Chapter 9 - Ocean Circulation

The Atmosphere and Ocean Circulation Systems Are Linked

The global atmospheric circulation system
• influences the movement of **air masses** in general "belts"
• stationary **wind belts** impact the surface of the oceans,
• winds creating currents that circulate waters in the oceans
• winds are under the influence of **coriolis effect**
• five large subtropical **gyres** encircle the major oceans basins

Currents in the oceans include **surface currents** and **deep currents**:
• surface currents are driven horizontally by effects of the wind.
• deep currents are driven horizontally and vertically by differences in density

Ocean circulation is also influenced by **seawater temperature and density**.
• Warm water in the tropics flows in currents to polar regions
• formation of sea ice concentrates the salt in seawater.
• density causes sold and salty water (concentrated by surface evaporation) to sinks

Deep-Ocean "Thermohaline" Circulation
• The deep ocean basins have slow moving currents.
*As currents move about the globe, evaporation increases salinity.
• **Increased salinity and cooling** increases seawater **density**, allowing it to sink to deep ocean.
• The movement of surface waters downward **supplies oxygen** to the seabed.
• Deep, slow-moving water picks up nutrients from seafloor and sinking decaying organic particles.
• **Upwelling** deep water supplies nutrients to the surface.
• Upwelling supplies the ingredients for **phytoplankton blooms**, providing food for the **food chain**.

Sea Ice and **Halosaline Circulation**
• Glaciers contribute large amounts of iceberg and sea ice to the polar ocean regions.
• Sea ice also forms where very cold air is in contact with the ocean surface.
• Currents in the upper sea (mixing zone) can inhibit the formation of sea ice.
• Water is most dense slightly above the freezing point and tends to sink whereas ice floats.
• Once sea ice starts to form the salt is either expelled back into the seawater
• Antarctic sea ice is 1 to 2 meters (3 to 6 feet); Arctic is 2 to 3 meters (6 to 9 feet) thick.
• Formation of sea increases the salinity and density of the seawater, which sinks
• This drives **thermohaline circulation** through the world's deep ocean basins.

Surface Currents involve large masses of water moving horizontally on the surface.
• The transfer of wind energy to water is not very efficient
• Only about 2% energy transfer of "friction" between water and air.
• Wind produces both waves and currents

• Surface currents occur in the "mixing zone" within and above the pycnocline
• (Pycnocline is the ocean layer of rapidly changing density).
• Effects of surface currents is to redistribute heat from equatorial to polar regions.

Mechanisms moving surface currents include:
• Wind: major mechanism (result of atmospheric circulation patterns).
• Solar heating: (direct heating by the sunnfluences surface waters but not water at depth).

• Tides: (affect currents in coastal regions)
• Geography: continents (and islands) influence direction and flow currents (acting as barriers to flow).

Subtropical gyres are large system of rotating ocean surface currents driven by global wind currents with the influence of **Ekman Transport** (see below) and continental geography (land masses restrict and deflect the flow of water currents).

Movement of Surface Currents
• Moving water (like wind) are influenced by the **coriolis effect**.
• Moving water is deflected to the RIGHT in the Northern Hemisphere.
• Moving water is deflected to the LEFT in the Southern Hemisphere.
The coriolis effect has a large influence on the movement of both surface water and deeper water. However, wind-driven currents move fastest near the ocean surface and diminish with depth. The difference in rate of movement results in a rotational process called Ekman transport.

Ekman Spiral and Ekman Transport
• Early sailors traveling noticed that the icebergs moved in a different direction than the wind (causing alarm as the icebergs were cutting across the paths of ships moving down wind).
• **Walfrid Ekman (1874-1954, a Swedish physicist)** resolved the problem of why wind currents and water currents were not the same. The force of wind affect surface water molecules, which in turn, “drag” (by “friction”) deeper layers of water molecules below them.
• The deeper below the surface, the slower the water moves compared to the water layer above it.
• Surface movement ceases at a depth of about 100 meters (330 feet).
• Both surface water and deeper water is deflected by the coriolis effect.
—90° to the right in the Northern Hemisphere
—90° to the left in the Southern Hemisphere.
• Depth is important: Each successively deeper layer of water moves more slowly to the right (or left), creating the Ekman Spiral effect).
• Because the deeper layers of water move more slowly than the shallower layers, they tend to “twist around” and flow opposite to the surface current.
• Net result is that net transport in surface currents is 90° from wind.
• This twisting character of ocean surface waters is called the **Ekman spiral**.
• Ekman transport is the net motion of a balance between the coriolis effect and turbulent drag forces.

Boundary Currents
• Boundary currents currents associated with gyres flow around the periphery of an ocean basin.
• Boundary currents are ocean currents with dynamics determined by the presence of a coastline.

Two distinct categories of boundary currents:
• western boundary currents
• eastern boundary currents.

Western Intensification of Boundary Currents
• Wind blows westward along the inter tropical convergence zone cause "western intensification."
• Wind blowing across the oceans "mounds" water on the western side of ocean basins-up to 2 m.
• The mounding of water is caused by converging equatorial flow and surface winds.
• The coriolis effect is most intense in polar regions, so current flowing eastward near the poles is more dissipated than currents flowing westward at the equator.
• The higher side of a "mound" is on the western side of the ocean basins, having a steeper "slope" and therefore faster moving.

Eastern boundary currents (EBC) are slow (km/day), wide (>1000 km), and shallow (<1/2 km)
• Examples: Canary, California, Benguela, Peru
• EBCs form along the "cool, dry" east side of ocean basins.

Western boundary currents (WBC) are fast (km/hr), narrow (<100 km), and deep (up to 2 km)
• Examples: Gulf Stream, Brazil, Kuroshio, E. Australian, Agulhas.
• WBCs form along the "warm, wet" west side of ocean basins.

Gyres and boundary currents are large scale, but are also complex. Boundary currents change constantly (called **meandering**) producing spinning cone-shaped masses of water - spinning off of larger boundary currents.

Eddie Currents
• The spreading and mixing of surface waters as currents move from one region to another, gaining intensity and dispersing energy as they move.
• Satellite temperature data reveals large spinning eddies in ocean basins along the margins of major currents.
• Warm core rings are rotating warm masses of water surrounded by colder water.
• Cold core rings are cold masses of water surrounded by warmer water.
• Spinning rings can last for years and serve as refuges for sea life (warm and cold water)
• can influence storm development (such as intensifying or reducing hurricane intensity).

The **Gulf Stream Current** is a fast moving ocean current.
• The **North Equatorial Current** moves east across the Atlantic Ocean in the Northern Hemisphere.
• Flow splits into the **Antilles Current** (east of the West Indies) and the **Caribbean Current** (around the Gulf of Mexico).
• Currents merge into the **Florida Current**. (~30-50 miles wide, moving 2-6 mph, a mile deep).
• Along the East Coast, the Gulf Stream experiences "**western intensification**."
• North of Cape Hatteras (NC) the current moves away from the coast and looses much of its intensity (by meandering) producing numerous warm and cold core rings.
• The Gulf Stream gradually merges eastward with the water of the **Sargasso Sea**, the rotating center of the North Atlantic Gyre (named for floating marine alga (seaweed) called **Sargassum** that accumulates in the stagnant waters.
• The volume of water moved by the Gulf Stream is about 100 times all the world's rivers combined!

Antarctic Circumpolar Current
• The Antarctic Circumpolar Current is the only current to completely encircle Earth.
• The current moves more water than any other current.
• The current is in a region of the world with intense winds and wave action.
• The region has lots of upwelling - very "rich" ocean basin (nutrients for plankton)

Climate Effects of Ocean Currents
• Cold water offshore results in dry condition on land (example: California).
• Warm water offshore results in more humid condition on land (example: Florida).
• Depends on seasonal wind patterns and water temperatures.
• Depends also on regional geography along coastal regions.

Upwelling and Downwelling
• **Upwelling** is the vertical movement of cold, nutrient-rich water from deep water to the surface, resulting in "high productivity" (plankton growth).

