COASTAL ENVIRONMENTS AND THE OCEAN

Most people love shorelines. Panoramic ocean views, sandy beaches on crystal-clear lagoons, swimming and surfing, going out in boats, or watching giant waves crash onto rocky shores. Understanding of coastal and oceanic processes isn't necessary for enjoying coastal regions. However, it is critical for people who live within or near a coast who can be safe and/or avoid damage to infrastructure, by understanding how coastal processes work. Yet, understanding our one ocean is critical to us all, because we are all connected through it, as you will see. Understanding the ocean is essential to comprehending and protecting this planet on which we live. (0)

Learning Objectives

List ways in which we affect the ocean and the ocean affects us.
Summarize the factors that control wave formation and the important features of waves.
Describe the origins of coastal currents.
Explain why some coasts are more affected by erosion than others.
Describe the formation of coastal erosional features, including stacks, arches, cliffs, and wave-cut platforms.
Summarize the origins of beaches, spits, bay mouth bars, tombolos, and barrier islands.
Explain the various mechanisms of sea-level change (eustatic, isostatic, and tectonic) and the implications for coastal processes.
Compare the positive and negative implications of human interference with coastal processes.

8.1 Significance of the ocean

Earth has one big ocean with many features

The ocean is the defining physical feature on our planet Earth—covering approximately 70% of the planet's surface. The vapor released into the atmosphere returns as rain, sleet, and snow, ever replenishing the planet with freshwater, which we all depend on. All life, including our own, exists because of the ocean. Our lives depend, now and forever, on the health of the ocean (Ocean Literacy Principles).

Video 8.1.1. Years 2021 to 2030 is the International Decade of Ocean Science for Sustainable Development. Learn in this video the purpose of the goal and the significance of having one ocean connecting us all. (1:20)

There is one ocean with many interconnected ocean basins, such as the North Pacific, South Pacific, North Atlantic, South Atlantic, Indian, Southern and Arctic. Ocean basins are composed of oceanic crust, the top of which is the seafloor. The seafloor is not a flat and uniform, instead it has islands and deeps, ridges and trenches, and rift valleys and plateaus, all geologic features. The ocean basins vary in size, shape and sea-scapes due to plate tectonics. How would Earth look like without ocean water? For millennia, humans did not know the answer to this question. But recent discoveries have proved that the bottom of the ocean is as rich in forms as our surrounding landscapes. These physical features of our ocean influence or determine the marine life found within the basins.

Video 8.1.2. The sea floor is not uniform and smooth, but rugged and diverse in its forms. This animation shows the Earth without ocean water. Do you see why there is only once ocean? (00:52).

The ocean is an essential part of Earth’s water cycle. Since it covers so much of the planet, most evaporation comes from the ocean, and most precipitation falls in the ocean. The ocean is connected to major lakes, watersheds, and waterways because all major watersheds on Earth drain to the ocean. Rivers and streams transport nutrients, salts, sediments, and pollutants from watersheds to coastal estuaries and to the ocean.

The ocean supports a diversity of life and ecosystems

The ocean is home to a great diversity of life. Ocean life ranges in size from the smallest living things, microbes, to the largest animal on Earth, blue whales. But most of the organisms in the ocean are microbes, which are the basis of all ocean food webs. Microbes are the most important primary producers in the ocean. Common microscopic life includes the phytoplankton–microscopic plants and bacteria. And we are all in debt to these tiny organisms.

Phytoplankton is at the base of the aquatic food web. Phytoplankton thrive in the shallow and warm parts of the ocean, such as the continental shelves. Similar to land plants, they contain chlorophyll and live on sunlight, consuming CO2 and producing oxygen. That’s right, oxygen for all of us to breathe! This is part of the reasons why the ocean dominates the carbon cycle. Half of the primary productivity on Earth takes place in the sunlit layers of the ocean. The ocean absorbs roughly half of all carbon dioxide and methane that are added to the atmosphere. Read more about the importance of phytoplankton here, on NASA’s Earth Observatory page. Without phytoplankton, we would not have fish to consume and our oxygen levels would be very depleted.

A photograph of microscopic organisms. Their shapes are elongated, donut-like or rectangular with segments.

Figure 8.1.1. Diatoms are part of the phytoplankton. Photo through a microscope. By G. Taylor. Public Domain.

The Ocean is a force for weather and climate

Earth would be a significantly different planet without the ocean, hostile to life or completely uninhabitable. The oceans, along with Earth's atmosphere, keep surface temperatures relatively constant around the globe. Together, they moderate the climate. But how? The ocean absorbs most of the solar radiation reaching Earth. This regulation makes our planet different from say, Venus, Mars or our moon, where the temperature variation is extreme from day to night.

But there is an active heat exchange between the ocean and the atmosphere. This heat exchange drives the water cycle and oceanic and atmospheric circulation in the form of winds, ocean currents, eddies, storms, jet streams, etc. Video 8.1.3. explains how the ocean, coupled with the atmosphere, drives the weather and climate on our planet.

Video 8.1.3. Using NASA's satellite data, this animation highlights key processes between the ocean and the atmosphere that impact every other Earth system (See Ch. 1, Earth systems; 6:00).

Heat exchange between the ocean and atmosphere can result in dramatic global and regional weather phenomena, impacting patterns of rain and drought. Significant examples include the El Niño Southern Oscillation and La Niña, which cause important changes in global weather patterns because they alter the sea surface temperature patterns in the Pacific. Another example is the formation of hurricanes and cyclones in warm oceans.

The ocean influences the climate by absorbing, storing, and moving heat, carbon, and water. Changes in the ocean-atmosphere system can cause changes to the climate that, in turn, cause further changes to the ocean and atmosphere. These interactions have dramatic physical, chemical, biological, economic, and social consequences. (0)

Composition of ocean water

Seawater has unique properties. It is salty, its freezing point is slightly lower than fresh water, its density is slightly higher, its electrical conductivity is much higher, and it is slightly basic. Balance of pH is vital for the health of marine ecosystems. Our ocean is abuffer solution, similar to our blood. A buffer solution is able to maintain the pH within a narrow range; it balances the addition of acids or alkalis. This self-regulation pattern is key for us and for the climate. This is because the pH controls the rate at which the ocean will absorb and buffer changes in atmospheric carbon dioxide CO2 (0). If the ocean becomes acidic, it cannot absorb carbon dioxide the way it has been doing it. In fact, at some point, the ocean can go from a sink for CO2 to a source, releasing the vast amounts that are dissolved in ocean water. This is one problem of ocean acidification.

The ocean’s water is a complex system of organic and inorganic substances. Water is the universal solvent. Thus, runoff and water moving through continents, and weathering rocks and soils on land, deliver ions, sediment, and a great variety of compounds to the ocean. Salts comprise about 3.5 percent of the mass of ocean water, but the salt content or salinity is different in various locations. (1) These variations in salt content produce ocean currents.

