Lecture(s) 9
Slides from atmosphere-ocean lectures
HAS 222d/253e  P.B.Rhines
ATMOSPHERE AND OCEAN

- finely layered, like a parfait, by fluid density, the atmosphere’s temperature decreases upward at about 7°C per km...80% of the mass of the atmosphere is in the troposphere, the lowest 8 to 10 km. and the temperature decreases 50 to 70°C from sea level to that altitude. The stratosphere above this level is more stratified, more stably layered. At the ground the pressure is about $10^5$ Newton.m$^2$ or Pascals. This simply reflects the weight of the air overhead.

In the deep sea the pressure, also the weight per square meter of the water overhead, rises to typically 400 times the atmospheric pressure at sea level. (water is 800 times denser than air at sea level. The upper 2.5m layer of ocean has the same heat capacity as the entire atmosphere above. The average ocean depth is 3800m yet the water in the atmosphere above if condensed would make a layer only 3 cm. deep!)

- solar radiation incoming (minus the simple reflection due to the whiteness..albedo..of clouds, snow and deserts) balances infrared radiation outgoing radiation. Without the atmosphere this balance gives a too-cold Earth (by about 35°C). With a one-pane-of-glass atmosphere model we have a too-warm Earth since convection in the air also cools the Earth. A distributed greenhouse effect gives a total downward radiation about 3 times the incoming solar radiation.

- But the radiation comes in more strongly in the tropics and exits more strongly near the poles. Heat- and water-flow carries the required energy poleward. the atmosphere is a heat engine, with Hadley convection cells driven by the difference between tropical and polar solar radiation, together with albedo differences and contrasts in evaporation of ocean water between tropics and polar regions.

- Clouds are the miniature heat engines the make the great general circulation go: the sun heats the ocean, the ocean warms the air and also evaporates moisture: both the ‘sensible’ and ‘latent’ heat fuels the vigorous overturning of the cloud visible as ‘cauliflower’ headed cumulus clouds. Where they bump up against the stratosphere they from ‘anvil clouds with flat tops.
– the ocean is also a heat engine, augmented by density differences due to the contrasts in salinity produced by evaporation and precipitation. But in addition the atmosphere blows winds on the sea, driving ocean currents through mechanical energy exchange…sort of two gear wheels, the atmosphere and ocean, meshed together and yet also forced by buoyant density differences. Ice and snow…the cryosphere are crucial components of the fresh-water cycling of the Earth…and they are disappearing…they affect albedo and ice can insulate the ocean from the atmosphere above. When the ocean surface freezes it rejects cold salty water (brine) which is very dense, while retaining nearly fresh water. Then when it melts in summer this ice makes a layer of quite fresh water at the surface.

– beside the density layering, the dominant feature that shapes the circulation of the atmosphere is the Earth’s rotation (through the Coriolis force). This force turns the north-south motions into east-west winds, which are the most visible part of the atmospheric circulation. Both the great overturning circulations and the east-west winds are cooperatively ventilating the tropics, warming the polar regions, and controlling rainfall, temperature and winds throughout the world.

– Ocean and atmosphere have many similar circulation features, jet streams (Science, 26 Jan 07), cyclones and anticyclones, global overturning circulations. Yet the size of these is 10 times smaller in the ocean, making ocean ‘weather’ more complex than atmospheric weather.

- The Earth’s spin is a vector sticking out of the North Pole. The strong rotation represents and angular momentum that is ‘inherited’ by the fluid oceans and atmosphere. A gyroscope illustrates the great strength of this spin: moving the spin axis requires great torque…after all, it involves changing the direction of the velocity, which requires a force.

- To gauge the strength of the Earth’s rotation, consider the ‘figure-skater effect’ which explains the westerly and easterly winds (the latter are the ‘trade winds’ in the tropics), weather systems, hurricanes and tornadoes. If air moves a distance L horizontally, it will gain a velocity roughly $10^{-4}L$: that is 100 m/sec for $L = 1000$ km. The air pressure provides a dominant force that balances this Coriolis force.
• Oceans and continents provide an interactive lower boundary for the atmosphere. Thus the oceans provide the water for the atmospheric heat engine...not a coolant so much as a propellant!