• Can bring cold, nutrient-rich water to the surface (photic zone) unless **thermocline** is strong and prevents it.
• Nutrients are **not food** but act like a **fertilizer**.
• Upwelling water rich in nutrients feeds phytoplankton, the base of the food chain.
• **Downwelling** is the vertical movement of surface water downward in water column.
• Regions where downwelling is occurring typically have low biological productivity.
• Downwelling takes dissolved oxygen down where it is consumed by the decay organic matter.

Where Upwelling Occurs:
• Diverging surface waters occur where surface waters are moving away from an area on the ocean surface.
• Equatorial upwelling occurs where SE trade wind blow across the **equator**; Ekman transport forces surface water movement to the south (south of the Equator), and to the north (north of the Equator).
• Upwelling of deep ocean waters is most intense in equatorial regions.

Coastal Upwelling and Downwelling
• **Coastal upwelling** occurs where wind blowing along a coastline is influenced by **Ekman current** moving surface waters offshore, or winds blowing off the land pull surface waters away from the coast, pulling deeper water up to replace surface waters.
• Coastal upwelling is influenced by coastal geometry, wind directions, and the influence of the coriolis effect (Ekman transport).
• **Coastal upwelling along the California continental margin**—revealed ocean-surface temperature imagery. Upwelling water along the coastline is colder than waters farther offshore.

Large Cycles in Ocean Climate Variability
• The ocean/atmosphere systems display cyclic changes beyond annual seasonal changes.
• **Longer-term cycles** also occur. Changes happening in one region can gradually impact other regions on multi-year to decade cycles.
• Even longer-term cycles are influenced by extraterrestrial pattern changes in the **orbit** and **rotation** of the Earth relative to the Sun over time.
• These changes impact the distribution of precipitation and influence the warming or cooling of climates over multi-year periods.
• Changes in sealevel over time linked to the accumulation and melting of **continental glaciers**.

El Niño/Southern Oscillation (ENSO)
• El Niño/Southern Oscillation (ENSO) in the Pacific Ocean [also called El Niño-La Niña Cycles]
• ENSO is associated with a band of warm ocean water that develops in the central and east-central equatorial Pacific.
• ENSO is perhaps the most important ocean-atmosphere interaction phenomenon to cause cyclic global climate variability.
• ENSO involves the interactions of ocean currents, ocean temperatures, and atmospheric effects, over time.

How the ENSO cycle works: It involves the **two large gyres** in the Pacific Ocean Basin
• West moving winds at the Equator help to drive the two Pacific Subtropical Gyres (North and South).
• In the **North Pacific Subtropical Gyre**, the western-intensified Kuroshio Current moves up the Asian seaboard (warming China, Japan), flows east with the North Pacific Current, then south as the California Current along the west coast of North America.
• In the **South Pacific Subtropical Gyre**, the western intensified East Australian Current moves south and merges with the Antarctic Circumpolar Current, the completes the gyre as the Peru Current (flowing northward along the west coast of South America).

ENSO Ocean Temperature Effects
• ENSO Cycles are influenced by ocean surface temperatures.
• **"El Niño"** periods ocean surface temperatures are much warmer than the **"La Niña"** periods.
• This is a reflection of the amount of cloud cover (deflecting incoming solar radiation) and winds driving cold upwelling currents to the ocean surface in the equatorial region.
• During "El Niño", the "Pacific Warm Pool" grows larger/more intense in the Eastern Pacific region.

ENSO Weather Effects
• The rising warm-moist air in the western Pacific contrasts with the cool sinking air along South America, resulting in the "**Walker Cell**."
• The **Walker Cell** operates perpendicular (East to West, not north to south like the **Hadley**, **Farrell**, and **Polar** circulation cells) because of temperature contrasts on opposite sides of the Pacific Basin along the equator.

Under **"normal year" ENSO conditions** (which is rare) cool water conditions persist along the west coast of South America (Peru).
• Trade winds blow to the west allow waters to upwell along the west coast of South America (some of the most productive waters in the world).
• West-moving winds drive surface currents westward across the Pacific Ocean where they heat up creating the "Pacific Warm Pool"- a thick thermocline in the western Pacific Ocean.

Under **"El Niño" (the warm phase of ENSO)** wind intensity of the Walker Cell circulation is diminished (Figure 9-26). El Niño is associated with high air pressure in the western Pacific and low air pressure in the eastern Pacific.
• "La Niña" (the cool phase of ENSO) is associated with below average surface water temperatures and high air pressures in the eastern Pacific and low air pressures in western Pacific. Air circulation in the Walker Cell is intensified.
• During El Niño - the "Walker Cell" circulation pattern is very week, and warm surface waters move in to and shut down upwelling in the Peru region (and causing both warm and wet conditions on land), and a collapse of fisheries offshore (associated with economic and ecological catastrophe). The warm conditions arrive around Christmas, so El Niño refers to the Christ Child in Peruvian weather.
• During La Niña - the "Walker Cell" circulation intensifies, increasing greater cooling and more upwelling along the coast, enhancing ocean productivity, but drought on land in South America.
• These fluctuating cycles of ocean surface water temperatures influence climate factors (warm/wet or cool/dry) conditions around the entire Pacific Basin, if not the entire world.

El Niño year (impacts)
• High and Low pressures reverse
• Winds are slack or blow against the Equatorial Current
• Mounds of warm water on eastern side of Pacific Basin
• Creates nutrient poor conditions in many regions. A **temperate thermocline** replaced with a **tropical thermocline**, this prevents mixing of deep cold nutrient rich water because of the buoyancy of extra warm surface water.

ENSO Impacts on Coastal California
• During El Niño periods, California's coastal ocean waters are warmer, and a more well-developed thermocline hinders coastal upwelling.
• Lack of upwelling reduces the nutrient supply for sea life, so marine specie either adapt and migrate elsewhere, or in many cases, loose populations due to competition for limited food resources.
• The southern tropical jet stream move north from the Central America region. As a result, Southern California gets more tropical moisture which can translate to increased rainfall if conditions are right.

• During La Niña periods, California's coastal ocean waters are cooler, only a weak thermocline can develop. As a result, there is stronger and well developed coastal upwelling. As a result, more food is available, and marine life flourishes in coastal waters.
• During La Niña periods, colder waters offshore translate to drier conditions on land.

Sea Level Changes Caused by Continental Glaciation Cycles
• Sea level changes caused by the melting of continental glaciers (Antarctica and Greenland).
• Geologic data shows that sea level has risen and fallen many times, sometimes 100s meters.
• Some are associated with mass extinctions.
• Sea levels are currently rising, and have been since the end of the last ice age

Ice Ages of the Pleistocene Epoch
• The peak of the last glaciation stage (called the Wisconsin Stage) was about 18,000 years ago.
• Large quantities of water that otherwise was in seawater was frozen in continental glaciers.
• Massive glaciers many miles thick over large portions of North America and Europe
• Modern Greenland and Antarctica are a fraction of the volume of the ancient massive ice sheets.
• Sea level fell around the world by as much as 400 feet below current sea level
• Low sea level exposing all the regions that are now continental shelves.
• There were many as 20 glaciation cycles in the last 2 million years or so, 4 of them were "major."

Glacial Cycles Interpreted From Ice Cores and Ocean Sediments
Drilling programs have collected ice cores from the Antarctic and Greenland ice sheets.
Many more cores have been collected from marine sediments from around the world.
• Evidence of glaciation cycles are well preserved in ocean sediments, including:
-- Glacial ice has tiny bubbles that preserve chemistry of the air and ice at the time it formed.
-- Sea sediments preserve organic and inorganic materials that can be studied and dated.
-- Shell material of foraminifera contain stable isotopes of carbon, oxygen and other elements that match the chemistry of seawater at the time that they lived.
-- Ice in polar regions is enriched in light isotopes of oxygen and carbon (light isotopes evaporate from seawater faster than heavy isotopes).
-- Sea water at the peak of glaciation cycles are enriched in the heavy isotopes of carbon and oxygen. The ratios of these isotopes are preserved in microfossil shell material.
-- Scientists have been able to clearly reconstruct a "sea level curve" compared with atmospheric greenhouse gases.

