Oceans and the Global Environment: taking physics and chemistry outdoors

the buoyancy-driven circulation

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www.ocean.washington.edu/courses/has221a-08
Logistics: Tues 2 Sept 2008

- reading: McKibben 3d chapter 92-138 A Promise Broken
  Kunzig 200-234 Greening the Ocean

(last week: McKibben 2d chapter 47-91 The End of Nature
  Kunzig 293-319 Ch 14 The Climate Switch
  43-85 Ch 3 The Rift in the Atlantic/ The Seafloor at Birth

all this is posted on the class website. See the website for 2 September, for
the list of all the reading so far.

- hurricane Gustav
Figure 3. Tropical Cyclone Heat Potential (TCHP, in kJ/cm^2) for August 28, 2008. Values of TCHP greater than 80 are commonly associated with rapid intensification of hurricanes. The forecast points from the NHC 5 am Saturday forecast are overlaid. Gustav is expected to cross over a portion of the Loop Current with extremely high value of TCHP of 120 after crossing Cuba. However, Gustav will then cross over a cold eddy, and will miss crossing the warm Loop Current eddy that broke off in July. Image credit: NOAA/AOML.

Hurricane Gustav apparently did only modest damage (~$10 billion doesn’t sound modest to me), at least far less than Hurricane Katrina just 3 years ago.

A strong controlling factor is the degree of warmth of the ocean beneath its path. These maps show the heat stored in that warm water, in the upper ocean. Gustav intensified near Cuba but then escaped over colder water, dropping to category 2 hurricane when it made landfall. You can see why predicting hurricane intensity and path is difficult.
the ocean is a heat/salt/fresh-water 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...albedo, latent heat, salinity production...

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 involves angular momentum, as with a spinning wheel, a toy top. This spin 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 a ring of fluid (air or water) about the North Pole moves northward, it comes closer to the Earth’s axis. Its angular momentum stays the same, hence its velocity about the Pole increases (by 100 m sec⁻¹ for 1000 km northward movement).

+ Angular momentum of fluid on the Earth is equal to the east-west velocity of the fluid multiplied by the distance to the central axis of the Earth.
The buoyancy-driven circulation: heat, salt, fresh water, ice
Convection in fluids:

heat engines: the idea of converting thermal energy into mechanical energy. Suppose a fluid is heat and cooled, as well as compressed and de-compressed. It experiences changes in pressure and volume.

For air, the equation of state of an ideal gas, \( PV = nRT \), tells us then how the temperature changes.

As the air changes cyclically, it generates mechanical energy, for example lifting a weight or propelling a car. The amount of that work is equal to the area enclosed by the curve on the P-V plane.

\[
V (=1/\rho)
\]
Convection is fluid flow driven by fluid buoyancy: dense fluid sinking, less dense fluid rising. The equation of state tend to associate warm temperatures with low density, so we have rising warm fluid, sinking cold fluid...or possibly rising low-salinity water and sinking high-salinity water.

Archimedes Principle tells us how the downward gravity force on a fluid region is balanced by an upward pressure force exerted at the edges of this region. If all the fluid is cool, with the same density, we then replace a sphere of cool fluid with a sphere of warmer fluid. If both have the same volume, the new warm fluid will weigh less than the cool fluid it replaced. Hence the upward pressure force will be larger than the downward gravity force and the warm fluid will rise. These are very small forces. For water, a 1°C rise in temperature causes a fractional density decrease of about $3 \times 10^{-4}$; the water is 0.03% less dense (this value is for 25°C water). For air, the thermal expansion coefficient is simply $1/T$ where $T$ is the temperature (in degrees Kelvin). Thus at room temperature (293°C Kelvin) the thermal expansion of air is $1/293$ or 0.34%, considerably greater than that of water.

So these buoyancy forces are very weak, yet they are what drive the entire circulations of the atmosphere and oceans.
Benjamin Thompson (Count Rumford) 1753-1814: American colonist in Concord (Rumford) New Hampshire; allied himself with the British as the Revolutionary War approached, escaped to England and then Germany; yet he later endowed a professorship at Harvard.

http://www.rumford.com/Rumford.html
Besides inventing efficient fireplaces, the double boiler, drip coffee makers, Rumford determined the conversion of mechanical energy into thermal energy (‘heat’). He experimented with gunpowder for the British, invented a nutritious soup for the poor, developed cultivation of the potato in Bavaria.