• **Mountain** ranges (dominantly the Himalayan plateau and Rocky Mts. of North America) shape the meandering pattern of the westerly winds and jet stream. The *northern hemisphere has far more land and mountains* than the southern hemisphere making it ‘wavier’, and giving it warmer polar temperatures (*more meridional* (i.e., north-south) *heat- and moisture circulation*)....Antarctica and the atmosphere above are colder than the Arctic. The *Antarctic ozone hole* is a consequence of this difference
Average vertical variation of temperature in the atmosphere. The troposphere (the lowest 8 to 10 km contains 80% of the mass of the atmosphere)

the zone radiating back directly to space has average temp of about 250K, close to the simple $\sigma T^4$ radiation temp

290K = average surface temp

255K (-18°C)..the simple radiation temp of Earth
solar radiation arrives at the top of the atmosphere: 1372 W/m² / 4 = 343 W/m² incident sunlight, then with albedo .... x 0.7 = 240 W/m² (numbers vary somewhat; 235 in fig below)

consider the differences between tropics and Arctic...(a) at 60N latitude the sunshine incident per unit area is 50% of the full intensity with the sun overhead; (b) the albedo (whiteness) is greater
Water....

is a primary Greenhouse Gas along with methane, ozone

\{Water vapor accounts for about 75 Watt meter\(^2\) ...with clouds 51 Watts/meter\(^2\) of extra downward radiation.}

\textbf{carbon dioxide accounts for about} 32 Watt meter\(^2\) ...with clouds 24\}

\textbf{sunshine causes}

\textbf{evaporation} which feeds atmosphere 13.7 Sverdrup (13.7 \( \times 10^9 \) kg/sec) ...137 Amazon rivers

\textbf{water vapor in atmosphere flows from warm latitudes to cold} latitudes, Eq -> poles ...at a rate of about 1 Sverdrup

the north-south/up-down movement, or ‘overturning circulations’ of Oceans and Atmosphere share this poleward flow

water \textbf{flows from seas to land} Big continents are dry. Mountains catch the rain, yet continents like Australia have few. The Flat Earth does not refer only to economics and medieval astronomy

\textbf{water vapor is stored form of heat}.....(scalding by steam: 2.26 million Joules per kg. ..to evaporate or condense water)

Water vapor carries \textbf{fully ½ the poleward heat transport of atmosphere} in a transport mode which is shared with the ocean.
consider the differences between tropics and Arctic…

- (a) at 60N latitude the sunshine incident per unit area is 50% of the full intensity with the sun overhead;
- (b) the albedo (whiteness) is greater:

  - Fresh snow or ice 60-90
  - Old, melting snow 40-70
  - Clouds 40-90
  - Desert sand 30-50
  - Soil 5-30
  - Tundra 15-35
  - Grasslands 18-25
  - Forest 5-20
  - Water 5-10
• But radiation is not everything. The one-pane-of-glass greenhouse model overpredicts the greenhouse ‘blanket’, giving a mean surface temperature of $2^{1/4} \times 255\text{K}$ the simple radiation temperature. This is 303K, or 30°C, warmer than observed (290K, 18°C)

  The reason is convection and circulation which cools off the Earth’s surface, heating the lower atmosphere with both sensible warmth and latent warmth in the form of water vapor.

http://oceanworld.tamu.edu/resources/oceanography-book/radiationbalance.htm
Latent Heat

- “Latent” heat is required to evaporate water
- Heat is released again when water vapour condenses
- Transports heat vertically

*Latent* = hidden
Figure 1.6. Schematic representation of the general circulation of the atmosphere during Northern Hemisphere summer. Because of maximum heating in the Northern Hemisphere tropics, the southern Hadley cell, from the summer to the winter hemisphere, is much stronger than its winter counterpart. (During southern summer the northern Hadley cell is much stronger.) Also shown in the figure are continuations of the tropical Hadley cell are the northern and southern mean extratropical circulations. These are the average result of highly structured circulations associated with extratropical synoptic waves (after Meehl, 1987; see Chapter 2 for details).
solar radiation (kilowatt-hours per square meter, per day) varies with latitude and season (here neglecting the great effect of cloudiness)

www.fao.org/DOCREP/003/X6541E/X6541E03.htm
Variation of Temperature With Latitude

- A simple radiative calculation gives an Earth with the correct average $T$, but wrongly distributed meridionally (north-south)

*slide from K. Carslaw, Univ. of Leeds*
Global Distribution of upward Longwave Radiation

Note that average emitted longwave radiation is equal to the absorbed solar energy (342 Wm\(^{-2}\) minus the 30% reflected)
Satellite image of water vapor (not cloud…it’s gaseous water which is normally invisible). This water vapor carries heat to the Arctic from the tropics. 

**moisture streamers:** (1 Sverdrup...$10^9$ kg/sec transport of water carries $2.2 \times 10^{15}$ watt thermal energy)

**poleward moisture flux at 70N**

*(Dickson et al. 2000)*
The General Circulation involves overturning circulations (‘conveyor belts’) in the north-south direction, like the Hadley convection cell shown below, in the tropics. Yet these north-south motions induce east-west winds by the ‘figure-skater effect’; that is, the Earth’s spin is concentrated or ‘diluted’ by moving air closer to the Pole, or farther from it, respectively.
A simple lab model of the atmospheric circulation shows these induced eastward and westward winds: a beaker of ice in the middle of a salad bowl filled with water, rotating (could be on a $1 turntable from your local antique shop)...makes jet streams, Hadley cell, ‘weather’, red and green.
The Trade Winds

- Columbus discovered the Trade Winds in 1492. They are the ‘slowing’ of the figure skaters spin as he stretches arms outward
Heat transport from tropics to polar regions.

