CHAPTER 5 THE PHYSICAL PROPERTIES OF WATER

Objectives

1. The major objective of this chapter is to introduce the unique characteristics and properties of water that make life as we know it possible and myriad physical and chemical interactions to occur in the oceans.

Key Concepts

Major Concept (I) *The many unique properties of water are a result of the two elements involved, hydrogen and oxygen, their ratios, the bond type, and the physical structure of the polar water molecule (take a look at fig. 5.1).*

Related or supporting concepts:

- In 1783 the English scientist Henry Cavendish determined that water was made up of hydrogen and oxygen.
- Shortly after Cavendish's discovery, the English scientist Sir Humphrey Davey discovered the formula for water is H_2O.
- Hydrogen and oxygen are bound together by sharing electrons, a type of bond called a covalent bond.
- Because of the shared electrons and the asymmetry of the bond, water molecules have a definite shape, a slightly negative end, and a slightly positive end. This is called a polar molecule.
- Due to its polarity, water can make weak bonds with itself (called hydrogen bonds) that means that even liquid water is slightly structured or ordered. This bonding also creates surface tension and enables water to be somewhat of a universal solvent.

Major Concept (II) *The temperature of a substance is a measure of the average kinetic energy of the atoms and molecules in the substance. Heat is a measure of the total kinetic energy of the atoms and molecules in a substance.*

Related or supporting concepts:

- The atoms and molecules in a substance are always in motion.
- This motion gives the atoms and molecules kinetic energy.
- The temperature of a substance is a measure of the average kinetic energy of the atoms and molecules in the substance.
- The colder a substance is, the slower the motion of its atoms and molecules.
- Temperature is measured in degrees using one of three scales:
    a. degrees Fahrenheit,
    b. degrees Celsius (or Centigrade), and
    c. degrees Kelvin.
- Heat is a measure of the total kinetic energy of the atoms and molecules in a substance.
- Heat is measured in calories. One calorie is the amount of heat needed to raise the temperature of 1 g of water by 1°C from 14.5°C to 15.5°C.

Major Concept (III) *Water exists in three forms or states in the range of temperature and pressure we find at Earth's surface. It exists as a solid (the mineral ice), as a liquid, and as a gas (water vapor). To change temperatures in any one state requires heat energy input or export, and changing states from one form to another often requires large energy exchanges (take a look at fig. 5.2).*

Related or supporting concepts:

- To go from ice to water (a change in state) requires an input of 80 calories per gram of ice with no change in temperature at 0°C. Conversely, 80 calories per gram of water will be released at 0°C when water becomes ice. This quantity of energy is called the latent heat of fusion.
- To convert water to water vapor at 100°C, you must add 540 calories per gram of water. Conversely, to convert water vapor back to a liquid, 540 calories per gram are liberated at 100°C as the latent heat of vaporization.
- When heat is removed from water vapor the temperature falls until it reaches the dew point. At the dew point water vapor will begin to condense to form liquid water drops.
- Therefore, you can see that tremendous amounts of heat (energy) are removed and liberated in different atmospheric processes around the globe.
- In some cases it is possible to:
    a. cool water below 0°C and remain liquid,
    b. boil water at temperatures below 100°C, and
    c. change the state of water from solid directly to gas in a process called sublimation.
- Sublimation occurs when snow or ice evaporates under very cold, dry conditions.
- The properties of water (its behavior) are altered with the addition of trace amounts of other compounds. These usually serve to lower the freezing temperature and elevate the evaporation or boiling point of water (think of the role antifreeze and coolant play in running your car).

Major Concept (IV)

The heat capacity of water is very high compared to the heat capacities of the land and the atmosphere.

