Lectures 7-8  Thurs 23.iv.09
HAS 222d Introduction to energy & environment
Atmosphere-ocean: circulation
The atmosphere/ocean system is a ‘heat engine’ largely driven by the sun…that is, a contraption in which heated fluid (air or water) expands and, under gravity, becomes buoyant and rises. The ‘input and output’ temperatures differ by very roughly 30°C and so the heat engine cannot convert more than about 10% of the heat flow to the Earth into mechanical energy of the circulation (10% is from the Carnot efficiency, \((T_1-T_2)/T_1\) using 300K and 270K as the absolute temperatures meet: Benjamin Thompson (Count Rumford) 1753-1814

[Image of Benjamin Thompson (Count Rumford) 1753-1814]

http://www.rumford.com/Rumford.html
determining the conversion of mechanical energy into thermal energy (‘heat’)

A cannon barrel is bored from solid iron by a pair of horses connected to an auger... (drill) ...Rumford built a box around the barrel, filled it with water and kept track of the rising water temperature. This established the equivalence of thermal energy and a known amount of mechanical energy (exerted at a rate of 2 horsepower!)
The origin of the Rumford brand name is traced to Count Rumford (Benjamin “James” Thompson of Woburn, Massachusetts), a gifted inventor and scientist. Thompson, who is said to have bootlegged physics courses at Harvard when still a poor boy, became one of the discoverers of the Law of Conservation of Energy, and left the endowment for the Rumford Professorship in 1814. The Rumford Chair of the Application of Science to the Useful Arts was given to those who showed exceptional achievements in Science and Cooking. Professor Horsford, founder of the Rumford Company, once occupied the Rumford Chair at Harvard. The Rumford brand logo depicts a cameo of Count Rumford in honor of his contributions to the fields of cooking and baking. “In what art or science other than cooking could improvements be made that would more powerfully contribute to increase the comforts and enjoyments of mankind?”

Rumford was a Royalist, unpopular in the American colonies, and at the Revolution fled to England and Germany, where he became the ‘Count’ choosing his New England town for his new title.
ATMOSPHERE AND OCEAN

- finely layered, like a parfait, by fluid density, the atmosphere’s temperature decreases upward at about $7^\circ$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 $70^\circ$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 $35^\circ$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.'
Water....
plays many roles in the global environment: carrying thermal energy, forming the oceans, as a solvent and essential element in photosynthesis

is a primary greenhouse gas along with methane, ozone
Water vapor: 75 Watts per meter$^2$ with clouds 51
CO2: 32 Watts per meter$^2$ with clouds 24
incoming sunshine...the Mother of all energy sources enters ocean

evaporation feeds atmosphere 13.7 Sv (13.7 megatonnes per second)...137 Amazon rivers

flows from warm latitudes to cold latitudes, Eq -> poles
the north-south/up-down movement, or ‘overturning circulations’ of O and A share this poleward flow

water vapor is stored form of heat....the energy required to evaporate water at room temperature is 2.5 million Joules per kg....this known as the specific heat of water (measured at constant pressure).
....so evaporation requires (absorbs) heating, and that heat energy is given up where the vapor condenses into rain or snow

Atmospheric poleward flow of water ~ 1.6 Sverdrup of flow ~ 16 Amazon rivers
Water vapor carries fully ½ the heat energy of atmosphere
ICE is less dense than water...about 92% of the density of water; it floats. This is unlike the behavior of most substances, which generally are denser as solids than as liquids (right). This is a result of the hexagonal structure of ice, which leaves much open space. The hexagon (six-sided polygon) form of ice leads to a 6-fold symmetry of snowflakes (seen in next figures).
The shape of the water molecule and the hydrogen bond (the electrostatic attraction between the oppositely charged parts of two nearby molecules): these determine the shape of the ice crystal. The hydrogen model is ‘polar’, with the oxygen atom so strongly attracting the electrons away from the two hydrogen atoms that the molecule has regions of net positive charge (the hydrogen atoms stripped of their electrons) and a region of net negative charge (where those electrons go). This means that the attraction between adjacent water molecules is very large in liquid water or ice; the boiling point of water is far greater than it would be without the inter-molecular attraction…called the ‘hydrogen bond’.

[Image of Water and Ice Structures]

http://www.indiana.edu/~g131/struct.html
"Under the microscope, I found that snowflakes were miracles of beauty; and it seemed a shame that this beauty should not be seen and appreciated by others. Every crystal was a masterpiece of design and no one design was ever repeated. When a snowflake melted, that design was forever lost. Just that much beauty was gone, without leaving any record behind."

Wilson "Snowflake" Bentley 1925
The 3000m thick ice cap contains a record of more than 100,000 years of Earth’s climate; it is the last remnant of the northern hemisphere glaciation during the last ice age. 100,000 years is about the length of the ice-age cycles currently. Ice-cores are drilled at the sites shown at left, all the way to bed-rock, and the annual layers of ice (compacted from each winter’s snowfall) tell us much about climate, year by year.

The ice flows slowly like a viscous fluid toward the ocean. This flow has accelerated in recent years, possibly due to the warming ocean where the glacial tongues meet the sea.
The biosphere as seen with satellite images of color (here ‘false color’ to bring out detail). Chlorophyll of primary production, vegetable matter (‘grass of the seas’) in ocean; snow-cover, forests, deserts on land and ‘blue deserts’ in ocean. The pattern shifts with the seasons, as the animated version shows. The fine detail shows the effects of major ocean currents and, particularly the role of upward flow of the ocean in bringing nutrient rich, cold, deep water up to the top few meters of the ocean where it joins the sunlight to make photosynthetic plankton. This upward flow occurs in most of the greenish regions note the bands of wet and dry land..from rain forests to deserts, which are tied to the cycling of fresh water evaporated from the oceans
Baffin Bay: Greenland at the right, Baffin Island at left. Sea ice can be seen on the west side of Baffin Bay flowing south from the Arctic. Low clouds appear on the east side of the Bay.

www.ocean.washington.edu/research/gfd/gfd.html
prediction of physical climate is not our only goal.