Impact of Ice-Age sea level changes on continents, humans, & extinctions
• At the peak of the last ice age sea level about **400 feet (120 m) lower** than today.
• Rivers and streams carved canyons that have flooded as sea level rose, creating fjords, estuaries and bays we see around the world today.
• What are now continental shelves were exposed land (coastal plains) that extended out to near the shelf break around continental landmasses.
• Much of the record of human prehistory is now submerged on continental shelves.
• Sea level change has had major impacts on humans and all "remaining" species alike.
-- The continental shelf in the Bering Straits region between Siberia and Alaska was exposed during the last ice age, allowing many species (including humans) to migrate between continents.
• A major mass extinction has been on-going since the last ice age.
-- When sea level was low, humans (and other species) were able to migrate throughout the world when what are today's "continental shelves" were "coastal plains"
-- "Human over-consumption" but climate change and sea-level-rise have also been major contributing factors (the two factors are linked).

Increasing CO_2 Concentrations in the Atmosphere and Oceans
• CO_2 concentrations and temperature have tracked closely of the last 300,000 years.
• The recent (if not alarming) increase in CO_2 concentrations in the atmosphere is a result of human consumption of fossil fuel, burning forests, and other land use changes.
• Earth's ecosystems are responding with measurable changes.
• Continental glaciers are melting faster (causing serious concerns about coastal flooding).
• Chemistry of ocean water is slowly growing more acidic (especially endangering ocean species that secrete $CaCO_3$ skeletal material).

Hypoxia and Eutrophication
• **Hypoxia** is oxygen deficiency in a biotic environment.
• **Eutrophication** is caused by excessive amounts of nutrients in a body of water (lake, sea, or parts of an ocean) which causes a dense growth of plant. When plant material sinks and decays, it sucks oxygen out of the water, resulting in death of animal life from lack of oxygen (hypoxia).
• Excessive amount of nutrients come from runoff from land, mostly agriculture and sewage waste.
• Hypoxia has become a major problem in many parts of the world where whole regions of the seabed are dead or dying because of lack of oxygen.
-- Eutrophication is a serious problem in the Gulf of Mexico near the Mississippi River delta.
• **Density stratification** in isolated ocean basins can lead to depletion of oxygen at depth at as microbial decay consumes free oxygen and then starts to break down sulfate ions ($^{-}HSO_4$) to hydrogen sulfide (H_2S).
• The **Black Sea** is an example where **halosaline density stratification** has lead to anoxic conditions at depth. The Black Sea is an inland sea that has anoxic conditions. Marine surface waters flow into the Black Sea from the Aegean Sea through the shallow **Bosphorus Straight**. Denser saline water trapped in the basin are unable to circulate out of the basin. A strong **pycnocline** prevents oxygen from reaching depths below about 100 meters.

Could the world's oceans become "anoxic?"
• Large portions of the world's ocean basins have gone "anoxic" in the geologic past.
• During the Late Cretaceous Period the world's ocean basins became density stratified.
• This period called the Cenomanian-Turonian 'Oceanic Anoxic Event' (OAE) about 90.5 and 91.5 million years ago (the Cenomanian and Turonian are named epochs of the Cretaceous Period).
• The world was much warmer in the Cretaceous Period, and there were no continental glaciers.
• The oceans were warmer, and a thick thermocline and intense pycnocline blocked oxygen-rich surface waters from penetrating deep water.
• Organic-rich deposits preserved in ocean sediments of the OAE show that there is no bioturbation, suggesting that plankton in the grew in the shallow mixing zone was not consumed if their remains sank into the anoxic condition that existed at the seabed.
• The same thing could happen if humans keep consuming carbon-based fuels at current pace.

Ocean Acidification
• Ocean acidification is the reduction in the pH of the ocean over an extended period (decades+).
• The primarily cause is the uptake of carbon dioxide from the atmosphere into seawater, but can also be caused by other chemical additions or subtractions from the ocean.
• Examples of ocean acidification are recorded in the geologic record associated with major periods of geologic eruptions and massive extraterrestrial impacts many groups of marine organisms with shells ~66 million years ago).
• **Anthropogenic ocean acidification**: In last 250 years, atmospheric CO_2 concentrations has increased from 280 parts per million to over 394 parts per million. Most is due to the burning of fossil fuels (coal, gas, and oil) and release of CO_2 and other acid-forming compounds by land use changes (such as burning off forests to be replaced by agriculture).

• Ocean acidification has potentially devastating ramifications for all forms of ocean life, from microscopic plankton to the largest animals at the top of the food chain.

The "**garbage patch**" is a popular name for concentrations of marine debris (mostly small pieces of plastic) that accumulate across the more stagnant central parts of the large gyres in the ocean basins. The central regions of ocean basins are areas of convergence and downwelling, so trash from sources on land and sea are carried long distances by currents, much of it ending up in a convergence zone "garbage patch." The largest garbage patch is in the north Pacific Ocean. Garbage is generally quite hazardous to sea life.

Chapter 10 - Waves

Waves are:
• **Short-term changes in sea level**.
• A wave is **energy** moving through water.
• Waves are generated by a "**disturbing force**" - something that transmits energy into a fluid medium (such as wind blowing on water). Example: A pebble hitting a puddle creates **ripples** (tiny waves) that propagate away from the source. Ripples grow smaller as they move away from the splash (source) until they diffuse away with increasing distance, or when it encounters the edge of the puddle.
• **Wind** is the primary disturbing force for waves in the ocean and large bodies of water.
• Waves are also generated by **earthquakes**, **landslides**, and **volcanic eruptions** (producing **tsunamis**), and **tides** are produced by gravitational interactions between the Earth, Moon and Sun.

Types of waves		
Wind Waves	**Tsunamis**	**Gravity Tides**
• Height = range from small ripples up to 60 feet (sometimes higher) • Speed = 10 – 75 mph • Periods = 5 – 25 sec.	• Height = open ocean less than 2 feet; -- onshore up to 300 feet • Speed = jetliner speeds 400-500 mph • Wavelength = 100’s of kilometers • Periods = minutes	Height = up to 50 feet plus Period 12 ½ to 25 hours

Terms Used To Describe Waves	
Crest - the highest part of a passing linear wave	
Trough - the lowest part of a passing linear wave	
Wavelength (L)	Distance between waves
Period (T)	Time between passing waves
Height (h)	Height from crest to trough (same as "amplitude")
Water depth (d)	Average water depth (determines wave behavior)

Characteristics of Waves
• Ocean waves are created by wind blowing over water.
• The distance between **two wave crests** or **two wave troughs** is called the **wavelength**.
• **Wave height** - the vertical distance between the highest (crest) and lowest (trough) parts of a wave.
• **Wave period** is the time interval (seconds) between passing wave crests (completing one cycle) and are measured as wave crests pass a stationary point (such as waves passing a **buoy**).
• **Wave speed** is a function of wavelength and wave period, and is related to the wind velocity where the waves form.
-- Wave speed (c) is the distance the wave travels divided by the time it takes to travel that distance.
-- Wave speed is determined by dividing the wavelength (L) by the wave period (T). [$c = L/T$].

What is important is the combination of the wave height and wave period.
• Wave period is directly related to the speed the wave is traveling.
• The longer the period, the faster the wave, and the more energy in contains.
• The greater the period the faster the wave moves .
• Also, the greater the period, typically the higher the wave breaks as it approaches the shore.

Wave base is the **depth of influence** of a passing water wave,
• **Wave base** is about **half the wavelength** of passing water waves.
• At depths greater than half the wavelength wave motion dies out—when water motion is less than 4% of its value at the water surface and is generally insignificant.

