1. Ocean Basics: Size and Scale: Cognate Test Items: #1

1. The surface area of the Earth is ~ 510 x 10^6 km^2. Oceans currently cover ~71% of the Earth's surface area at an average depth of ~3700 m. Approximately 74% of the world's ocean area is > 3000 m deep.

2. The ocean is broken down into multiple sub-regions both vertically and by proximity to continental and masses. Distinction between different ocean regions is usually made by a combination of bathymetry, distance from land, and/or light penetration. In this course, the term ***open ocean*** will be used to refer to ocean waters > 200 m deep and beyond the ***continental shelf break*** the edge of the ***continental shelf*** where the seafloor transitions to ***continental slope***. The ***continental shelf*** is the portion of the continental crust extending into the ocean that is nearly flat. Open ocean waters are removed from hard boundary conditions and land influences.

3. Earth is ~ 4.6 Billion years old. Earth's oceans first formed ~4.0-4.4 Bya. The atmosphere and oceans reached chemical ***steady-state*** ~1-2 Bya.

4. The latest phase of ***ocean basin*** growth started ~ 200+ Mya with "modern" ***ocean basins*** as we know them forming after the opening of the Antarctic circumpolar seaway (25-30 Mya) and closure of the circum-equatorial seaway (<6.5 Mya). The modern oceans are connected but are typically separated into 5 major ***ocean basins*** by geography and alignment of the continental land masses: the ***Arctic***, the ***Atlantic***, the ***Indian***, the ***Pacific*** Ocean, and the ***Southern*** Ocean. In 2000, an international agreement defined the ***Southern*** Ocean as the waters between 60°S and the Antarctic continent. The ***Southern*** Ocean is separated from the other ocean basins by the ***Antarctic Circumpolar Current***, a surface current that flows eastward around the Antarctic continent.

2. Properties of Seawater: Items: 2, 3, 4

1. Seawater is 96.5% water and 3.5% dissolved salts and other minor and trace constituents (by weight). ***Salinity*** is a measure of the average concentration of dissolved salts in a water body. The average salinity of seawater is 35 parts-per-thousand (ppt) or 35 g salt per 1000 g seawater. (Note: Actual measurement of ***salinity*** is difficult, and the appropriate ***salinity*** scale and units are still debated in the oceanography field).

2. Major ion composition of the world's oceans has been relatively stable for ~ 100+ million years. The major cations Sodium (Na^+), Magnesium (Mg^{2+}), Calcium (Ca^{2+}), Potassium (K^+) and the major anions Chloride (Cl^-), Sulfate (SO_4^{2-}), and Carbonate (CO_3^{2-}) and Bicarbonate (HCO_3^-) make up >3.49% of the dissolved salt ions in seawater. In open ocean water, the absolute concentrations of these major ions changes with ***salinity*** but their relative proportions stay the same, this is ***Marcet's Principle***, or the ***Constancy of Composition of Seawater***.

3. These dissolved salt ions in seawater make it a high ionic strength, non-ideal solution with chemical and physical properties different from pure, freshwater. Dissolved salts

increase the ***density*** of seawater (1.025 g/cm^3 for 35 ppt) as compared to freshwater (1.000 g/cm^3 for pure, 0 ppt, water). Dissolved salts depress the ***freezing point*** of seawater (~-2°C for 35 ppt) as compared to freshwater (0°C for pure, 0 ppt, water). Dissolved salts lower the ***temperature of maximum density*** for seawater (<-2°C for 35 ppt) as compared to freshwater (4°C for pure, 0 ppt, water). Dissolved salts elevate the ***boiling point*** of seawater as compared to freshwater. Dissolved salts increase the ***conductivity*** of seawater as compared to freshwater. Dissolved salts increase the ***viscosity*** (a measurement of internal friction within a fluid) of seawater as compared to pure (freshwater). Dissolved salts lower the ***compressibility*** of seawater as compared to pure (freshwater). Dissolved salts increase the ***velocity of sound*** in seawater as compared to pure (freshwater). Dissolved salts increase the ***vapor pressure*** of seawater as compared to pure (freshwater). Dissolved salts lower the ***specific heat capacity*** of seawater as compared to pure (freshwater). Dissolved salts increase the ***surface tension*** of seawater as compared to pure (freshwater).

4. Besides the major dissolved salt ions, there are many other minor and trace constituents in ocean seawater. These materials can occur in ***dissolved***, ***colloidal***, or ***particulate*** (and some volatile, gaseous) phases. These include ***inorganic*** and ***organic*** constituents, dissolved gasses, and living organisms. ***Organic*** matter is defined as matter derived from life processes whereas ***inorganic*** matter is derived from the non-living Earth (hydrogenic and lithogenic, even some cosmogenic material). Oceanographers generally distinguish between ***dissolved*** and ***particulate*** matter by an operational (defined by how it is measured) size cutoff and sinking characteristics. Generally matter is considered to be in the ***particulate*** phase if it sinks (settles) through the water column and it has an effective diameter > 0.45 microns (μm, 10^{-6} m) for ***inorganic*** matter and > 0.70 μm for ***organic*** matter. ***Colloidal*** matter refers to matter generally below the operational size cutoff for ***particulates*** that consists of an agglomeration of insoluble and soluble ***organic*** and ***inorganic*** matter. ***Colloidal*** matter does not sink.

3. Open Ocean Water Column Structure: Items: 5, 6, 7, 8

1. Oceanographers often start any discussion of the physical properties of seawater by defining a '***parcel***' of seawater with uniform properties bounded by dimension in cartesian units of x-y-z (think of a cube with dimensions of length x width x height).

2. Oceanographers use the term ***water column*** to describe a volume consisting of a fixed area of seawater extending from the ocean surface to the seafloor.

3. ***Water masses*** are bodies of water with fairly uniform characteristics, including ***temperature*** and ***salinity***, and having their sources in particular regions of the ocean.

4. The ***salinity*** of a ***parcel*** of seawater changes as the average concentration of dissolved salts in the parcel changes. Increasing ***salinity*** adds major ions to a water parcel that often have higher ***densities*** than pure water thereby increasing the overall ***density*** within the ***parcel***. Dissolved ions also reduce molecular spacing between water molecules in a seawater ***parcel*** increasing ***density***. So, in general, seawater ***density*** increases as ***salinity***

increases and seawater ***density*** decreases as ***salinity*** decreases.

5. The ***pressure (p)*** acting on a ***parcel*** is the normal force per unit area acting on a ***parcel*** of water. ***Horizontal pressure gradients*** drive horizontal circulation (flow) in the ocean. In the ocean the downward force of gravity acting on the ocean (and atmospheric) column is generally balanced by the upward ***pressure gradient force***. This is called ***hydrostatic balance***. So, ***pressure*** increases with depth in the ocean from the surface. Seawater is slightly compressible so the ***density*** of a ***parcel*** of seawater does change slightly with increasing depth. Seawater ***density*** tends to increase with increasing ***pressure*** and decrease with decreasing ***pressure***. ***Pressure*** can also affect ***temperature***.

