2.2: The hydrosphere and the oceans

> *How inappropriate to call this planet Earth,*
> *when clearly it is Ocean."*
>
> *Arthur C. Clarke*

Water is the most abundant substance at the earth's surface. Almost all of it is in the oceans, which cover 70% of the surface area of the earth. However, the amounts of water present in the atmosphere and on land (as surface runoff, lakes and streams) is great enough to make it a significant agent in transporting substances between the lithosphere and the oceans.

Water interacts with both the atmosphere and the lithosphere, acquiring solutes from each, and thus provides the major chemical link between these two realms. The various transformations undergone by water through the different stages of the hydrologic cycle act to transport both dissolved and particulate substances between different geographic locations.

Table2.2.1: Inventory of water on Earth

Reservoir	Volume / 10^6, km^3	Percent of total
Oceans	1370	97.25
Ice caps and glaciers	39	2.05
Deep groundwater	5.3	0.38
Shallow groundwater	4.3	0.30
Lakes	0.125	0.01
Soil moisture	0.065	0.005
Atmosphere	0.013	0.001
Rivers	0.0017	0.0001
Biosphere	0.0006	0.00004
Total	**1408.7**	**100**

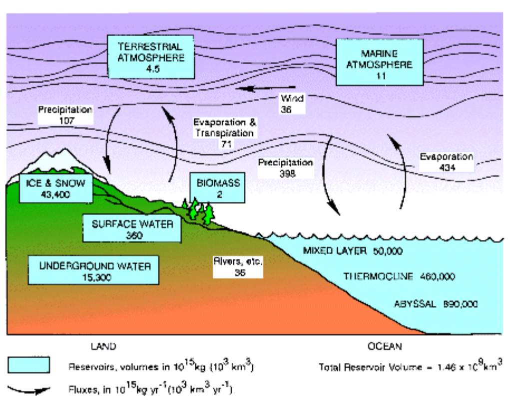
Where did the water come from?

It appears to have been bound up in the silica-based materials such as micas and amphiboles which accreted to form the Earth. The heat released during this process would have been sufficient to drive off this water, which amounted to about 0.01% by mass of the primordial material.

The hydrologic cycle

The *hydrologic cycle* refers to the steady state that exists between evaporation, condensation, percolation, runoff, and circulation of water. The cycle is driven by solar energy, mainly through direct vaporization, but also by convective motion induced by uneven heating.

The major interphase transport process of the hydrologic cycle is evaporation of water from the ocean. However, 90% of this vapor falls directly back into the ocean as rain, while 10% is transported over the land. Of the latter, about two-thirds evaporates again and one third runs off to the ocean.



The climatic hydrologic cycle at global scale [from *NRC*, 1986].

Figure 2.2.1: The climatic hydrological cycle at global scale (Diagram and text from a page at the Web site of the Institute for Global Environment and Society)

The movement of water on the earth's surface and through the atmosphere is known as the hydrologic cycle. Water is taken up by the atmosphere from the earth's surface in vapor form through evaporation. It may then be moved from place to place by the wind until it is condensed back to its liquid phase to form clouds. Water then returns to the surface of the earth in the form of either liquid (rain) or solid (snow, sleet, etc.) precipitation. Water transport can also take place on or below the earth's surface by flowing glaciers, rivers, and ground water flow.

The amounts of water precipitated onto the land and oceans are in approximate proportion to the relative surface areas, but evaporation from the ocean exceeds that from the land by about 37,400 $km^{-3}\ yr^{-1}$. This difference is the amount of water transported to the oceans by river runoff. When water condenses from the atmosphere in the form of rain, it is slightly enriched in H_2O^{18}. During epochs of glacial buildup the fraction of H_2O^{18} in the oceans consequently decreases. Observation of H_2O^{18}/H_2O^{16} ratios in marine sediments is one way of studying the timing and extent of past glaciations. Since the degree of heavy isotope enrichment of condensed water is temperature dependent, this same method can be used to estimate mean world temperatures in the distant past.

The hydrologic cycle also has important effects on the energy budget of the earth. Atmospheric water vapor (along with carbon dioxide and methane) tends to absorb the long-wavelength infrared radiation emitted by the earth’s surface, partially trapping the incoming shorter-wavelength energy and thus maintaining the mean surface temperature about 30° higher than would be the case in the absence of water vapor. Of the 51% of the solar radiation incident on the atmosphere that reaches the earth’s surface, about half of this (23%) is used to evaporate water. During the ten days that an average molecule resides in the atmosphere, it will travel about 1000 km. The atmospheric transport of water from equatorial to subtropical regions serves as an important mechanism for the transport of thermal energy; at latitudes of about 40°, as much as one-third of the energy input comes from release of latent heat from water vapor formed in equatorial regions.