When cannon barrels were bored out it was noticed that the metal became very hot. Rumford captured that heat in a wooden box filled with water, and estimated how much work was done and how much thermal energy produced. It’s a bit tricky because cutting metal involves breaking molecular bonds, so not all the mechanical energy goes into heating the water. But this key physical principle: the conservation of energy and transformation from mechanical work (= force \times \text{distance moved}) to thermal energy (‘heat’) is largely due to him.
The Rumford Chair of the Application of Science to the Useful Arts at Harvard was given to those who showed exceptional achievements in Science and Cooking. It led to the founding of the Rumford Company by Eben Horsford.

Rumford Company - Baking Powder - 10 oz by Rumford Company
Buy new: $2.39
In Stock
(3)
Grocery: See all 4 items
In 1751, the captain of an English slave-trading ship made a historic discovery. While sailing at latitude 25°N in the subtropical North Atlantic Ocean, Captain Henry Ellis lowered a "bucket sea-gauge", devised and provided for him by a British clergyman, the Reverend Stephen Hales, down through the warm surface waters into the deep. By means of a long rope and a system of valves, water from various depths could be brought up to the deck, where its temperature was read from a built-in thermometer. To his surprise Captain Ellis found that the deep water was icy cold.

But it was not until several decades later, in 1797, that another Englishman, Count Rumford, published a correct explanation for Ellis's "useful" discovery: "It appears to be extremely difficult, if not quite impossible, to account for this degree of cold at the bottom of the sea in the torrid zone, on any other supposition than that of cold currents from the poles; and the utility of these currents in tempering the excessive heats of these climates is too evident to require any illustration."

So there you have it: two Benjamins (Franklin and Thompson) in the years of the American Revolution, one a patriot colonial and one a Royalist exile, but both inventors and scientists of the highest order.
The Role of the Atlantic Conveyor in Climate

The cold water discovered in the subtropical Atlantic by Ellis in 1751 was, as Rumford theorised, brought there by a current which had originated in the polar region; temperature measurements in the real ocean and computer models show there is a southward outflow of cold deep water from the Arctic throughout the Atlantic. This cold water is replaced by warm surface waters, which gradually give off their heat to the atmosphere as they flow northward towards Europe. This acts as a massive "central heating system" for all the land downwind.

The heat released by this system is enormous; it measures around $10^{15}$ Watts, equivalent to the output of a million large power stations. If we compare places in Europe with locations at similar latitudes on the North American continent, its effect becomes obvious. Bodø in Norway has average temperatures of $-2^\circ$C in January and $14^\circ$C in July; Nome, on the Pacific Coast of Alaska at the same latitude, has a much colder $-15^\circ$C in January and only $10^\circ$C in July. And satellite images show how the warm current keeps much of the Greenland-Norwegian Sea free of ice even in winter, despite the rest of the Arctic Ocean, even much further south, being frozen.

It is not just the ocean alone that is warming the polar regions: the atmosphere and ocean both carry heat from the warm tropics to the cold, high latitudes. It is a shared enterprise!

If the Atlantic 'Conveyor Belt' circulation is switched off in a computer model, a different climate forms in the virtual world. There is little change in ocean temperatures near the Equator, but the North Atlantic region becomes much colder than it is in reality, and the South Atlantic and other parts of the Southern Hemisphere become warmer. This experiment reveals that the Atlantic circulation moves heat from the South Atlantic below the Equator across the tropics to the North Atlantic — the heat is not coming directly out of the tropical region.

http://www.pik-potsdam.de/~stefan/essay.html
FIGURE 10.27 A vertical cross section of the Atlantic Ocean shows the various water masses that form layers at different depths. Antarctic Bottom Water is the densest water mass, and it flows northward from around Antarctica. North Atlantic Bottom Water sinks near Greenland and flows southward over the top of Antarctic Bottom Water. Intermediate-depth water masses are formed and sink at the Antarctic and subpolar convergences. The near-surface layers are more complex. Note the tongue of Mediterranean Water that spreads across the North Atlantic Ocean from the Straits of Gibraltar at about 2000 to 3000 m depth between 20°N and 55°N.
hydrographic section carried out in WOCE (world ocean circulation experiment) in the 1990s
section view of temperature (in degrees Celsius, actually ‘potential temperature’) from south to north in Pacific Ocean, at 150°W longitude (red=warm, blue=cold)

Each number at the top is the site of a lowered profile made from a ship. The section spans latitudes from about 63° South to 56° North (13,500 km)