6. The ***temperature*** (***T***) of a ***parcel*** of seawater changes as heat content changes. But water is slightly compressible so if ***pressure*** on a water ***parcel*** increases with no exchange of heat with the surrounding water, ***temperature*** increases slightly, and conversely, if ***pressure*** on a water ***parcel*** decreases with no exchange of heat with the surrounding water, ***temperature*** decreases slightly. Therefore, ***temperature*** of seawater is often expressed as ***potential temperature (θ)***, the ***temperature*** a water parcel would have if it was moved ***adiabatically***, no exchange of heat, from one ***pressure*** to another, ***reference pressure***. Estimation of ***potential temperature (θ)*** of a parcel of water is a function of the *in situ* ***temperature***, ***salinity***, and ***pressure*** of the water ***parcel*** and the ***adiabatic*** lapse rate as it is moved from its initial pressure to the ***reference pressure***. But, in general, increasing ***temperature*** tends to increase molecular kinetic energy within a seawater ***parcel*** and therefore increases molecular spacing and decreases seawater ***density***. Likewise lower ***temperature***s decrease molecular kinetic energy within a seawater ***parcel*** and therefore decreases molecular spacing and increases seawater ***density***. So, in general, seawater ***density*** increases as ***temperature*** decreases and seawater ***density*** decreases as ***temperature*** increases.

7. The overall ***density*** of a parcel of seawater (ρ_{SW}), or the mass of per unit volume ($\rho_{SW} = m_{SW}/V_{SW}$), is a nonlinear function of ***temperature (T)***, ***salinity (S)***, and ***pressure (p)*** that is mathematically determined by the ***Equation of State for Seawater***, $\rho_{SW} = \rho_{SW}(T, S, p)$. The nonlinearity of the ***Equation of State for Seawater*** means that the ***density*** change of a seawater ***parcel*** for a given change in ***temperature***, ***salinity***, and/or ***pressure*** can be different for parcels of equal ***density*** but with different ***temperatures***, ***salinities***, and ***pressures.*** In the field of Oceanography, for convenience, you will often see ***density*** referenced to pure water expressed as ***density,*** $\sigma_{SW} = \rho_{SW}(T, S, p) - 1000\ kg/m^3$. You may also see it expressed referenced to surface ***pressure*** as ***in situ density***, $\sigma_t = \rho_{SW}(T, S, 0) - 1000\ kg/m^3$. Or, since ***density*** is often as expressed as ***potential density*** (σ_θ) for a given reference ***pressure***, where ***T*** is replaced by ***potential temperature (θ):*** $\sigma_\theta = \rho_{SW}(\theta, S, p) - 1000\ kg/m^3$. Due to the slight compressibility of seawater, seawater ***density*** is primarily a function of ***pressure***, especially at depths > 1000 m, so the use of ***potential density*** (σ_θ) allows Oceanographers to trace water ***parcels*** and ***water masses*** throughout the ocean.

8. For certain applications in surface waters a simple linear approximation to the ***Equation of State for Seawater*** with a condition specific (T, S, p) and an averaged ***thermal expansion coefficient*** and ***haline contraction coefficient*** can be used to explore changes

in seawater ***density***. In such a case, a linear approximation to the ***Equation of State for Seawater*** at constant pressure at temperature (T) = 10°C and salinity (S) = 35 may be written as:

$$\Delta\rho_{SW} \cong \Delta\rho_{SWf} - \Delta\rho_{SW0} \cong [\beta_S * (S_{SWf} - S_{SW0}) - \alpha_T * (T_{SWf} - T_{SW0})]$$

Where:
$\Delta\rho_{SW0}$ ***= reference or initial density (kg/m^3) = 1025.0 kg/m^3***
S_{SW0} ***= reference or initial salinity = 35***
T_{SW0} ***= reference or initial temperature (℃) = 10℃***
α_T ***= thermal Expansion Coefficient=0.15 kg/(m^3·℃)***
β_S ***= haline Contraction Coefficient=0.78 kg/m^3***
$\Delta\rho_{SWf}$ ***= new or final density (kg/m^3)***
S_{SWf} ***= new or final salinity***
T_{SWf} ***= new or final temperature (℃)***
$\Delta\rho_{SW}$ ***= change or difference in density (kg/m^3)***

9. The linear approximation to the ***Equation of State for Seawater shows*** that each unit change in ***salinity*** has a greater effect on ***density*** than each unit change in ***temperature.*** Still, since ***temperature*** varies over a much wider range in ocean surface waters than does ***salinity, temperature*** tends to have the greater influence on ***density*** of ocean ***surface waters.***

10. The uppermost layer of a typical ocean ***water column*** is well stirred by winds, waves, and currents. This region of the water column is called the ***surface mixed layer*** and varies in depth from a few meters to a maximum of a few hundred meters. It is characterized by relatively uniform ***temperature*** and ***salinity*** with depth. Below the ***surface mixed layer***, ***salinity***, ***temperature***, and ***density*** change significantly to a depth of about 800-1000 m. Below 1000 m in a typical static open ***water column***, temperature and ***salinity*** is relatively uniform and ***density*** increases gradually with depth due to ***pressure***. Oceanographers often categorize waters by layers or ***masses*** of ocean water with distinct ***temperature*** and ***salinity*** characteristics: ***surface water*** (typically < 1000 m; influenced by surface mixing); ***intermediate water*** (typically 500-1500 m), and ***deep water*** (typically > 1500 m). The term ***bottom water*** describes ***deep water*** that is in contact with the seafloor. ***Water masses*** are named for both their source region and the ocean layer in which they are found.

11. Ocean ***salinity*** varies over a relatively small range (33-37) with the most variation in near surface waters (< 200 m) due to ***evaporation*** and ***precipitation***. Variation in surface ocean salinity drives the ocean ***halocline***, a change in ***salinity*** with depth from ~ 0-1000 m. Open ocean ***salinity*** (>1000 m) is typically between 34.5 to 35. Depending on the relative rates of ***evaporation*** and ***precipitation*** (or other freshwater inputs) at a given location, the ocean ***halocline*** can be either increasing or decreasing ***salinity*** with depth.

12. Ocean ***temperature*** varies over a large range, generally from ~-2℃ to ~30℃+. The largest variation in ocean ***temperature*** in an open ocean water column occurs near the

ocean surface due to heat exchange across the ***atmosphere-ocean interface***. Variation in ***atmosphere-ocean*** heat exchange drives the slope of the ocean ***thermocline***, a change in ***temperature*** with depth from ~ 0-1000 m. Since heat exchange with the atmosphere varies seasonally by latitude, the ***thermocline*** is typically subdivided into the ***surface mixed layer***, a variable ***seasonal thermocline,*** and the more stable ***permanent thermocline*** from ~200-1000 m. The ***temperature*** of deep ocean bottom waters (>1000 m) is typically between 2℃ to 4℃. This very large sink heat results in an ocean ***thermocline*** that generally decreases in ***temperature*** with depth.