Related or supporting concepts:

- Heat capacity is a measure of how much heat a substance can absorb or release for a given change in temperature. Substances with a high heat capacity require the transfer of large amounts of heat energy for small changes in temperature.
- Water has a very high heat capacity compared to other naturally occurring earth materials. The heat capacity of water is much higher than most other liquids because of the hydrogen bonding between water molecules.
- Heat capacities of some common materials are:

Material	Heat Capacity (calories/g/°C)
acetone	0.51
aluminum	0.22
ammonia	1.13
copper	0.09
grain alcohol	0.23
lead	0.03
mercury	0.03
silver	0.06
water	1.00

- The heat capacity of water is 1.0 calorie per gram per °C (cal/g/°C).
- Temperature variations on land range from a high of about 50°C in the Libyan desert in summer to about -50°C in the Antarctic for a range of 100°C.
- Temperature variations in the ocean range from a high of about 28°C in equatorial regions to a low of about -2°C in Antarctic waters for a total range of only 30°C.
- People who live by large bodies of water have a good understanding of the effect of different heat capacities of land and water. In Milwaukee it is common to hear weather predictions of daytime high temperatures for the city with the additional comment “cooler by the lake” in the summer and “warmer by the lake” in the winter.

- The high heat capacity of water and its ability to hold heat makes it possible for surface currents to redistribute excess heat in equatorial regions to higher latitudes as they flow away from the equator on the western sides of ocean basins.

Major Concept (V) *The polar nature and hydrogen bonding in liquid water create three very significant properties of water: cohesion, surface tension, and viscosity.*

Related or supporting concepts:

- Water has more structure or order than many other liquids. The continual making and breaking of hydrogen bonds in the liquid provides a weak force to hold water molecules together called cohesion.
- This cohesion between water molecules is particularly important at a surface or boundary where it is manifested as surface tension (or water's ability to cling to a surface and itself).
- Surface tension creates a thin skin, or membrane. This is what makes it possible to fill a glass above the rim, to float a needle on the surface, and for insects to walk on water.
- Water also has viscosity, which is an internal frictional resistance to motion or shearing of water molecules past one another. This resistance is quite small and constant at any temperature, regardless of the rate or intensity of the applied shearing force.

Major Concept (VI) *The density of water is extremely sensitive to changes in temperature, salinity, and pressure.*

Related or supporting concepts:

- The density of seawater is greater than the density of freshwater because seawater contains dissolved salts.
- The density of pure water at 3.98°C, or approximately 4°C, is 1.0 g/cm^3. The density of seawater of average salinity is about 1.0278 g/cm^3. Because of this, fresh water will float on ocean water.
- Pressure has relatively little effect on density compared to salinity and temperature, however, the density will increase with increasing pressure (or depth) and becomes important in the deep sea where salinity and temperature remain nearly constant.
- Pressure increases with depth in the oceans. Pressure increases by about 1 atmosphere, for each increase of 10 m (33 ft) in depth.
- One atmosphere is equal to the pressure exerted by a column of mercury 76 cm (30 in) high. In English quits 1 atmosphere is equal to 14.7 lb/in^2.
- The pressure in the deepest ocean trench at 11,000 m (36,000 ft) below sea level is about 1100 atmospheres.
- A column of water the height of the average depth of the oceans (about 4000 m or 13,000 ft) would be shortened by only 37 m (121 ft) as a result of compression. This is a change in length of just 1.7 percent!
- The behavior of water density with changes in temperature for a given salinity are plotted in figure 5.6 in your text.
- The density of fresh water increases with decreasing temperature down to 4°C. As water cools even more, it is structured in a crystalline lattice that actually increases the molecular spacing, thus decreasing the density. Because of this, ice will float on water and water freezing in cracks exerts tremendous expansive pressure.
- At salinities above 24.7 ppt the density of seawater will continue to increase with decreasing temperature until the water freezes. At salinities below 24.7 ppt the density of water will increase with decreasing temperature until it reaches a maximum value and will then decrease until the water freezes—just as pure water behaves.

Major Concept (VII) *Water has been called the universal solvent because of its exceptional ability to dissolve a wide variety of materials.*

Related or supporting concepts:

- The polar nature of the water molecule and its hydrogen bonding allow water to dissolve salts and many other compounds easily.
- Polar water molecules are able to attract and surround ions in seawater. This is illustrated in figure 5.7.
- Salts are supplied to the oceans by underwater volcanism and runoff from land.

Major Concept (VIII) *The water on, in, and around Earth transmits energy in many forms, including light, heat, and sound*.

