Total (atmosphere plus ocean) flux

Northward flux in NH, Southward flux in SH

Latitude

Energy Transports

- Separated into atmospheric and oceanic components:

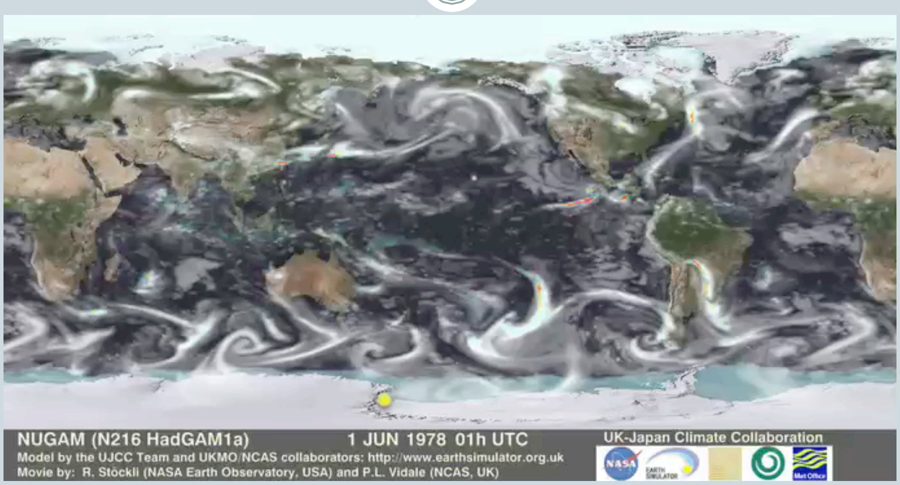


Latitude

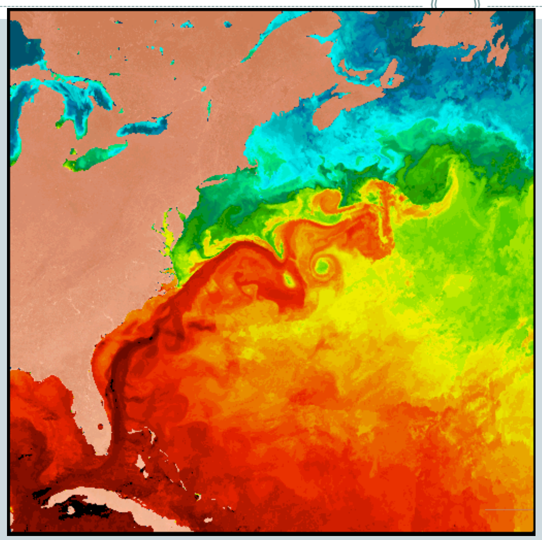
Total (atmosphere plus ocean) flux

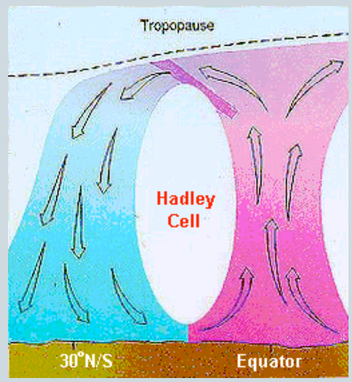
Atmosphere is larger in midlatitudes, ocean is larger in deep tropics

Atmospheric and Oceanic Energy Transports



Atmospheric and Oceanic Energy Transports





Energy Balance in 1-Dimension

- Conservation of energy, vertically integrated over atmosphere and ocean:

$$\frac{\partial E}{\partial t} + \frac{\partial F}{\partial y} = Q_{solar} - Q_{out}$$

F = northward flux of energy by the atmosphere and the ocean (could be internal (thermal) energy, potential energy, or latent energy – by mean flows or eddies)
y = latitude

(I've ignored the complications of spherical geometry here – see the handout for the calculations in spherical coordinates)

The Famous "Energy Balance Model"

- Assume the flux is proportional to the gradient:

$$F = -D\frac{\partial T}{\partial y}$$

- Resulting model is

$$\frac{\partial E}{\partial t} = Q_{solar} - Q_{out} + D\frac{\partial^2 T}{\partial y^2}$$

Energy Balance Model (EBM)

- Assuming steady state and using linear parameterization of outgoing radiation:

$$Q_{solar} - (A + BT) + D\frac{\partial^2 T}{\partial y^2} = 0$$

- Can be integrated to obtain temperature structure with latitude
- Interesting twist: add reflection by ice when the temperature goes below freezing
  - Can study ice-albedo feedback changes in different climates (snowball Earth, etc)
  - This is project 1…

EBM Weaknesses

- Ignores changes in vertical structure of temperature
  - Temperatures aloft radiate, not the surface
- Diffusive assumption likely not valid in tropics
  - Flux there is by Hadley circulation and ocean
  - Hadley circulation acts to flatten temperatures very effectively: enhanced diffusivity there?
- Ignores latent heat flux (moisture)
  - We'll see that this is rather important in the energy budget
- How good is diffusive form for fluxes in midlatitudes?

How good is the diffusive approximation?

- In the midlatitudes, flux is:
  - Primarily in the atmosphere (ocean flux is smaller)
  - Primarily due to eddies (as opposed to the mean flow, as in the tropics)
- Turbulence theory, under a few assumptions, predicts diffusive transport of conserved quantities by eddies

Mixing Length Theory

- Let's consider transport of a conserved scalar ξ by eddies: $\overline{v'\xi'}$

  Overbar: time mean
  Prime: deviation from time mean

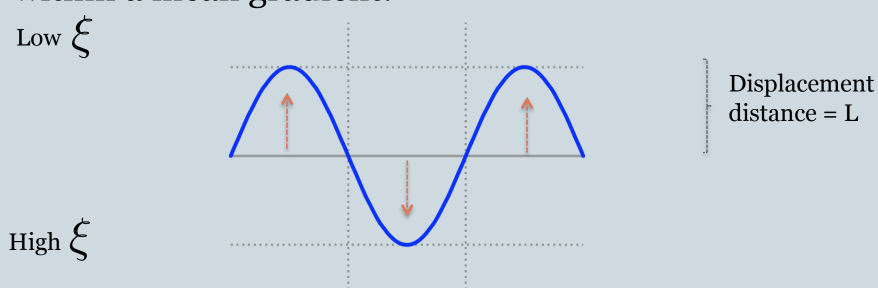
- First, write the flux as the product of the standard deviations of the quantities, and a correlation coefficient

$$\overline{v'\xi'} = k|v'||\xi'|$$

  - This can be considered to be the definition of the correlation coefficient

Mixing Length Theory

- Next, consider fluctuations of the scalar occuring within a mean gradient:



If ξ is conserved over its displacement, this generates fluctuations in ξ that are equal to

$$|\xi'| = -L\frac{\partial \xi}{\partial y}$$

Mixing Length Theory

- Combining, we have

$$\overline{v'\xi'} = k|v'||\xi'|$$
$$= -kL|v'|\frac{\partial \xi}{\partial y}$$

- Or, $\overline{v'\xi'} = -D\frac{\partial \xi}{\partial y}$ with $D = kL|v'|$
- Diffusivity is proportional to length scale times velocity scale (eddy intensity)

Usefulness of Mixing Length Theory

- Good for conserved tracers only
- Quantities like mixing length and eddy intensity may not be constant over parameter regimes
- Still considered a useful framework for thinking about energy fluxes though