

CHAPTER 8

CIRCULATION AND OCEAN STRUCTURE

Objectives

1. To understand the role that the oceans play in the thermal or heat budget of our planet.
2. To build a picture of the structural (spatial and temporal) consequences of these density interactions (controlled by temperature and salinity), that allow us to measure and delineate the internal, layered structure of the world's oceans, and explain much of the deep horizontal and vertical oceanic circulation.
3. To understand how we can decipher the complex internal structure of the oceans with relatively simple measurements of temperature and salinity.
4. Finally, if the oceans are driven as a part of the surface heat engine of the atmosphere and hydrosphere, then an enormous energy resource waits to be tapped. We will look at some of the best-proposed ways to tap this energy.

Key Concepts

Major Concept (I)

The salinity of mid-ocean surface waters is controlled by global patterns of precipitation and evaporation. Higher salinities are found where surface waters evaporate the most, while lower salinities are found where rainfall is abundant.

Related or supporting concepts:

- The average ocean salinity is about 35 ppt.
- Sea surface salinities in the tropics are a relatively low 34.5 ppt due to high rainfall, which dilutes the surface water.
- Salinity reaches its highest values of about 36.7 ppt near 30° North and South where there is little precipitation, and evaporation strips water from the sea surface and concentrates the salts.
- The salinity drops again to about 34 ppt at higher latitudes between 50° and 60° North and South where annual precipitation is again high and low average temperatures reduce the rate of evaporation.
- At polar latitudes the salinity of the water varies annually. In the winter the formation of sea ice concentrates the salt and increases the salinity. In the summer the melting ice reduces the salinity.

Major Concept (II)

Water mass density is controlled by water temperature and salinity. Many combinations of temperature and salinity can create the same density (see fig. 8.1).

Related or supporting concepts:

- Less dense water masses remain at the ocean's surface, while more dense waters tend to sink to an equilibrium level. These simple physical reactions, coupled with wind, tidal, and wave generated forces, means that the density of the ocean waters changes with depth, latitude, and proximity to coastal regions in a fairly predictable (and observable) manner.
- The surface 100 m (330 ft) of the world's oceans is well-mixed, and therefore homogeneous in its density.
- Layers of increasing density occur at depths from 100–1000 m (330–3300 ft). The plot of density with depth reveals a rapid change until about 1000 m (330 ft), with deeper waters of very similar or slowly increasing density. The sharp break in the slope of the plot is termed the pycnocline.
- Temperature also decreases rather rapidly with depth below the 100 m (330 ft) level to the 1000 m (3300 ft) depth. The zone where the temperature changes most rapidly with depth is called the thermocline. Similar in behavior to density, below 1000 m (3300 ft), the temperature of the oceans is relatively uniform, with gradual decreases down to the bottom.
- As with temperature and density, salinity increases rapidly from 100–1000 m (330–3300 ft), then remains nearly uniform below 1000 m (3300 ft). The zone where the most rapid changes in salinity with depth occur is called the halocline (halo- for halite, the mineral name for common table salt).

- A water column where the density of the water increases with depth is said to be stable. If the density decreases with depth the water column is unstable and will generally lead to overturn and mixing of the water column. A water column with no changes in density, temperature, or salinity can therefore be called isopycnal, isothermal, and isohaline, respectively.
- In the open ocean seasonal temperature changes are more important than changes in salinity in controlling density.
- Near continental margins variations in salinity become more important in controlling density because of freshwater runoff. Very cold freshwater runoff at high latitudes can have such a low density that it will not sink. Instead it will remain at the surface as a freshwater lid.

Major Concept (III) *Dense water sinking in the oceans reaches an equilibrium depth and is then driven horizontally by the continued sinking of dense water behind it. Water at the surface moves into the zone of sinking, while at some other point in the ocean, water must rise to replace it.*

Related or supporting concepts:

- Areas where water masses move downward are called downwelling zones, and conversely, areas where water rises are called upwelling zones.
- There is approximately a constant volume of water in the oceans so whenever currents remove water from one location it must be replaced from another location. This idea is called continuity of flow.
- Downwelling brings oxygenated waters to the depths, while upwelling can bring needed nutrients and decomposition products to surface waters.
- Wind-driven surface currents can generate upwelling or downwelling zones in various ways. Wind blowing offshore creates upwelling in coastal regions. Where surface currents and winds converge, downwelling can occur. Where surface winds and wind-driven currents diverge, upwelling can occur in the open ocean.
- Rates of upwelling and downwelling are slower than oceanic surface (wind-driven) currents with rates of 0.1–1.5 m/day compared to 1.5 m/sec. This is important, as it means that 1000's of years are required for upwelling or downwelling processes to complete a cycle of overturn in the deep ocean.
- The velocity of horizontal flow on the deep sea floor is only about 0.01 cm/sec.
- The motion of water masses through the oceans can be mapped using chemical tracers. These tracers change their distribution with time as currents flow and are often components added to the oceans by human actions. A good example would be radioactive isotopes introduced into the environment by nuclear testing in the late 1950s and early 1960s.

Major Concept (IV) *Measurements of water salinity, temperature, and density allow oceanographers to map the layered structure of the oceans.*

Related or supporting concepts:

- The oceans have a layered structure and distinct water types.
- These water types, or masses, obtain their characteristic physical properties (density, salinity, temperature) at the surface of the oceans.
- The density of a water mass will determine the depth at which it is stable.
- Depth zones are often defined as: surface, 0–200 m (0–650 ft); intermediate, 300–2000 m (1000–6500 ft); deep, 2000–4000 m (6500–13,000 ft); and bottom, depths below 4000 m (13,000 ft).
- The volume of water in a water mass, and hence its thickness and horizontal extent, are determined by the rate of its formation and the area over which it is forming.
- For this summary we will concentrate on the Atlantic Ocean (fig. 8.6):
 - a. North Atlantic Deep Water (NADW): Waters of a salinity of 34.9 ppt, and temperature of 2–4°C sink as the waters of the Norwegian Sea, Labrador Current, and cooler Gulf Stream converge and move southward.
 - b. Antarctic Intermediate Water (AAIW): Waters converge at 40°S with a temperature of 5°C and 34.4 ppt salinity it rides just above the deep water.

- c. Antarctic Bottom Water (AABW): Waters generated along the edge of Antarctica are very cold (-0.5°C), salty (34.8 ppt), and are the densest waters created in the oceans. These waters creep northward along the bottom, wedging below the North Atlantic Deep Water.
 - d. South Atlantic Surface Water (SASW): This water type is formed where North Atlantic Deep Water is forced to the surface in the area near 60°S , splits, and part of it moves northward.
 - e. Mediterranean Intermediate Water (MIW): The temperature of this water is 13°C and it is very salty (37.3 ppt). MIW exits the Straits of Gibraltar, mixes somewhat with Atlantic waters, and drops to a depth of about 1000 m (3300 ft) as it moves out into the Atlantic. This unique water mass is traceable some 2500 km (1500 mi) from the Straits of Gibraltar.
- The Atlantic Ocean is relatively narrow and confined, so that water types and masses are more readily definable and traceable than in most of the other oceans, and have been studied the most extensively.
 - Specific water types can be created in bordering seas and then enter ocean basins. One example has already been discussed, Mediterranean Intermediate Water. A second example is water from the Red Sea.
 - Red Sea water with a salinity of 40–41 ppt enters the Indian Ocean and spreads out at a depth of 3000 m (10,000 ft) more than 200 km (124 mi) south of its source.
 - Temperature and salinity profiles for the world's oceans are shown in fig. 8.7a–f in your book.
 - There is relatively little internal mixing between water masses. Horizontal mixing tends to be more important than vertical mixing because whenever a water mass is displaced vertically by turbulence, buoyancy forces return it to its original depth.

Major Concept (V)

Temperature and salinity can be plotted for each water mass via a temperature versus salinity graph; thereby defining distinct T-S curves for each geographical region in the world's oceans.

Related or supporting concepts:

- T-S curves for geographically related areas of the oceans are similar, and fall into groups or families we call water masses.
- A water mass with only one temperature value and one salinity value over its entire extent is called a water type. (For example, Antarctic Bottom Water is a water type.)
- Some organisms have become specifically adapted to very narrow ranges of temperature and salinity-- therefore, some can act as biological indicators of water masses or even water types.

Major Concept (VI)

The information gained by examining the ocean waters in such detail for temperature and salinity is so valuable that techniques for measuring these properties have been used and perfected for well over a hundred years.