Wave Orbits and Orbital Depth
• Passing waves create a **vertical circular current** in the water.
• This orbit-like motion is revealed by particles in the water.
• The **orbital motion** of a wave is greatest at the surface and diminishes with depth.
• Orbital depth is the depth to which the orbital motion of the wave energy can be felt.
• Orbital depth is equal to **half of the wavelength**.
• At the sea surface, orbital diameter is equal to wave height.
• As depth increases, less wave energy can be felt.
• The orbital depth is the depth where zero wave energy remains.
• Example, if a wave at the surface has a height of 4 meters and a wavelength of 48 m, then the depth where no motion from the wave exists is 48/2 or 24 meters.

Deep-Water Waves and Shallow-Water Waves
• The depth of the water determines the character of wave behaviors.
• **Deep-water waves** are waves passing through water greater than half of its wavelength.
-- Deep-water waves are **waves of oscillation**.
-- A wave of oscillation is a wave in the open ocean where movement in the water below a passing wave is in a vertical circular motion.
• **Shallow-water waves** are waves that are interacting with the seabed in depths less than half it wavelength.
-- Shallow-water waves are called **waves of transition** because they change character as the move shoreward and dissipate their energy interacting with the seabed onto the shore.

Wind waves change as they approach the shore:
• As a wave approaches shallow water its begins to transform when it's **orbital depth comes in contact with the seabe**d (when $d < L/2$).
• The friction caused by waves interacting with the seabed causes waves to **slow down** as the move onshore.
• The **friction** of the seabed begins to slow the bottom of the wave; whereas the top of the wave does

not slow as quickly..
• **Circular motion** within the wave becomes interrupted and becomes **elliptical**.
• As waves approach the beach, their wavelengths (L) and velocity decrease. However the period (T) stays the same. The shortening of the wavelength results in an increase in wave height as it moves into shallow water.
• A wave breaks when the water depth (d) is about the same as the wave height (h). Where a wave curls over on itself is called a **breaker**.
• Breakers then turn into a turbulent front called "**surf**" that moves onto the beach.
• When the dying wave runs up on the beach and then retreats it is called "**swash**."

Breakers
• When a wave approaches shore, the base of the wave encounters the bottom—the front of the wave slows down and the back overtakes the front. This forces the water into a peak where the top (crest) curves forward.
• This peak will eventually fall forward in a tumbling rush of foam and water called a **breaker**.
• Waves break on or near shore, they also crash over reefs or offshore sandbars if water depths are shallow.
• **Wave steepness** is the ratio of **height to wavelength**.
• When wave steepness exceeds a **ratio of 1:7**, breakers form.

Slope of the seabed/beach creates different kinds of "Breakers"
• Three types of breaking waves: spilling breakers, plunging breakers, and surging breakers.
• Breakers may be one or a combination of these types.
• G**entle slopes** produce **spilling breakers**. Spilling breakers begin far from shore and take a relatively longer time to reach the beach. The breaking crest slides down the front of the wave in a flurry of foam as the wave moves shoreward. Spilling breakers give surfers a long slow ride.
• **Moderate slopes** produce **plunging breakers**. Plunging breakers build up rapidly into a steeply leaning crest. The crest curls further forward of the rest of the wave before crashing down in the surf zone. Plunging breakers are dangerous because the crash into shallow water.
• **Steep slopes** produce **surging breakers**. Surging breakers occur where waves slam directly on the shoreline. With no gentle slope the waves surge onto a steep beach, producing no tumbling surf. Surging breakers also create huge splashes on a rocky cliff shoreline.

Wave Trains
• A wave train is a group of waves of equal or similar wavelengths traveling in the same direction.
• Individual waves move from the back to the front of a wave train, gradually building up, peaking, then declining as it moves to the front of the wave train. The result is that **individual waves within a wave train are moving about twice as the wave train itself**.
• Surfers watching advancing waves may notice that the first waves to arrive decline in intensity as they arrive as the following waves build higher.
• After the highest crest passes, the trailing waves decline in intensity as the wave train passes.

Origin of Wind Waves
• Wind waves form from wind blowing on the ocean surface.
• The key factors influencing wave intensity include **fetch**, **wind duration**, **wind strength**, and **proximity to wind source area**.
• Wind energy is gradually transferred to the waves forming on a body of water, causing waves to absorb energy and **grow in amplitude and period over distance and time**.
• The transfer of wind energy to wave energy is not very efficient (only about 2% of the energy is actually transferred) but it is the size of the area that that the wind is impacting, as well as how strong the wind is blowing that matters.

Wind-Wave Input Factors:
• **Fetch** is the "length" (distance) wind blows over open water. This is the uninterrupted distance over which the wind blows without significant change in direction.
• **Duration** is how long the wind blows. Strong wind that does not blow for a long period will not generate large waves.
• **Wind strength**: The stronger the wind, the bigger the waves. The wind must be moving faster than the wave crests for energy to be transferred.
• **Proximity**: Separation of wave trains by period. Long-period waves move faster than shorter-period waves and will separate and advance before wave trains with shorter periods.

Wind-Wave Output Factors: (Waves!)
• Wave height increases.
• Wavelength increases.
• Wave period increases.
• Direction - wave travel in the direction that the wind blows.

Wave Equation: Large Fetch + Long Duration + Strong Winds (wind speed) = Large, Long Period Waves

Fetch is important because the interrelationship between wind speed and duration, both functions of fetch, is predictive of wave conditions.

"Sea" and "Swell"
• A **storm** generates winds that impact a region over open water.
• The area impacted by the wind is called a "**sea**."
• The waves generated by the storm will move out and away from sea are called "**swell**."
• Sea is a general area where wind waves are generated, mixed period and wavelengths. Seas are typically a chaotic jumble of waves of many different sizes (wave heights, wavelengths, & periods).
• **Fully Developed Sea**: Max size waves can grow given a certain fetch, wind speed and duration.

• **Ocean swell** refers to series of ocean surface waves that were not generated by the local wind.
• Swell refers to an increase in wave height due to a distant storm.
• Ocean swell waves often have a long wavelength.
• As waves move out and away from the storm center, they sort themselves out into groups of similar speeds and wavelengths.
• This produces the smooth undulating ocean surface called a swell.
• Swells may travel thousands of miles from the storm center until they strike shore.
• Swells are generated by storms over the open ocean, but many ocean swells originate in the oceans around **Antarctica** where there is high winds with **nearly infinite duration and fetch**.

How Waves Form
When the wind starts to blow, the surface of a water body will go through a progression as waves form and intensify.
• When the wind starts to blow, the ocean surface will change from **calm** (mirror-like) conditions to form **capillary waves (ripples), chop, wavelets, to waves** (each with increasing wavelengths, wave heights, and wave periods).
• Smaller wave features can form on existing larger wave features, adding to the complexity of the water's surface.

Ripples (Capillary Waves) are very small waves with wavelengths less than 1.7 cm or 0.68 inches. The formation of capillary waves is influenced by both the effects of surface tension and gravity.

• The ruffling of the water's surface due to pressure variations of the wind on the water. This creates stress on the water and results in tiny short wavelength waves called ripples.
• The motion of a ripple is governed by surface tension.
• Ripples are the first waves to form when the wind blows over the surface of the water and are created by the friction of wind and the surface tension of the water.
• These tiny little waves increase the surface area of the sea surface and if the wind continues to blow, the size of the wave will increase in size and become a wind wave.

• **Chop** refers to small waves causing the ocean surface to be rough (mixed wave forms).
• **Ripples** and **small wavelets** form and move independently of large **waves** moving through an area, creating rough and irregular wave patterns.

• A "**cat's paw**" is the imprint that a light breeze that ruffles small areas of a water surface. When generated by light wind in open water, a nautical name for them is "cat's paw" waves, since they may resemble paw prints.
• On the open ocean, much larger ocean surface waves (seas and swells) may result from coalescence of smaller wind-caused ripple-waves.