13. Ocean ***density*** increases with depth due to ***pressure*** alone, but the largest differences in the ocean ***density*** gradient occur in the upper 1000 m of the ocean due to the combined effects of ***temperature*** and ***salinity*** The change in ***density*** with depth in the upper 1000 m of the ocean is the ocean ***pycnocline***. Since ocean ***temperature*** varies over a much greater range than ***salinity***, ***temperature*** generally controls the slope of the main ***pycnocline*** (some exceptions are estuaries and polar waters). And since ***temperature*** generally decreases with depth, ***density*** generally increases with depth in the upper 1000 m of the ocean. Likewise the shape and base of the ocean main (permanent) ***pycnocline*** is typically coincident with the base of the ocean main (permanent) ***thermocline***.

14. The combined effects of ***temperature***, ***salinity***, and ***pressure*** result in a static ocean water column that is ***stratified. Stratification*** is layering of fluids according to ***density***. The more ***stratified*** a water column is, the more ***stable*** it is. Ocean ***stability*** generally increases with depth as ***density*** and ***stratification*** increase. ***Stratification*** inhibits the mixing of ocean waters because energy is required to break down ***stratification***.

4. Light and Sound in the Ocean: Items: 9, 10

1. In the atmosphere, sound is ***attenuated***, or reduced in ***intensity*** over distance, more rapidly than light, so light can travel further in the atmosphere than in the ocean. Conversely, sound can travel much further in the ocean than in the atmosphere.

2. The ratio of the speed of light in air to the speed of light in seawater is about 1:1.33, so light is ***transmitted*** efficiently across the atmosphere-ocean interface. But light ***attenuates*** exponentially with depth in seawater as a function of ***wavelength*** due to ***absorption*** and ***scattering*** by water and ***dissolved*** and ***particulate*** matter.

3. Light of red ***wavelengths attenuates*** rapidly in the water column; blue-green light penetrates deeper. In the clearest ocean waters, the depth of the ***photic zone*** (the depth above which there is enough light energy for ***photosynthesis***) is approximately 200 m but blue light can be detected as deep as ~1000 m.

4. Light penetration depths, and hence the depth of the ***photic zone***, are much shallower in more ***turbid*** coastal waters.

5. The ratio of the speed of sound in air to the speed of sound in seawater is about 1:4.5, so sound does not pass efficiently across the atmosphere-ocean interface. But since sound is

a compression wave, the slight ***compressibility*** of seawater enables sound generated in water to travel long distances. Sound propagation is also affected by ***reflection*** off boundaries and surfaces as well as ***attenuation*** due to ***spreading*** and ***absorption*** by materials in the water column.

6. Sound waves with longer wavelengths can travel further than shorter ***wavelengths*** in the ocean. Sound waves can also ***refract*** at boundaries between water masses with different properties. ***Salinity*** has a minor effect on the speed of sound in open ocean seawater. The speed of sound in seawater is controlled primarily by ***pressure*** and ***temperature***. Higher ***temperature*** seawater is less ***compressible***, so sound velocities are higher at higher ***temperatures***. Seawater under higher ***pressure*** is less ***compressible*** so sound velocities are higher at higher ***pressures***. A great thumb-rule to remember is that "***sound is lazy***" so it will "bend", or **refract**, towards regions of lower sound velocity as it travels through the ocean.

5. Open Ocean Surface Currents: Items: 11, 12, 13, 14

1. To mathematically describe fluid motion in the oceans, Physical Oceanographers assume: ***Conservation of Mass*** (water and salt); ***Conservation of Energy***; ***Conservation of Momentum***, and; ***Conservation of Angular Momentum***. ***Conservation of Mass*** leads to the (volume) ***Continuity Equation***. ***Conservation of Energy*** leads to ***ocean heat balance*** and the ***Wave Equations***; ***Conservation of Mass*** and ***Momentum*** leads to the ***Navier-Stokes equations***; and ***Conservation of Angular Momentum*** leads to ***Conservation of Fluid Vorticity***.

2. The dominant forces Physical Oceanographers use for determining ocean dynamics and circulation are: ***Gravity*** (includes ***buoyancy*** differences); horizontal pressure gradients which constitute the ***Pressure Gradient Force (PGF)***; fluid ***friction and viscous forces***; and the ***Coriolis force***. The ***Equations of motion*** that determine the ***acceleration*** and ***advection*** of a unit parcel of seawater are a balance between these forces.

3. The Sun is the source of energy that drives atmospheric circulation and ultimately the surface circulation of the ocean on Earth.

4. Over the course of a year, astronomical and atmospheric factors lead to surplus of ***net radiative energy*** reaching the surface of the Earth in the tropics and a deficit of ***net radiative energy*** reaching the surface of the Earth at the poles. The imbalance between ***net radiative energy*** gains and losses reaching the surface of the Earth at different latitudes results in net heat transport via atmospheric circulation and ocean circulation away from the tropical regions poleward towards the poles. Unequal heating of the atmosphere from underlying ocean and land surfaces on a rotating Earth produces atmospheric circulation and wind patterns.

5. ***Momentum*** is transferred from the atmosphere to the ocean via a ***tangential shear stress*** (pressure) due to ***friction o***f the fluid atmosphere moving across the fluid ocean surface (wind). The ***frictional*** effects between the winds and the ocean surface produce

broad-scale horizontal water movements of the ocean surface, called ***surface currents***, that tend to resemble the patterns of surface winds.

6. For a non-rotating Earth, the ***friction*** of wind blowing the atmosphere across the ocean surface transfers momentum to a thin layer of water at the ocean surface and moves it in the same direction as the wind. But, in this transfer, a great deal of energy is lost to heat and the generation of ***turbulence*** so the velocity of the thin layer of surface water is only a small percentage of the wind's speed. This thin layer of surface water moves across a thin layer of water beneath it and through ***friction*** transfers momentum to this deeper layer, again moving it in the same direction as the wind but at a significantly lower velocity than the layer above it. The process continues downward through successive layers, like pages in a book, each with a lower speed than that of the layer above until ocean layer velocities at depth approach zero. This is why ***surface currents*** do not extend past a maximum of ~1000 m.

7. The generation of ***turbulence*** in the ocean ***surface mixed layer*** enhances the downward transfer of ***horizontal momentum*** through the water column as well as the transfer of heat, the exchange of gases with the atmosphere, and chemical ***diffusion***.

8. Since the Earth does rotate, the thin layer of surface water set in motion by the wind is deflected to the right of the wind vector (direction) in the Northern Hemisphere (NH) and to the left of the wind vector (direction) in the Southern Hemisphere (SH). This deflection is the ***Coriolis effect*** and is due to the ***Coriolis force***, an apparent force acting on a mass of water that is perpendicular to the direction of motion and to the axis of Earth's rotation.

9. ***Coriolis forcing*** is zero at the equator and increases poleward.