Here we see (in false color) spring plankton growth (primary productivity) in Baffin Bay. The whole food chain is active here, up to the sea birds and great whales.

The ocean’s overturning circulation makes possible the great biological food chain of the Arctic.
Here the dovekie (bird) relationship with ocean plankton is suggested.. with fish being an intermediary.
The Hadley cell is a convection pattern created by heating of the air near the Equator...upward motion near the Equator and downward motion at latitude 20 to 30° north and south. The Earth’s rotation takes this pattern and creates westward winds (called ‘easterly’) at the Equator and eastward winds (called ‘westerly’) away from the Equator.
Here the easterly ‘trade’ winds can be seen (called the trades because of sailing ships trading between Asia, N. America and Europe). The westerly winds dominate our weather at higher latitude.
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 cold ‘polar’ region contrasts with the warm subtropics, making a Hadley cell (overturning circulation, up-down, north-south). However the Earth’s rotation breaks this cell into storms and concentrated jet streams.
Surface air temperature (degrees C) on two January days (in 1993 and 2001). Heat radiates to space everywhere, but in absence of strong solar radiation at high latitude, this outward infrared heat radiation cools the air rapidly. Here the blue (cold) air is flowing south from Arctic to Canada to US. These ‘cold air outbreaks’ are guided by the Rocky Mountains, and occur frequently in winter. When the cold air flows out over the ocean it is rapidly warmed by the ocean, and storms intensify there.
the atmosphere is a giant heat engine, driving a comfort-control system for the Earth’s biosphere:

- solar heating produces north-south contrast in temperature and hence density of air; this is a transformation from *thermal energy* to *mechanical, potential energy, PE* because gravity will try to put the dense fluid beneath
- the cold, dense air of the Arctic slides southward underneath the less warm, less dense air of the tropics (a transformation from *PE* to *KE*, kinetic energy).
- the Earth’s rotation (spinning about the North Pole) is ‘concentrated’ by these southward flows, making strong westward and eastward winds, jet streams, and violent weather. These large concentrations of KE are the ‘output’ of the heat engine.

this complicated figure shows the circulation (actually the curves are isobars..constant pressure curves) at several levels in the northern hemisphere. The colors show pressure at sea level (not temperature), just as in a normal weather map. The blue storms intensify over the oceans (Pacific left, Atlantic at center).
The ocean circulation looks complex, but it is doing similar things; here the warm (red) currents carry water and heat northward while deep cold currents (black) return the flow.

Melted ice floats as fresh water (or low salinity water) near the surface (purple) and moves southward. It insulates the ocean from the cold atmosphere above. This buoyant water is the basis for the idea that global warming may slow down the ocean circulation.
The oceans are doing similar things, but with very different patterns. Heat moving north, fresh water moving south in ocean.... Subpolar Atlantic and exchange with the Arctic: well-defined passages, ridges, gaps. The red line is lies along the section plotted in the next figure.
water temperature (degrees C) on an east-west section through the North Atlantic Ocean; Canada at left, Europe at right (see previous figure for location). The red (warm) water is moving northward through the section, leaning to the east on Europe due to the Coriolis force. The blue, cold water is moving south, also banked up on the slopes of Greenland and Labrador. The densest waters are in thin layers near the bottom (note the ocean surface is at the top, the depth scale is at left).
Lab model of the overturning circulation of the ocean. The horizontal velocity is much greater than the vertical velocity because of the ratio width:depth of oceans (~1000:1 or greater).
water vapor: 50-70% of the greenhouse effect; 
½ the flow of thermal energy from Equator to Poles; 
oceans dominate storage of heat, carbon, water 
global precipitation rate $F = 5.2 \times 10^{14}$ m$^3$/year...16 Sverdrups 
stock of water in the air: $M = 1.3 \times 10^{13}$ m$^3$ (liquid equivalent) 
residence time of water in the air: $M/F = 9.1$ days (see Sph.Cow)

area of Earth $5.1 \times 10^{14}$ m$^2$  
mass of ocean $1.4 \times 10^{21}$ kg... 2.5cm
water evaporates from the Great Lakes when cold north winds blow over them. It soon condenses back into water, as cloud droplets which then rain or snow out...The lake water has become cloud, and then the cloud piles up as deep snow, downwind of the lakes. This is called 'lake-effect snow'.
Satellite image of water vapor (not cloud...its gaseous water which is normally invisible). This water vapor carries heat to the Arctic from the tropics.  

*moisture streamers:* (1 Sverdrup...$10^6$ m$^3$/sec transport of water carries $2.5 \times 10^{15}$ watt thermal energy)

poleward moisture flux at 70N  
*(Dickson et al. 2000)*
more water vapor, being carried by storms. The bright colors are towering cumulus clouds near the Equator.
floating sea ice in the Arctic Ocean melts somewhat in summer, but recently this summer melt-back has increased greatly, changing both climate and ecosystems of the far North. The tall Greenland ‘ice mountain’ is visible. Greenland is a large island, extending ¼ of the way between Pole and Equator, it strongly affects winds and storms in the Atlantic, which are transporting heat and moisture north toward the Arctic.