Oceanic circulation

About 97% of the earth’s water is contained in the two reservoirs which comprise the oceans. The upper mixed layer contains about 5% of the total; it is separated from the deeper and colder layer by the thermocline. Mixing between these two stratified layers is very slow; of the total ocean volume of 6.8 $10^{18}\ m^3$, only about 0.71 $10^{15}\ m^3$, or about 0.01%, moves between the two layers per year. The mean residence time of a water molecule in the deep layer is about 1600 years.

The large-scale motions of ocean water are the primary means by which chemical substances, especially those taken up and excreted by organisms, are transported within the ocean. An understanding of the general patterns of this circulation is essential in order to analyze the observed distribution of many of the chemical elements in different parts of the ocean and in the oceanic sediments.

Atmospheric circulation

The circulation of the surface waters of the ocean is driven by the prevailing winds. The latter arise from uneven heating of the earth’s surface, and are arranged in bands that parallel the equator.

Although the motion of the waters at the surface of the ocean are driven by the winds, they do not follow them in a simple manner. The reasons are threefold: the Coriolis effect, the presence of land masses, and uneveness in the sea level due to regional differences in temperature and atmospheric pressure.

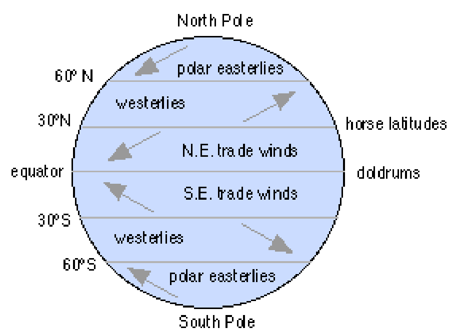


Figure 2.2.2: Atmospheric winds

The most intense heat input into the atmosphere occurs near the equator, where the heated air rises and cools, producing intense local precipitation but little surface wind. After cooling and losing moisture, this air moves north and south and descends at a latitude of about 30°. As it descends, it warms (largely by adiabatic compression) and its relative humidity decreases. The extreme dryness of this air gives rise to the subtropical desert regions between about 15° and 30°. Part of this air flows back toward the equator, giving rise to the northeast and southwest trade winds; the deflection to the east or west is caused by the Coriolis effect. Another part of the descending air travels poleward, producing the prevailing westerlies. Eventually these collide with cold air masses moving away from the polar regions, producing a region of unstable air and storm activity known as a polar front. Some of this polar air picks up enough heat to rise and enter into polar cell circulation patterns.

The flow of air in the prevailing westerlies is subject to considerable turbulence which gives rise to planetary waves. These are moving regions in which warm surface air is lifted to higher levels, producing lines of storms that travel from west to east, and exchanging more air between the polar and temperate regions.

Surface currents of the oceans

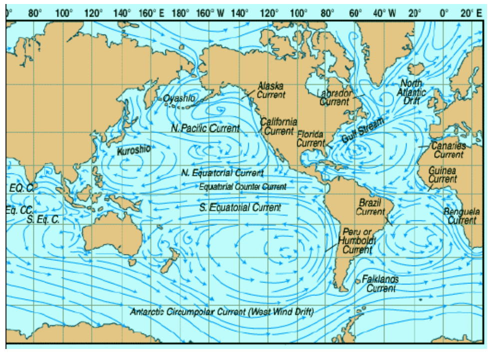


Figure 2.2.3:

In the Northern hemisphere, the Coriolis effect not only deflects south-moving objects to the east but it also causes currents flowing parallel to the equator to veer to the right of the direction of flow, i.e. to the north or south.

In addition, prevailing westerly winds and the eastward rotation of the earth cause water to pile up by a few centimeters at the western edges of the oceans. The resultant downhill flow, interacting with Coriolis forces, produces a *western boundary current* that runs south-to-north in the northern hemisphere. A similar but opposite effect gives rise to a south-flowing *eastern boundary current* on continental east coasts.

Thermohaline circulation

In contrast to the upper levels of the ocean, the deep ocean is *stratified*; the density increases with depth so as to inhibit the vertical transport of water. This stratification divides the deep oceans into several distinct water masses which undergo movement in a more or less horizonal plane, with adjacent masses sometimes moving in opposite directions.

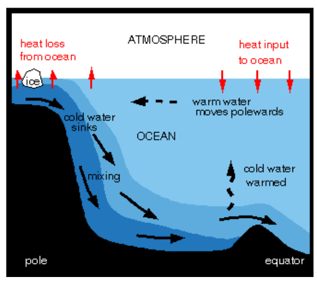


Figure 2.2.4: As the cold water fills up the deepest regions and spills over ridges into other deep basins, it creates huge undersea cascades which rival the greatest terrestrial waterfalls in height and the largest rivers in volume. For more on this, see the Feb. 1989 *Scientific American*

The winds and atmospheric effects outlined above affect only the upper part of the ocean. Below 100 meters or so, oceanic circulation is driven by the *density* of the seawater, which is determined by its temperature and its salinity. Variations in these two quantities give rise to the *thermohaline circulation* of the deep currents of the ocean.