The ocean and humans are inextricably interconnected

The ocean affects every human life. We are all interconnected through our ocean. The ocean supplies freshwater as rain and nearly all Earth’s oxygen! The ocean moderates the Earth’s climate, influences our weather, and affects human health. Food, medicines, and mineral and energy resources all come from the ocean.

Our ocean supports jobs and national economies, serves as a highway for transportation of goods and people, and plays a role in national security. The ocean feeds our spirit and minds too. The ocean is a source of inspiration, recreation, rejuvenation, and discovery. It is also an important element in the heritage of many cultures, such as the rich cultures of the Pacific Islands, and many identify as coming out of the ocean, the Mother Ocean. Indeed, our ocean is the cradle of life; the earliest evidence of life is found in the ocean. The millions of different species of organisms on Earth today are related by descent from common ancestors that evolved in the ocean and continue to evolve today.

Humans affect the ocean in a variety of ways. Laws, regulations, and resource management affect what we take out and put into the ocean. Human development and activity leads to pollution, changes to ocean chemistry (ocean acidification), and physical modifications (changes to beaches, shores, and rivers). In addition, humans have removed or killed most of the large vertebrates from the ocean.

Changes in ocean temperature and pH due to human activities can affect the survival of organisms and impact biological diversity. Examples are coral bleaching due to increased temperature and inhibition of shell formation due to ocean acidification. Much of the world’s population lives in coastal areas. Coastal regions are susceptible to natural hazards (tsunamis, hurricanes, cyclones, sea level change, and storm surges).

Picture of bleached coral, showing white colors and no life.
Figure 8.1.2. Bleached Staghorn coral. Bleached corals loose all the algae that lives inside their tissue. Acid ocean water and changes in ocean temperature are thought tocause this disease.
By M. Kieffer, CC BY-SA 2.0.

The ocean is largely unexplored

Less than 15% of the ocean has been explored, making it the least explored part of our planet. The next generation of explorers and researchers will find great opportunities for discovery, innovation, and investigation.

Understanding the ocean is more than a matter of curiosity. Exploration, experimentation, and discovery are required to better understand ocean systems and processes. Our very survival hinges upon it. The field of science that studies oceans is called oceanography. Researchers study the ocean in ships, research vessels and more recently, using robots, subsea observatories, unmanned submersibles in the water and satellites in space.

Ocean exploration is truly interdisciplinary. It requires close collaboration among biologists, chemists, climatologists, computer programmers, engineers, geologists, meteorologists, physicists, animators, and illustrators. And these interactions foster new ideas and new perspectives for inquiries.

Video 8.1.4. The ocean remains to be explored. It is more than a matter of curiosity. Why do we need to explore the ocean? (1:22).

Key Takeaways

Everyone is responsible for caring for the ocean. The ocean sustains life on Earth and humans must live in ways that sustain the ocean. We need individual and collective actions to effectively manage ocean resources for all.

8.2 Ocean Currents

Throughout the ocean there is an interconnected circulation system powered by wind, tides, the force of Earth’s rotation, the Sun, and water density differences. The shape of ocean basins, and adjacent land masses, influence the circulation path. The “global ocean conveyor belt” moves water throughout all the ocean basins, transporting energy (heat), matter, and organisms around the ocean. Changes in ocean circulation have a large impact on the climate and cause changes in ecosystems. (0)

Video 8.2.1. What causes ocean currents? Watch this animation by TED Talk (4:33)

“What Causes Ocean Currents.” story map by Esri.

Surface currents

Ocean water moves in predictable ways along the ocean surface. Surface currents can flow for thousands of kilometers and can reach depths of hundreds of meters. These surface currents do not depend on the weather. (2)

Global wind currents

Winds on Earth are either global or local. Global winds blow in the same directions all the time and are related to the unequal heating of Earth by the Sun, that is that more solar radiation strikes the equator than the polar regions, and the rotation of the Earth. Water in the surface currents is pushed in the direction of the significant wind belts:

Trade winds are consistent winds that flow east to west between the equator and 30 degrees North and 30 degrees South latitude.

Westerlies are the prevailing winds that blow from the west in the middle latitudes.

Polar easterlies are winds that flow from the east between 50 degrees and 60 degrees north and south latitude, as well as the north and south poles.

Rotation of the Earth

Earth's rotation steers winds and surface ocean currents. In simple terms, the Coriolis Effect causes non-anchored objects (like planes or currents) to appear to move to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The objects themselves are moving straight, but the Earth is rotating beneath them, so they seem to bend. (2)

Video 8.2.2. Visualize the surface ocean currents in our globe. This animation is a high-resolution model developed by NASA (3:02).

As wind or ocean currents move, the Earth spins underneath it. As a result, an object moving north or south along the Earth will appear to move in a curve, instead of in a straight line. Wind or water that travels toward the poles from the equator is deflected to the east, while wind or water that travels toward the equator from the poles gets bent to the west. The Coriolis effect bends the direction of surface currents to the right in the Northern Hemisphere and left in the Southern Hemisphere. (2)

An example might make the Coriolis effect easier to visualize. If an airplane flies five hundred miles due north, it will not arrive at the city that was due north of it when it began its journey. Over the time it takes for the airplane to fly five hundred miles, that city moved, along with the Earth it sits on. Therefore, the airplane will arrive at a city to the west of the original city (in the Northern Hemisphere) unless the pilot has compensated for the change. So, to reach his intended destination, the pilot must also veer right while flying north.

Deep currents

Thermohaline circulation drives deep ocean circulation. Thermo means heat, and haline refers to salinity. Differences in temperature and salinity change the density of seawater. The thermohaline circulation results from density differences in water masses because of their different temperature and salinity. (5)

image

Figure 8.3.1. The red and blue bands in the ocean symbolize the direction in which the main currents move. The red color represents warm, low salinity water that travels at shallow levels. The blue color represents cold, high salinity water that moves at depth. Thermohaline Circulation, Wikicommons, CC-BY-SA

Lower temperature and higher salinity yield dense water. When a volume of water is cooled, the molecules move more slowly, and the same number of molecules takes up less space, thus, the water is denser. If salt is added to a volume of water, the number of molecules in that volume increases. This also leads to increased density. Changes in temperature and salinity of seawater take place at the surface. Water becomes dense near the poles. Cold polar air cools the water and lowers its temperature, increasing its salinity. Freshwater freezes out of seawater to become sea ice, which also increases the salinity of the remaining water. This frigid, very saline water is very dense and sinks, a process called downwelling. (1)

Two things then happen. The dense water pushes deeper water out of its way, and that water moves along the bottom of the ocean. This deep-water mixes with less dense water as it flows. Surface currents move water into the space vacated at the surface where the dense water sank. Water also sinks into the deep ocean off Antarctica. Since unlimited amounts of water cannot sink to the ocean's bottom, water must rise from the deep ocean to the surface somewhere. This process is called upwelling. (1)