10. So, except at the equator, each layer of water put into motion by the layer above is deflected in direction because of the ***Coriolis effect***. The deflection of the thin layer of surface water relative to the initial wind vector varies but can be up to 45° to the right (NH) or left (SH) of the wind direction at mid-latitudes and above. When viewed from above, the changes in current direction and decreased current velocity of each layer with increased depth form a 'spiral' called the ***Ekman spiral***. If the ***Ekman Spiral*** is integrated over the upper <200 m of the ocean, this sets up ***Ekman Transport*** where the net transport of surface waters (< 200 m) is in a direction approximately 90° to the right of the original wind vector in the Northern Hemisphere and 90° to the left of the original wind vector in the Southern Hemisphere.

11. There are regions of the ocean where the winds and surface currents set up ***Ekman Mass Transport*** that results in the net transport of surface waters en masse away from or towards a boundary.

12. The moving of water away from an area or boundary like a coast is called ***divergence*** and moving of water towards an area or boundary like a coast is called ***convergence***.

13. A ***divergence*** of water from a coast results in a depressed sea surface height along the coastline that establishes an onshore ***horizontal pressure gradient***. The ***PGF*** and ***volume continuity*** acts to reestablish an equilibrium (even) sea surface by ***upwelling*** colder, nutrient rich *intermediate waters* from below the ***Ekman Layer*** to the surface which spread outward along the coast. A ***convergence*** of water along a coast sets up an elevated sea surface height on the coast that establishes an offshore ***horizontal pressure gradient***. The ***PGF*** and ***volume continuity*** acts to reestablish an equilibrium (even) sea surface by ***downwelling*** warmer, nutrient poor surface waters along the coast which sink and spread outward from the coast at ***intermediate*** depths below the ***Ekman Layer***.

14. In coastal regions, ***Ekman Mass Transport*** of surface waters towards or away from the coast can be caused by winds blowing more or less parallel to the shore. At ***coastal upwelling*** centers, the prevailing wind direction relative to the coast sets up ***Ekman Mass Transport*** leading to the ***divergence*** of warmer, nutrient-poor surface waters away from the coast. These waters are replaced by colder, nutrient-rich waters upwelled from below. ***Coastal upwelling*** regions are among the most ***productive*** fisheries in the world. Coastal regions where the prevailing wind direction relative to the coast sets up ***Ekman Mass Transport*** leading to the ***convergence***, stacking, and ***downwelling*** of warmer, nutrient-poor surface waters along the coast tend to be low-productivity regions.

15. The ***Coriolis effect*** acting on the westward flowing equatorial currents (near, but not at the equator) in the Northern and Southern Hemisphere sets up ***Ekman Mass Transport*** that causes surface waters to ***diverge*** away from the equator to be replaced by colder waters from below. This process is known as ***equatorial upwelling***.

16. As ocean surface waters move horizontally, they can stack up against boundaries with other water masses or land. This creates ocean surfaces with differential ***geopotential heights*** relative to a reference ***geopotential surface*** thereby establishing a ***horizontal pressure gradient***. Differences in water ***temperature*** and ***salinity*** can also affect ***density*** setting up ***horizontal pressure gradients*** but in surface waters the ***horizontal pressure gradient*** is mostly a function of relative sea level. The ***pressure gradient force (PGF)*** is the force due to a pressure difference across a horizontal distance. This moves surface waters horizontally from regions of higher pressure to lower pressure.

6. Open Ocean Surface Circulation: Items: 15, 16

1. The surface circulation of most of the major ocean basins is dominated by large, roughly circular patterns, called ***gyres***, centered at about 30° latitude. As seen from above, they flow clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. The locations of major oceanic ***gyres*** are largely determined by the locations of the Earth's major wind belts, the blocking effects of the continents, and the effects of the Earth's rotation.

2. Due to ***Ekman transport*** in relation to prevailing winds, water at and near the surface is moved towards the middle of the ***gyres*** centered at ~ 30°N and ~ 30° S from all sides, producing a broad mound of water as high as one meter at the center of the ***gyre***. This

sets up a pressure gradient with a ***pressure gradient force*** directed off the mound. The ***Coriolis force*** will act on the resultant current until it balances the ***pressure gradient force***, achieving what is called ***geostrophic balance***. Water then flows parallel to pressure contours (***geostrophic flow***), circling the mound. In the Northern Hemisphere, water flowing down the sloping mound of the ***gyres*** is deflected to the right due to the ***Coriolis effect***, reinforcing the clockwise circulation of the ***gyres***. In the Southern Hemisphere, water flowing down the sloping mound of the ***gyres*** is deflected to the left due to the ***Coriolis effect***, reinforcing the counterclockwise circulation of the ***gyres***.

3. An added effect of the Earth's eastward rotation is the westward displacement of the ocean ***gyre*** mounds within their ocean basin. ***Fluid vorticity*** must be conserved as a ***parcel*** moves around an ocean ***gyre***. A combination of the steeper ocean-surface slopes on the western sides of the ***gyres***, ***frictional*** drag along the coast, changes in the ***Coriolis effect*** with latitude, and torque from ***wind stress*** help produce higher water speeds in the western regions of the ***gyre***. These ***western boundary currents*** are narrow (< 100 km), deep (up to 1000 m) bands of strong poleward flow of warmer waters from the Tropics towards the mid-latitudes along the western edge of the ***gyre***. ***Western boundary currents*** are balanced by wider (up to 1000 km), shallower (< 500 m) areas of slower equatorward flow of cooler waters from mid-latitudes back to the Tropics along the eastern edge of the ***gyre***. ***Gyres*** play a major role in transporting heat away from the Tropics towards the poles.

4. The fast-moving ***western boundary currents*** are also distinguished by the formation of large rotating ***warm*** and ***cold water rings***. ***Meanders*** in the current become pinched off to form ***eddies,*** rings of water with rotational current directions distinct from the direction of the main current.

5. A counterclockwise direction of rotation in the Northern Hemisphere is often described as ***cyclonic*** whereas a clockwise direction of rotation is ***anticyclonic***. In the Southern Hemisphere, a counterclockwise direction of rotation is ***anticyclonic*** and a clockwise direction of rotation is ***cyclonic***.

6. ***Mesoscale eddies*** formed along western boundaries that are ***anticyclonic*** in rotation tend to trap warmer waters at their center and have a slightly elevated sea surface height. These eddies are therefore referred to as ***warm-core eddies***. ***Mesoscale eddies*** formed along western boundaries in the Northern Hemisphere that are ***cyclonic*** in rotation tend to have cooler waters at their center and a slightly depressed sea surface height. These eddies are therefore referred to as ***cold-core eddies***. These ***warm- and cold- core eddies***, can reach sizes of up to 325 km in diameter, have rotational speeds of over 0.5 m/sec and can extend to the seafloor.

