PHYSICAL AND CHEMICAL PROPERTIES OF WATER

I. CONTENTS - *TOPICS COVERED*

II. THE MOLECULAR STRUCTURE OF WATER

A. The Special Properties of Water are Due to its Chemical Structure

1. A water molecule is composed of two hydrogen atoms covalently bonded to one central oxygen atom

- **Water molecules have a bent "L" shape, with the hydrogen atoms bound to one side of the oxygen atom – this produces special properties**

2. The hydrogen-oxygen bond of water is polar, which means that the hydrogen has a positive electrical charge and the oxygen has a negative charge

3. The positive and negative charges attract, forming a hydrogen bond between water molecules that are close together

- **The hydrogen bond is like an ionic bond**

4. Hydrogen bonds are weak compared to the covalent bonds that connect the hydrogens and oxygen of the water molecule. However, they are much stronger than the bonds that form between most other molecules.

B. Water Exists in Three Physical States on the Earth: Solid (Ice), Liquid, and Gas (Water Vapor)

1. These changes of state represent changes in the relations between water molecules and the motion of the molecules

- **In water vapor, the molecules are moving rapidly and are not associated with one another.**
- **In liquid water, molecular motion is slower and transient 3-dimensional associations of molecules, connected by hydrogen bonds, occur.**
- **In solid ice, molecular motion is slower still, and each molecule has a fixed place within a crystal structure, which is held together by hydrogen bonds.**
- **Because of the hydrogen bonds between water**

molecules, it takes an unusual amount of energy to melt ice or evaporate liquid water.

C. Latent Heat of Vaporization

1. When water is heated to 100^{o}C, additional heat must be applied in order to cause the water to evaporate (form steam). This added heat is called the **latent heat of vaporization**.

   This latent heat must also be removed when water vapor condenses.

2. The latent heat of vaporization is very important in moderating Earth's climate.

   There is a global pattern of greater evaporation of water form the oceans at low latitudes, transport of water vapor toward the poles, and greater precipitation at high latitudes.

   This results in removal of heat (latent heat of vaporization) from low latitudes and release of this heat at high latitudes as the water vapor condenses

D. Latent Heat of Fusion

1. When water is cooled to 0°C, an additional amount of heat must be removed in order to form ice. This additional heat is called the **latent heat of fusion**.

   This latent heat must also be added when ice melts.

2. The latent heat of fusion is very important in moderating Earth's climate.

   During periods of global warming, melting of the ice caps acts as a large thermal "heat sink" for excess heat coming from the equator

   This results in a global thermal buffer effect.

F. Dissolved Substances Change Water's Boiling and Freezing Points

1. The salt in seawater raises its boiling point and decreases its freezing point, to about -2^{o}C. The change increases with the amount of salt in water.

2. Note that any dissolved substance affects freezing and boiling point (antifreeze, ethylene glycol, works on this principle). This is because the dissolved substance affects the association between water molecules.

III. THE HEAT CAPACITY OF WATER

A. Water Has an Unusually High *Heat Capacity*

1. Defined as the amount of heat required to raise the temperature on water one degree centigrade

2. An increase in temperature equals an increase in the motion of water molecules. It takes lots of heat to make water molecules move faster, because of hydrogen bonds

3. The high heat capacity of water is also important in moderating climate. Coastal areas have less variable

temperatures than inland areas, because water temperature changes slowly in response to changes in the amount of heat from the sun.

IV. THE SURFACE TENSION OF WATER

A. Water Has High *Surface Tension*

1. Defined: surface tension is resistance to penetration or stretching of the surface

2. Surface tension is high because of the cohesion of the water molecules due to hydrogen bonds.

3. Water surfaces can support small objects that are denser than water and would otherwise sink.
   These include some aquatic animals. (Water striders, freshwater insects, are the most familiar example.)

4. Surface tension damps (tends to decrease) capillary waves, the small waves that are the first to form as wind blows over a water surface.

V. THE VISCOCITY OF WATER

A. Water Has a High *Viscocity*

1. Defined: viscosity is the resistance of a liquid to motion.

2. The viscosity of water is high compared to that of chemically similar liquids (for example, alcohol)

3. The viscosity of water is low compared to that of chemically dissimilar liquids (for example, oil)

4. The viscosity of water is important to marine organisms.
   It helps to prevent tiny plants and animals (plankton) from sinking
   It also causes resistance to the motion of larger, swimming animals.

VI. THE COMPRESSIVE NATURE OF WATER

A. Water is Not Very *Compressive*

1. Even at the very high pressures of the deep sea
   About 500 times the pressure at the sea surface

2. This property is also important to marine organisms.
   If they lack air-filled cavities (like lungs or swim bladders), they can often tolerate large changes in depth and pressure without major ill effects.

VII. WATER DENSITY

A. Water Density Decreases with Increasing Temperature

1. Warm water is less dense than cold water

B. Water Density Increases with Increasing Salt Content

1. Saltwater is denser than freshwater

C. Water Density Profoundly Affects Ocean Circulation

1. Increases in seawater density with decreasing temperature (especially) and with increasing salt content cause the vertical circulation of ocean water.

This is essential to the ventilation, or supply of oxygen, to the deeper parts of the ocean.

2. Seawater (in contrast to pure or freshwater) has its greatest density at its freezing point.

D. Water Density Profoundly Affects Sea Life

1. Decreased seawater density with increasing temperature creates a warm surface layer which suspends ocean plant life (phytoplankton) near the surface where they can get enough sunlight to grow.

F. Ice is Less Dense than Water, so Ice Floats

1. Ice and its snow cover insulates bodies of water and helps keep the underlying water from freezing.

VIII. WATER AS A SOLVENT

A. Water is a Very Good Solvent

1. Defined: a solvent is fluid that can dissolve substances

2. Water dissolves rocks (very slowly)

The dissolved minerals from rocks is a primary source of many salts found in seawater

3. Water also dissolves and makes available substances essential to marine organisms

like fertilizers and carbon dioxide (for plants) and oxygen (for animals).

IX. THE TRANSPARENCY OF WATER

A. Water is Transparent to *Visible* Light

1. This allows plant growth to substantial depths.

2. Water does gradually absorb light.

This prevents plant growth below about 200 m depth even in the clearest ocean water.

B. Water is NOT Transparent to *Ultraviolet* light or to *Infrared*

1. Absorption of UV light protects sensitive organisms.

2. Absorption of UV and Infrared acts to heat up water.

X. WATER AND SOUND

A. Water Transmits Sound Well

1. Many organisms rely on sound for echolocation or for communication.

2. Many oceanographic instruments rely on sound transmission by seawater – for example:

Echo sounders to measure depth

Bioacoustics to measure animal abundance and location

SEAWATER CHEMISTRY AND OCEAN SALINITY

I. CONTENTS - *TOPICS COVERED*

Water the Universal Solvent
Salinity of Seawater
Salts and Dissolved Ions
Sources of Seawater Ions
Principle of Constant Proportion
Dissolved Gases in Seawater
Buffering of Seawater's pH (acid-base balance)

II. WATER AS A SOLVENT

A. Water is a Very Good Solvent

1. **Water's universal solvency is due to its**
   - **Relatively low liquid viscosity**
   - **Strongly polar nature**
   - **Unique hydrogen bonding character.**

2. **Water dissolves rocks and atmospheric gases**
   - **The dissolved minerals from rocks is a primary source of many salts found in seawater**
   - **Gases from the atmosphere are dissolved into seawater at the ocean's surface**

3. **Water can hold a tremendous amount of ions and gases in solution**

4. **Water's ability to dissolve and retain mineral ions and gases makes it a readily available storehouse of essential substances to marine organisms**
   - **Nutrients**
   - **Building Materials**
   - **Carbon dioxide (for plants)**
   - **Oxygen (for animals)**

III. SALINITY OF SEAWATER

A. Concentration of Dissolved Solids in Seawater

1. **Salinity Defined: The total quantity (concentration) of dissolved inorganic solids in water.**

2. **Salinity is approximately equal to the weight, in grams, of salt dissolved in 1000 g of seawater.**
   - **This would be the salt concentration in parts per thousand (‰).**

3. **Salinity of ocean water varies from 3.3% to 3.7% or 33‰ to 37.0‰**

4. **The average ocean salinity is 35.0 ‰.**

5. Salinity has no units. (The PSU or "practical salinity unit" is incorrect, although frequently used.)

- This means that 1000 g of average seawater contains 965 g of water and 35 g of salts.