Video 8.2.3. This animation first depicts thermohaline surface flows and the sinking of water in the dense ocean near Iceland and Greenland. Then it reveals the global thermohaline circulation (1:23)

Upwelling occurs along the coast when the wind blows water strongly away from the shore. This leaves a void that is filled with deep water that rises to the surface. Upwelling is significant where it occurs. During its time on the bottom, the cold deep water has collected nutrients that have fallen through the water column. Upwelling brings those nutrients to the surface. That nutrient supports the growth of plankton and forms the base of a vibrant ecosystem. California, South America, South Africa, and the Arabian Sea all benefit from offshore upwelling. Upwelling also takes place along the equator between the North and South Equatorial Currents. Winds blow the surface water north and south of the equator, so deep water undergoes upwelling. The nutrients rise to the surface and support a great deal of life in the equatorial oceans. (2)

8.3 Waves and Shoreline Currents

Waves

Waves form on the ocean and lakes because energy from the wind is transferred to the water. The stronger the wind, the longer it blows, and the larger the area of water over which it blows (the fetch), the larger the waves are likely to be.

The essential parameters of a wave are its wavelength (the horizontal distance between two crests or two troughs), its amplitude (the vertical distance between a trough and a crest), and its velocity (the speed at which wave crests move across the water). Relatively small waves move up to about 10 km/h and arrive on a shore about once every 3 seconds. Huge waves move about five times faster (over 50 km/h), but because their wavelengths are so much longer, they arrive less often – about once every 14 seconds. (4)

As a wave moves across the water's surface, the water itself mostly moves up and down and only moves a small amount in the direction of wave motion. As this happens, a point on the water surface describes a circle with a diameter equal to the wave amplitude. This motion is also transmitted to the water underneath, and the water is disturbed by a wave to a depth of approximately one-half of the wavelength. (1)

Orbital motion of waves
Figure 8.3.1. The orbital motion of a parcel of water (black dot) as a wave moves across the surface. S. Earle, CC-BY

The one-half wavelength depth of disturbance of the water beneath a wave is known as the wave base. Since ocean waves rarely have wavelengths higher than 200 m, and the open ocean is several thousand meters deep, the wave base does not frequently interact with the ocean's bottom. However, as waves approach the much shallower water near the shore, they start to "feel" the bottom, and they are affected by that interaction. The wave "orbits" are both flattened and slowed by dragging, and the implications are that the wave amplitude (height) increases, and the wavelength decreases (the waves become much steeper). The ultimate result of this is that the waves lean forward, and eventually break. (4)

wave orbits as they approach shore
Figure 8.3.2. Waves flatten when approaching shores. S. Earle, CC-BY.

Shoreline Currents

Waves usually approach the shore at an angle, and this means that one part of the wave feels the bottom sooner than the rest of it, so the part that feels the bottom first slows down first. In open water, these waves had wavelengths close to 100 m. In the shallow water closer to shore, the wavelengths decreased to around 50 m, and in some cases, even less. Even though they bend and become nearly parallel to the shore, most waves still reach the shore at a small angle, and as each one arrives, it pushes water along the shore, creating what is known as a longshore current within the surf zone where waves are breaking. (3)

image
Figure 8.3.3. Formation of Longshore Current. S. Earle, CC-BY

Another significant effect of waves reaching the shore at an angle is that when they wash up onto the beach, they do so at an angle, but when that same wave water washes back down the beach, it moves straight down the slope of the beach. Figure 8.2.2 shows the upward-moving water, known as the swash, pushes sediment particles along the beach, while the downward-moving water, the backwash, brings them straight back. With every wave that washes up and down the beach, particles of sediment are moved along the beach in a zigzag pattern. (1)

image

Figure 8.3.4. The movement of particles on a beach as a result of swash and backwash. S. Earle, CC-BY

The combined effects of sediment transport within the surf zone by the longshore current and sediment movement along the beach by swash and backwash is known as longshore drift. Longshore drift moves a tremendous amount of sediment along coasts (both oceans and large lakes) around the world, and it is responsible for creating a variety of depositional features. A rip current is another type of current that develops in the nearshore area and has the effect of returning water that has been pushed up to the shore by incoming waves. If part of a beach does not have a strong unidirectional longshore current, the rip currents may be fed by longshore currents going in both directions. (1)

image

Figure 8.3.5. The formation of rip currents on a beach with strong surf. S. Earle, CC-BY.

Hazards associated with waves and currents

Any place where the ocean and land are in contact can pose a hazard to people. Rip currents flow straight out from the shore and are fed by the longshore currents. They die out quickly outside the surf zone but can be dangerous to swimmers who get caught in them. Typically they reach speeds of 1 to 2 feet per second, but some have been measured at 8 feet per second, faster than an Olympic swimmer. Because rip currents move perpendicular to shore and can be very strong, beach swimmers need to be careful. A person caught in a rip can be swept away from shore quickly. The best way to escape a rip current is by swimming parallel to the shore instead of towards it, since most rip currents are less than 80 feet wide. A swimmer can also let the current carry him or her out to sea until the force weakens, because rip currents stay close to shore and usually dissipate just beyond the line of breaking waves. Occasionally, however, a rip current can push someone hundreds of yards offshore. The most important thing to remember if you are ever caught in a rip current is not to panic. Continue to breathe, try to keep your head above water, and don’t exhaust yourself fighting against the force of the current. (6)

Graphic showing how to escape a rip current.

Figure 8.3.6. Rip Currents National Weather Service, Public Domain.

Storm Surge

In coastal areas, most of the damage done by tropical storms is from storm surges. The water piles up at a shoreline as storm winds push waves into the coast. Storm surge may raise sea level by 9.1 m (30 ft) or more, which can be devastating in a shallow land area when winds, waves, and rain are heavy. Storm surges can cause extensive damages, eroding beaches and coastal highways, destroying buildings and boats, and affecting inland rivers and lakes. The following videos will explain further what happens during a hurricane storm surge and what are how we mitigate or prevent further damage.

Video 8.3.1. Storm surge is water from the ocean that is pushed toward the shore by the force of the winds swirling around the hurricane. It is the greatest threat to life during a hurricane. Source: NOAA (2:35).

To better respond to storm surges, scientists forecast the extent of flooding using computer models. Geographic Information Systems, GIS, are key to simulate and visualize the impacts of a surge. Scientists then work with governors and agencies to plan, prepare and respond when a surge happens.

Video 8.3.2. Major storm surge is forecasted for coastal areas in the US due to Hurricane Irma.

Key Takeaways

Storm surge is the most deadly part of a hurricane or tropical storm.