7. Removed from western boundaries, atmospheric circulation can also sometimes set up ***Ekman transport*** which leads to the ***convergence*** or ***divergence*** of waters in smaller scale in rotational ***eddies*** a few kilometers in diameter. ***Anticyclonic*** eddies stack warmer surface waters at their center resulting in a higher sea surface height and net ***downwelling*** of warmer waters at the core. These ***eddies*** are therefore also referred to as ***warm-core***

eddies. Eddies with ***cyclonic*** motion tend to move warmer surface waters away from their center resulting in a depressed sea surface height and net ***upwelling*** of cooler waters from below at the core. These ***eddies*** are referred to as ***cold-core eddies***. The 'trapping' and vertical movement of different water masses with oceanic ***eddies*** often makes them "hot" spots for biological and physical processes.

8. In the northern ***Indian Ocean*** which extends to only 20°N, the surface circulation is dominated by the ***monsoon*** wind systems and undergoes dramatic seasonal reversals in direction.

9. In Tropical latitudes, under normal conditions, warm surface waters are piled up in the ***western margin*** of the ***ocean basin***s by the steady trade winds and westward flowing equatorial currents. The resulting downhill flows of water in an easterly direction are called ***equatorial counter currents***.

10. In the ***Southern Ocean*** around Antarctica, where there are no blocking continents, flows the largest volume surface current, the ***Antarctic Circumpolar Current***. It is also known as the ***West Wind Drift Current***, after the strong winds driving it.

11. In the high latitudes of the Northern Hemisphere, where current flow is driven by ***cyclonic*** wind systems and modified by land masses, smaller counterclockwise subpolar ***gyres*** form, bringing cold water currents south to the western basins. One of these, the ***Labrador Current***, carries icebergs, like the one instrumental in the sinking of the Titanic, into the North Atlantic shipping channels.

12. Farthest north, the Arctic Ocean, which is almost completely surrounded by land and largely covered by ***sea ice***, has a single clockwise ***gyre***, the ***Beaufort Gyre***, located in the ***Beaufort Sea***. Circulation and water column structure in the ***Arctic Ocean*** is influenced by ***sea ice***, limited exchange with the lower latitude ocean basins, and by freshwater inputs from four major river systems and multiple smaller rivers that discharge into the basin.

7. Density-Driven, Deep Ocean Circulation Items: 17, 18, 19

1. ***Convection*** is fluid motion driven by ***density*** differences. Small differences in seawater ***densities*** drive the ***convective flow*** and circulation of the deep ocean. The ***density*** variations driving ***density-driven circulation*** of the deep ocean are due to differences in ***temperature*** (thermo-) and ***salinity*** (haline-) so it is also referred to as ***thermohaline circulation***.

2. Thinking back to water column ***stratification*** and ***stability***, surface water that is more ***dense*** than the surrounding surface water results in an ***unstable*** water column. Dense surface waters will therefore sink until they reach a depth where they are more ***dense*** th n the waters above them but less ***dense*** than the waters below. As ***stability*** is established, these waters spread horizontally as more water of the same ***density*** arrives from the surface above. More ***dense*** seawater displaces less ***dense*** seawater as it sinks. The

displaced less ***dense*** water is pushed towards the surface where it can be conditioned by the same physical process that lowered the ***density*** of the initial surface waters.

3. The ***temperature*** of surface waters can decrease thereby increasing ***density*** due to a lowered heat content due to ***latent*** and ***sensible*** heat exchange with the atmosphere. The ***salinity*** of surface waters can increase thereby increasing ***density*** due to ***evaporation*** of water to the atmosphere or through the formation of ***sea ice***. As seawater freezes, it is the water that freezes so salts are rejected as ***brine*** and eventually released to the surrounding surface water. This ***brine rejection*** increases the ***salinity*** of the surrounding surface water. ***Advection*** of and mixing with different ***water masses*** can also change surface water ***density***.

4. For conditioned surface waters to sink past the base of the main ***pycnocline***, they must become very ***dense*** compared to the waters around them. This typically requires the combined effects of both decreasing ***temperature*** and increasing ***salinity***. Sinking is promoted by an inertial "kick" which further lowers water column stability. Wind mixing or gravity are the major forcing agents that facilitate and sustain surface water sinking.

5. There are limited regions of the world's oceans where conditions are right to promote ***deep water convection*** and the formation and circulation of ***deep*** and ***bottom waters***. These regions are found primarily in the polar regions: marginal seas bordering the ***North Atlantic*** in the ***Arctic*** and near major ***ice shelves*** off of Antarctica in the ***Southern Ocean***.

6. ***Density-driven circulation*** can form bottom waters but can also form ***intermediate waters*** and ***deep waters*** in the ***Mediterranean Sea*** and other areas. As conditioned ***dense*** waters sink, they may be physically-mixed somewhat with less ***dense*** waters around them. They will continue to continue to sink towards the seafloor as long as they remain more ***dense*** than the waters around them. If they do not remain more ***dense*** than the waters below them, they will establish a new equilibrium at an ***intermediate*** depth and then spread. ***Mediterranean Intermediate Water*** is a water mass which forms in the warm but highly salty ***Mediterranean Sea***. It flows into the Atlantic and spreads outward for over two thousand kilometers just below the ***thermocline*** at a depth of approximately 1,000 meters.

7. ***Density-driven circulation*** drives ***convective*** flows that are much slower than ***wind-driven advective*** flows associated with ***surface ocean circulation***. Due to ***density*** differences, sinking water ***masses*** are slow to mix with surrounding water, maintaining their narrow ***temperature*** and ***salinity*** ranges. This permits ***water mass*** identification and tracing.

8. ***Deep water convection*** is the only means by which ***bottom*** and ***deep waters*** are formed in the oceans. It allows for a means to exchange properties between deep and surface ocean waters (heat, salinity, gasses, other constituents). ***Deep waters*** are replenished with modified surface waters that before sinking were actively exchanging gases with the atmosphere. This phenomenon is referred to as ***ocean ventilation***.

9. There are two main mechanisms for ***deep ocean convection***: ***open ocean convection*** and ***shelf-slope convection***.

10. ***Open ocean convection*** occurs in limited regions of marginal seas where warmer waters cool as they exchange heat with the atmosphere becoming more ***dense***. Smaller subpolar ***gyres*** cause cooler surface waters to ***diverge*** leading to the ***upwelling*** of colder ***intermediate waters*** which cool further becoming even more ***dense***. Additionally, ***sea ice formation*** increases the ***salinity*** of surface waters in the subpolar ***gyre*** therefore increasing the ***density*** to the point of ***instability***. Surface wind mixing causes ***dense*** surface waters to sink. These waters may be physically-mixed somewhat with less ***dense*** waters around them as they sink but they will continue to sink towards the seafloor as long as they remain more ***dense*** than the waters around them. When these waters reach the seafloor or a depth where they are less ***dense*** than the waters below them, they spread.