A **squall** is a a sudden violent gust of wind or a localized storm. A squall line is a line of thunderstorms that can form along or ahead of a cold front. It contains heavy precipitation, hail, frequent lightning, strong straight-line winds, and possibly tornadoes and waterspouts.
• At sea, a squall is used to describe a relatively rapid change in weather from calm or mild weather to sudden strong winds and intense precipitation, usually associated with passing a cold front.

Beaufort Wind Force Scale for sea conditions
The **Beaufort wind force scale** relates wind speed (velocity) to observed conditions at sea (including wave height) or impact of features on land. It is a numbered scale from 0 to 12 to describe sea conditions and wave size.
• Zero "0" on the Beaufort scale represents the calmest of seas (the water is so smooth that it looks like glass).
• A 12 on the Beaufort scale represents hurricane force waves (Figure 10-21).

Wave Interference Patterns
Wave interference occurs where waves from different sources collide.
• **Constructive wave interference** occurs where waves come together in phase or crest meets another crest (or trough meets another trough).
• **Destructive wave interference**: Waves come together out of phase or crest meets a trough.

Rouge waves are large, unpredictable, and dangerous (also called 'extreme storm waves') are those waves which are greater than twice the size of surrounding waves.
• They often come unexpectedly from directions other than prevailing wind and waves.
• They are often steep-sided and associated with unusually deep troughs.
• Some rouge waves are a result of constructive interference of swells traveling at different speeds and directions.
• As these swells pass through one another, their crests, troughs, and wavelengths sometimes coincide and reinforce each other.
• This process produces large, towering waves that quickly form and disappear.

Behavior of Waves
Waves can bend when they encounter obstacles or changes on the sea floor. Wave behavior includes **refraction, diffraction, and reflection**.

• **Refraction** involves **bending**. Wave refraction starts when wave base starts to interact with the sea bed and slow the waves down, causing them to bend toward shore. Refraction occurs when wave **swells approach the beach at an angle**.

• **Diffraction** involves **spreading (or dispersion)** of wave energy. Wave diffraction refers to various phenomena which occur when a wave encounters an obstacle or change in geometry of the seabed. For example waves are diffracted when they when they pass an island, or when they pass a point or other structure, such as a jetty at the mouth of a harbor.

• **Reflection (bouncing)** involves crashing into a solid surface (such as a seawall or cliff) and reflecting back to sea. Reflection can result in **standing waves**—waves that move back and forth (oscillate) in a vertical position waves strike an obstruction head-on and then are reflected backwards in the direction they came from.

Tsunamis

A tsunami is a very long and/or high sea wave or coastal serge of water caused by an earthquake or other disturbance.
• Tsunamis get their name from Japan (where they are fairly common): "Tsu"[harbor], "nami" [wave].
• Tsunamis are caused by displacement of the earth's crust under an ocean or body of water of any size. When the solid earth moves, the water above it also moves with it.
• Tsunamis can also be generated by earthquakes, volcanic explosions, underwater landslides, even asteroid impacts.
• Tsunamis are the result of both the initial shock waves and the following motion of the water readjusting to a stable pool (sea level).
• Tsunamis can travel great distances throughout the world's ocean.
• Their energy is dissipated when they approach shorelines where they come onshore as a great surge of water, with or without a massive "tidal wave" crashing onshore.
• Although most tsunamis are small (barely detectible), some modern tsunamis have reached inland elevations many hundreds of feet above sea level.

Tsunami Characteristics:
• Tsunamis are usually less than 2 feet in the open ocean.
• In deep ocean, tsunami wavelengths are long, commonly 100's of miles.
• Tsunamis always behave like shallow water waves ($d < L/20$) because no ocean deep enough!
• Undetectable by ships in open ocean because wavelengths are so long (slow rise and fall as wave passes).
• Open ocean tsunami velocity is 400 – 500 mph. So about 4 – 5 hours from Alaska to San Diego (or Hawaii).
• Wave stacks up on continental shelf, about ½ of the time a trough arrives first (sea recedes from shore).
• Waves 30 – 100 ft are common – locally run-up can be higher.
• Highest is thought to be +300 ft., 66 million years ago from asteroid collision in the Gulf of Mexico.

The United States and other countries have collaborated in developing a **Tsunami Warning System**

Chapter 11 - Tides
Tides are one of the most reliable and predictable phenomena in the world.

What are tides and how they are created?
• Tides are cause by the gravitation pull of extraterrestrial objects, the **Sun** and **Moon** being the most significant tidal forces on planet Earth.
Tides are **very long-period waves** that move through the oceans in response to gravitational forces exerted on the oceans by the Moon and Sun.
• Water will flow in the direction of gravitational pull. However, because the Earth is rotating, this gravitational pull is constantly changing causing daily tide cycles.
• Both the solid earth and the oceans are impacted by tidal forces, but oceans can move because they are fluid.
• Tidal forces create "bulges"on the ocean surface.
• The largest tidal effect is from the Moon due to its proximity to Earth; a smaller tidal effect is from the Sun. The Sun's gravitational pull on the Earth is about half (~44%) of the Moon's gravitational pull.

• Tides are **consistently predictable** because the rotation of the Earth is a consistent 24 hours (a **solar day**).
Tides are influenced by a **lunar day** (a consistent 24 hours 50 minutes).
• **Tides advance 50 minutes each day**. This is because the Moon rises 50 minutes later each day.

• Tides arise in the oceans and move toward the coastlines where they appear as the daily rise and fall of the ocean surface.
• Large lakes can have tides, but they are small because of the comparatively small volume of water.

A **tidal range** is the difference in height between the **highest high water (HHW)** and the **lowest low water (LLW)**. Tidal ranges vary from region to region, influenced by the geography of coastlines.

Tidal Currents
• A **tidal current** is a horizontal flow of water that accompanies the rising and falling of the tides. Tidal currents can be strong on shallow continental shelves and coastlines with restricting geography (such as in bays, inlets, narrow straits, lagoons, and estuaries). Tidal currents are relatively weak in the open ocean.
• An **incoming tide** along a coast is called a **flood current**
• An **outgoing tide** is called an **ebb current**.
• The strongest currents usually occur near the time of the highest and lowest tides.
• Tidal currents are typically weakest midway between the flood and ebb currents and are called **slack tides**.
• Daily tides move vast quantities of water along coastlines, filling in and emptying coastal bays and estuaries, flushing out stagnant waters, and moving nutrients in and out.
• The ebb and flood tides cause rivers in delta regions to reverse their flow directions and bring in **seawater** to mix with **freshwater** (creating **brackish** waters).
• The speed of tidal currents can reach up to several miles per hour.

Phases of the Moon and Tides
• Tides are periodic short term changes in the elevation of the ocean surface caused to the gravitational attraction of the moon and sun, AND the rotational motion (inertia) of the of the Earth.
• The gravitational pull of the moon is slightly stronger than the sun. However, sometimes the gravitational forces of the Sun and moon join together to make higher tides .

Spring Tides and Neap Tides
• During **full moon** or **new moon phases**, the gravitational forces of the Sun and Moon are maximized, producing very large ranges of tidal highs and lows called spring tides.
• During a **full moon**, the Earth and the Sun and Moon are approximately aligned, producing very large ranges of tidal highs and lows (producing “**spring tides**”).

• During the **quarter moon phases**, the gravitational forces of the Sun and Moon are at their minimum, producing very small ranges of tidal highs and lows (producing “**neap tides**”).
• A **neap tide** is the **lowest level of high tide**; a tide that occurs when the difference between high and low tide is least.

The Effects of Elliptical Orbits of Earth and Moon On Tides
• It take the Earth 365.242 days for the Earth to orbit the Sun (1 **year**).
• The moon completes one orbit around the Earth in Earth **27.3 days** (called the **sidereal month**).
• However, due to the Earth's motion around the Sun it has not finished a full cycle until it reaches the point in its orbit where the Sun is in the same position (**29.53 days**) - this is the time from **one full moon to the next.**
• Both the Earth and the Moon have orbits that are slightly **elliptical** (not circular). This has an influence on the intensity of tide cycles.