B. Measuring Salinity

1. In the past, salinity of seawater was measured by evaporating the water and weighing the amount of salt remaining.

2. Since that approach is difficult and inaccurate, electrical conductivity of seawater is now used to measure salinity.
   - Measuring of the Chlorinity (Total halogen ions)
   - Salinity (in %o) = 1.80655 x Chlorinity (in %o)

3. Conductivity increases as salt content of the water increases.

4. Conductivity gives very accurate salinity data: 35.0000%o.

5. Conductivity (and temperature and depth) are measured by instruments called CTDs (Conductivity Temperature Depth)
   - These instruments can make thousands of measurements/hour.

B. Salinity Modifies the Physical Properties of Water

1. Heat Capacity decreases with increasing salinity.

2. Freezing Point of water drops with increasing salinity.

3. Evaporation Rate of water slows with increasing salinity

4. Osmotic pressure rises with increasing salinity

5. These properties are termed colligative properties

C. Salinity and Seawater Density

1. Salinity, temperature, and depth (pressure) can be used to calculate density, which is important to understanding vertical circulation of the water.

2. Salinity is greatest in warm, tropical surface waters, where there is more evaporation than precipitation and polar regions where large amounts of sea ice form.

3. Salinity is lowest where there are large inputs of freshwater from rivers or melting glaciers

D. The Major Dissolved Solids in Seawater

1. When salts dissolve in water, they break apart into two types of ions:
   - Cations - positive electrical charge
   - Anions - negative electrical charge

2. Salts are electrically neutral because the cation and anion charges are opposite and equal.

- Examples are: Sodium chloride, NaCl, dissociates to Na^+ and Cl^-.

- Magnesium sulfate, MgSO4, dissociates to Mg2+ and SO42-.

3. Six *major ions* make up> 99% of the total dissolved in seawater. They are:

- sodium ion (Na^+),
- chloride (Cl^-),
- sulfate (SO_4^{2-}),
- magnesium ion (Mg^{2+}),
- calcium ion (Ca^{2+}), and
- potassium ion (K^+).

- See Figure 7.3 and Table 7.1 (page 172) in the text

4. The *major ions* are *conservative.* This means that they have constant ratios, to one another and to salinity, in almost all ocean water.

- Another way of saying this is that sea salts have constant composition.

- They almost always consist of 55% sodium ion, 31% chloride, 8% sulfate, 4% magnesium ion, 1% calcium ion, and 1% potassium ion.

- The main exception is where freshwater is mixing with seawater.

  - River water has a different composition than seawater, for example, it contains more calcium ion.

E. Minor and Trace Dissolved Ions in Seawater

1. Every naturally-occurring element has been found in seawater

2. The minor and trace dissolved ions account for only about 1.5% of the total dissolved solids in seawater

3. See Figure 7.3 and Table 7.2 (page 173) in the text

4. Some, however, have minuscule dissolved concentrations:
   - Iron, 0.06 parts per billion (ppb)
   - Lead, 0.002 ppb.
   - Gold, 0.005 ppb.

5. Many of the minor ions in seawater are *Nonconservative*

- Their concentrations vary geographically and with depth, most often due to uptake and release by organisms.

IV. SOURCES OF THE OCEAN'S SEA SALTS

A. There are Two Primary Sources for Sea Salts

1. Weathering of rocks on land (the cations)
2. Outgassing from the interior of the earth (anions)

B. The Weathering of Rock on Land is a Very Slow Processes

1. Breakdown by water, with dissolved carbon dioxide, which makes it slightly acidic.

2. Rivers carry the dissolved cations to the ocean.

3. Weathering may have been somewhat faster on the early Earth, but even at the present rate it would take only about 8 to 260 million years to replace all the salts in seawater with those in the river inflow.

C. Outgassing from Mantle is an Equally Slow Process

1. The halogen- and sulfur-based anions are mainly derived from the continuous, long-term outgassing of the mantle via volcanic venting – mainly from the mid-ocean ridge system

D. The Time It Takes to Replace the Total Amount of an Ion in Seawater with Ions from the Source Reservoirs is called the Residence Time

1. $$\text{Residence time} = \frac{\text{Amount of ion in ocean}}{\text{The rate at which the ion is added to (or removed from) the ocean}}$$

2. See Table 7.3 (page 178) for residence times

3. Residence times vary greatly for various dissolved solids
   - Chlorine (Cl^-) = 100,000,000 years (greatest time)
   - Iron (Fe) = 200 years

4. Since the residence times for all the ions in seawater is much less than the age of the Earth and the oceans, some processes must remove the ions from seawater to keep them from building up to even higher concentration.

5. Both organic and inorganic processes at work

V. PRINCIPLE OF CONSTANT PROPORTION

A. Ocean's Salt Composition and Concentration is Stable

1. This means that there is no significantly change over time
   - The term for this quality is "Steady State"

2. The "steady state" results from the removal rate of salts from the ocean being equal to the input rate.

   - This balance holds because the removal rate of salts is related to their concentration, and increases when their concentration increases.

B. Salt Removal Processes Include:

1. Formation of evaporites (salt deposits left behind when seawater evaporates)

2. Burial of sediment porewater (the water between sediment grains) sediments, especially biogenic sediments, for Ca^{2+} (calcium ion) as calcium carbonate.

3. Hydrothermal vents, especially formation of the mineral chlorite within the cracks and fissures of the vents, which removes Mg^{2+} (magnesium ion).

C. Evidence Indicates that Sea Salt Concentration and Composition has been about the Same for at Least the Last 1.5 Billion Years

1. The tolerances of bacteria that probably lived 3.8 bybp indicate that sea salt concentration and composition were not too different, even that long ago.

D. Another Important Group of *Nonconservative* Substances Dissolved in Seawater are the *Nutrients*.

1. These are fertilizers essential for the growth of plants, including algae.

2. Major nutrients include nitrate, phosphate, and silicate (the latter required only by siliceous organisms).

3. Nutrients are depleted in surface waters, where plants grow, and are found in higher concentrations in deep waters, where the plant and animal remains that sink from surface waters decay.

VI. DISSOLVED GASSES IN SEAWATER

A. Most of the Gasses Found in the Earth's Atmosphere Readily Dissolve in Seawater

1. Major ones include nitrogen, oxygen, and carbon dioxide

2. The amount of gasses able to dissolve in seawater increases with decreasing temperature

3. See Table 7.4 (page 179)

B. Several Important Gases are *Nonconservative,* Including Oxygen and Carbon Dioxide

1. Oxygen

- Oxygen dissolves in ocean surface water from the atmosphere.

- Photosynthesis is also a source of oxygen to ocean surface waters.

- **Oxygen is consumed by respiration. Rarely, animals and bacteria use all of the oxygen in sub-surface waters, which become anoxic. This can only happen if the waters are isolated from the atmosphere in some way.**

2. Carbon Dioxide

- **Carbon dioxide is consumed during photosynthesis and released during respiration**

- **It can also be exchanged with (dissolved from and released to) the atmosphere.**

- **Carbon dioxide can react with water to form bicarbonate and carbonate ions.**

$$CO_2 + H_2O \rightarrow HCO_3^- + H^+ \rightarrow CO_3^{2-} + 2H^+$$

- **These reactions control the acidity (pH) of seawater.**

- **Organisms use carbonate ion and calcium ion to make calcium carbonate shells, which sink after the organisms die to form calcareous sediments.**

ATMOSPHERIC CIRCULATION

I. CONTENTS - *TOPICS COVERED*

Structure of the Atmosphere
Composition of Air
Atmospheric Pressure
Winds and the Coriolis Effect
Global Wind Bands
Seasonal Variability in Winds
Effects and Features of Wind
Hurricanes
Clouds, Weather, and Climate

II. STRUCTURE OF THE ATMOSPHERE

A. The Atmosphere Consists of a Series of Layers

1. The layers of the atmosphere are defined by temperature shifts

- **Troposphere (clouded layer)**
  - **Temperature decreases with elevation**
  - **The layer where "weather" occurs**