11. ***Shelf-slope convection*** occurs in shallow basins of the ***continental shelf*** that are separated from deeper waters by a ***sill*** or by a ***shelf break***. Intense cooling and/or ***evaporation*** over the semi-enclosed area produces ***dense*** water that sinks and spreads to fill the basin separated from the open ocean by the ***shelf*** or ***sill***. In some shelf-slope systems intense ***evaporation*** can cause ***salinity*** and therefore ***density*** to increase even further. In polar ***shelf-slope*** systems, ***sea ice*** formation can also increase ***salinity*** and surface water ***density***. Once conditioned surface water fills the shallow basin, gravitational forcing towards deeper waters beyond the ***shelf-break*** provides the mechanism for waters to sink towards the bottom. These waters may be physically-mixed somewhat with less ***dense*** waters around them as they sink but they will continue to sink towards the seafloor as long as they remain more ***dense*** than the waters around them. When these waters reach the seafloor or a depth where they are less ***dense*** than the waters below them, they spread.

12. ***Open ocean convection*** tends to dominate ***deep water convection*** in the Arctic. Prominent areas of ***open ocean convection*** occur in the ***North Atlantic*** in the ***Greenland Gyre***, the ***Labrador Se***a, and the ***Irminger Sea***. These regions contribute to the formation of ***North Atlantic Deep Water***. The presence of a deep, ***dense*** layer of warmer, saltier North Atlantic water below fresher surface waters forms the ***Arctic halocline*** that tends to inhibit ***open ocean convection*** in the ***Arctic Ocean***. ***Open ocean convection*** can occur in very limited areas in the ***Southern Ocean*** near Antarctica.

13. ***Shelf-slope convection*** tends to dominate ***deep water convection*** in the ***Southern Ocean*** near Antarctica. Antarctica is covered by massive ***ice sheets*** that in some regions extend off the continent onto the ***continental shelf*** in the form of ***ice shelves***. The surface waters in the shallow basins off the front of Antarctica's major ***ice shelves*** are subject to intense cooling and ***sea ice formation*** increasing ***salinity*** and surface water ***density***. Additionally, ***sea ice*** is pushed away from the continent by ***katabatic winds*** (downsloping, drainage winds, bringing down higher density air) which creates areas of persistent open water called ***polynyas*** where already ***dense*** surface waters are re-exposed to the cold atmosphere allowing further cooling and additional ***sea ice formation***. This

leads to the formation of very ***dense*** waters that sink past the shelf break. The regions off the Ross and Ronne ***ice shelves*** are very important areas for the formation of ***Antarctic Intermediate Waters*** and ***Antarctic Bottom Waters (AABW)***, the most ***dense*** water mass in the ocean. There also is some limited ***shelf-slope convection*** near ***ice shelves*** off the Greenland ***ice sheet*** driven by ***katabatic wind*** forcing.

14. In the ***North Atlantic Ocean***, most deep waters form from ***deep convection*** in the ***Greenland Gyre***. Mixing with warmer intermediate waters may produce the warmer, saltier waters of the ***Norwegian Sea Deep Water***. These deep water masses form the sources of deep water in the Arctic Ocean. ***Deep ocean convection*** also occurs in the ***Labrador Sea***. Both of these water masses flow into the North Atlantic to produce ***North Atlantic Deep Water (NADW)***. A less important source of deep water forms in the ***Irminger Sea***.

15. ***Deep ocean convection*** drives ***thermohaline circulation*** which connects surface waters to deeper waters. This drives the '***global ocean conveyor belt***' which is a name for a system of ***global overturning circulation***, or ***meridional overturning circulation*** that connects all the world's oceans.

16. The ***global ocean conveyor belt*** is made up of massive, slow moving currents that connect warmer surface waters to colder deeper waters below. It circulates water on a global scale at time scales of 10^2 to 10^3 years. Water leaving the surface via ***thermohaline circulation*** may not return to the surface for hundreds or thousands of years.

17. The ***global ocean conveyor belt*** connects both poles and all the world's major ocean basins. It plays a very important role in exchanging constituents like gases and nutrients between surface and deep waters, it can even transport biological organisms. But one of the most important aspects of the ***global ocean conveyor belt*** is the role it plays in regulating regional and global climate. Areas of deep water formation are important areas where the oceans give off heat towards space. The Earth's Climate history shows periods when the ***global ocean conveyor belt*** has slowed or changed modes affecting regional and global climate so future changes have the potential to abruptly change climate.

18. One of the most important branches of the ***global ocean conveyor belt*** is ***Atlantic meridional overturning circulation (AMOC)***. Warm surface waters are carried poleward from the Tropics along the ***western boundary*** of the Atlantic basin to the ***North Atlantic*** by the ***Gulf Stream***. The warm ***Gulf Stream*** and ***North Atlantic Currents*** are primarily responsible for the relatively warm climate of western Europe. Warm, surface waters are entrained in the ***North Atlantic Drift Current*** which feeds ***open ocean convection*** regions in the ***Greenland, Labrador, and Irminger Seas***. Here, ***North Atlantic Bottom Water*** forms, sinks, and moves south along the bottom to the ***Southern Ocean*** until it encounters the most dense water mass on Earth, ***Antarctic Bottom Water***, and rises again towards the surface. Northwestern Europe owes its relatively moderate climate to this Atlantic branch of the ***global ocean conveyor belt***. Subtle changes in ***AMOC*** can have profound effects on the Northern Hemisphere and global climate. ***AMOC*** exhibits significant decadal variability and climate scientists are actively studying the impact of

climate change on a slowing of ***AMOC***, with potential significant changes for the climate of Europe and other locations.

8. Open Ocean Waves Items: 20, 21, 22

1. An ***open ocean wave*** is a pattern of rising and falling water level that is transmitted along the sea surface. ***Waves*** occur at the ocean surface (atmosphere-ocean interface) or internally in the ocean at the interface between ***density*** layers.

2. Wind, gravity, and earthquakes disturb the water surface and generate ***waves*** in the open ocean. After a ***wave*** passes, the water surface is restored by gravity or, for the smallest ripples, by surface tension. The ***Coriolis force*** plays a role in restoration of the ocean surface in the case of ***planetary waves*** like ***tides***.

3. The patterns of rising and falling water observed on the open ocean surface are complex and ever changing. ***Open ocean waves*** for the most part ***progressive waves*** that transmit energy outward from an initial disturbance without the physical transport of water so open ***ocean wave*** patterns can be investigated through the use of the characteristics of ***ideal waves***. ***Standing wave*** forms such as ***seiches*** also occur in oceanic systems.

4. ***Ideal open ocean waves*** can mathematically be approximated and modeled using the ***wave equation.***

5. The pattern exhibited by open ***ocean waves*** can be described uniquely by a number of characteristics including ***wave height (H)***, ***wavelength (L)***, ***wave period (T)***, and ***wave speed (C)***. ***Wave*** characteristics are determined by the factors that generate the ***wave***.

6. The highest point of each ***wave*** is the ***wave crest***, and the lowest point is the ***wave trough***. The vertical distance between the ***wave crest*** and ***wave trough*** is the ***wave height (H)***. The greater the ***wave height (H)***, the greater is the associated potential ***wave energy (E)***. ***Wave energy*** for a given area is often described by ***significant wave height (H_S)***, the average height of the highest 1/3 of all ***waves*** occurring in a particular time period.