Be prepared — during a storm surge event stay tuned to NOAA Weather Radio or television station and listen carefully for any advisories or specific instructions from local officials.

Tsunamis

A particular type of wave is generated by an energetic event affecting the seafloor, such as earthquakes, submarine landslides, and volcanic eruptions. Called tsunamis, these waves are created when a portion of the seafloor is suddenly elevated by movement in the crustal rocks below that are involved in an earthquake. The water is suddenly lifted, and a wave train spreads out in all directions from the mound carrying enormous energy and traveling very fast (hundreds of miles per hour). A series of long-period waves (on the order of tens of minutes) that are usually generated by an impulsive disturbance that displaces massive amounts of water, such as an earthquake occurring on or near the sea floor. Underwater volcanic eruptions and landslides can also cause tsunami. The resultant waves much the same as waves propagating in a calm pond after a rock is tossed. While traveling in the deep oceans, tsunami have extremely long wavelengths, often exceeding 50 nm, with small amplitudes (a few tens of centimeters) and negligible wave steepness, which in the open ocean would cause nothing more than a gentle rise and fall for most vessels, and possibly go unnoticed. Tsunami travel at very high speeds, sometimes in excess of 400 knots. Across the open oceans, these high-speed waves lose very little energy. As tsunami reach the shallow waters near the coast, they begin to slow down while gradually growing steeper, due to the decreasing water depth, much in the same way that wind waves form (Figure 8.2.1). The building walls of destruction can become extremely large in height, reaching tens of meters or more as they reach the shoreline.

The effects can be further amplified where a bay, harbor, or lagoon funnels the waves as they move inland. Large tsunami have been known to rise to over 100 feet! The amount of water and energy contained in tsunami can have devastating effects on coastal areas. (6)

8.4 Topography and Landforms

Topography of the sea floor

Oceans cover 71% of Earth's surface and hold 97% of Earth's water. The water the oceans hold is critical to plate tectonics, volcanism, and, of course, life on Earth. We know more about the surface of the Moon than the floor of the oceans. Whether this is true or not, the critical point is that the ocean floor is covered with an average of nearly 4,000 m of water, and it is pitch black below a few hundred meters, so it is not easy to discover what is down there. We know a lot more about the oceans than we used to, but there is still a great deal more to discover. (4)

Earth has had oceans for a very long time, dating back to the point where the surface had cooled enough to allow liquid water, only a few hundred million years after Earth's formation. At that time, there were no continental rocks, so the water that was here was likely spread out over the surface in one giant (but relatively shallow) ocean. (4)

We examined the seafloor's topography from the perspective of plate tectonics, but here we are going to take another look at the essential features from an oceanographic perspective. The essential features are the extensive continental shelves less than 250 m deep (pink); the vast deep abyssal plains between 3,000 and 6,000 m deep (light and dark blue); the mid-Atlantic ridge, in many areas shallower than 3,000 m; and the deep ocean trench north of Puerto Rico. (4) These features are connected by continental slopes, which is the transition area between continental shelves and abyssal planes.

An image showing the relative height of the Atlantic Ocean sea floor. Colors indicate different heights, with a high ridge found in the middle of the ocean, forming the Mid-Oceanic Ridge
Figure 8.4.1. Topography of the Atlantic Ocean Sea Floor NASA, Public Domain.
Of course, it is more complicated than this, even in this simplified form. Figure 8.4.2 shows a generalized cross-section of the Pacific Ocean which has short continental shelves that quickly turn to continental slopes, dropping from about 200 m to several thousand meters over a distance of a few hundred kilometers. The continental slopes connect to abyssal plains – exceedingly flat and from 4,000 m to 6,000 m deep; volcanic seamounts and islands; and trenches at subduction zones that are up to 11,000 m deep.

•Image showing general features of the seafloor between Japan and British Columbia. The highest points are the Emperor Seamounts in the middle, and the lowest point is the trench of the coast of Japan.
Figure 8.4.2. Generalized Topography of the Pacific Ocean Sea Floor, S. Earle CC-BY-4.0.
The ocean floor is entirely underlain by mafic oceanic crust, while the continental slopes are underlain by felsic continental crust (mostly granitic and sedimentary rocks). Moreover, the denser oceanic crust floats lower on the mantle than continental crust does, and that is why oceans are oceans. Although the temperature of the ocean surface varies widely, from a few

degrees either side of freezing in polar regions to over 25°C in the tropics, in most parts of the ocean, the water temperature is around 10°C at 1,000 m depth and about 4°C from 2,000 m depth to the bottom. (4)

The deepest parts of the ocean are within the subduction trenches, and the deepest of these is the Marianas Trench in the southwestern Pacific (near Guam) at 11,000 m. Other trenches in the southwestern Pacific are over 10,000 m deep; the Japan Trench is over 9,000 m deep, and the Puerto Rico and Chile-Peru Trenches are over 8,000 m deep. Shallow trenches tend to be that way because they have significant sediment infill. There is no recognizable trench along the subduction zone of the Juan de Fuca Plate because it has been filled with sediments from the Fraser and Columbia Rivers. (4)

Landforms of Coastal Erosion

Large waves crashing onto a shore bring a tremendous amount of energy that has a significant eroding effect, and several unique erosion features commonly form on rocky shores with strong waves. When waves approach an irregular shore, they are slowed down to varying degrees, depending on differences in the water depth, and as they slow, they are bent or refracted. That energy is evenly spaced out in the deep water, but because of refraction, the waves' energy, which moves perpendicular to the wave crests, is being focused on the headlands. On irregular coasts, the headlands receive much more wave energy than the intervening bays, and thus they are more strongly eroded. The result of this is coastal straightening. An irregular coast, like the west coast of Vancouver Island, will eventually become straightened, although that process will take millions of years. (4)

An image of a coastline showing he process of headlands being cut back and the flanking beaches being widened.

Figure 8.4.3. Coastal Straightening. S. Earle, CC-BY.

Wave erosion is highest in the surf zone, where the wave base is impinging strongly on the seafloor and where the waves are breaking. The result is that the substrate in the surf zone is typically eroded to a flat surface known as a wave-cut platform. A wave-cut platform extends across the intertidal zone. (4)

Resistant rock that does not get eroded entirely during the formation of a wave-cut platform will remain behind to form a stack. Here the different layers of the sedimentary rock have different resistance to erosion. The upper part of this stack is made up of rock that resisted erosion, and that rock has protected a small pedestal of underlying softer rock. The softer rock will eventually be eroded, and the big rock will become just another boulder on the beach.

Basalt sea stack in a black lava beach under the mountain Reynisfjall near the village Vík í Mýrdal, southern Iceland. The three basalt see stacks in the background are the famous Reynisdrangar.

Figure 8.4.4. Basalt Sea Stack. Wikicommons, CC-BY-SA.