Related or supporting concepts:

- Water masses (and water reservoirs) transmit heat energy by molecular conduction, density driven currents or convection, and by direct radiation.
- Water is a poor conductor and heat is transferred inefficiently in water by conduction.
- Convection transfers heat in the oceans as water is cooled and sinks with increasing density or is warmed and rises as a result of a decrease in its density due to the higher temperature.
- The oceans are heated from above by solar radiation. The water at shallow depths absorbs this energy.
- Heat energy in shallow water can be transferred to greater depth by mixing, or turbulence, in the water and by conduction.
- Surface cooling can increase the density of the surface layer and make it sink. Surface cooling can be due to:
    a. the transfer of heat from warm water to the cold atmosphere by conduction and convection, and,
    b. the transfer of water vapor to the atmosphere by evaporation and the subsequent condensation of the water vapor in the atmosphere.
- Light energy can be absorbed by and transmitted through seawater. Roughly 45% of the incident light at the sea surface penetrates to a depth of one meter beneath the surface and only 20% reaches a depth of 10 m (33 ft). Only about 1% of the light remains at a depth of 150 m (500 ft). The red (or long) wavelengths of light are absorbed most rapidly while the blue-green (or short) wavelengths penetrate to the greatest depth. Virtually all light is absorbed in the upper 1000 m (3300 ft). See figure 5.9.
- Light passing from air to water is both reflected back from the surface and refracted (its path is bent) as it passes into the water due to the difference in density between the air and the water.
- Coastal water varies in color. It may be green, yellow, brown, or red depending on the nature of the material in the water; silt from rivers, microscopic organisms, or even dissolved organic substances.
- Open-ocean water is often clear and blue.
- The color of an object is due to the particular wavelength of light that reflects off of the object and can be seen by our eyes. Objects in deep water often appear dark because only the blue light that penetrates to the greatest depth is illuminating them.
- Particles suspended and compounds dissolved in the water will absorb and scatter light, thus reducing its penetration below the surface. The depth of penetration will decrease as the amount of suspended and dissolved material in the water increases.
- The attenuation of light with depth can be measured with a simple device called a Secchi disk. A Secchi disk is a white disk that is lowered into the water until it disappears from view.
- In water with large amounts of suspended sediment or marine organisms a Secchi disk may disappear at depths of 1–3 m (3–10 ft). In the open ocean it may still be visible at depths of 20–30 m (65–100 ft) and in one measurement in Antarctica's Weddell Sea a Secchi disk didn't disappear until it reached a depth of 79 m (260 ft).
- Changes in light attenuation with depth are measured with instruments that project a beam of light over a fixed distance to an electronic photoreceptor that measures the intensity of the beam.
- Multi-color sensors are used to study the variable attenuation of sunlight with depth as a function of wavelength.
- Light transmission data can be used to adjust the color and clarity of underwater photographs and video.
- The Marine Optical Buoy (MOBY, see fig. 5.12) was deployed in 1997 to measure light and color at the surface and at three different depths in order to improve satellite measurement of sea-surface color.

Sea-surface color is used to measure the abundance of single-celled plant-like organisms as an indicator of biological productivity.

- Sound is transmitted very efficiently in seawater. The velocity of propagation of sound in seawater is roughly five times as great as in air due to its higher density.
- Sound propagating in the oceans can be used to locate organisms and objects either by listening for the sounds that they produce or by sending pulses of sound into the water to be reflected back from the target of interest.
- Depth recorders routinely detect echoes coming from groups of small organisms that form dense layers at night as they rise to the surface to feed and then disperse during the day. These layers are known as deep scattering layers.
- Sound is also used to locate objects underwater using a system called sonar. Sonar is an acronym that stands for "sound navigation and ranging."
- Sound is also used extensively as a simple and accurate means of determining the depth of seawater (fig. 5.13). Precision depth recorders (PDR's) transmit pulses of sound that reflect from the bottom and return to the surface (fig. 5.14). By knowing the average velocity of sound in water and the time required for the sound to travel downward and up again, the depth can be easily calculated.
- It is also possible to send communications large distances through the oceans with extremely low frequency (ELF) sound antennas.
- At a depth of about 1000 meters, the salinity, temperature, and pressure create a layer of minimum sound velocity called the SOFAR (SOund Fixing And Ranging) channel (fig. 5.16). Sound will oscillate up and down in this channel and propagate long distances with very little loss of energy.
- Long-term changes in ocean temperature are being monitored in a project known as ATOC (Acoustic Thermometry of Ocean Climate). The ATOC experiment sends sound pulses through the sofar channel across very long distances. The travel-time of these pulses is carefully measured to detect changes in the speed of sound in the water caused by changes in temperature.
- In the 1950s and 1960s the United States Navy installed large arrays of hydrophones on the seafloor to monitor submarines. These arrays were known as sound surveillance systems (SOSUS). SOSUS arrays have been used by scientists to monitor sounds made by marine organisms and underwater volcanoes.