- **Stratosphere (ozone layer)**
  - **Temperature increases with altitude**
  - **Little circulation in stratosphere**
  - **Exceptions are injections of volcanic eruptions**

- **Mesosphere**
  - **Temperature decreases with increasing altitude**

- **Thermosphere**
  - **Temperature increases with increasing altitude**

2. The atmosphere is warmed at the surface and cooled at the top

B. The Atmosphere is Density Stratified

1. The atmosphere is most compressed at the surface

2. Pressure decreases with altitude

III. COMPOSITION AND PROPERTIES OF AIR

A. Air is Composed of Transparent, Odorless Gases

1. Nitrogen – N_2 - (78.1%)

2. Oxygen – O_2 - (20.9%)

3. Other gases: Ar (0.9%); CO_2, water vapor, and inert gases (variable ~ avg. 1.4%)

4. Variable amounts of dust particles

- Terrigenous materials from land (wind-carried)
- Sea salt from ocean surface

B Atmospheric Pressure Varies Both Vertically and Horizontally

1. Measure of air density

2. Pressure increases when cooled or when water vapor content decreases

3. Air density decreases when air is warmed

4. Standard surface air pressure is 760 mm mercury (Hg)

5. High pressure zone defined as > 760 mm Hg

6. Low pressure zone defined as < 760 mm Hg

7. Geographically-continuous regions of equal surface pressure are represented on maps as *isobars*

IV. WINDS ON A ROTATING EARTH AND THE CORIOLIS EFFECT

A. Winds on a Non-rotating Earth Would Be Fairly Simple

1. Hemispherical atmospheric circulation systems

2. Large wind cells in each (northern and southern) hemisphere

3. Warm air rises at the equator, cools as water vapor condenses as rain

4. Dry air rising aloft cools, then sinks at the poles

5. Surface winds blow from the equator to the poles

B. Winds on a Rotating Earth Are More Complex

1. Equator moves eastward at 1700 kilometer/hour

2. Rotational decreases poleward (with increasing latitude)

- 850 km/hr at 60^{o} N and S latitude

3. Earth rotation causes deflection of moving objects relative to Earth's surface

- **Moving objects are deflected to the right in the northern hemisphere**
- **Moving objects are deflected to the left in the southern hemisphere**

C. The Deflection of Objects on a Rotating Sphere is Called the Coriolis Effect

1. The Coriolis Effect is a special term for the effects of global-scale centrifugal forces on Earth

2. Moving air and ocean water masses are significantly affected by centrifugal forces

3. Moving air masses move along curved paths (deflected) instead of straight paths.

4. The Coriolis Effect greatly complicates the Earth's wind patterns

- **Hemispherical wind cells get divided into several smaller latitudinal systems**

V. LATITUDINAL WIND BANDS

A. Latitudinal Wind Bands are Deflected by Coriolis Effect

1. Winds veer to the right in northern hemisphere

2. Winds veer to the left in the southern hemisphere

B. Atmospheric Circulation is Broken Up Into Six Major Wind Bands or Belts

1. Northeasterly and Southeasterly Trades

- **Termed the "Hadley" cells (0 - 30° latitude),**
- **Separated by a belt of low pressure called the equatorial doldrums**
  - **Coincides with the intertropical convergence zone (ITCZ)**
- **Bordered on their high latitude side by a subtropical high pressure belt**
- **Strong, steady wind system**
- **Typically associated with warm moist air**

2. Northern and Southern Westerlies

- **Termed the "Ferrel" cells (30 - 60° latitude)**
- **Bordered on their high latitude side by the Polar Front**
- **Bordered on their low latitude side by a subtropical high pressure belt**
- **Winter storm systems typically ride this belt from west to east**

3. The Northern and Southern Polar Easterlies

- **Termed Polar cells (60 - 90° latitude)**
- **Bordered on their low latitude side by the polar jet stream**
- **Consists of very cold dry air**
- **Winter storm systems typically develop at the low latitude edge of this belt**

C. Air Either Rises or Falls Where Latitudinal Wind Bands Meet

1. Equatorial warm air rises, sinks at ~30°N

2. At 30°N some moves back towards equator as trade winds

- **NE in northern hemisphere**
- **SE in S. hemisphere (directions from which they blow)**

3. Trade winds converge at equator

- **Intertropical convergence zone (ITCZ).**

4. At 30°N the remaining air flows towards poles as the Westerlies

5. Westerlies meet colder, dense air flowing from poles towards equator

- **These air masses converge at Polar (Antarctic) Front**

D. Jet Streams are Narrow Bands of Strong Winds at the Polar Front

1. Jet streams vary seasonally, as the cells migrate

2. The jet streams are typically found along the Polar Front

E. Winds Influence Climate

1. Climate is the long-term averaged weather

2. Wind's influence at mid-latitudes:

- **Low rainfall coupled with high evaporation**
- **Typically light and variable winds (horse latitudes)**
- **Dominated by high atmospheric pressure**

3. Wind's influence in equatorial regions:

- **High rainfall coupled with cloudiness**
- **Typically light and variable winds (doldrums)**
- **Dominated by low atmospheric pressure**

VI. SEASONAL VARIABILTY IN WINDS

A. Causes of Seasonal Changes:

1. Caused by differential solar heating of ocean and land

2. Product of high heat capacity of water

B. Weather Characteristics of Summer:

1. Low pressure areas over land caused by warm rising air

2. High pressure over ocean

C. Weather Characteristics of Winter

1. Winter produces the opposite effect

- **High pressure areas over land caused by cold sinking air**
- **Low pressure over ocean**

D. Characteristics of Monsoons

1. Regional seasonal changes in winds

2. A result of continent configurations

3. Summertime pattern:
  - Warming land with rising air draws cooler, moist air from ocean
  - Result yields monsoon rains

4. Wintertime pattern:
  - Winds reverse, cool continental air is drawn towards ocean
  - Result is dry weather.

E. Characteristics of Local Wind Patterns Near Coastlines

1. Sea breeze pattern:
  - Warm land air rises, replaced by cool sea air
  - Called onshore winds
  - Typically a daytime phenomena

2. Land breeze pattern
  - sea air rises, replaced by cool land air
  - Called offshore winds
  - Typically a nighttime phenomena

3. Fluctuation between sea and land breezes a daily occurrence

VII. EFFECTS AND FEATURES OF WIND

A. Mountain topography Has an Effect on Surface Winds

1. Winds rise and cool, leading to condensation of water vapor

2. Precipitation occurs on windward side of topographic high

3. Dry air found on leeward side (this area termed the rain shadow)

B. Characteristics and Significance of Jet Streams:

1. High speed winds of upper troposphere

2. Polar jet streams found at 60°N and 60°S

3. Steers storm systems within the Westerlies

4. Sub-tropical jet streams at 30°N and 30°S

5. Greatest oscillation in winter

VIII. HURRICANES

A. Hurricanes Form From Trade Winds in Equatorial Regions

1. Initiated over warm waters (>27°C)

2. Begins as pressure disturbance (termed easterly wave)

3. Involves the convergence of rotating winds

4. Starts as low pressure with moist winds at 10 - 20°N and S
  - Starts as tropical depression
  - Builds to become tropical storms

5. **Becomes hurricanes when wind speed >75 knots**

6. **Moves westwards**

7. **Dissipates over land or cold water**

IX. CLOUDS, WEATHER, AND CLIMATE

A. Clouds Heat and Cool the Earth

1. **Require condensation nucleii**

2. **Types of clouds:**
   - **cold air with precipitation (cumulonimbus)**
   - **warm air rises (nimbostratus, altostratus, cirrostratus and cirrus).**

Ocean circulation

I. CONTENTS - TOPICS COVERED

The Atmosphere – Ocean Interface

Wind-Driven Surface Currents

Geostrophic Gyres

Countercurrents and Undercurrents

Other Important Currents

Upwelling and Downwelling

Surface Currents' Affect on Climate

El Nino and the Southern Oscillation

Thermohaline Circulation

II. THE ATMOSPHERE – OCEAN INTERFACE

A. The Atmosphere and Ocean Are Dynamic Fluid Layers

1. **Both are dynamic, density-stratified, multi-layered, fluid spheres**
   - **The Atmosphere**
     - **Troposphere (dense, weather layer)**
     - **Stratosphere (ozone layer)**