Arches and sea caves are related to stacks because they all form because of the erosion of non-resistant rock. (4)

Decorative image showing a basalt outcrop with a hollowed out sea cave and arches underneath.

Figure 8.4.5. Akun Island Basalt Sea Cave. S. Hillebrand, US Fish and Wildlife Service, Public Domain.

Submarine Canyons

Submarine canyons are narrow and deep canyons located in the marine environment on continental shelves. They typically form at the mouths of sizeable landward river systems, both by cutting down into the continental shelf during low sea levels and by continual material slumping or flowing down from the mouth of the river or a delta. Underwater currents rich in sediment pass through the canyons, erode them and drain onto the ocean floor. Steep delta faces and underwater flows of sediments are released down the continental slope as underwater landslides, called turbidity flows. The erosive action of this type of flow continues to cut the canyon, and eventually, fan-shaped deposits develop on the ocean floor beyond the continental slope. (4)

Screen capture from NASA WorldWind software of margin of the Bering Sea with the larger submarine canyons highlighted

Figure 8.5.6. Berignian Margin Canyons. Wikicommons, BB-CY-SA.

Landforms of Coastal Deposition

Some coastal areas are dominated by erosion, an example being the Pacific coast of Canada and the United States, while others are dominated by deposition, examples being the Atlantic and Caribbean coasts of the United States. However, on almost all coasts, deposition and erosion are happening to vary degrees most of the time, although in various places. On deposition-dominant coasts, the coastal sediments are still being eroded from some areas and deposited in others.

The main factor in determining if the coast is dominated by erosion or deposition is its history of tectonic activity. A coast like that of British Columbia is tectonically active, and compression and uplift have been going on for tens of millions of years. This coast has also been uplifted during the past 15,000 years by isostatic rebound due to deglaciation. The coasts of the United States along the Atlantic and the Gulf of Mexico have not seen significant tectonic activity in a few hundred million years, and except in the northeast, have not experienced post-glacial uplift. These areas have relatively little topographic relief, and there is now minimal erosion of coastal bedrock. (4)

On coasts dominated by depositional processes, most of the sediment being deposited typically comes from large rivers. An obvious example is where the Mississippi River flows into the Gulf of Mexico at New Orleans; another is the Fraser River in Vancouver. No large rivers bring sandy sediments to the west coast of Vancouver Island, but there are still long and wide sandy beaches there. In this area, most of the sand comes from glaciofluvial sand deposits situated along the shore behind the beach, and some come from the erosion of the rocks on the headlands. (4)

Image showing the difference between winter (rough weather) and summer (calm weather) beaches. Sand is stored offshore on the winter beach and on sure during summer.
Figure 8.4.7. Winter and Summer Beach Deposition by S. Earle, CC-BY.
Most beaches go through a seasonal cycle because conditions change from summer to winter. In summer, sea conditions are calm with long-wavelength, low-amplitude waves generated by distant winds. Winter conditions are rougher, with shorter-wavelength, higher-amplitude waves caused by strong local winds. As seen in Figure 8.4.7, the heavy seas of winter gradually erode sand from beaches, moving it to an underwater sandbar offshore. The gentler waves of summer gradually push this sand back toward the shore, creating a broader and flatter beach. (4)

•Image of a spit forming due to longshore currents.
Figure 8.4.8. Goose Spit at Comox on Vancouver Island. U.S. Fish and Wildlife Service, Public Domain.
The evolution of sandy depositional features on seacoasts is primarily influenced by waves and currents, especially longshore currents. As sediment is transported along a shore, either it is deposited on beaches, or it creates other depositional features. For example, a spit is an elongated sandy deposit that extends out into open water in the direction of a longshore current. (4)

A spit that extends across a bay to the extent of closing, or almost closing it off, is known as a baymouth bar. Most bays have streams flowing into them, and since this water must get out, rarely, a baymouth bar will completely close the entrance to a bay. In areas where there is sufficient sediment being transported, and there are nearshore islands, a tombolo may form.

Tombolos are common where islands are abundant, and they typically form where there is a wave shadow behind a nearshore island. This becomes an area with reduced energy, and so the longshore current slows, and sediments accumulate. Eventually, enough sediments accumulate to connect the island to the mainland with a tombolo. (4)

Image of barrier islands off the south shore of Long Island.
Figure 8.4.9. Barrier Islands of South Shore Long Island. L. Chiou, CC-BY-SA.
In areas where coastal sediments are abundant and coastal relief is low (because there has been little or no recent coastal uplift), it is common for barrier islands to form. Barrier islands are elongated islands composed of sand that form a few kilometers away from the mainland. They are common along the US Gulf Coast from Texas to Florida, and along the US Atlantic Coast from Florida to Massachusetts. North of Boston, the coast becomes rocky, partly because that area has been affected by a post-glacial crustal rebound. (4) Barrier islands do an excellent job of blocking incoming storm surges from hurricanes, but since they are made almost entirely of sand they shift and move with every storm event. Though they are largely unstable for building and infrastructure, many people live on barrier islands and have to regularly face coastal hazards. The 2000 U.S. Census estimates that there are 1.4 million people living on barrier islands, with a population density of three times that of the coast.

Key Takeaways

Tectonic activity, sea level changes, and force of waves influence the physical structure and landforms of the coast.

8.5 Sea Level Change

Sea-level change has been a feature on Earth for billions of years, and it has important implications for coastal processes and both erosional and depositional features. Figure 8.5.1 shows the variation in sea level height in millimeters since 1993. How would you describe the trend?

•Graphic showing rate of change of sea level over the past 25 years.

Figure 8.5.1. Satellite Sea-level observations. NASA (2019), Public Domain.

Why does the sea level rise? What are three important mechanisms that produce the change? Video 8.4.1. explains it in simple terms

Video 8.5.1. Oceanographer Josh Willis from NASA's Jet Propulsion Laboratory narrates this video about the causes of sea level rise and how sea level has changed over the last two decades, as observed by the Jason series of satellite missions (1:58).

Eustatic sea level change

Eustatic sea-level changes are global sea level changes. Here, the sea level increases or decreases due to changes in the volume of glacial ice, that is, more glacial ice on land means less liquid water in the oceans; or less glacial ice on land means more water in the oceans and higher sea levels. The sea level can also change when the shape of the seafloor changes, driven by plate tectonic processes. For example, if the rate of seafloor spreading changes at mid-ocean ridges, the seafloor's shape near the ridges will change, they can become wider or higher, which affects sea level because the volume of water is being displaced.

Over the past 20,000 years, there have been approximately 125 meters (410 feet) of eustatic sea-level rise due to glacial melting. Most of that took place between 15,000 and 7,500 years ago during the significant melting phase of the North American and Eurasian Ice Sheets. At around 7,500 years ago, the rate of glacial melting and sea-level rise decreased dramatically, and since that time, the average rate has been in the order of 0.7 mm/year. Anthropogenic climate change has accelerated sea-level rise starting around 1870. Since that time, the average rate has been 1.1 mm/year, and it has been escalating. Since 1992, the average rate has been 3.3 mm/year! (4) It may not sound as much, but the population is affected by the millions.