The ocean and atmosphere share the job of transporting heat and fresh-water poleward from the overheated tropics. It is sort of a ‘leap-frog’ process, with the ocean acting as a reservoir for both heat and fresh-water.

The heat transport in a simple fluid like the ocean is equal to the product

\[ C_p \times T \times M \]

that is, T, the temperature (°C) times \( C_p \), the specific heat capacity (Joules/(kg °C) or equivalently, Joules/(kg °K)) \( \times M \), the mass flow rate (kg/sec).\ldots the units multiply to Joules/sec or Watts. The warmer, northward flowing ocean currents near the surface, like the Gulf Stream, have nearly the same mass flow rate as the cold deep currents flowing southward. The magnitudes shown in the next figure are about 2 x 10\(^15\) Watts (that is, 2 petaWatts) for the ocean contribution to heat transport. \( C_p \) is roughly 4000 Joules/(kg °C)

Hence the heat transport in this case depends on the temperature difference between northward and southward flowing currents. (In some situations we reference the temperature to absolute zero, using degrees Kelvin, but it doesn’t matter if the mass flow is equal and opposite in the two directions).

footnotes:

The specific heat capacity is the amount of heating required to raise the temperature 1 degree C (or K). When fluid flows in one direction hot, and comes back cold, it is the temperature difference that matters (the same value of \( M \) applying in both directions).

A useful alternate expression for heat transport is

\[ \rho C_p T A V \]

where \( \rho \) is the density of the fluid (kg/m\(^3\)), \( A \) is the cross-sectional area of the current (m\(^2\)) and \( V \) is the velocity. Thus, \( \rho AV = M \).

These formulas are examples of the general expression for the transport of a quantity of ‘stuff’ dissolved in a fluid: transport of stuff (kg/sec) = concentration of the ‘stuff’ (kg of stuff/ kg of fluid) \( \times \) transport of fluid (kg of fluid/sec).
Global meridional heat transport divides roughly equally into 3 contributing modes:
1. warm winds blowing northward, cold winds southward (dry static energy) atmosphere \( \sim 3 \ \text{pW (} \approx 3 \times 10^{15} \ \text{Watts)} \)
2. warm ocean currents flowing north, deep cold currents flowing south (sensible heat) ocean \( \sim 2.5 \ \text{pW} \)
3. moist air from evaporation in subtropics (green zone below) blowing northward, raining out at high latitude, returning south in ocean (a joint atmosphere/ocean mode) \( \sim 2.2 \ \text{pW} = 1.0 \ \text{Sv} \) (1 megatonne per sec)

The three modes of poleward transport are comparable in amplitude, and distinct in character

(residual method, TOA radiation 1985-89 and ECMWF/NMC atmos obs

Error est.: \( \pm 9\% \) at mid-latitude; Bryden est 2.0 \( \pm 0.42 \ \text{pW} \) at 24N

Sources: Keith, Tellus 97; Trenberth J Clim 2001
The overturning circulations of the ocean (the ‘conveyor belts’) involve warm, upper-ocean water flowing northward like the Gulf Stream (red), then sinking in the subArctic zone, and southward flow as deep, cold currents (black).
topography of the northern Atlantic/Arctic ocean basins, with Greenland’s ‘ice mountain’. Note the vertical heights are greatly exaggerated but otherwise the detail is accurate. The black curve at about 60° North latitude is the section of temperature shown on the next figure.
Erika Dan temperature section from Labrador to Greenland to Ireland, 60N

Worthington and Wright, 1962

Warm currents (red) fed by the Gulf Stream flow north, leaning on Europe.

Deep, cold currents (blue) flow round the rim of the ocean, winding southward.
Predicted change in the atmosphere by late in this century: warmer, more water vapor, shifted storm tracks, enhancement of bands of dry and wet (precipitation); note dry regions will get drier, wet regions get wetter

IPCC climate models evaluated at 2080-99;
Rainfall in Perth, Western Australia: increasingly severe drought over the past 30 years
Greenland’s freshwater discharge has tripled in the past decade to 150 km$^3$ yr$^{-1}$, putting in the league with Arctic rivers (Rignot & Kanagaratnam, Science 2006); summer melt area greatly increased (Steffen & Huff, CIRES website)

*If all of Greenland’s ice were to melt, the sea surface would rise 7 m, world-wide.*
• upcoming in Weeks 8-10:
  – what causes societies to succeed or fail? (J. Diamond: *Collapse*)
  – global energy…
    • Roberts: peak oil
  – alternative energy sources
    • solar, hydro (rivers and tides), biofuels
    • nuclear
  – can-do strategies: looking forward
    – Pacala: wedges of carbon remission
    – Diamond: Collapse: what causes societies to succeed or fail (hint: environment)