- **Mesosphere (middle layer)**
- **Thermosphere (ionized layer)**

- **The Ocean**
  - **Surface zone (mixed layer)**
  - **Pycnocline (middle layer with rapid density change)**
  - **Deep zone (cold stable layer)**

2. Convection in the atmosphere is driven by latitudinal variations in solar input (uneven heating of the planet), which in turn powers the wind-driven ocean surface currents

- **Convection is the transfer of energy via mass transfer**
- **Equatorial regions have a heat surplus**
- **Polar regions have a heat deficit**
- **Atmosphere and ocean act in concert in an attempt to redistribute the excess heat from low to high latitudes**

3. The more fluid atmosphere convects (moves) much more rapidly than the underlying ocean

- **Air currents (wind) flow rates up to 200 kilometers per hour**
- **Ocean currents flow rates up to 10 kilometers per hour**

B. The Atmosphere and Ocean are in a Never-Ending Dynamic State of Heat Energy Exchange

1. This exchange is powered by solar energy

2. Exchange of solar-derived heat between the ocean and atmosphere is the heart of the hydrologic cycle

- Evaporation
- Condensation
- Precipitation

C. The Atmosphere–Ocean Interface is a Very Dynamic Interface

1. The great density difference between bottom of atmosphere and the ocean surface
2. Large difference in flow regimes between the two (see A3 above)
3. Friction coupling between moving air (wind) and water
4. Exchange of heat and gasses
5. Significant changes in surface area as a function of wind speed
    - Calm conditions – smooth seas; minimum surface area
    - Stormy conditions - rough seas; much higher surface area

III. WIND-DRIVEN SURFACE CURRENTS

A. Surface Currents Mainly Confined to the Surface Zone

1. Involve about 10% (by volume) of the world ocean
2. Flow horizontally
3. Typically extend down to about 400 meters (top of the pycnocline)
4. Driven by wind-driven friction (ocean-air coupling)

- **Terrigenous materials from land (wind-carried)**
- **Sea salt from ocean surface**

B. Wind is the Primary Agent Responsible for Surface Currents

1. **Friction coupling between wind and ocean surface causes surface water to get piled up perpendicular to direction of wind**
2. **Higher pressure on upwind side of piling up water**
3. **Piled-up water flows "downhill" toward low pressure side of pile**
   - **Net water current flow is in the "downwind" direction**
4. **A persistent wind can generate an ocean surface current beneath it.**

5. **Factors involved in the initial generation of an ocean surface current:**
   - **Wind persistence**
   - **Wind strength**
   - **Length of continuous stretch of ocean surface under a a persistent wind current (termed a fetch)**

6. **The prime global-scale winds responsible for surface current generation are the powerful Westerlies and the persistent Trades (Easterlies)**

7. **Once generated, the direction of a surface current will**

become affected by the Coriolis effect

- Surface currents deflected to the right in the Northern Hemisphere
- Surface currents deflected to the left in the Southern Hemisphere
- Ocean surface currents not found along the equator tend to follow curved paths

8. Continents and ocean basin topography will block surface current flow and further deflect the surface flow into a circular pattern

9. The combination of the Coriolis effect and ocean basin margins produce circular surface current flow around the periphery of ocean basins
   - These circular-flowing surface currents are called gyres.
   - See Figures 9.2 to 9.4 (page 210)

C. The Different Ways Currents Flow

1. Upwelling: ascending water masses
2. Downwelling: sinking water masses
   - Maintain continuity of flow, vertical movement (0.1 - 1.5m/day)
   - Sinking waters may take 1000 years to reach great depths.
3. Horizontal water movement:
   - Convergence (meeting) and divergence (spreading out)

D. Influence of Ekman Spiral and Ekman Transport:

1. Coriolis effect acts on surface current water
   - Deflects it from the wind direction

2. Deflected by Earth's rotation

- **Right in N. hemisphere**
- **Left in S. hemisphere**

3. Transfer through the water column of wind-driven motion with depth to about 100 -150m down

- **Top layer of current (directly powered by wind) transfers some of its kinetic energy to the layer beneath it.**
- **This is repeated for numerous horizontal sheets of water in the the ocean column down to about 100 meters.**
- **The Coriolis effect affects each of the moving horizontal layers**
- **The key point is that each layer responds only to the layer above it, and since there is a time lag involved, each horizontal layer in the current will have a unique direction.**
- **The overall effect is to produce a vertically-oriented helix pattern of current directions – Called the Ekman Spiral**
- **See Figure 9.5 on page 211**

4. Current speed in the Ekman spiral decreases with depth

5. Net result:

- **Overall water movement is at 90° to wind direction**
- **Net current motion is called the Ekman Transport**
- **Dependent on wind persistence.**

6. In nature we find that the overall water movement is around 45° - not the theorized 90°

- Another factor is working against the Coriolis effect
- Attributed to a current-induced pressure gradient (pile-up)
- See Figures 9.6 and 9.7 (pages 211 and 212)

7. A deflecting surface current converges, creating a hill of water piling up on one side of the in the direction of the deflection

- Current tends to want to turn towards the "downhill"
- direction from the "hill" – opposite to Coriolis effect
- Overall effect is a path between wind direction and 90° to the wind direction
- See Figures 9.6 and 9.7 (pages 211 and 212)

IV. GEOSTROPHIC GYRES

A. Geostrophic Gyres Defined

1. Circular, basin-peripheral surface currents that are in balance between the pressure gradient and the Coriolis effect.
2. Geostrophic gyres of the Northern Hemisphere are independent to the ones in the Southern Hemisphere

B. Major Geostrophic Gyres of the World Ocean

1. There are five great Geostrophic gyres in the world ocean

- Northern Atlantic
- South Atlantic

- **North Pacific**
- **South Pacific**
- **Indian Ocean**

2. There is another major surface current that is technically not a gyre:

- **The West Wind Drift or Antarctic Circumpolar Current**
- **Not confined to the periphery of a single ocean basin**

3. The convergence between Northern and Southern Hemispheric gyres does not coincide with the geographic equator

- **Coincides with the meteorological equator**
- **Displaced about 5° to 8° north of geographic equator**

4. Pattern of driving winds and positions of continents shape the gyres

C. The Major Surface Currents Within Geostrophic Gyres

1. The major currents within a single Geostrophic gyre have different characteristics

- **Each current reflects differences in the factors that shape them**
- **Each gyre has a similar set of unique currents**
- **Each current within a gyre blends into one another**

2. Currents are classified by geographic position within the gyre

- **Western boundary currents**

- ✓ **The Gulf Stream: Northern Atlantic**
- ✓ **The Brazil Current: Southern Atlantic**
- ✓ **The Japan or Kuroshio: North Pacific**
- ✓ **The East Australian Current: South Pacific**
- ✓ **The Agulhas Current: Indian Ocean**

- **The Eastern Boundary Currents**
    - ✓ **The Canary Current: North Atlantic**
    - ✓ **The Benguela Current: South Atlantic**
    - ✓ **The California Current: North Pacific**
    - ✓ **The Peru or Humboldt Current: South Pacific**
    - ✓ **The West Australian Current: Indian Ocean**

- **The Transverse Currents**
    - ✓ **North Equatorial Currents: North Atlantic and Pacific**
    - ✓ **South Equatorial Currents: South Atlantic and Pacific**

3. The Western Boundary Currents

- **The fastest and deepest of the three current types**
    - ➢ **Up to 10 km/hr**
    - ➢ **Can reach down to 1500 m deep in places**

- **Form narrow, deep currents along the eastern margins of ocean basins**
- **Move warm water poleward**
- **Each individual current moves massive amounts of water**
    - ➢ **Up to 50 million cubic meters per second**

- **Maintains its identity for very long distances**
    - **Sharp boundaries with coastal circulation system**
- **Prone to form warm-and cold-water eddies**
- **Coastal upwelling uncommon**
- **Waters derived from trade wind belts**
- **Waters tend to be very clear and nutrient poor**
- **Likely responsible for unusual abyssal ocean bottom storms**
- **See Figures 9.8 to 9.12 for illustrations (pages 213 to 218)**