Video 8.5.2. As human activity warms our planet, the ocean absorbs over 90 percent of the excess heat. This increases water volume and melts ice sheets and glaciers, contributing to sea level rise. Watch the video to learn how much global sea level is rising each year, what that looks like in everyday terms, and why it matters. Source: NASA (1:54)

Isostatic sea level change

Isostatic sea-level changes are local sea level changes. When the crust goes up (uplift) or goes down (subsides) the sea level changes. The crust goes up on down due to changes in its loading, following the principle of isostacy. For example, when mountains grow the crust piles in reverse faults and folds. As a result of the overload, the crust will sink. These changes can alter the coastline and the sea level locally. Another example is when glacial caps melt. The crust can "bounce back up" since it lost load. Almost all of Canada and parts of the northern United States were covered in thick ice sheets at the peak of the last glaciation. Following the melting of this ice, there has been an isostatic rebound of continental crust in many areas. This ranges from several hundred meters of rebound in the central part of the Laurentide Ice Sheet (around Hudson Bay) to 100 m to 200 m in the peripheral parts of the Laurentide and Cordilleran Ice Sheets – in places such as Vancouver Island and the mainland coast of BC. Although the global sea level was about 130 m lower during the last glaciation, the glaciated regions were depressed at least that much in most places, and more than that in places where the ice was thickest. (7)

Emergent and submergent coasts

Coastlines where the sea level is falling are called emergent. There are many features associated with emergent coasts. The shorelines can be rocky, with sea cliffs.

Where the shoreline is rocky, waves refracting around headlands attack the rocks behind the point of the headland. They may cut out the rock at the base, forming a sea arch that may collapse to isolate the point as a stack, (Fig. 8.4.5). Rocks behind the stack may be eroded, and sand eroded from the point collects behind it, forming a tombolo, a sand strip that connects the stack to the shoreline. Where sand supply is low, wave energy may erode a wave-cut platform across the surf zone, exposed as bare rock with tidal pools at low tide. Sea cliffs tend to be persistent features as the waves cut away at their base, and higher rocks calve off by mass wasting. If the coast is emergent, these erosional features may be elevated compared to the wave zone. Wave-cut platforms become marine terraces, with remnant sea cliffs inland from them. (4)

Coastlines where the sea level is rising are called submergent. Features associated with submergence coasts include estuaries, bays, and river mouths flooded by the higher water. Fjords are ancient glacial valleys now flooded by post-Ice Age sea level rise. Barrier islands form parallel to the shoreline from the old beach sands, often isolated from the mainland by lagoons behind them. Some scientists hypothesize that barrier islands formed by rising sea levels as the ice sheets melted after the last ice age. Accumulation of spits and far offshore bar formations are also mentioned as formation hypotheses for barrier islands.

Estuaries and fjords commonly characterize coastlines in areas where there has been a net sea-level rise in the geologically recent past. This valley was filled with ice during the last glaciation, and there has been a net rise in sea level here since that time. Uplifted wave-cut platforms or stream valleys characterize coastlines in areas where there has been a net sea-level drop in the geologically recent past. Uplifted beach lines are another product of relative sea-level drop, although these are difficult to recognize in areas with vigorous vegetation.

Video 8.5.3. How do science use modeling to make better decision for the city of Norfolk, VA? (2:34)

Backyard Geology: Sea-level changes recorded in rocks

While it seems fairly obvious that there are no real coastlines in Arizona, the rocks throughout the state attest to their existence in the past. In fact, Arizona had coastlines multiple times.

Image showing rocks of the Grand Canyon. The rocks show a sea level drop over geologic time.
Figure 8.5.2. Rocks of the Grand Canyon show different environments where they were deposited.
Figure 8.5.2 shows the three uppermost layers of the Grand Canyon, the Coconino Sandston, the Toroweap Formation and the Kaibab Formation. Though these layers were deposited millions of years ago, they encode the environments present at their time of deposition. The older Coconino Sandstone is a 275 million-year-old wind-blown sand which forms a dramatic cliff in the present day. This sandstone was deposited as sand dunes on firm land. The Toroweap Formation was formed in an intertidal zone, as sea-level was rising and falling but ultimately inundating the arid lands. The youngest Kaibab Formation, 270 million-year-old, is a limestone that was deposited in a shallow marine (ocean) environment. Together, these rock show that sea-level came into the continent, or transgressed, in just 5 million years, and much of Arizona was entirely under water!

Key Takeaways

Sea level changes over time have expanded and contracted continental shelves, created and destroyed inland seas, and shaped the surface of land.
We are experiencing an eustatic (global) sea level change. Scientists observe and collect data using satellites to understand hazards and challenges related to sea level change.

8.6 Human Intervention

Mitigation and modification of coastal change

There are various modifications that we make to influence beach processes for our purposes. Sometimes these changes are effective and may appear to be beneficial, although in most cases, there are unintended negative consequences that we do not recognize until much later. (4) In this section we will mention some of the most common beach interventions intended to stop coastal erosion.

Seawalls

A Seawall is a wall or embankment to protect the shore from erosion or to act as a breakwater. They are enjoyable amenities for the public, but they have geological and ecological costs. When a shoreline is “hardened” in this way, crucial marine habitats are lost, and sediment production is reduced, which can affect beaches elsewhere. Seawalls also affect the behavior of waves and longshore currents, sometimes with negative results. (1)

Figure 8.6.1. Seawall. Wikimedia Commons, Public Domain.

Groins and Jetties

Groins have an effect similar to that of breakwaters, although groins are constructed perpendicular to the beach, and they trap sediment while slowing the longshore current. Most of the sediment that forms beaches along our coasts comes from rivers, so if we want to take care of the beaches, we have to take care of rivers. When a river is dammed, its sediment load is deposited in the resulting reservoir, and for the century or two, while the reservoir is filling up, that sediment cannot get to the sea. During that time, beaches (including spits, baymouth bars, and tombolos) within tens of kilometers of the river’s mouth (or more in some cases) are at risk of erosion. (4)

image

Figure 8.6.2. Groins structures. National Park Service, Public Domain.

Coasts are prime real estate land that attracts the development of beach houses, condominiums, and hotels. This kind of interest and investment leads to ongoing efforts to manage the natural processes in coastal areas. Humans who find longshore drift is removing sand from their beaches often use groins in an attempt to retain it. (1)

Jetties are another type of shore perpendicular structure and are placed adjacent to tidal inlets and harbors to control inlet migration and minimize sediment deposition within the inlet. Similar to groins, jetties may significantly destabilize the coastal system and disrupt natural sediment regimes (NPS).