Southern Ocean

60°S

Equator

Hawaii

55° N Aleutian Islands

note vertical exaggeration of the figure; the isotherms are nearly horizontal
salinity (in kg of salt per kg of seawater), $150^0 W$
(brown = large, blue = small)
density of ocean water 150° west, Pacific
add 1000 to these numbers to get density in kg per cubic meter. A typical value is
1027 kg/m³ varying by a about 2 kg/m³ (also called ‘parts per thousand’).
dissolved oxygen (in micro mols per kg of seawater), 150°W
(purple = large, yellow = small)
nitrate concentration in sea-water, $150^\circ W$
(in micromols nitrate per kg seawater)
the northern Atlantic Ocean...with its seafloor topography and the ice-mountain of Greenland (note vertical exaggeration of the picture! Greenland is about 3 km tall and 2000 km long...it lies between 60° N and 83° N, which is ¼ of the way from North Pole to Equator.
Erika Dan temperature section from Labrador to Greenland to Ireland, 60N
(red = warm, blue = cold) Near Ireland warm water is moving north near the surface (red arrows), while cold (near freezing) waters move south at the bottom (blue arrows). They lean to the right on the sloping sides of Greenland and Labrador due to the Earth’s rotation. This is one of the most active parts of the global ‘conveyor belt circulation’. The deep, cold waters supply North Atlantic Deep Water to the entire world ocean. 

Worthington and Wright, 1962
When we add Earth's rotation to this heat convection, the ‘figure skater effect’ reorganizes the horizontal circulation.

Basically, the ‘conveyor belt circulations’ now drive strong horizontal currents and lots of spinning, swirling eddies and strong, concentrated ‘jet streams’

This true both in the atmosphere and ocean which have remarkable similarities

The ‘weather’ of the ocean (that is, the 100 km wide eddies) coexists with the global general circulation (the ‘conveyor’) just as the weather of the atmosphere coexists with its general circulation (the easterly and Westerly winds and the atmospheric conveyor belt circulation which transports heat from warm latitudes toward the poles.

**FIGURE CC3.1** In a saucepan heated at the center of its bottom, water will establish a circulation in which heated water rises to the surface, spreads toward the pan’s sides and cools, and then sinks back to the bottom. This toroidal-shaped convection cell is established because the water density is decreased when it is heated and increased when it is cooled. The idealized toroidal convection cell depicted would, in practice, normally be distorted because saucepans are usually heated across their entire base, not just at the center, and by turbulence in the flow patterns caused by variations in the rate of heating and cooling.
When the Earth’s rotation comes into play, this pattern of convection currents is deflected at right angles into ‘east-west’ currents. The east-west flow breaks into complex, swirling eddies which we call ‘weather’.
Still images from the video of convection with Earth’s rotation...simulated in a bowl with an ice-filled cylinder in the middle. The ‘Arctic’ at the center cools the fluid, but rather than just flowing in a simple convection pattern as in the previous slides, Earth’s rotation and the figure-skater effect give the flow strong east-west acceleration. We see round eddies and jet streams snaking around them. These structures do the work of carrying heat from the warm latitudes to the cold latitudes. There are actually 2 jet streams: fluid sinks at the cold ‘northern’ wall and moves south. The angular momentum principle says that this fluid will develop a westward flow (turning to its right).

Conversely, the fluid rising in the warm latitudes flows north to complete the circuit, but is deflected into an eastward jet stream, very intense. These complex ‘weather’ patterns do the necessary work of the atmospheric ‘heat engine’, moving heat poleward and converting thermal energy into kinetic energy of motion. The ocean has similar instabilities and eddies and jet streams, only they are 10 times smaller in width.
Southern hemisphere and northern hemisphere circulations: weather introduces new time-scales into high latitude life. Left is south polar view, right is north polar view. There are natural cycles over 10 years and longer; as well as global warming related change in weather patterns, temperature and rainfall. The jet streams are seen at the 300 HPa level (where just a few contours are selected to highlight the jets). There is a strong symbiosis between the synoptic highs and lows at the surface, the jet, and the smoother, faster stratospheric polar vortex above. Note the much more zonal nature of the SH flow. One glitch: colors in the NH are SLP while colors in SH are 850 HPa temperature. ... sorry for this confusion!

(dynamic height at 1000 Hpa (colors: blue = low pressure cyclones, red=high pressure anticyclones), 300 Hpa, 30 Hpa 1993 (NH), 1996 (SH) winters, 100 days each)
There are just a few sources of dense, deep ocean water in the world: in the far northern Atlantic and near Antarctica in the south.