3. The Eastern Boundary Currents

- **Have virtually opposite characteristics compared to the western boundary currents**
- **Slower and more shallow of the western boundary currents**
    - **Up to 2 km/hr**
    - **Typically reaches down to less than 500 m deep in places**
- **Form broad, shallow currents along the eastern margins of ocean basins**
    - **Up to 1000 kilometers wide**
- **Move cold water towards the equator**
- **Each individual current moves relatively small amounts of water compared to its western counterpart**
    - **Up to 15 million cubic meters per second**
- **Has diffuse boundaries separating from coastal currents**
- **Coastal upwelling common**

- **Waters derived from mid-latitudes**
- **See Figures 9.8, 9.9 and 9.12 for illustrations (pages 213, 214, and 218)**

4. The Transverse Currents

- **Directly derived from the trade winds and mid-latitude Westerlies**
- **Tropical trade winds drive the east to west transverse currents**
  - **The convergent effect of the trades cause the east to west current to be stronger than its west to east counterpart**
- **Mid-latitude Westerlies drive the west to east transverse currents**
- **Moderately shallow and broad**
- **Links the western and eastern boundary currents**

5. The West Wind Drift Current

- **Generated by the unimpeded Southern Hemisphere mid-latitude Westerlies**
  - **No continental interference**
- **Carries more water than any other current in the world ocean**
  - **100 million cubic meters per second**
- **Technically a transverse current**

V. COUNTERCURRENTS AND UNDERCURRENTS

A. Equatorial Countercurrents

1. Lack of persistent equatorial winds allows a west-to-east backward flow of water between the North and South Equatorial Currents

2. Form very narrow surface currents along the intertropical convergence zone

3. Helps balance mass transfer flow of equatorial waters

B. Countercurrents Can Exist Beneath Surface Currents

1. Subsurface countercurrents are termed “undercurrents”

- Flow beneath surface currents but in the opposite direction
- Flow velocities of averaging up to 5 kilometers per hour

2. Undercurrents found beneath most of the major surface currents

3. These currents can be very large in volume

- Volume can equal the opposite-flowing overlying surface current
- Best studied undercurrent is the Pacific Equatorial Undercurrent
  - Also called the Cromwell Current

4. Undercurrents probably help to balance the mass transfer flow of ocean circulating ocean waters

VI. OTHER IMPORTANT SURFACE CURRENTS

A. Monsoon Currents:

1. Reversal of normal surface current circulation of the Equatorial Current

2. Caused by a northward shift in the position of the intertropical convergence zone (ITCZ) during the summer months

3. Reversal of regional high and low pressure cells

4. Characterized by a summer rainy season

5. A temporary “seasonal” current

6. Best developed is the Southwest Monsoon Current in the Indian Ocean

B. High Latitude Cold Currents:

1. Non-geostrophic currents originating in polar regions

2. These smaller sized currents move from high latitude to low latitude

    - Powered by polar easterlies
    - Modified and shaped by geographic obstacles

3. Don’t appear to be controlled by the Coriolis effect, gravity, or friction

4. The Greenland and Labrador Currents are good examples

VII. WIND-INDUCED UPWELLING AND DOWNWELLING

A. Wind-driven Horizontal Currents Can Induce Vertical Water Motion

1. Upwelling – Ascending water movement

    - Brings up cold, nutrient-rich waters

2. Downwelling – Descending water movement

    - Caused by water driven against edge of a continent
    - Important for global-scale mixing of ocean

3. Equatorial Upwelling

    - Generated by divergence of the opposing Equatorial Currents
    - Direct effect on global climate and the marine life found along the equator

4. **Coastal Upwelling**
    - **Caused by winds blowing either parallel or offshore along a coastline**
    - **Effect of the Ekman transport**
    - **Brings up cold nutrient-rich waters**
    - **Affects regional climate**

VIII. SURFACE CURRENTS AFFECT WORLD CLIMATE

A. Causes of Seasonal Changes:

1. Caused by differential solar heating of ocean and land

2. Product of high heat capacity of water

B. Weather Characteristics of Summer:

1. Low pressure areas over land caused by warm rising air

2. High pressure over ocean

C. Weather Characteristics of Winter

1. Winter produces the opposite effect

- **High pressure areas over land caused by cold sinking air**
- **Low pressure over ocean**

IX. EL ÑINO / SOUTHERN OSCILLATION (ENSO)

A. Causes Large Climatic Fluctuation

1. Breakdown in the normal atmospheric circulation patterns in the Pacific

2. Irregular cycle, occurs every 2 - 10 yrs.

3. The 1997-1998 weather season was last large El Nino

4. The 1982-1983 season was another major episode

B. **Obvious Signs That an El Ñino is Underway**

1. **Diminishment of the Equatorial Trade winds**
2. **The appearance of unusually warm water off the coast of Ecuador and Peru.**

C. **<u>The Sequence of Events</u> -**

1. **Southern Oscillation - Prevailing Trades Weaken -**
   - **Sub-tropical high in the eastern Pacicfic**
   - **Low pressure cell over Indonesia**
2. **Weak westerlies develop and the Indonesia low moves eastward**
3. **East to west sea slope collapses (sea level rises in the east by up to 20 cm)**
4. **East-Pacific surface waters warm (7°C) warm layer suppresses upwelling of cooler water**
5. **See Figures 9.17 and 9.18 in the text (pages 223-224)**

D. **Some Global Environmental Effects of El Ñino: Vary from event to event**

1. **Marine productivity declines - Upwelling ceases off Peru**
2. **Storm frequency increases- greater precipitation in the western Americas**
3. **Drought in Indonesia, Australia, and Africa (Sahel)**
4. **Winters storms grow or decrease in intensity**
5. **Increased precipitation in the southeastern US**

X. THERMOHALINE CIRCULATION

A. **Ocean Water Masses Possess Distinct Characteristics**

1. **Characteristics include**
    - **Temperature**
    - **Salinity**
    - **Density**
2. **Characteristics determined by:**
    - **Heating**
    - **Cooling**
    - **Evaporation**
    - **Dilution**
    - **Concentration**
3. **Five common water masses**
    - **Surface water**
    - **Central water**
    - **Intermediate water**
    - **Deep water**
    - **Bottom water**

B. Controlled by Temperature and Salinity

1. **Temperature and Salinity Relationships:**
    - **Many combinations of temperature and salinity can yield the same density**
    - **Density of water increases with depth**
2. **The Temperature – Salinity Diagram**
    - **Study Figure 9.19 in the text (p226)**
    - **T-S Curves:**
        - ➢ **Depth distribution of temperature and salinity are distinctive**
        - ➢ **Plot of temperature vs. salinity forms a T-S diagram**

- Depth plots are T-S curves

- **T-S Curves and Water Masses:**
  - T-S curves for large areas of the ocean are vertically similar
  - Define water masses by depth and location
  - Water masses are related by density.

C. Formation of and Downwelling of Deep Water

1. Form mainly in Polar oceans
2. Antarctic Bottom Water (AABW)
   - Generation of icy-cold brines due to sea ice formation
   - Cold salty water sinks
   - Forms a very slow northward-traveling bottom current
3. North Atlantic Deep Water (NADW)
   - Similar to ABW but far less extensive
   - Sits over the top of the ABW
4. Mediterranean Intermediate Water (MIW)
   - Excess evaporation exceeding freshwater input
   - Saltier, but warmer than the AABW and NADW
   - Intermediate density to bottom/deep waters and surface waters

D. Seasonal Temperature Changes Create Seasonal Thermocline

1. Affect surface density
2. Can form sinking water masses, or freshwater lid.

E. Thermohaline Circulation Patterns

1. Thermohaline circulation driven by density differences between water masses, i.e. gravity driven

2. Starts as large volumes of very cold/dense water sinking rapidly (downwelling) in small areas within polar regions

3. Moves equatorward (horizontally) as very slow bottom and deep currents

4. Eventually slowly rises as diffuse upwelling into broad regions of ocean within the temperate and tropical zones

- **Rises on average at 1 centimeter per day**

5. These upwelled water masses eventually move back to to the polar regions as surface currents to start the cycle over again

- **The thermohaline cycle takes about 1000 years**

6. Illustrations of thermohaline circulation are shown in Figures 9.22, 9.23, and 9.25

7. Upwelling "holds up" the thermocline

8. Regions in the ocean where two unique water masses of equal density, but different temperatures and salinities, converge can mix readily; a new hybrid water mass with an intermediate temperature and salinity profile results, but typically with a greater density than the parent water masses; this is termed"caballing"

9. The thermohaline and surface currents work together in a continuous, connected global circulation circuit

- **Acts as a global heat-transporting conveyor belt**
- **Helps distribute solids, gases and nutrients**
- **Mixes the water masses**
- **Helps move pelagic organisms worldwide**

XI. STRUCTURE OF OCEANIC WATERS:

A. Atlantic and Arctic Oceans:

1. Cooling at high N. latitudes produces North Atlantic Deep Water

- NADW (2 - 4°C, 34.9‰)
- Sinks, moves southward

2. In the South Atlantic:

- Antarctic Intermediate W ater (AAIW; 5°C, 34.4%o)
- Antarctic Bottom Water (AABW; 0.5°C, 34.8%o).
- Surface waters: 25°C, 36.5%o .