Major Concept (IX)

Two states of water, solid and water vapor (or ice and fog), can produce particularly hazardous conditions.

Related or supporting concepts:

- Sea ice forms at polar latitudes. As the water freezes it excludes the salt molecules from its crystalline structure lowering its density and allowing it to float. The salts that are left behind concentrate to increase the salinity of the near-surface water and slightly lower its freezing point.
- Sequences of freezing and thawing continue to exclude more and more salt and the salinity of the ice will decrease each time.
- With the first freezing of a thin layer of ice on the sea, waves and wind break it apart into small pieces called pancakes (fig. 5.17).
- Pancakes gradually freeze together to form larger pieces called floes, some of which float on the water and some of which are attached to land are called fast ice.
- Freshwater ice that enters the sea (icebergs) comes from glacial ice. These can be very hazardous to navigation as most of the iceberg is below the surface.
- Icebergs may have different shapes depending on where they came from (fig. 5.19):
    a. Icebergs from narrow valley glaciers are irregular in shape and may tower above the water surface. They are called castle bergs.
    b. Icebergs that break off flat continental ice sheets are usually larger than castle bergs. These massive, relatively flat icebergs are called tabular bergs.
- Studies in Antarctica indicate that the glaciers that extend out to sea and create the permanent shelf ice that surround the continent are receding. At the same time it appears that the shelf ice is calving large bergs at an increasing rate.
- Large accumulations of condensed water vapor (water droplets) close to the ground are called fog.

- The three types of fog encountered are:
    a. advective fog, formed when air warmed by the underlying water is saturated by water vapor and then moves over colder water to condense.
    b. sea smoke, dry, cold air moving over the sea from the land is warmed and picks up water vapor from the sea and rises to cool and condense.
    c. radiative fog, the result of warm days and cold nights – warm moisture laden air over the land cools at night and the water vapor condenses.

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–IX) of the appropriate major concept identified in this section:

polar molecule	heat capacity	radiation
echo sounding	fog	covalent bond
sea ice	hydrogen bond	viscosity
refraction	SOFAR channel	density
cohesion	calorie	conduction
absorption	land ice	latent heat
convection	attenuation	iceberg
deep scattering layer	precision depth recorder	sonar

Test Your Recall

Answer the following questions to test your understanding

FILL IN THE BLANK

1. Heat energy is measured in ________________________ in the cgs system.
2. Water molecules attract and bond to each other with __________________________ bonds.
3. The asymmetrical arrangement of hydrogen atoms in the water molecule results in it being a _____________ molecule.
4. Ice can change directly to a gas through the process of _________________________________.
5. The maximum density of fresh water occurs at ____________ °C.
6. Heat is redistributed through the ocean basins as warm water moves and carries heat energy with it in a process known as ______________________________.
7. Charged atoms are called ______________.
8. The color of light that penetrates to the greatest depth is ________________.
9. Sound can be trapped and travel long distances in the __________________ channel.
10. Sheets of newly formed sea ice are broken into smaller pieces called ________________________ by waves and wind.
11. Sea floor sediments can be resuspended to form a turbid layer near the bottom called the ___________________________ layer.
12. Water is made up of _______________________ and ______________________.
13. One _________________________ is the amount of heat required to raise the temperature of 1 gram of water 1°C.