**FIGURE 10.26** The densest water masses that flow along the ocean floor are created by cooling at only a very few locations. Deep water-mass circulation is still not well understood. The densest bottom water is formed in the Weddell Sea near Antarctica. It sinks, then flows around Antarctica and northward into each of the oceans. Cold, dense water is also formed near Greenland and in the Norwegian Sea. It flows south until it meets and flows over the more dense Antarctic Bottom Water (see Figure 10.27) or returns northward in the gyre circulation. Bottom currents flow in gyres in each basin and are modified by topography. Currents are intensified on the western boundaries of the oceans. The western boundary current in the Atlantic Ocean flows southward from the zone of deep water-mass formation near Greenland, and the western boundary currents in the Pacific and Indian oceans flow northward from the Southern Ocean around Antarctica. Return flows on the eastern boundary are more diffuse.
Model of the oceanic conveyor belt circulation, driven by sources of deep water entering in the far north: Caitlin Whelan, summer undergraduate fellow GFD lab UW 2007
Model of the oceanic conveyor belt circulation, driven by sources of deep water entering in the far north: Caitlin Whelan, summer undergraduate fellow GFD lab UW 2007

Fluid is pumped into the model ocean in the far north, and flows south along the western boundaries of each ocean basin, then recirculates in big gyres near the sea floor. This peculiar circulation occurs because of the ‘stiffening’ of the fluid by its planetary angular momentum.

Vertical walls (simulating continents)
the elevation of the sea surface (a time-average), once waves, tides, and the gravity irregularities have been removed: so, this is (by hydrostatic pressure ideas, the pressure field, showing the gyres of circulation (Maximenko & Niiler)
and the result is this circulation of the oceans: ‘gyres’ that look like the wind yet are concentrated on the western sides of the oceans in currents like the Gulf Stream and Kuroshio (‘Black Current’) off Japan.
Riding on top of that mean pressure field is a complex pattern of small eddying circulations...like weather. Most of them drift westward. (here seen from the TOPEX/Poseidon satellite of NASA; D. Chelton, Science 2005)

- How does this strange pattern of circulation happen? Why the concentration of flow on the western sides of the oceans?
- Enter the Rossby wave, and at the rim of the oceans, the topographic Rossby wave.
A more complete picture of the global ‘conveyor belt’ circulation driven by buoyancy forces, in the three major oceans (connected by the Southern Ocean round Antarctica)

The intense boundary currents that flow along the ocean floor, carrying the conveyor belt circulation, can be explored with detailed observations; here with moored current meters and the tritium chemical tracer (next slide). Since tritium entered the ocean from the atmosphere in the nuclear bomb testing period of the early 1960s, it is a perfect ‘marker’ or ‘colored dye’ revealing the deep circulation.
Tritium (from nuclear bomb tests) invades the ocean, acting as a tracer of the circulation (possibly the only positive benefit from nuclear testing). The high tritium concentration in the deep southward flow along the western North Atlantic verifies that this water was recently at the sea surface in the far North. It is not very ‘hot’ though; 1 tritium unit is defined as one tritium atom in $10^{18}$ normal hydrogen atoms. The half-life of tritium is about 12 years, and it decays to helium-3 which can be measured with a mass spectrometer.

Here you can see the plume of high tritium content pressed against the deep ocean ridge, 4 km beneath the sea surface.

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**Fig. 2** The tritium results for the section. *a.* The tritium isopleths (solid lines) for the undercurrent hug the ridge, and extend over the ridge in a manner parallel to the isotherms (dashed lines). The far-northern water, marked in this way, occupies only a small part of the broader southward flow at this time. Note also the westward enhancement of the shallow (350 m) tritium maximum, and the associated thermal structure (that is, the dip in the 18 and 19 °C isotherms). ⊙ Current meter positions. *b.* The temperature–tritium relation for the stations. ○ Stations outside of the current; ⊙ corresponds to undercurrent stations. For comparison, the $T_p-^3\text{H}$ curves for a central Sargasso Sea station (*Panulirus*) and an upstream section (see Fig. 1a) are shown.
A cross-section of tritium concentration showing two time periods: 1972-73 and 1981. In a decade the tritium-bearing waters have moved south from the Greenland-Iceland region (the shallow zone at the right side of the figures). These images run from 10° South to 80° North latitude and from the sea surface to 6 km depth.

**Figure 10.31** (a) Tritium distribution with depth in the western North Atlantic Ocean (1972-1973). Released primarily by nuclear bomb tests in the 1950s, tritium has spread throughout the ocean surface layers and is being transported steadily into the deep oceans with North Atlantic Deep Water which is formed by the cooling of surface waters in the North Atlantic. (b) Distribution in 1981. The values are corrected for the radioactive decay that occurred during the 9 years between the two surveys. The strong source in the surface layer at 60°N in the outflow from the Arctic Ocean where the Soviet Union did most of its nuclear bomb testing. Comparing the two diagrams shows the progressive movement of tritium into the deep layer as North Atlantic Deep Water continuously forms, sinks, and moves southward.
More recently ‘Freons’ from refrigeration and spray cans have polluted the atmosphere (causing the famous ozone hole over Antarctica). Here we use them as tracers to show the very same deep circulation, southward from where the water was at the surface and could dissolve the gas from the atmosphere.