4. Arctic Ocean controlled by salinity.

- Surface low salinity waters
- Affected by seasonal ice formation.
- At intermediate depths: Norwegian and Greenland currents

B. Pacific Ocean:

1. No counterpart of NADW, isolated from Arctic
2. No source of deep water, sluggish deep water circulation
3. Subtropical lens of warm, salty water.

C. Indian Ocean:

1. Isolated from Arctic, no source of deep water
2. Sluggish deep water circulation

D. Mediterranean:

1. Mediterranean Intermediate Water (MIW, 13°C, 37.3%o)
2. Outflows at depth, mixes in Atlantic

E. Red Sea:

1. Outflow at 40 - 41%o.

XII. MEANS OF STUDYING OCEAN CURRENTS

A. Two Primary Methods to Measure Currents

1. Float method

- **Movement of a drift bottle or free-floating object**
- **Example is the rubber duck**
- **Floats can be on surface or submerged to whatever depth**

2. Flow method

- **Current is measured as it flows past a fixed object**
-

OCEAN WAVES

I. CONTENTS - *TOPICS COVERED*

II. WHAT IS AN OCEAN WAVE?

A. Defined

1. In general, an ocean wave is any periodic, circular displacement of the ocean surface or subsurface interface

2. Ocean waves are water mass disturbances expressed as a ribbon of kinetic energy that is moving at the speed of the traveling wave form

- **Energy is moving, but the water itself moves very little**

B. How Are They Generated?

1. Waves are produced by a generating (water disturbing) force and a restoring (water calming) force

2. Ocean waves come in many sizes, ranging from capillary waves (ripples) to tides.

- **For capillary waves, the generating force is wind and the restoring force is the surface tension of the water**

- For wind waves and sea swell, the generating force is the wind and the restoring force is the Earth's gravity.

- Storm surges are partly due to variations in atmospheric pressure over the sea surface, often augmented by winds and tides.

- For tsunami, the generating force is usually a vertical movement of the sea floor and the restoring force is the Earth's gravity.

- For tides, the generating force is the gravity of the moon and sun.

3. Waves are also generated within the ocean
   - Termed internal waves

   - Mainly along pycnoclines and near the surface

C. What are the Physical Aspects of an Ocean Wave?

1. An ocean wave transfers energy from water particle to water particle in the direction of travel (forward)
   - Causes water particles to move in circles or ellipses, called orbits

   - The lateral propogation of orbiting water particles causing other water particles to orbit allows the transmittal of energy across the ocean surface – causes the waveform to move

   - This type of wave is called an orbital wave

   - Orbital waves occur at the ocean-atmosphere and within the ocean along density boundaries

   - Because orbital ocean wave forms move in the direction of the energy propagation, they are termed progressive waves

2. Ocean waves have distinctive characteristics
   - Wave crest - highest part of wave (peak)

   - Wave trough - lowest part of wave (valley)

   - Wave height (H) - vertical distance between crest and trough

   - Wavelength (L) - horizontal distance between two successive waves

   - Wave period (T) - Time it takes for one wave to move a distance of one wavelength

   - Wave frequency - Number of waves passing fixed point per one second

   - See Figure 10.2 for wave anatomy

3. Wavelength determines size of the water particle orbits

4. Progressive decrease in the diameter of orbits with depth
   - Size of orbit at surface = wave height
   - Wave motion (orbit) is virtually absent at a depth corresponding to about ½ of the wavelength
     - Termed the wave base (Figure 10.3)

5. Difference in particle speed within a single orbit causes the upper portion to move slightly more forward than bottom portion (see Fig. 10.4)
   - Orbits traces are not completely closed
   - Small net forward motion of water column
   - Forward mass transfer of water termed Stokes Drift

III. CLASSIFICATION OF OCEAN WAVES

A. Classified by the Disturbing Force that Creates Them

1. Disturbing Forces
   - Energy that causes waves to form
   - Several different types of disturbing forces

2. Wind over the ocean causes wind waves

3. Storm surges, seismic sea wave, or pressure change causes seiches

4. Underwater earthquakes. landslides, or meteor impacts causes tsunami

5. Nearby celestial body gravity causes tides

B. The Difference Between Free and Forced Waves

1. Free waves continue to propagate away from the region of generation after the disturbing force has been removed
   - Examples are wind swell and tsunamis

2. Forced waves will cease to propagate soon after the disturbing force has been removed
   - Example is the tides

C. Overcompensation of Restoring Force Allows Ocean Waves to Propagate

1. Cohesion restoring force for capillary waves

2. Gravity is the restoring force for wind waves, seiches, tsunamis, and tides

3. The overcompensation of the restoring force is what causes the circular orbit motion in waves

D. The Amount of Wave Energy in the Ocean Varies

According to Wave Type

1. Most wave energy is in the form of wind waves

2. See Figure 10.5

IV. DEEP WATER- VERSUS SHALLOW-WATER WAVES

A. Water Depth Controlling Factor for Orbit Shape

1. Waves traveling in water depths that are greater than 1/2 the wave's wavelength have circular orbits
   - Waves with circular shaped orbits are termed deep water waves
   - Wind waves are the only shallow water type

2. Waves traveling in water depths shallower than 1/20th of their original (deep water) wavelength have elliptical orbits
   - Waves with elliptical shaped orbits are termed shallow water waves
   - Seiches, tsunamis and tides are shallow water types

3. Waves traveling in depths between 1/2 and 1/20 of their original wavelength are termed transitional waves

4. See Figure 10.6

B. Wave Velocity is a Function of Wavelength

1. The longer the wave, the faster the wave energy propagates

2. Deep water wave velocity formula - $C = L/T$
   - C is speed (in meters/second), L is wavelength, and T is time or period (in seconds)

3. Shallow water wave velocity formula - C = sq root 3.1d
   - C is speed (meters/second) and d is the period (in seconds)

4. When deep water waves enter shallow depths:
   - The wavelength shortens (bunches up)
   - The wave slows down
   - The circular orbits become elliptical
   - Indian Ocean

V. GENERATION OF WIND WAVES

A. Wind Waves Defined

1. Wind waves are gravity waves generated by the transfer of wind energy into the surface waters

2. Wind waves range in size from between 2 cm to 3 meters

3. Wavelengths range from 60 to 150 meters

B. Wind Generates Wind Waves, Swell, and Currents

1. Friction coupling between wind and ocean surface causes surface water to get piled up perpendicular to direction of

wind

2. Higher pressure on upwind side of piling up water – lower pressure on downwind side

3. Piled-up water flows "downhill" (under influence of gravity) toward low pressure side of pile (wave form)

- Net water current flow in "downwind" direction

- Capillary size waves first form
  - Smaller than 2 centimeters
  - Controlled by surface tension

- Capillary waves build into wind waves

- The region of rough ocean surface where wind waves are being generated is termed "seas"

  - Made up of chaotic variety of wind waves of different height, wavelength, period, and speed

C. Swell Formation and Dispersion

4. The process of wave separation, termed dispersion, creates "clean" ocean swell out of stormy seas

- Smooth undulation of sea surface

- Swell can travel thousands of kilometers across ocean basins to break as surf on a distant shore