7. The horizontal distance between two successive ***wave crests***, or two successive ***wave troughs***, is the ***wavelength (L)***. ***Wavelength*** can also be used to estimate ***wave number*** (***κ***) which is mathematically equivalent to ***2π/L***.

8. The time it takes for two successive ***wave crests*** (one ***wavelength***) to pass a fixed point is the ***wave period (T)***. The ***average wave period (T_P)*** is the average period of the highest 1/3 of all ***waves*** occurring in a particular time period. The ***frequency*** of a wave ***(f)***, or the number of successive wave crests or troughs that pass by a fixed point each second is equal to 1/***T***. Once a wave forms, its ***frequency*** and ***period*** remains constant. The ***wave period*** can be used to estimate the ***angular frequency*** of the wave (***ω***) = **2π/T.**

9. The ***wave phase velocity, or celerity (C)***, or the distance a ***wave crest*** travels per unit time is = ***ω/κ*** or can be determined by dividing the ***wavelength (L)*** by the ***wave period (T)***.

10. A side view of an ideal ocean surface with a ***wave*** moving from left to right would show ***water parcels*** near the surface moving in clockwise circles called ***orbits***. If the wave moves from right to left, then the ***orbits*** are counterclockwise. The diameter of the ***orbits*** of water parcels at the ocean surface is equal to the ***wave height***.

11. The diameter of the ***orbits*** of the water parcels decreases with increasing depth below the ocean surface. ***Orbital motion*** is negligible below a depth of about one-half the ***wavelength***.

12. Wind is the most common factor disturbing the still water surface, generating turbulence and generating ***open ocean waves***. The disturbed water surface is restored to a still condition by ***gravity*** or, for the smallest ripples, by surface tension. Wind is almost always acting on the sea surface to form ***waves.*** Air flowing over the water surface first generates small ripples, called ***capillary waves***, which are small enough to be restored by surface tension.

13. ***Roughening*** of the water surface by ***capillary waves*** increases the transfer of wind energy to the ocean surface. As ripples grow to ***waves*** with ***wavelengths*** of centimeters and greater, the restoring force changes from surface tension to gravity.

14. The size of ***open ocean waves*** produced by the wind increases with ***wind speed***, ***wind duration***, and the ***distance*** over water which the wind blows unimpeded (***fetch***).

15. The increase in the size of open ocean waves produced by the wind has limits. When the ratio of ***wave height*** to ***wavelength***, called the ***wave steepness*** of an ***open ocean wave***, exceeds 1 to 7, the ***wave*** breaks and forms ***whitecaps***. In a fully developed sea, the wind energy input to generate ***waves*** is balanced by energy lost by the breaking ***waves*** and the ***waves*** have reached their maximum size.

16. ***Waves*** located in the area of generation and still under the force of generation are called ***forced waves*** or ***sea***. Waves that have traveled out of the area of generation are called ***free waves,*** or ***swell.***

17. Unusually high ***open ocean waves***, called ***rogue waves***, may form in areas where ***waves*** generated by strong storms encounter oncoming currents. ***Waves*** higher than $2*H_S$ are considered ***rogue waves***.

18. ***Deep-water waves*** are open ***ocean waves*** occurring in water with a depth greater than one-half the ***wavelength***. There is no significant interaction between the ***orbital motion*** associated with ***deep-water waves*** and the sea bottom. Their ***wave celerity*** is independent of the water depth. Once a ***deep-water wave*** forms, its ***wave period*** remains constant. Hence, the ***wave speed*** of an individual ***deep-water wave*** is determined by its ***wavelength***. The greater the ***wavelength***, the greater is the ***wave celerity***.

19. Because waves of long ***wavelengths*** travel faster than smaller ***waves***, ***swell*** leaving the same area of generation eventually sort into groups of similar ***waves*** traveling together called ***wave trains***. When ***wave trains*** interact, they work together either to form a new series of ***wave groups*** (constructive interference), or to form wave-free regions separating these ***wave groups*** (destructive interference).

20. The speed of these ***wave groups***, called ***group speed***, is about one-half the speed of the individual ***waves***. Individual waves can be observed passing through a ***wave group*** before disappearing into the wave-free region and then reappearing at the back end of another ***wave group***.

9. Shallow-Water Waves: Items: 23, 24

1. ***Waves*** that occur in water with depths less than one-half their ***wavelengths*** do interact with the bottom and some of their characteristics are altered. As they advance through water whose depth is decreasing, some of their ***wave*** characteristics are increasingly altered. Although the ***wave period*** remains constant, ***waves*** interacting with the ocean bottom slow down, their ***wavelengths*** shorten, and ***wave heights*** increase.

2. ***Shallow-water approximations of the wave equation*** are used to mathematically describe the behavior of ***shallow-water waves***.

3. ***Waves*** existing where the water depth is between one-half and one-twentieth the ***wavelength*** are called ***transitional waves*** or ***intermediate waves***. These ***waves*** exhibit the increasing effects of the ocean bottom as water depth decreases.

4. ***Waves*** existing where the water depth less than one-twentieth the ***wavelength*** are called ***shallow-water waves***. These waves are strongly affected by the ocean bottom because of the relatively shallow water depth.

5. The ***wave celerity*** in ***shallow-water waves*** is related to water depth, rather than ***wave period*** as it is for ***deep water waves***. The shallower the water, the slower the ***wave speed***. In shallow water, the ***orbits*** of the water parcels gradually flatten from circular to elliptical and ultimately to back-and-forth motion as the bottom is approached.

6. With a gently sloping sea bottom, ***waves*** approaching a shoreline at other than a right angle are bent, or ***refracted***, so their ***crests*** turn to a more parallel alignment with the shore. This ***refraction*** focuses ***wave energy*** on a headland and disperses ***wave energy*** along a bay coastline.

7. As a ***wave*** enters shallow water, ***wave height*** increases and ***wavelength*** decreases. As the ratio of ***wave height*** to ***wavelength***, called ***wave steepness***, increases, the ***wave*** becomes less stable.

8. The ***breaking*** of ***shallow-water waves*** is dependent on a number of factors such as the slope of the ocean bottom, with the relationship between ***wave height*** and mean water

depth being of major importance. Generally, the greater the ratio between ***wave height*** and water depth, the more likely the ***wave*** will ***break***.

9. A band of nearly continuous ***breaking waves***, or ***breakers*,** along the shore is called ***surf***.

10. ***Breaking waves*** are being investigated as an important mechanism contributing to the exchange of energy and material across the air-sea interface. ***Ocean waves*** are a potential source of renewable energy.

11. ***Tides*** are ***shallow-water ocean waves*** of global dimensions, generated by the gravitational attraction of the Moon and the Sun. ***High tide*** is the crest of the ***wave*** and ***low tide*** the ***trough***.