The total amount of CFC-11 dissolved in the North Atlantic ocean water is about 103 million moles. About ½ of this is in the deep waters shown in these figures.

- CFC-11 tracer concentration, ingested into from atmosphere into the ocean at the sea surface, flowing at about 1200m depth below the surface, southward toward the Equator
  - (Lebel, Smethie, Rhein et al. Deep-Sea Research 2008)
  - The units of CFC-11 concentration are normally pico-moles per kg of seawater, but here moles per square kilometer.

Data taken in 1995-1998

EPO W&W
smethie CFCs

mid-depth

deeper

~ 3800m

deepest

Fig. 8. Map of station CFC-11 inventories [mol km$^{-2}$] in the ISOW density layer. Light gray lines represent the 500, 2500, and 4500 m isobaths.

Fig. 9. Map of station CFC-11 inventories [mol km$^{-2}$] in the DSOW density layer.
Upper: cross-section from Canada (left) to Scotland (right) of CFC-11, showing the waters that last saw the atmosphere in the Labrador Sea (ULSW, CLSW), the Norwegian Sea farther north (ISOW), the Arctic and Norwegian Sea (DSOW) and the Antarctic (AABW). This ‘Freon’ tracer has been banned by the Montreal protocol, because it has caused the ‘ozone hole high above Antarctic to worsen…Chlorine eats ozone through a complex set of chemical reactions.

Lower: cross-section of the North Atlantic from North America to Africa (24.5° North latitude). The CFC concentration is smaller than it was farther north or south, nearer the sinking regions that are its sources.
50° to 60° North latitude

24.5° North latitude

Fig. 2. Vertical sections of CFC-11 [ppbv kg⁻¹] (a) from Labrador to Greenland (X147) and Greenland to Scotland (X151.5) and (b) from North America to Africa along 24.5°N (OCEANS). The neutral density surfaces defining the water mass boundaries (Table 2) are plotted as bold dashed lines. The upper boundary for ULSW is denser in the subpolar region than in the subtropics and tropics as discussed in the text. See Fig. 1 for station locations.
ship tracks involved in collecting this CFC data. Each dot is a station, where a vertical profile was made.

Fig. 1. WOCE and pre-WOCE stations used in this analysis. Stations marked in black were occupied in 1997; in blue in 1998; in green in 1995; and in violet in 1991–1994. Enlarged symbols and cruise labels are for stations used in the vertical sections presented in Fig. 2. The 4500, 2000, and 500m isobaths are shown. Color version on ESR website. Data are available from www.whoi.edu.
for comparison, the temperature and Freon-11 cross-sections at about 60° North: CFC-11
That’s a long story about where water sinks in the oceans, but where does it come back to the surface .... where does it upwell from the deep? Nutrient chemists may have the best answer, since they use this upwelling to feed the ecosystem up near the sea surface.
question:  what is the residence time $T$ of water in the ocean

(that is, knowing the rate of rainfall and evaporation at the surface of the sea, how long on average does it take to renew the entire ocean?

If the global ocean ‘conveyor belt’ circulation is driven by sinking of dense waters at a rate $25 \times 10^6$ m$^3$ per second,

- what is the average residence time of waters in the deep, before they return to the surface?
- What is the average upwelling velocity of the water returning to the surface?
- What is the residence time of water in the atmosphere?

In a steady-state system $T = \frac{M}{F}$ where $T$ is the residence time, $M$ is the mass of the system and $F$ is the inflow or outflow of mass in and out of the system (think of a river flowing in one end of a lake, and out the other). For water we can approximately use volume instead of mass because its density does not vary greatly.

The global precipitation rate is about $5.2 \times 10^{14}$ m$^3$/year
The total volume of water in the atmosphere is $1.3 \times 10^{13}$ m$^3$
The total volume of water in the oceans is $1.35 \times 10^{18}$ m$^3$
The radius of the Earth is about 6380 km.
The surface area of the world’s oceans is about $3.58 \times 10^{14}$ m$^2$.

Note: it may be easier to think of an average vertical column of ocean and atmosphere: In that column there is about 2.5 cm (0.025 m) of water (as vapor or droplets) in the atmosphere, about 3730 m of seawater, and the average precipitation is about 1 m per year.