Perigee is when the Moon is closest to the Earth.
Apogee the moon the farthest from the Earth.
Perihelion is when Earth is closest to the Sun (in early January).
Aphelion Earth is farthest from the Sun it is called (in early July).

• Because the moon has a greater influence on tides, the highest tides happen at perigee when there is a a full or new moon. This happens a couple times a year and are called **king tides**.
• **King tides** occur when the Earth, Moon and Sun are aligned at perigee and perihelion, resulting in the largest tidal ranges seen over the course of a year.

Types of Tidal Cycles
If the Earth were a perfect sphere with no continents, all parts of the planet would have two equally proportioned low and high tides every lunar day as the Earth rotates. However, the large continental land masses block the westward movement of the tidal bulges.
• This blocking of the tidal bulges results in the development of complex tidal patterns within each ocean basin. As a result, different parts of ocean basins have different types of tides.

Diurnal Tides—a region where there is only one high tide and one low tide each lunar day. For example, the Gulf of Mexico has diurnal tides.
Semidiurnal Tides—a region that experience 2 high tides and two low tides of approximately equal size each lunar day. For example, the Atlantic Coast of North America has semidiurnal tides.
Mixed Semidiurnal Tides—a region where the two high tides and two low tides differ in height. For example, West Coast of the North America (including here in San Diego) has mixed semidiurnal tides.

Regional Tidal Variations
Tidal ranges vary considerably around the world and are influenced by factors including shoreline and continental shelf geometries, latitude, size of the body of water, and other factors
• Equatorial regions have very minimal tides compared with higher latitudes.
• Tidal currents are influenced the influence of the coriolis effect. Ebb and flood currents influenced by the coriolis effect create circular flow patterns in large bays.

What is Sea Level?
"Sea level" is generally used to refer to **mean sea level (MSL)**. A common accepted definition of mean sea-level standard is the **midpoint between a mean low and mean high tide** at a particular location.
• Sea level is an average level for the surface of one or more of Earth's oceans from which heights such as elevations may be measured.
• Sea level varies for place to place due to gravitational differences in the solid earth, and variations in sea water characteristics (water density) and atmospheric pressure effects.
• MSL is a standardized geodetic reference point for geographic locations.
• Sea levels are different for each ocean basin.
• Sea level is about 20 cm higher on the Pacific side of North America than the Atlantic due to the water being less dense (on average) than on the Pacific side.
• Variations in sea level are due to the prevailing weather and ocean conditions.
• Differences in MSL are also related to the gravity variation cause by different densities rocks in the lithosphere and depth of the ocean basins. For instance mid-ocean ridges (MORs) tend to be low gravity areas.

Changes of the Sea Level
• Sea levels are constantly changing around the globe.
• Long-term trends in sea level rise are linked to global climate change.
• Sea level changes are primarily due to the melting and freezing of the icecaps due to global temperature changes.
• Sea level change is also due to the expansion and contraction of the total water mass due to global temperature changes.
• The dramatic rise in sea level over the past 20,000 years—estimated at about 120 meters (400 feet)!
• In most places around the coastline of North America sea level is rising, however, in some places sea level is falling. In northeastern North America the land is rising due to glacial rebound (an isostatic adjustment caused by the melting of the great Laurentide continental glacier). In Alaska and other part of the West Coast, tectonic forces are pushing up coastal regions, some of these were rapid adjustments associated with massive earthquakes.

Amphidromic Points and Co-tidal Lines
Amphidromic points are locations where there are little or no tide in the ocean. (This is also related to influence of continental land masses interfering with the westward movement of tidal bulges and the influence of the coriolis effect.)
• The closer to the amphidromic the lower the tidal range.
• There are about 1 dozen amphidromic points in the oceans.
• About five in the Pacific Ocean.
• One near Hawaii - there is little tide change there, so beaches tend to be narrow.

A **cotidal line** is a line on a map connecting points at which a tidal level, especially high tide, occurs simultaneously.
• Cotidal lines are hypothetical tidal crest rotating around an amphidromic point.
• Cotidal lines rotate around amphidromic points about every 12 hours.
• They rotate left in Northern Hemisphere, and rotate right in Southern Hemisphere.

What is a "Tidal Wave?"
It is a term often confused with the term "tsunami." They are different.
• Tsunamis are seismic sea wave formed by rapid displacement of the seafloor, such as by earthquakes, volcanic explosions, or landslides).

• Tsunamis are not related to tides. Tsunamis are generally unpredictable, especially close to the source of the disturbance, with only minutes to hours to warn large coastal populations.
• A **tidal bore** is a surging flow of a large about of water moving with the incoming tide that funnels a large amount of water into a river mouth or a narrow bay.
• Tidal bore can produces sizable waves (**tidal surges**, similar to tsunamis) that move inland along rivers and estuaries.
• Tidal bore characteristics are often predictable, but can be influenced by storm surges and high sea waves causing potentially hazardous conditions.

Storm Surge and Storm Tides
A **storm surge** is a wind-driven current of water that piles water into shallow coastal areas and onshore areas with low coastal elevation.
• Storm surges are typically associated with large low pressure tropical cyclones (hurricanes and typhoons) and strong extratropical storms that move into shallow neritic zone environments, and often have enhanced effects where coastal geography, such as a shallow bay or estuary, that cause water to accumulate.
• Storm surge effect are most catastrophic when they occur in association with high tide, and are often the cause of the greatest death & destruction associated with large storms.
• Storm surge can be forecast in association with developing large storms.

Subdivisions of the Intertidal Zone
The **intertidal zone** is the region where land surface is intermittently exposed between the lowest-low water and the highest-high water. The intertidal zone is between the **subtidal** and **supratidal zones.**
• Tidal ranges influence the distribution of sediments and the habitats occupied by plants and animals.
• The **subtidal zone** is the submerged region lying below the low-tide mark but still shallow and close to shore.
• The **supratidal zone** is the typically vegetation-free "splash or spray" zone above the high water line where **back-beach dunes** accumulate.
• A **wrackline** is an accumulation of shell material and debris that typically marks the location of the last high tide cycle on a beach or after a storm surge.

Tidal Forces In Other Planet Systems
• Tidal features have been observed in other planet systems.
• Jupiter’s moon, **Europa**, is covered with large cracks that are attributed to Jupiter’s enormous gravity pulling on the moon, causing the thick ice crust to fracture.
• Tidal forces release heat, enough to melt large quantities of ice below its surface, allowing the Solar System’s largest oceans to remain liquid.
• Jupiter's moon, **Io**, is perhaps the most geologically active moon in the Solar System.
• Tidal forces between Jupiter and its other moons are generating heat within the moon that are driving volcanic activity, recycling the planets crust every few million years.
• Tidal forces also play a role in the heat generated within planet Earth, and may have a significant influence on plate-tectonics and magnetic reversals associated with the core.

Chapter 12 - Coastlines
Coastlines are a dynamic interface between land and sea.
• Coastlines preserve evidence of many process from the past (hundreds to millions of years).
• Coastlines are shaped by an ongoing series of processes involving daily wind and wave action, occasional storms and superstorms, earthquakes and massive tsunamis.
• Coastlines reflect process of their origin including erosion of bedrock features, and are influence by the regional geology, geography, and climate.

• About 75% of the worlds megacities are on coastlines.
• According to the United Nations. presently about 40% of the world's population lives within 100 kilometers of the coast, with hundreds of millions living in low-lying coastal areas (below ~10 meters).

• Wave erosion is persistent and intense, especially when storm waves combine with high tides.
• Coastal landforms are generally delicate, and short-lived features.
• The sediment supply to coasts are offset by erosion rates along shorelines.
• Sediment supply is influenced by climate factors and geography, and can vary significantly from place to place, season to season, and by isolated events, such as changes caused by a massive superstorm.