It all starts when seasonal ice begins to form in the polar regions. Because the salts dissolved in seawater cannot be accommodated within the ice structure, they are largely excluded from the new ice and remain in solution. This increases the density of the surrounding unfrozen water, causing it to sink into the bottom ocean.

There are two major locations at which surface waters enter the deep ocean. The northern entry point is in the Norwegian Sea off Greenland; this water forms a mass known as the North Atlantic Deep Water (NADW) which flows southward across the equator.

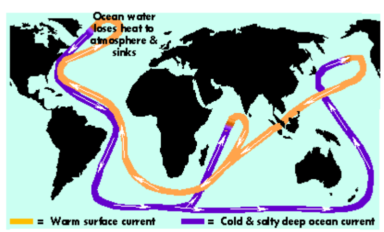


Figure 2.2.5: From Don Reed, Marine Geology 130 at San Jose State U.

Most of the transport into the deep ocean takes place in the Weddell Sea off the coast of Antarctica. The highly saline water flows down the submerged Antarctic Slope to begin a 5000-year trip to the north across the bottom of the ocean. This is the major route by which dissolved CO_2 and O_2 (which are more soluble in this cold water) are transported into the deep ocean where it forms a water mass known as the Antarctic Bottom Water (AABW) which can be traced into all three oceans.

In the south, a flow from the antarctic region forms a water mass known as the Antarctic Bottom Water (AABW) which can be traced into all three oceans.

The Pacific Ocean lacks any major identifiable direct source of cold water, so it is less differentiated and its deep circulation is sluggish and poorly defined.

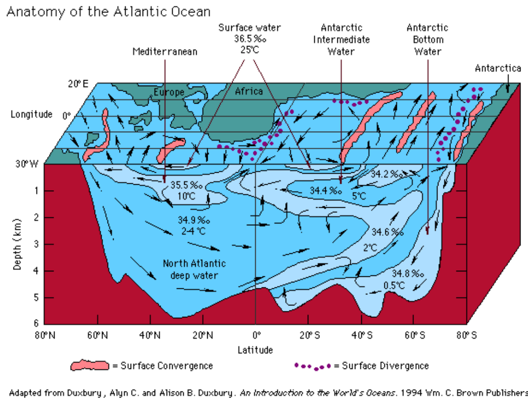


Figure 2.2.6: Temperature and salinity profiles in a north-south subsection of the Atlantic ocean.

As is apparent from the figure above, the vertical profiles of temperature and especially of the salinity are not uniform. To some extent, these two parameters have opposite effects: in equatorial regions, temperatures are higher (leading to lower density) but evaporation rates are also higher (leading to higher density). In polar regions, the formation of sea ice raises the density of the seawater (because only a small proportion of salt is incorporated into the ice).

The nature and extent of the deep ocean currents differ in the Atlantic, Pacific, and Indian oceans. These currents are much slower than the surface currents, and in fact have not been measured directly; their existence is however clearly implied by the chemical composition and temperature of water samples taken from various parts of the ocean. Estimated rates are of the order of kilometers per month, in contrast to the few kilometers per hour of surface waters. The deep currents are the indirect results of processes occuring at the surface in which cold water of high salinity is produced as sea ice forms in the arctic and antarctic regions. This water is so dense that it sinks to the bottom, displacing warmer or less saline water as it moves.

Coastal Upwelling

Recirculation of deep water to the surface occurs to a very small extent in many regions, but it is especially pronounced where water entering the Antarctic Bottom mass displaces other bottom water, and where water piles up at the western edges of continents. This latter water flows downhill (forming the western boundary currents mentioned above) and is replaced by colder water from the deep ocean. The deep ocean contains few organisms to deplete the water of the nutrients it receives from the remains of the dead organisms floating down from above; this upwelled water is therefor exceptionally rich in nutrients, and strongly encourages the growth of new organisms that extend up the food chain to fish. Thus the wind-driven upwelling that occurs off the west coast of South America is responsible for the Peruvian fishing and guano fertilizer industry.

> *About every seven years these prevailing winds disappear for a while, allowing warm equatorial waters to move in. This phenomenon is known as El Niño and it results in massive kills of plankton and fish. Decomposition of the dead organisms reduces the oxygen content of the water, causing the death of still more fish, and allowing reduced compounds such as hydrogen sulfide to accumulate.*

Matthias Tomczak's Introduction to physical oceanography is an excellent source of more information on the topics covered above.

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