Breakwaters

Images showing a breakwater off the coast of Long Beach, California

Figure 8.6.3. Breakwater off Long Beach, CA. GoogleEarth, Fair Use, modified by M. Wilson.

Another approach to reduce erosion or provide protected areas for boat anchoring is the construction of a breakwater, an offshore structure against which the waves break, leaving calmer waters behind it. Unfortunately, this means that waves can no longer reach the beach to keep the longshore drift of sand moving. The drift is interrupted, the sand is deposited in the quieter water, and the shoreline builds out, forming a tombolo behind the breakwater, eventually covering the structure with sand, rendering it obsolete. (1) During WWII, the U.S. Navy built a series of breakwaters just offshore of Long Beach, California, in order to maintain a deep port and serve as a deterrent to enemy submarines (Figure 8.6.3). While it served its purpose, it changed the dynamics of the beach itself, halting wave formation and destroying habitat. Additionally, trash and debris from the Los Angeles River builds up in the marina and cannot escape.

Beach Replenishment

Image showing sand being brought to the beach for replenishment

Figure 8.6.4 Sand dredging pumping sand back to the beach. Wikimedia Commons, Public Domain.

Sand for longshore drift and beaches comes from rivers flowing to the oceans from inland areas. Beaches may become starved of sand if sediment carried by streams and rivers is trapped behind dams. To mitigate, beach replenishment may be employed where sand is hauled from other areas by trucks or barges and dumped on the depleted beach. Unfortunately, this can disrupt the ecosystem that exists along the shoreline by exposing native creatures to foreign sandy material and foreign microorganisms and can even bring in foreign objects that impact humans on replenished beaches. Visitors to one replenished east coast beach found munitions and metal shards in the sand which had been brought from abandoned test ranges from which the sand had been dredged. (1)

Showcase your understanding

Humans affect the ocean in a variety of ways. Laws, regulations and resource management affect what is taken out and put into the ocean. Human development and activity leads to pollution, changes to ocean chemistry (ocean acidification) and physical modifications (changes to beaches, shores and rivers). In addition, humans have removed most of the large vertebrates from the ocean. (0)

Sustainable Development

The ocean provides tremendous economic resources to the people of the world, and therefore humans will continue to affect it. Sustainable development of the ocean can occur with some efforts.

8.7 Attributions and References

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Media Attributions
8.1 Earle, S (n.d.) Chesterman Beach near Tofino. Retrieved May 8, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/06/Chesterman-Beach-near-Tofino.png

Chesterman Beach near Tofino on the west coast Vancouver Island. The strip of sediment connecting the main beach to the rocky island is a tombolo. S. Earle, CC-BY
8.1
Video 8.1.1. UNESCO. (2017). One Planet, One Ocean [Online video]. Retrieved May 10, 2022 from https://www.youtube.com/watch?v=YyiuLwhUpH4&ab_channel=UNESCO

The Intergovernmental Oceanographic Commission of UNESCO is a global community that enables nations to work together to study our ONE shared OCEAN and observe its changes. Join us to #SaveOurOcean and call for an International Decade of Ocean Science for Sustainable Development from 2021 to 2030!
Video 8.1.2. NASA. (2019). Draining Earth's oceans, revealing the two-thirds of Earth's surface we don't get to see. [Online video]. Retrieved May 13, 2021 from: https://youtu.be/-uOwv_Krqk8

Animation using satellite imagery showing the features of a water-less sea floor.
Figure 8.1.1. Taylor, G. (2008). Diatoms through the microscope [Photograph]. Public domain, via Wikimedia Commons.

Video 8.1.3. NASA. (2012). The ocean: A driving force for weather and climate. [Online Video]. Retrieved May 3, 2022 from:
https://www.youtube.com/watch?v=6vgvTeuoDWY&ab_channel=NASAGoddard

Using satellite data, this animation highlights key processes in the ocean system that impact every other Earth system.
Figure 8.1.2. Kieffer, M. Bleached Staghorn coral. [Photograph]. Public domain, via Wikimedia Commons.

Bleached corals loose all the algae that lives inside their tissue. Acid ocean water and changes in ocean temperature are thought to cause this disease.
Video 8.1.4. UNESCO. (2020). Ocean literacy principle #7. [Online Video]. Retrieved May 11, 2022, from
https://www.youtube.com/watch?v=y0XgfVyZ9zw&feature=emb_imp_woyt&ab_channel=UNESCO

Ocean Literacy is defined as 'the understanding of human influence on the Ocean and the Ocean's influence on people'. In the context of the UN Decade of Ocean Science for Sustainable Development 2021 – 2030 (Ocean Decade), Ocean Literacy is expected to play a key role to transform ocean knowledge to action.
8.2
Video 8.2.1. Verduin, J. (2019). How do ocean currents work? TED Ed animation. Online video, directed by Cabong Studios.
https://ed.ted.com/lessons/how-do-ocean-currents-work-jennifer-verduin. CC BY–NC–ND 4.0

Jennifer Verduin dives into the science of ocean currents with this engaging and educational animaationn.
Video 8.2.2. Shirah, Greg (2011) Perpetual Ocean. Retrieved May 13, 2021 from
https://svs.gsfc.nasa.gov/3827

This visualization shows ocean surface currents around the world during the period from June 2005 through December 2007. The visualization does not include a narration or annotations; the goal was to use ocean flow data to create a simple, visceral experience.
Figure 8.2.1 Wikicommons (2009) Thermohaline Circulation. Retrieved May 13, 2021 from
https://commons.wikimedia.org/wiki/File:Thermohaline_circulation.png

Map showing global thermohaline circulation.
Video 8.2.3. NASA. (2013). The Thermohaline circulation [Video]
https://www.youtube.com/watch?v=1uuqvu–6Yg&t=51s&ab_channel=NASAVideo

This animation first depicts thermohaline surface flows over surface density, and illustrates the sinking of water in the dense ocean near Iceland and Greenland. The surface of the ocean then fades away and the animation pulls back to show the global thermohaline circulation.
8.3

Figure 8.3.1 Earle, S (n.d.) Retrieved May 8, 2021 from
https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/orbital-motion-of-a-parcel-of-water-1.png

The orbital motion of a parcel of water (black dot) as a wave moves across the surface.
Figure 8.3.2 Earle, S. (n.d.) Retrieved May 12, 2021 from
https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/The-effect-of-waves-approaching-a-sandy-shore-1.png

Image showing how orbits flatten as waves approach shore.
Figure 8.3.3 Earle, S. (n.d.) Retrieved May 12, 2021 from
https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/longshore-current-by-waves-approaching-the-shore-1.png

Image showing formation of longshore current
Figure 8.3.4 Earle, S (n.d.) Retrieved May 12, 2021 from
https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/swash-and-backwash-1.png