14. The heat capacity of any substance divided by the heat capacity of pure water is called the
________________________ ___________________ of that substance.
15. ______________________________ is the resistance to motion or internal friction of a fluid.
16. Water is the universal ____________________________.
17. The ______________________ striking the ocean surface is one form of electromagnetic radiation.
18. When light passes from the air into the water, its path is bent or _________________________________.
19. If a ___________________ wave or signal is sent into the water and the time required for the return of the ___________________ is measured accurately, the _______________________ to the object may be determined.
20. Pieces of land ice that break off and fall into the sea are called ___________________________.

TRUE - FALSE

1. Heat and temperature are two ways of measuring the same physical property of a material.
2. In order to change the state of water from a solid to a liquid, you must raise its temperature.
3. Like nearly all substances, the density of fresh water increases as it freezes.
4. Water has a relatively high heat capacity.
5. The coldest water in the oceans naturally sinks to the greatest depths.
6. Most of the light that reaches the sea surface penetrates to depths of about 50 meters.
7. Light is refracted when it passes from the atmosphere into water because the velocity of light in water is slower than in air.
8. Icebergs float with only about 12% of their mass above water.
9. Icebergs in the North Atlantic rarely drift further south than the Arctic Circle.
10. Fog formation plays an important role in transferring water and heat between the atmosphere and the ocean surface.
11. Sound is transmitted poorly in water; it travels much slower and over shorter distances than in air.
12. Shorter wavelengths of light are attenuated very rapidly with depth in the ocean.
13. More substances dissolve in water than in any other common liquid.
14. As seawater freezes, salts are excluded from the crystal lattice.
15. The heat capacity of water is nearly five times that of aluminum.
16. The addition of salt to water changes its boiling and freezing points.
17. Hydrogen and oxygen bond to form the water molecule with an angular separation between the hydrogens of 105 degrees.
18. Under certain conditions, it is possible to cool water below zero degrees centigrade and have it remain a liquid.
19. The oceans are primarily heated from below by heat from the core.
20. The center of the SOFAR channel is at a depth of about 200 m.

MULTIPLE CHOICE

1. The heat necessary to change the state of water between a solid and a liquid is called the
   a. latent heat of vaporization.
   b. latent heat of solidification.
   c. latent heat of fusion.
   d. latent heat of liquefaction.
   e. none of the above.
2. The property of a substance that describes its resistance to motion or internal friction is its
   a. heat capacity.
   b. surface tension.
   c. density.
   d. cohesion.
   e. viscosity.
3. The three atoms in a water molecule are held together by
   a. oxygen bonds.

b. covalent bonds.
c. surface tension.
d. hydrogen bonds.
e. gravity.

4. The density of seawater
    a. is greater than fresh water.
    b. increases with increasing depth in the oceans.
    c. changes with changing temperature.
    d. increases with increasing salinity.
    e. all of the above.
5. The density of fresh water
    a. reaches a maximum at 4°C.
    b. decreases with decreasing temperature below 4°C.
    c. increases with decreasing temperature down to 4°C.
    d. all of the above.
    e. none of the above.
6. Heat is added to the oceans by the sun in a process called
    a. radiation.
    b. conduction.
    c. convection.
    d. advection.
    e. sublimation.
7. A Secchi disk is used to measure
    a. refraction of light in water.
    b. attenuation of light in water.
    c. convection of heat in water.
    d. surface tension of water.
    e. density of water.
8. Sound travels in seawater at a nearly constant velocity of approximately
    a. 500 meters per second.
    b. 1500 meters per second.
    c. 750 meters per second.
    d. 350 meters per second.
    e. 2000 meters per second.
9. Sound in seawater
    a. travels in curved paths because of small changes in velocity.
    b. is affected by changes in water temperature.
    c. is unaffected by changes in pressure.
    d. a and b above.
    e. b and c above.
10. The deep scattering layer (DSL)
    a. can be detected with PDR's.
    b. is a chemical boundary in the water.
    c. is a biological phenomena.
    d. a and c above.
    e. b and c above.
11. Water molecules, even in flowing water, can link together by
    a. hydrogen bonds.
    b. covalent bonds.
    c. ionic bonds.
    d. super glue.
    e. none of the above.
12. The heat necessary to change water from a liquid to water vapor is called the
    a. latent heat of fusion.
    b. latent heat of vaporization.

c. latent heat of freezing.
d. dew point.
e. none of the above.