Related or supporting concepts:

- A wide variety of seawater characteristics are studied by oceanographers who go to sea aboard sophisticated research vessels that serve as platforms for launching diverse sampling and measuring instruments.
- Research time at sea is very expensive and, for a large vessel, can total as much as \$25,000 per day for the ship and crew alone. The expenses associated with the research team and their equipment is added to these basic operating expenses.
- Oceanography during the first half of this century depended on robust mechanical sampling and measuring devices that were lowered from the surface on cables. They descended to a pre-determined depth, took a sample or made a measurement, and they were brought back to the surface for analysis.
- One example of such a device is a mechanical water bottle like the one shown in figure 8.10. Water can be sampled in bulk from any depth in the oceans using remotely controlled closing bottles, lowered on thin steel cable or hydrowire, sometimes with spring-loaded closing devices at each end of the bottle (actually a hollow cylinder with gaskets). The ends of the bottle are then closed or tripped by weights (messengers) dropped down the wire when the bottle is at the precise depth. Signals for opening and closing can now be transmitted electronically to more sophisticated bottles.

- While oceanographers still use bottom corers, grabs, dredges, and nets, the use of water bottles with attached thermometers is decreasing.
- Direct-reading instruments are available that transmit data on conductivity, temperature, and depth continuously down into the sea and are called CTDs (see fig. 8.11).
- CTDs provide a depth profile of salinity by measuring the conductivity and temperature of the water. Conductivity is a function of salinity and temperature so the temperature has to be measured to obtain accurate salinity values for a given conductivity.
- CTD systems still require a ship to stop and remain on station while they are lowered and recovered.
- A modified CTD called Seasoar allows sampling while a vessel is under way (see fig. 8.12). It can be towed at depths that range from the surface to about 350 m (1100 ft).

Major Concept (VII) *Large amounts of solar energy are stored in the oceans.*

Related or supporting concepts:

- The transparency and heat capacity of water allow it to store large amounts of heat energy.
- This heat can be extracted independent of daily and seasonal changes in the intensity of solar radiation.
- Systems designed to extract this heat are called ocean thermal energy conversion (OTEC) systems (see fig. 8.15).
- OTEC systems depend on the difference in temperature between ocean surface water and water at a depth of 600–1000 m (2000–3300 ft).
- Presently there are two OTEC designs, a closed cycle and an open cycle system.
- In the closed system warm surface water is passed over an evaporator chamber filled with Freon or ammonia that is vaporized by the relatively warm temperature of the water. The vapor builds up pressure in a closed chamber that can be released to turn a turbine, which then generates power. After passing through the turbine the gas is then sent to condenser where it is cooled by cold water pumped up from depth. Once in liquid form the Freon or ammonia is then returned to the evaporator to complete the cycle.
- In the open system large amounts of seawater are converted to steam in a low-pressure vacuum chamber and the steam is used as the working substance in place of Freon or ammonia. Passing the steam through the condenser creates desalinated water.
- Either system can be located onshore, offshore, or on a ship that would be free to move from place to place.
- OTEC requires at least a 20°C difference in temperature between surface and deep water to generate useful amounts of energy. This means that these plants would have to be located at latitudes between 25°N and 25°S where surface water is appreciably warmer than deep water.
- Estimates indicate that about 0.07% of the solar energy absorbed by tropical surface water could be extracted with OTEC systems. While this is a small percentage, it still represents a large amount of energy.
- OTEC systems have the potential to change the local ecosystem. Pumping cold, deep water to the surface will also transfer nutrients that are more highly concentrated at these depths to the surface. This could alter the surface productivity.

Matching Key Terms with Major Concepts

At the end of the chapter in the textbook is a list of key terms. You should be able to match each of these with one of the previously listed major concepts. To test your ability, try to match the following key terms with the number (I–VII) of the appropriate major concept identified in this section:

thermocline
water type
downwelling
isopycnal

upwelling
CTD
T-S curves
sigma-t

divergence
water mass
hydrocast
convergence

Test Your Recall

Answer the following questions to test your understanding

FILL IN THE BLANK

1. The mixing of two water masses to form a denser water mass that sinks is called _____.
2. Thermohaline circulation is also known as _____ - _____ circulation.
3. Surface convergence leads to vertical _____.
4. The zone of rapid change in density with depth is called the _____.
5. Land and water respond differently to cycles of solar radiation because they have very different _____.
6. Density of seawater is controlled primarily by changes in _____ and _____.
7. A zone of rapid change in temperature in seawater is called the _____.
8. If salinity is constant over depth, it is said to be _____.
9. Circulation that is driven by density differences caused by changes in temperature and salinity is called _____ circulation.
10. The densest water in the oceans is _____ Bottom Water.
11. Areas in which water sinks are called _____ zones, while areas where water rises are called _____ zones.
12. Surface _____ means an area where waters are driven together.
13. _____ are distinguished from one another by different densities caused by temperature and salinity variations.
14. Water sampling bottles can be opened at specific depths by sending a _____ down a wire.
15. The process of obtaining a water sample at some depth is called a _____.
16. An instrument that measures conductivity and temperature changes as it descends is a _____.
17. _____ depends on the difference in temperature between surface water and water at 600–1000 m (2000–3300 ft) depth.
18. When a water column is unstable and begins to mix, vertical _____ of the water takes place.
19. Where surface waters flow away from each other, a surface _____ occurs.
20. When there is a strong habitat relationship with organisms and water masses, these organisms are _____.

TRUE - FALSE

1. Salinity may be increased by evaporation or the formation of sea ice.
2. Water is incompressible so density does not depend on pressure (or depth).
3. Caballing is the process of forming sea ice.
4. The layered water structure in the Pacific is the best studied.
5. There are no real seasons in the tropics.

6. Oceanographers typically measure density to five decimal places.
7. The angle at which the Sun's rays strike the Earth changes dramatically from summer to winter at mid-latitudes.
8. The heat capacity of the land is lower than that of the water.
9. The salinity of mid-ocean waters is controlled primarily by large-scale precipitation/evaporation patterns.
10. Many combinations of salinity and temperature can produce the same density of water.
11. The mixed layer extends to a depth of about 500 m (1650 ft) in most areas of the world.
12. Increasing density with depth produces an unstable water column.
13. Areas where surface ocean winds or currents converge experience upwelling.
14. Upwelling and downwelling are very slow processes.
15. The densest water produced in the world's oceans is North Atlantic Deep Water.
16. Water from the Mediterranean extends across the Atlantic at a depth of about 1000 m (3300 ft).
17. The water of the Indian Ocean is quite homogeneous.
18. Arrowworms always point north, or into the current.
19. Despite darkness, wind, waves, heat, or cold, data are taken, for there may not be a second chance on the briny deep.
20. Antarctic Bottom Water is a water type.

MULTIPLE CHOICE

1. Heat that is absorbed at the sea surface is mixed downwards by
 - a. winds.
 - b. waves.
 - c. currents.
 - d. downwelling.
 - e. all of the above.
2. The layered structure of the oceans is a result of
 - a. the addition and loss of heat at the surface.
 - b. surface precipitation and evaporation patterns.
 - c. air movement driving surface water.
 - d. all of the above.
 - e. b and c above.
3. The oceans have a well-mixed surface layer approximately ____ m thick.
 - a. 50
 - b. 100
 - c. 500
 - d. 800
 - e. 1000
4. A zone of rapid change in temperature is called the:
 - a. thermocline
 - b. caloricline
 - c. pycnocline
 - d. halocline
 - e. tempocline
5. Osmotic pressure will
 - a. increase with increasing temperature.
 - b. drive salt water across a membrane toward fresh water.
 - c. drive fresh water across a membrane toward salt water.
 - d. a and b above.
 - e. none of the above.
6. Annual mid-ocean surface temperature changes in the tropics are about _____ °C.
 - a. 1–5
 - b. 0–2
 - c. 3–6
 - d. 2–4
 - e. 6–8
7. A zone with rapid changes in density with depth is called the