Classifications of Coastlines and Shoreline Features
Three different classification schemes of coastlines (they overlap and complement each other):
a. Primary or Secondary Coastlines
b. Active or Passive Margins
c. Emergent or Submergent Coasts

Primary and Secondary Coastlines
• **Primary**: Young coasts formed by terrestrial influences, not significantly altered by marine processes.
• **Secondary**: Coasts that have been significantly changed by marine processes after sea level has stabilized.

Primary Coasts - 5 Types
• **Ria Coasts**: Drowned river valleys caused by a rise in sea level. Examples: Chesapeake Bay.
• Glacial Coasts: Coastlines influenced by recent glacial activity such as glacial cut "U shaped" valleys called "**fjords**." Examples: Norway, British Columbia, Alaska, Hudson Valley, New England region, Long Island.
• **Deltaic Coasts**: Coastlines associated with active river and delta systems. Examples: Mississippi and Nile Rivers.
• **Volcanic Coasts**: Coastlines associated with recent or active volcanoes (mostly basaltic or andesitic volcanoes). Examples: Hawaii, Aleutian Islands, Japan, Philippines, Indonesia.
• **Fault/tectonic Coasts**: Coastlines associated with major active fault systems along continental margins. Example: San Andreas fault going off shore at San Francisco.

Secondary coasts are coastlines that have been significantly changed by marine processes after sea level has "stabilized" allowing "erosional" and/or "depositional" processes to dominate shaping of the landscape. (However, to explain this better, we need to examine the other classifications of coastlines first).

• Both **primary and secondary coasts** are influenced by whether they are **"active" or "passive" continental margins** (the second method of "coast classification").
• Both primary and secondary coasts are influenced by whether they are "**emergent**" or "**submergen**t" coastlines (the third method of "coast classification" - discussed below).
• Passive margins tend to be submergent due to the ongoing rise in sea level (Figure 12-10). In contrast, active margins can be both "emergent or submergent" depending on local tectonic forces, such as caused by faulting.

Coastlines on "Active" vs. "Passive" Continental Margins
In North America, the **Pacific Coast is an "active continental margin"** whereas the **Atlantic Coast is a "passive continental margin."**

Active continental margins are coastal regions characterized by mountain-building activity including earthquakes, volcanic activity, and tectonic motion resulting from movement of tectonic plates.
• Active margins typically have a narrower and steeper continental shelf and slope. They can also be subsiding or uplifting.
• Active continental margins are also associated with subduction zones, often include a deep offshore trench.
• The Pacific Coast is an active margin that is characterized by narrow beach, steep cliffs, rugged coastlines with headlands and sea stacks.

Passive continental margins occur where the transition between oceanic and continental crust which is not an active plate boundary.
• Passive margins are characterized by wide beaches, barrier islands, broad coastal plains.
• Offshore passive margins typically have a wider and flatter continental shelf and slope. They are usually slowly subsiding.
• Examples of passive margins are the Atlantic and Gulf coastal regions which represent setting where thick accumulations of sedimentary materials have buried ancient rifted continental boundaries formed by the opening of the Atlantic Ocean basin.

Erosional coastal landforms or features (on Secondary Coastlines)
Emergent coastlines typically have sea cliffs carved by wave and current action along the shoreline. The geometry of a coastline is largely a reflection of how some rocks along a coastline are more resistant to erosion.

Sea Cliffs and Wave-Cut Platforms
• **Sea cliffs** form where persistent wave erosion carves into elevated coastlines.
• Waves erode the base of cliff, causing it to subside or fail.
• Waves carve a flat surface where they scour the seabed leading up the the beach creating a **wave-cut platform**.
• When sea level locally falls falls (such as from uplift of a regional earthquake) wave action scours out a new wave-cut platform, leaving remnants of the old seabed surfaces exposed as expose wave-cut bench.
• A **wave-cut bench** is a flat bench-like platform of rock typically preserved in the upper surf zone associated with an actively eroding sea cliff on an emergent coastline.
• **Headlands** are rocky shorelines that have resisted wave erosion more than surrounding areas, forming points or small peninsulas that jut seaward. Small sandy beaches typically occur in **bays** between headlands.
• **Sea stacks** are large rocky outcrops that have resisted wave erosion and stand offshore as the beach and sea cliff continues to erode landward
• A **sea cave** is an underground passage or enclosed overhang carved into a sea cliff carved by focused wave action.
• A **sea arch** is a natural rock arch caved by wave action. Sea arches form where two caves join together or where a cave cuts through a narrow fin of rock.
• **Marine terraces** are elevated step-like benches formed by the combined effects of long-term wave erosion during the rise and fall of sea level on an emergent coastline.
• **Marine terraces are old wave-cut platforms and benches** that have been elevated by the land rising relative to the ocean surface.

Impact of Ice Ages and Sea-Level Changes on California's Landscapes
California landscapes preserve preserve evidence of geologic, geographic, and climatic changes caused by ice ages.
• During the ice ages, alpine glaciers and ice caps covered upland regions in the Sierra Nevada

Range and Cascades volcanoes, but lower elevations were ice free.
• The formation of continental glaciers in North America and Europe caused sea level to fall almost 400 feet, causing the shoreline to migrate seaward as much as 10 to 70 miles westward of the current coastline in some locations in California.
• This rise and fall of sea level happened with each glaciation cycle (of which there were many through the ice ages of the Pleistocene Epoch).
• In places where the California coastline is slowly rising (**emerging**), each of the major glaciation cycles is preserved as a step-like bench, called a marine terrace.
• The age of marine terraces have been well established in many locations in California.
• Marine terraces are used to measure the rates of tectonic changes along coastlines (uplift, subsidence, fault motions, etc.

Depositional coastal landforms or features:
• **Spits** are ridges of sand projected from land into the bay.
• A **Bay-mouth bar** is a sandbar that stretches across a bay, separating it from the ocean.
• **Barrier islands** are ridges of sand islands that run parallel to the coast.

Emergent and Submergent Coasts
Submergent coastlines display characteristics caused when sea level rises or the land sinks down. Submergent coastlines:
• Contain estuaries and barrier bars, and barrier island systems.
• Ridges that separate valleys that propel into the sea.

Emergent coastlines display characteristics caused when sea level drops or the land rises (from tectonic uplift).
• In some regions around the world, tectonic forces are pushing rocks up along coastal regions, mostly in regions associated with active continental margins. There areas are called emergent coasts and display features including **sea cliffs** and **marine terraces**.
• Where sea level is rising faster than land is rising, or where coastal areas are sinking, it is called a submergent coast.
• Submergent coasts are associated with passive continental margins with wide coastal plains and continental shelves.
• Estuaries are associated with submergent coastlines formed when sea level rises and floods existing river valleys.
• Active margins can have both emergent and submergent coastlines in close proximity to each other.

Common Shoreline Features of Beaches and Barrier Islands
A **beach** is an accumulation of mostly sand (and some gravel) along a shoreline where wave action winnows away finer sediment.
• Beaches occur in the intertidal zone (the zone between highest and lowest tides).
• Above the high tide line the upper supratidal part of the beach is mostly impacted by wind (forming dunes) and storm surges.

A **barrier island** is a long and typically narrow island, running parallel to the mainland, composed of sandy sediments, built up by the action of waves and currents.
• Barrier islands serve to protect the mainland coast from erosion by surf and tidal surges.
• Examples include the Outer Banks in North Carolina and Padre Island in Texas.
• Barrier islands are most common on submergent coastlines associated with low-relief regions such as is present along the Atlantic Coast and Gulf Coast of the eastern United States.
• They form where the sea floor remains shallow for a long distance offshore.

• An **estuary** is the mouth of a river or stream where the tide-driven flow allows the mixing of freshwater and ocean saltwater.
• A **lagoon** is a saltwater-filled bay or estuary located between a barrier island and the mainland.
• A **tidal flat** is a nearly flat coastal area (at or near sea level) that is alternately covered and exposed by the tides, and consisting of unconsolidated sediments.