13. When ice changes directly to a gas, the process is termed
    a. vaporization.
    b. evaporation.
    c. desiccation.
    d. sublimation.
    e. none of the above.
14. The addition of salt to water changes its
    a. porosity.
    b. salinity.
    c. boiling point.
    d. freezing point.
    e. b, c, and d above.
15. Seawater of average salinity freezes at about
    a. 32°F.
    b. 0°C.
    c. -2°C.
    d. -10°F.
    e. none of the above.
16. The density of pure water at 4°C is
    a. 1 g/cm^3.
    b. 10 g/cm^3.
    c. 100 g/cm^3.
    d. 1000 g/cm^3.
    e. none of the above.
17. The three ways in which heat energy is transmitted are
    a. consumption, convection, and reduction.
    b. conduction, convection, and radiation.
    c. conditional, conversion, and realistic.
    d. all of the above.
    e. none of the above.
18. As water freezes
    a. water molecules become more widely spaced.
    b. the ice becomes less dense.
    c. ice floats on water.
    d. all of the above.
    e. none of the above.
19. The light that penetrates deepest in the ocean is
    a. red.
    b. green.
    c. blue.
    d. yellow.
    e. magenta.
20. The attenuation of light commonly involves
    a. stretching and flattening.
    b. absorption and focusing.
    c. scattering and absorption.
    d. scattering and shrinking.
    e. none of the above.

Visual Aids : Test Your Understanding of the Figures

1. Study figure 5.4 carefully. Can you explain why ice, regardless of its temperature, floats in water?
2. Study figure 5.7. How can water help dissolve materials that are nonpolar such as greases, oils, fats, or hydrocarbons? (Hint - What are the primary components of soaps?)
3. Study figure 5.9. Do longer or shorter wavelengths of light penetrate water best? Do higher or lower frequencies of light penetrate better?

Study Problems

1. If 7.4 seconds elapse between an outgoing sound pulse from a PDR and its return echo to the ship, what is the depth of the water in meters?
2. Using figure 5.6 in the text, determine the temperature of maximum density and the freezing temperature for water with a salt content of 15 g/kg.
3. Using figure 5.9 in the text, determine what percent of the available light with a wavelength of 0.00007 cm at the surface successfully penetrates to a depth of 1 meter and to a depth of 10 meters. What about light with a wavelength of 0.00006 cm?
4. Read section 5.6 in the text carefully. Now calculate the pressure in pounds per square inch at the bottom of the Challenger Deep in the Mariana Trench at a depth of 11,020 meters. Do the same for the mean depth of the world's oceans (3729 meters). How tall of a column of mercury would be required to produce these pressures (express your answer in miles)?

Answer Key for Key Terms and Test Your Recall

KEY TERMS

polar molecule (I,VII)	heat capacity (IV)	radiation (VIII)
echo sounding (VIII)	fog (IX)	covalent bond (I)
sea ice (IX)	hydrogen bond (I,V)	viscosity (I,V)
refraction (VIII)	SOFAR channel (VIII)	density (VI)
cohesion (V)	calorie (III)	conduction (III,VIII)
absorption (VIII)	land ice (IX)	latent heat (III)
convection (VIII)	attenuation (VIII)	iceberg (IX)
deep scattering layer (VIII)	precision depth recorder (VIII)	sonar (VIII)

FILL IN THE BLANK

1. calories	2. hydrogen	3. polar
4. sublimation	5. 4	6. convection
7. ions	8. blue	9. SOFAR
10. pancakes	11. nepheloid	12. hydrogen, oxygen
13. calorie	14. specific heat	15. viscosity
16. solvent	17. light	18. refracted
19. sound, echo, distance	20. icebergs	

TRUE - FALSE

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

MULTIPLE CHOICE

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

STUDY PROBLEMS

1. 5550 meters
2. Temperature of maximum density = +0.84°C
   Freezing temperature = -0.80°C
3. Wavelength of 0.00007 cm : 36% at 1 m, 0% at 10 m
   Wavelength of 0.00006 cm : 74% at 1 m, 47% at 10 m
4. Challenger Deep: 16,199.4 pounds per square inch and 0.52 miles.
   Ocean Mean Depth: 5481.7 pounds per square inch and 0.18 miles