- Progressive groups of swell of similar origin traveling together across the ocean are called wave trains
  - Surfers call it ocean "corduroy"

5. The shape of wind waves is different than that of swell
- Wind waves have sharp crests

- Swell have more rounded crests

5. Factors affecting wind wave and swell development
- Wind persistence (duration)

- Wind strength (intensity)

- Size of fetch - Length of continuous stretch of ocean surface under a a persistent wind current

  - Illustration of a fetch in Figure 10.11

6. Global-scale winds responsible for wind waves and swell
- Powerful mid-latitude Westerlies

- Winter storm systems

- Persistent Trades (Easterlies)
  - year-round

- Tropical hurricane
  - Summer/fall season

7. Once generated, the movement and direction of ocean swell will Not be much affected by the Coriolis effect
   - Remember it is the translation of wave energy – Not water particles across the ocean

D. Classifying Fully Developed Seas

1. A fully developed sea is defined as the maximum wave size theoretically possible for a wind of specific strength, duration, and fetch

2. "Whitecaps" or "combers" form when wave steepness becomes unstable

   - Wave height to wavelength exceeds 1:7 ratio

2. See Table 10.2 for the conditions necessary for a given wind speed

3. Theoretical maximum sized fully developed seas with waves heights averaging 15 meters (50 feet)

4. Largest measured open ocean swell is 112 feet!

VI. ROGUE WAVES

A. Interference Between Wave Trains Makes Rogue Waves

1. Attributed to constructive interference

2. Occurs both out at sea and along shorelines
   - Called surf beat along shorelines

3. Very unpredictable and dangerous to ships
   - Huge Supertankers and Cargo Ships are even susceptible to these waves

4. Surface currents can help generation of rogue waves

VII. WIND WAVES MEETING THE SHORELINE

A. Wind Waves and Swell Approaching Shore Will Change Character

1. "Feel" bottom at ½ the wave's wavelength

2. Wave will slow down

3. Wavelength will decrease, but period remains the same

4. **Wave height will increase**

5. **Wave crest will become peaked**

6. **Water particle orbits begin to change from to circular to flattened ellipses**

B. Wind Waves and Swell Lines Approaching Shore May Change Shape and/or Direction

1. **Refraction – Wave lines approaching the shoreline at an angle will experience slowing and bending**

   - **Wave lines bend towards the nearest point of shore**
   - **Refracting waves attempt to line up with shoreline**
   - **Refracted wave lines focus (wrap around) wave energy at headlands**
   - **Refracted waves lines diffuse wave energy in bays**

2. **Diffraction – Wave lines that change shape and direction due to interruption of wave train as it moves around an object**

   - **Smaller secondary diffraction waves are generated on by the wave train interruption**

3. **Reflection – Waves lines that bounce off vertical barriers and propagate back in the direction form which it came**

   - **Barriers such as seawalls, breakwaters, and bluffs**
   - **Standing waves can result within enclosed waters such as harbors and bays**

C. Wind Waves and Swell Meeting Shore Will Break

1. **As the wavelength shortens, the height to wavelength ratio approaches the 1:7 instability ratio**

2. **Water particles in the top of wave begins to move faster than the actual wave energy form**

3. **The crest of the wave moves ahead past its supporting base and the wave breaks**

4. **A wave breaks when the wave height to water depth approaches a 3:4 ratio**

   - **A three foot waves breaks in four feet of water**

5. Wave energy dissipated as heat, sound and work

6. Waves break against the shore in different ways.
- Plunging waves – Steep and hollow
- Spilling waves – gradual-sloped, and mushy

VIII. INTERNAL OCEAN WAVES
A. Defined:

1. Waves formed between ocean layers of different denisties

SEICHES, TSUNAMI, AND TIDES

I. CONTENTS - *TOPICS COVERED*
Seiches
Storm Surges
Tsunami !
Tides
Tides Affect on Marine Organisms
Tidal Power

II. WHAT IS A SEICHE?
A. Defined

1. A seiche is a rhythmic rocking back-and-forth of a body of water within a confining basin
   - Confined basins include harbors, bays, and inlets
   - Seiche wave periods range from minutes to more than a day

2. Each confined body of water has a specific resonating frequency dependent on two factors
   - Size or shape of the basin
   - The amount of water in the basin

3. Energy can be harmonically added to a seiche, thereby increasing its amplitude
   - The process of swinging ever so higher on a swing set is a similar phenomena

4. A seiche in the form a wave that rises and falls at the ends of a basin, but with only a back-and-forth motion in the middle of the basin is called a standing wave
   - Standing waves oscillate vertically, with little to no forward movement
   - Lake Geneva in Switzerland is an example

B. How Are Seiches Generated?

1. Seiche waves are generated and set into motion by a

disturbing force acting on the basin water

- Persistent wind that suddenly stops
- Ocean swell (surf beat)
- Storm surge
- Landslide
- Tsunami
- Tidal bore

C. Coastal Damage by Seiches is Rare

1. Only when associated with large storm surge and spring tides

2. The rareness is attributed to the low wave height of seiches (centimeters to 3 meters max)

III. STORM SURGE

A. Defined

1. An abrupt bulge of water driven ashore by a storm system
   - Hurricanes
   - Winter frontal systems

2. A storm surge can be up to 1 meter high in deep water

3. A storm surge can add up to 10 meters in water height when it crams up against a shoreline

4. Technically not a wave
   - It has a crest
   - It does not have a trough
   - It has no period or wavelength

5. Storm surges are short-lived (typically hours)
   a. The time it takes for a storm center to pass

B. How is Storm Surge Generated?

1. Created underneath an atmospheric center of very low pressure
   - Intense storm systems like hurricanes
   - Low pressure causes ocean surface to bulge
   - Bulge moves with low pressure center

2. When the storm surge meets the shoreline it piles up very rapidly
   - Acts like an intense, very high incoming tide
   - Can add up to 10 meters of water above normal sea level
   - Storm surges are typically accompanied by storm-generated wind waves and swell

C. Coastal Damage by Storm Surge Can Be Catastrophic

1. Combination of storm surge, large surf, and high tides spells disaster low lying coastal areas

2. Storm surge waters can batter low lying coastal areas much like a small tsunami

3. Storm surges up to 40 feet high have been extremely deadly in various shorelines of the world that are low lying and have high population densities
    - Bangladesh
    - The Netherlands
    - Florida and the Gulf Coast of U.S.A.

IV. TSUNAMI!

A. Defined

1. Tsunami are very long wavelength shallow water progressive (gravity) waves caused by the rapid displacement of ocean water
    - Tsunami is mistakenly called a tidal wave
    - Seismic sea waves are tsunami
    - Not all tsunamis are seismic sea waves

B. The Nature of Tsunami

1. Tsunami are shallow water waves because they always travel in water depths shallower than ½ their wavelength
    - Tsunami wavelengths are up to 200 kilometers

5. Tsunami waves travel very fast
    - Calculated by the shallow water wave equation:

$$C = \sqrt{gd}$$

where C is speed, g is acceleration due to gravity, and d is water depth (typically 15,000 feet in the Pacific)

- up to 500 miles per hour
- Can cross the Pacific Ocean basin in 10 hours

4. Tsunami waves in open ocean only 1-2 meter in height
    - Ocean vessels on the high seas wouldn't notice one

5. Tsunami resemble a swiftly rising tide (a tidal bore) rather than a breaking wave when they make shore
    - Picture a super gigantic "mush burger" wave

- **Unlike a normal sea wave, the tsunami wave keeps driving onshore for minutes**

C. How are Tsunami Generated

1. Tsunami are generated by several water disturbing forces which acts to displace surface water

- **Earthquake/Faulting (sea bottom displacement)**
- **Shoreline or underwater landslide event**
- **Volcanic eruption**
- **Bolide impact**

2. Seismic sea waves are generated when the ocean bottom is rapidly raised, or lowered, along an underwater fault zone during a large earthquake, i.e. large fault rupture

- **Up-lifted sea bottom causes an initial "bump" in the ocean surface**
  - **Crest of tsunami wave forms first**
- **Down-dropped sea bottom causes an initial "dimple" in the ocean surface**
  - **Trough of tsunami wave forms first**

3. After a tsunami is generated, the wave typically disperses into multiple crests

- **The first wave often is not the largest**
- **Because of the long wavelength, the crests may be separated by 10s of minutes or even hours.**

D. Tsunami Are Classified Into Two Categories

1. Based on their proximity to origin

- **Local**
- **Far traveled**

2. Local tsunamis primarily affect a small area and are usually caused by landslides (often underwater) which are triggered by earthquakes or volcanic eruptions.