Coral Reefs, Keys, and Atolls
Biogenous carbonate sediments can accumulate faster than sea level is rising.
Skeletal reefs (including **coral reefs**) thrive in the surf zone, and are able to weather wave action, although they can be heavily damaged by superstorm wave energy.
The sediments generated by wave erosion and **bioerosion** (critters eating critters) contribute to the buildup of carbonate islands (**keys**) and **atolls** associated with **fringing reefs** forming around extinct and eroding volcanic islands.
Keys and reefs of the world experience exposure and erosion during low sea levels during the ice ages.

Shoreline erosion depends on several factors:
1) **Amount of sediment to buffer land**: If the sand supplied to a beach is less than the amount removed by shoreline erosion processes, the beach will retreat landward.
2) **Amount of tectonic activity**: Uplift along the coastline allows erosion to provide sediments to a coastline. If the coast is not rising, then shoreline will retreat landward.
3) **Topography**: Coastal uplands provide more sediments to beaches than flat coastal plain regions.
4) **Composition of land**: Hard bedrock (such as granite) is harder to erode than softer unconsolidated deposits.
5) **Waves and weather**: The greater the waves and storm-generated currents, the more material can be eroded.
6) **Coastline configuration**: Coasts facing prevailing storm waves are eroded faster than isolated bays and down-wind protected shorelines.

Seasonal Erosional Changes to a Beach Profile
• **During the winter**, storm-wave energy is most intense. Waves wash up on the beach and erode sand, and transport it offshore to where wave-driven currents aren't so strong and the sand accumulates on offshore bars. Heavier materials (gravel and boulders) are concentrated on the beach.
• **During the summer**, lower wave energy prevails, and the sand gradually migrates back onshore, gradually expanding the beach seaward.

Longshore Currents and Longshore Drift
A **longshore current** is a current that flows parallel to the shore within the zone of breaking waves.
• Longshore currents develop when waves approach a beach at an angle.
• Longshore currents cause sediment transport called longshore drift.
• **Longshore drift** is the movement of sediments along a coast by waves that approach at an angle to the shore but then the swash recedes directly away from it.
• The water in a longshore current flows up onto the beach, and then back into the ocean in a “sheet-like” formation.
• As this sheet of water moves on and off the beach, it can transport beach sediment back out to sea.
• Objects floating in the longshore current move in a zigzag pattern up and down the beach as it moves down current.

Rip Currents
A rip current (or just “**rip**”) is a current that flows away from the coast.

• **Rip currents** form when wave break strongly in one direction, but weakly in another.
• In the surf zone, breaking waves produce currents that flow both along the shore and out to sea.
• Rip currents typical form on beaches with a sand bar and channel system in the nearshore area.
• A rip current forms as a narrow fast-moving current of water moving in an offshore direction. • Obstructions in the water can also deflect current offshore. Rip current vary in size and speed (up to 6 miles an hour, or faster than an olympic swimmer).
• Rip currents move offshore and dissipate beyond the breaker zone.
• If caught in a rip current, swim parallel to shore to leave the current before heading for shore.

A rip current is different than a rip tide
• A **rip current** is current associated with the swift movement of tidal water through inlets and the mouths of estuaries, embayments, and harbors caused by the rise and fall of tides.
• **Tidal currents** (including rip tides) are strong erosional forces where they are restricted at the mouths of inlets and straights between bodies of water.
-- One example includes the narrow straights of the Verrazano Narrows (between Staten Island and Brooklyn on Long Island, NY).
-- Another example is the Golden Gate Narrows between San Francisco and Marin County in northern California.
In both examples, the seabed has been scoured deeply by the daily tidal flows.
• Tidal flows redistribute sediments building submerged tidal deltas at opposite ends of the channel that need to be dredged frequently to mitigate hazards to shipping.

Coastal Littoral Cells
A **coastal cell** is a relatively self-contained "compartment" within which sediments circulate.
• A coastal cell contains a complete cycle of sedimentation including **sources**, **transport paths**, and **sinks**.

San Diego's Coastal Erosion Problems Related To the Oceanside Coast Cell
• In the San Diego area, the Oceanside Coastal Cell extends from Dana Point to La Jolla Canyon; some of the sand is lost to Carlsbad Canyon as well.
• Streams and cliff erosion provide sediments to the shore zone.
• Most of the sand moves south along the coast and eventually drains down La Jolla Canyon and is deposited as turbidity flow deposits on the La Jolla Canyon deep-sea fan in the San Diego Trough.
• The dominant swell direction in northern San Diego County is from the northwest.
• This creates longshore currents that move sediments (longshore drift) from north to south along area beaches.
• Large waves (swell) especially during high tides in stormy conditions can erode, transport, and deposit large quantities of sediments.
• The sand on northern San Diego County beaches are mostly derived from sediments derived from coastal erosion in the shallow nearshore, beach, and sea cliffs along the coast between Dana Point and Oceanside (much of it from along the undeveloped coast within Camp Pendleton north of Oceanside).
• In addition, large quantities of sandy sediments are contributed to beaches from streams (small rivers) that, during episodic floods, dump large amounts of fresh sediment into the nearshore environment, contributing about half of the sand supply to area beaches over time.
• The amount of sand from river sources is highly variable with the seasonal weather, year to year.

The "Dam Problem"
• Dams have been constructed on most of the small rivers and streams throughout upland regions of San Diego County.
• The intentions of dam construction were to store water (reservoirs) and to reduce flood damage in

low-lying communities.
• The problem is that dams have largely shut off the supply of sand from rivers and streams to the shore.
• Construction of highway and railroad bridges, dikes, and causeways also restrict the flow of sediment-bearing water, preventing the migration of sediment to the coast.
• As a result, less sand is finding its way to the shore, resulting in narrower beaches.
• Without the protection of well-developed beaches, erosion of the sea cliffs are progressively endangering homes and infrastructure along the coast.

Shoreline Erosion Problems
• Shoreline changes quickly with natural forces; they are not a stable landforms.
• Coastlines, especially on the East Coast and Gulf regions, are constantly changing, especially from the impacts of superstorms.
• These coastal regions are underlain by unconsolidated sediments that are easily eroded by strong currents.
• They remain relatively stable, as long as there is a new supply of sediment to replace materials eroded by longshore currents, tides, and storm waves.
• Loss of the sand supply makes down current areas susceptible to beach loss and coastal erosion (a major problem for Southern California's coastal communities).
• Many attempts have been made, often at great expense, to try to prevent the effects of erosion and deposition along coastlines.
• Common construction efforts include jetties, groins, and seawalls to protect harbors, infrastructure, and communities.

Jetties and Groins, and other structures used to protect properties from the destruction by the sea
• **Jetties** are built at entrances to rivers and harbors. Their purpose is to protect properties from storm and wave damage, and to keep sand out of channels (so that there is no beach).
• Jetties require high maintenance costs to manage because they impede longshore drift (which is continues relentlessly).
• Most the costs are for **dredging** sand from one side, and moving it down current to replenish sand to community beaches.
• **Groins** are built as barriers perpendicular to the beach in an attempt to stabilize shorelines. Their purpose is to trap sand migrating along the shore by longshore drift.
• **Breakwaters** are structures used to protect boats from large waves (jetties and groins are forms of "breakwaters").
• **Seawalls** are walls built to protect land structures from large waves and coastal erosion .
• **Rip Rap** are piles of large boulders put on the beach or shoreline. They are cheap but take up beach space and are not as permanent as a seawall, and are unsightly and dangerous. However, they do create habitat for sea life that needs a hard substrate to live.
• **Beach nourishment** adds large amounts of sand to the beach to keep water away from land structures. Sand is dredged form harbor areas or mined from sand bars offshore and pumped onshore in slurries.

Dam construction: The easy way to kill a coastal community.
• **Dams on rivers trap sediments** that would otherwise find their way to ocean beaches.
• A classic example was the construction of a dam on Matilija Creek in Ventura County. The dam is currently being demolished in order to return the sediment flow to sensitive habitats along the river downstream, but also to return a sediment supply to the Ventura County coastline. Many other dams constructed in the 19th and 20th century are being removed for the same reasons.