- a. thermocline.
 - b. pycnocline.
 - c. densocline.
 - d. halocline.
 - e. isopycnal.
8. The densest water in the ocean basins
- a. flows northward from Antarctica across the sea floor.
 - b. is created in the Weddell Sea.
 - c. moves as a result of thermohaline circulation.
 - d. a and c above.
 - e. all of the above.
9. In the open ocean
- a. temperature is more important than salinity in determining density.
 - b. salinity is more important than temperature in determining density.
 - c. salinity is more important than pressure in determining density.
 - d. a and c above.
 - e. b and c above.
10. If the density of the water increases with depth, the water column is:
- a. isopycnal.
 - b. stable.
 - c. convergent.
 - d. unstable.
 - e. neutral.
11. Upwelling and downwelling water moves at rates of about
- a. 0.5–1.0 m/day.
 - b. 0.3–2.5 m/s.
 - c. 0.1–1.5 m/day.
 - d. 1–4 m/s.
 - e. 2–6 m/day.
12. The thickness and horizontal extent of water layers in the oceans are related to
- a. the latitude at which they form.
 - b. the rate at which they form at the surface.
 - c. the size of the surface region over which they form.
 - d. b and c above.
 - e. all of the above.
13. Sea surface temperatures in tropical latitudes in the summer are generally between _____ °C.
- a. 25–30
 - b. 10–15
 - c. 5–20
 - d. 40–45
 - e. 50–60
14. Water in the central North Atlantic at a depth of 1000 m (3300 ft) comes from
- a. the Sargasso Sea.
 - b. the Red Sea.
 - c. the Gulf Stream.
 - d. the Mediterranean Sea.
 - e. the Black Sea.
15. A water mass with only one temperature and one salinity value over its entire extent is known as a
- a. lens.
 - b. chaetognath.
 - c. water type.
 - d. water column.
 - e. water body.
16. Upwelling waters bring up _____ from deeper waters.
- a. nutrients

- b. decomposition products
 - c. manganese nodules
 - d. deep-water sediments
 - e. a and b above.
17. To maintain a constant thermal structure on Earth, the planet must
- a. gain heat from the sun.
 - b. lose heat to space.
 - c. create heat in its interior.
 - d. gain and lose approximately equal amounts of heat.
 - e. none of the above.
18. If we consider the heat budget of a small area of the ocean, among other things we must know is (are) the
- a. total energy absorbed and heat re-radiated to space.
 - b. loss of energy due to evaporation.
 - c. transfer of heat into and out of the area.
 - d. warming and cooling of the atmosphere.
 - e. all of the above.
19. The thermocline extends from about
- a. 500–2500 m.
 - b. 100–1000 m.
 - c. 300–1500 m.
 - d. 0–2000 m.
 - e. none of the above.
20. A CTD measures
- a. conductivity.
 - b. depth.
 - c. temperature.
 - d. all of the above.
 - e. none of the above.

Visual Aids: Test Your Understanding of the Figures

1. Examine figure 8.1 carefully. In general, is density more dependent on temperature or salinity?
2. Look carefully at the variation of temperature and salinity with depth illustrated in figure 8.4. Knowing the effects of temperature and salinity on density, draw a profile of density with depth. Compare your plot with figure 8.3.
3. Look carefully at figure 8.6. What happens to Antarctic bottom water as it reaches the equator?
4. Examine figures 8.7c and 8.7d carefully. What is the approximate salinity and temperature of Antarctic Bottom Water?

Study Problem

1. Deep horizontal movement due to thermohaline flow occurs at velocities of about 0.01 cm/sc. At this rate, how long would it take North Atlantic Deep Water to travel from its point of origin near 60°N to roughly 40°S (remember that the circumference of a very nearly spherical Earth is 40,000 km)? Express your answer in years.

Answer Key for Key Terms and Test Your Recall

KEY TERMS

thermocline (II)
 water type (IV,V)
 downwelling (III)
 isopycnal (II)

upwelling (III)
 CTD (VI)
 T-S curves (V)
 sigma-t (III)

divergence (III)
 water mass (IV,V)
 hydrocast (VI)
 convergence (III)

FILL IN THE BLANK

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|------------------|-------------------------------------|--------------------------|
| 1. caballing | 2. density-driven | 3. downwelling |
| 4. pycnocline | 5. heat capacities | 6. temperature, salinity |
| 7. thermocline | 8. isohaline | 9. thermohaline |
| 10. Antarctic | 11. downwelling, upwelling | 12. convergence |
| 13. water masses | 14. messenger | 15. hydrocast |
| 16. CTD | 17. ocean thermal energy conversion | 18. overturn |
| 19. divergence | 20. biological indicators | |

TRUE - FALSE

1.T 2.F 3.T 4.F 5.T 6.T 7.T 8.T 9.T 10.T 11.F 12.F 13.F 14.T 15.F 16.T 17.F 18.F 19.T 20.T

MULTIPLE CHOICE

1.e 2.d 3.b 4.a 5.c 6.b 7.b 8.e 9.d 10.b 11.c 12.d 13.a 14.d 15.c 16.e 17.d 18.e 19.b 20.d

STUDY PROBLEM

1. 3523 years