Image showing movement of particles on a beach as a result of swash and backwash
Figure 8.3.5 Earle, S. (n.d.) Retrieved May 12, 2021 from
http://opentextbc.ca/geology/wp-content/uploads/sites/110/2015/08/rip-currents-on-a-beach-with-strong-surf.png

Image showing formation of rip currents
Figure 8.3.6 National Weather Service (n.d.) Rip Currents. Retrieved May 13, 2021 from
https://www.nps.gov/calo/learn/news/images/RC-Break-the-Grip-of-the-Rip1.jpg

Graphic showing how to safely escape a rip current.
Video 8.3.1. NOAA. (2013). Hurricane Storm Surge Retrieved May 13, 2021 from
https://youtu.be/pvY0KIdmQdM

Storm surge is water from the ocean that is pushed toward the shore by the force of the winds swirling around the hurricane. It is the greatest threat to life during a hurricane. Transcript.
Video 8.3.2. NCAR. (2017). Storm Surge Visualization. Retrieved May 13, 2021 from
https://youtu.be/q6W_20bwqWo

Visualization from a storm surge forecast from Hurricane Irma in 2017. The simulation demonstrates how quickly storm surge flooding can occur, coastal inundation in less than 12 seconds.
Video 8.3.3. VOA Learning English. (2012). The Terror of a Tsunami. Retrieved May 13, 2021 from https://youtu.be/eenxXImtgm4

Video showing destruction from a tsunami

8.4

Figure 8.4.1 NASA. (June 22, 2011) Topography of the Atlantic Ocean Sea Floor.

Image showing the relative height of the Atlantic Ocean sea floor. Colors indicate different heights, with a high ridge found in the middle of the ocean, forming the Mid-Oceanic Ridge

Figure 8.4.2 Earle, S. (n.d.) Generalized Topography6 of the Pacific Ocean Sea Floor. Retrieved May 25, 2021 from https://opentextbc.ca/geology/wp-content/uploads/sites/110/2015/08/generalized-topography-of-the-Pacific-Ocean-sea-floor.png

Image showing general features of the seafloor between Japan and British Columbia. The highest points are the Emperor Seamounts in the middle, and the lowest point is the trench of the coast of Japan.

Figure 8.4.3. Earle, S. (n.d.). Coastal Straightening. Retrieved May 25, 2021 from

An image of a coastline showing the process of headlands being cut back and the flanking beaches being widened.

Figure 8.4.4 Wikicommons (2014) Basalt sea stack. Retrieved May 25, 2021 from https://commons.wikimedia.org/wiki/Commons:Featured_picture_candidates/File:Reynisfjara,_Su%C3%B0urland,_Islandia,_2014-08-17,_DD_164.JPG#/media/File:Reynisfjara,_Su%C3%B0urland,_Islandia,_2014-08-17,_DD_164.JPG'

Basalt sea stack in a black lava beach under the mountain Reynisfjall near the village Vík í Mýrdal, southern Iceland. The three basalt see stacks in the background are the famous Reynisdrangar.

Figure 8.4.5. Hillebrand, S. (2006). Akun Island basalt sea cave. Retrieved May 25, 2021 from https://digitalmedia.fws.gov/digital/collection/natdiglib/id/4961

Decorative image showing a basalt outcrop with a hollowed out sea cave and arches underneath.

Figure 8.4.6. Wikicommons. (2012). Beringian Margin canyons. Retrieved May 25, 2021 from https://commons.wikimedia.org/wiki/File:Beringian_Margin_canyons.png

Screen capture from NASA WorldWind software of margin of the Bering Sea with the larger submarine canyons highlighted

Figure 8.4.7 Earle, S. (n.d.) Winter and Summer Beach Deposition. Retrieved May 25, 2021 from

Image showing the difference between winter (rough weather) and summer (calm weather) beaches. Sand is stored offshore on the winter beach and on sure during summer.

Figure 8.4.8 US Fish and Wildlife Service (n.d.) Goose Spit at Comox on Vancouver Island. Retrieved May 25, 2021 from https://opentextbc.ca/physicalgeologyearle/wp-content/uploads/sites/145/2016/03/comox-2.png

Image of a spit forming due to longshore currents.
Figure 8.4.9 Chiou, L. (2016) Barrier Islands of South Shore Long Island. Retrieved May 25, 2021 from
https://upload.wikimedia.org/wikipedia/commons/thumb/e/e0/LI_Barrier_Islands-1.jpg/366px-LI_Barrier_Islands-1.jpg

Aerial image of a barrier island.
8.5
Figure 8.5.1. NASA. (2019). Satellite Sea-level observations. Retrieved May 13, 2021 from
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Graphic showing rate of change of sea level over the past 25 years.
Video 8.5.1. Willis, J. (2015, Sep 2) Watching Rising Seas from Space. Retrieved June 1, 2021 from https://youtu.be/z2UKvrU5rOk

Video showing Oceanographer Josh Willis from NASA's Jet Propulsion Laboratory narrates this video about the causes of sea level rise and how sea level has changed over the last two decades as observed by the Jason series of satellite missions.
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Video showing the causes for sea level rise.
Video 8.5.3. NASA. (2020). Impacts of Sea Level Rise on Coastal Virginia. Retrieved May 13, 2021 from https://youtu.be/8Pn4rQZ0rHQ

Video showing how sea level rise affects coastal Virginia
Figure 8.5.2 Wilson, M. (2021). Grand Canyon Sequence.

Image showing the uppermost rock types of the Grand Canyon and how they have changed composition due to sea-level changes over time.
8.6
Figure 8.6.1. Wikimedia Commons. (2007). Isle of Wight Centre for the Coastal Environment. Retrieved June 1, 2021 from https://commons.wikimedia.org/wiki/File:Seawallventnor.jpg

Image showing a seawall
Figure 8.6.2. National Park Service. (n.d.) Groins and Jetties. Retrieved June 1, 2021 from https://www.nps.gov/articles/groins-and-jetties.htm

Image showing groins and jetties on a coastline
Figure 8.6.3 Wilson, M. modified from GoogleEarth (2021) Breakwater off Long Beach, CA.

GoogleEarth image with the breakwaters labeled with arrows.

Figure 8.6.4. Wikimedia Commons. (2017). Retrieved June 1, 2021 from https://pixabay.com/photos/dredging-nourishment-beach-sand-2955269/

Image showing sand being brought to the beach for replenishment
Video 8.6.1. Ocean MOOC (2017) From Ocean Science to Ocean Sustainable Development. Retrieved May 13, 2021 from https://youtu.be/Bo3bJfJtKUU

Video showing how sustainable development can occur through the 5 P's: peace, people prosperity partnership and planet

Instructor Resources

Alt Text for Draining Earth's oceans, revealing the two-thirds of Earth's surface we don't get to see Video

Transcript for Hurricane Storm Surge Video