- **These are sometimes very severe and occur with virtually no warning.**

3. The largest local tsunami on record occurred in Lituya Bay, Alaska due to a landslide.

- **From damage to trees, it is estimated to have reached more than 1500 feet up the mountainside**
- **A wave about 150 feet high swept down the bay and out to sea**
- **Four of six people aboard three boats anchored in the bay survived.**

4. Tsunami can hit coastlines that are thousands of kilometers from the point of tsunami generation

5. **They are free gravity waves like ocean swell**

6. **They do lose energy the further they travel**

7. **The Pacific basin is notorious for abundant far-traveled tsunami**

8. **Tsunami can be predicted after an earthquake**

D. When Tsunami Meet the Shoreline

1. **Fast-moving tsunami waves change radically when they encounter the shoreline very**
    - **Slows down**
    - **Wavelength shortens dramatically**
    - **Tremendous increase in wave height**
    - **First wave encountered may be either the trough or the crest**
        - **Trough – Appears like a Super low low tide**
        - **Crest - Looks like a humungous tidal bore**

2. **Low-lying areas along coastlines are at serious risk when a tsunami hits**
    - **A very rapid onslaught of sea water rushes onshore**
    - **The driving surge pushes inland as Sea level**

3. **Examples of devastating far-traveled tsunami events**
    - **Hilo, Hawaii – 1946**
    - **Alaska, 1964**
    - **Japan – 1703, 1960**
    - **Lisbon, Portugal – 1755**
    - **Indonesia – 1883**
    - **Flores Island - 1992**
    - **New Guinea – 1998**

E. Tsunami Prediction and Warning Network

F. Important Tsunami Safety Tips

1. **If you are in a coastal community less than 50 feet above sea level, and you feel a severe earthquake (one that makes it almost impossible to stand up, which is causing substantial damage to buildings, or is opening cracks in the ground**), RUN for the highest point you can reach within minutes.
    - **Once you see the wave, you cannot outrun it. If all else fails, some people have survived by climbing trees.**

2. **Even if you have felt no earthquake, or only a mild one, a sudden recession of water is** always **a danger sign.**
    - Run away from the water **to high ground.**

3. Remember - more severe waves can follow for hours.
   - Do not return to low-lying areas for 24 hours.

4. Ships at anchor should weigh anchor and head to sea.

5. Ships at dock should also, if there is a warning due to a distant earthquake.
   - However, if at dock during a severe earthquake, it is questionable whether the best choice is to jump ashore and run inland, or to try to ride it out aboard (loose mooring lines if possible.)

6. Tsunami warnings for distant sites are still inexact.
   - They can warn that a tsunami *might* occur, and approximately when, but the danger at a particular location depends on topography, the particular characteristics of the wave, and other factors

   - This results in many false alarms, leading people to disregard alarms when they occur

V. TIDES

A. Tides Defined

1. Tides are the regular rise and fall of sea level that occurs either once a day (every 24.8 hours) or twice a day (every 12.4 hours).

2. Tides are waves with very long periods (24.8 or 12.4 hours) and wavelengths (thousands of km)

3. Tides are shallow-water waves (that is, their speed is slowed by friction with the ocean bottom) even in the deepest parts of the ocean.

B. The Equilibrium Theory

1. Tides are caused by the combination of several forces:
   - Gravitational attraction between the Earth and moon

   - Gravitational attraction between the Earth and sun

   - Centripetal "forces" that result from the moon's orbiting around the Earth and the Earth's orbiting around the sun.

   - Another important factor is the land blocking the free motion of the tide around the earth

2. The moon is the strongest gravitational force
   - Being closest, it is responsible for most of the tide

3. The Earth and Moon are both orbiting around the center of gravity of the Earth-moon pair

   - A point of rotation within, but not at Earth's center

- **See Figure 11.13 in the text**

4. At all points of the Earth's surface, there are two forces acting to produce lunar tides:

- **The gravity of the moon, and**
- **A centrifugal force that acts parallel to the Earth-moon axis, outward or away from the moon.**

5. Gravity (tidal forces) becomes weaker with distance

- **The gravitational attraction of the moon is strongest for the side of the Earth closest to the moon**
- **The gravitational attraction of the moon is weakest for the opposite side**
- **On the other hand, the centrifugal force is the same everywhere**

6. Because there is a slight excess of gravity on the side of the Earth nearer the moon, the ocean "bulges" toward the moon on that side

7. Because there is a slight deficiency of gravity on the side of the Earth which faces away from the moon, the ocean "bulges" away from the moon on that side, also

8. The Earth rotates beneath the bulges

- **We would expect 2 high and 2 low tides each day**
- **This in fact occurs in most places**
  - **This is termed a semidiurnal tide**
- **However, some places have only 1 high and 1 low tide a day**
  - **This is termed a diurnal tide**

9. The Earth-Sun system acts like the Earth-Moon system, except that the tide generated is smaller

- **The observed tide is the sum of lunar and solar tides**

10. The relative positions of the Earth, sun, and moon change during a month

- **When the Earth, sun, and moon are aligned (new and full lunar phases), the tidal forces reinforce each other and there are unusually large tides**
  - **Termed spring tides**
- **When the Earth, sun, and moon form a right angle (first and third quarter lunar phase), the lunar and solar tides partly cancel out, so tides are smaller than average tides**
  - **Termed neap tides**

11. This model of tides (the equilibrium model) is not useful for actually predicting tides
    - Does not take into account many important factors
        - Size of the ocean basin
        - Shape of the ocean basin
        - Bottom topography of ocean basin
        - Northern or Southern Hemisphere

12. A more sophisticated model was created that could accurately predict the tides – the dynamic model of tides

C. The Dynamic Theory of the Tides

1. The dynamic theory of tides describes the tides in terms of a very large number (> 400) of factors that influence them

2. The dynamic model of tides considers the fact that the tide is trapped within each ocean basin
    - Acts like a standing wave which rotates around a center point called a node
    - In the case of tides, the node is called an amphidromic point.

3. In the northern hemisphere, tides rotate counterclockwise due to the Coriolis effect

4. In the southern hemisphere, tides rotate clockwise

5. Some ocean basins, due to their shape, have more than one amphidromic point
    - There are about 12 in the world's oceans

D. There are Three Major Types of Tides:

1. Diurnal tides have 1 high and 1 low per day
    - They are found in Australia, Antarctica, and the Gulf of Mexico
2. Semidiurnal tides have 2 equal highs and lows each day
    - They are found in the Atlantic and Indian Oceans

3. Mixed tides have two unequal highs and lows each day.
    - They are found in the Pacific Ocean.

VI. TIDES AFFECT ON MARINE LIFE

A. Tides Have Important Effects on Marine Organisms

1. Tidal currents are often the strongest currents in coastal areas

2. Important to migration and reproduction of animals

    - For example, larvae may rely on such currents to move them toward or away from the coast

- **Another is fish like the grunion**

3. Intertidal organisms are strongly influenced by the periodic advance and retreat of the ocean

- **They are often arranged in patterns (intertidal zonation) which depend on the amount of time the area of beach is exposed to the air.**

4. Tides affect navigation of ships

- **Depth of bottom**
- **Tidal Currents**

5. Tides affect on surfing conditions

- **Surfers rely on tides for choosing when to surf**
- **Some locals are best at low tide**
- **Some spots are best at high tide**

VII. TIDAL POWER

A. Humans Have Harnessed the Power of Tides

1. Electrical energy generation

- **Much like a regular hydroelectric dam system**
- **Better because it can work both ways**
- **An inexhaustible source of energy**
- **Only practical at certain coastal localities**

3. Flood control purposes

- **Regulate tidal bores and currents**
- **Safer conditions for river mouths and inlets**
- **Also useful for storm surge events**