12. Seismic sea ***waves***, called ***tsunamis***, are ocean pressure ***waves***, generated by submarine earthquakes, volcanic eruptions, or landslides. ***Tsunamis*** have such a long wavelength that they travel as ***shallow-water waves*** across an ocean basin. As ***tsunamis*** approach the coast, interaction with the bottom results in a rapid decrease in ***wave speed*** and ***wavelength*** and a rapid, potentially dangerous, increase in ***wave height***.

10. Ocean Tides: Items: 25, 26

1. Tides are ***planetary oceanic waves*** that result in the regular rise and fall of the ocean surface that occurs over a period of several hours or more each day depending on the location on Earth. ***Tides*** are measured at coastal locations as local changes in sea (water) level. The difference in height between water levels at ***high*** and ***low tide*** is called ***tidal range*** and the time between successive ***high tides*** is called ***tidal period***.

2. Although the effects of the ***tide*** are observed along the shore as local changes in water level and water ***currents*** generated in response to the resultant ***pressure gradient***, ***tides*** are actually ***progressive waves*** developed from the gravitational interaction and motions of the Sun, Moon, and the Earth acting on ocean waters.

3. The observed ***tide*** at a given location on Earth is a function of the ***astronomical tide***, the rise and fall of water due solely to interaction between the Earth, Moon, and Sun, and the ***meteorological tide***; the rise and fall of water due to wind and changes in atmospheric pressure. ***Local tidal water levels*** are also influenced by other factors such as ***friction***, water depth (***bathymetry***), bottom ***topography***, coastline ***geomorphology***, and the weather.

4. Fundamental to the formation of the ***tides*** is the gravitational attraction between the Earth and the Moon and Sun. This attraction is determined by both the masses of these objects and the distance between them. The greater the masses, the greater is the attraction, while the greater the distance, the smaller is the attraction. Although its mass is considerably smaller than that of the Sun, the Moon has a greater influence on the tides because it is so much closer to Earth than is the Sun. The magnitude of the gravitational attraction of the Sun or the Moon will not be the same at all places on Earth's surface because due to the

curvature of the Earth; not all places on Earth at any given time are the same distance away from the attracting body. Places on the Earth nearest to each respective celestial body will experience a greater gravitational attraction towards the Sun or the Moon than places on the opposite side of the Earth.

5. Because of gravitational attraction, the Earth's ocean facing (and nearer) the Moon is pulled more strongly by the Moon than is the ocean on the more distant opposite side of the Earth. A similar effect on ocean water is produced by the Sun.

6. When modelled in a rotating frame, resultant (***tide-producing***) forces, or ***tide generating force (TGF)*** on Earth are the difference between gravitational and centrifugal (inertial) forces. The vertical component of the ***TGF*** is negligible compared to the Earth's own gravitational pull. The ***Tractive Force***, which creates ***tidal bulges***, is the horizontal portion of the ***TGF*** which acts tangentially to the Earth's surface. It is directed away from Moon on the side of Earth opposite Moon and toward Moon on the side of Earth facing Moon.

7. Earth and Moon revolve around a common center of mass once each lunar month. This turning motion, combined with the Moon's gravitational attraction, causes egg-shaped ***bulging*** of the ocean surface. One ocean ***tidal bulge*** is towards the Moon and the other is on the opposite side of the Earth. A similar interaction between the Earth and Sun produces ocean ***tidal bulges*** on Earth that line up towards and away from the Sun.

8. On a theoretical Earth with no friction, the ocean ***tidal bulges*** would remain aligned with the celestial body contributing to their formation. A place on the coast that is moved by the Earth's rotation through the ***tidal bulges*** would experience rising and falling sea level. These changes in sea level are the ***tides*** produced under theoretical conditions by astronomical factors acting alone.

9. The large range of astronomical variables involved in the production of the theoretical tides is dominated by the changing alignment of the Moon, Sun and Earth, including the changing positions of the Moon and Sun relative to the Earth's equator and the changing distances of the Moon from the Earth, and the Earth from the Sun, due to their elliptical orbits.

10. Because the Moon's monthly revolution about the Earth is in the same direction as Earth's daily rotation, a point on the Earth must make a full rotation and more (with about 24 hours and 50 minutes elapsing) to catch up with the advancing Moon. This Moon-based day is also called the ***tidal day***.

11. The ocean ***tidal bulges*** produced by the Moon remain in the same alignment relative to the Moon, but change their latitudinal positions on Earth from day to day as they follow the Moon during its monthly revolution about the Earth. This occurs because the Moon's orbit is inclined to the Earth's equatorial plane. This is called ***declination***.

12. During one lunar month the Moon's latitudinal position, or ***declination***, moves from being directly over the equator to within five degrees of the Tropic of Cancer (23.5 degrees North), back to the equator, on to within five degrees of the Tropic of Capricorn (23.5 degrees South), and then back to the equator where another cycle begins.

13. When the Moon is directly over the equator, its associated ***tidal bulge***s are centered on the equator. In theory, almost all coastal locations would rotate through the two ***tidal bulges*** and experience two equal ***high tides*** and two equal ***low tides*** per tidal day. This is known as a ***semidiurnal tide***.

14. Different tidal patterns exist when the Moon, and the midpoints of its associated ***tidal bulges***, are either north or south of the equator. While ***semidiurnal tides*** are observed at the equator at all times, most locations between the equator and the high latitudes experience two unequal ***high tides*** and two unequal ***low tides*** per ***tidal day***. This is known as a ***mixed tide*** and this difference in heights between successive ***high (or low) tides*** is called the ***diurnal inequality***.

15. When the Moon is above or nearly above the Tropic of Cancer or Capricorn, the ***diurnal inequality*** is maximum, and the ***tides*** are called tropic tides. When the Moon is above or nearly above the equator, the ***diurnal inequality*** is minimum and the ***tides*** are known as ***equatorial tides***.

16. When the Moon and its associated ***tidal bulges*** are either north or south of the equator, most points at high latitudes would in theory experience one ***high and one low tid***e per tidal day. This is known as a ***diurnal tide***.

17. The Sun produces a ***TGF*** about 45% of the ***TGF*** related to the Moon, due to the much greater distance between the Sun and Earth.

18. Sun-related ocean ***tidal bulge***s are produced the same way as those resulting from Earth-Moon interactions. The gravitational attraction between the Earth and Sun and Earth's annual revolution around the mutual center of mass of the Sun and Earth produce a second set of similar but smaller ***tidal bulges*** aligned with the Sun.

19. The mid-points of Sun-related ***tidal bulges*** follow the Sun just as Moon-related bulges track the Moon. Their latitudinal positions go through a yearly cycle.

20. The separate sets of ocean ***tidal bulges*** related to the Moon and Sun act at times together and at times in opposition as they produce the astronomical component of the ***tides***. These ***tides*** are dominated by the Moon-related ***tidal bulges*** while the Sun-related ***tidal bulges*** play a modifying role.

21. Twice monthly the positions of the Sun, Moon, and Earth are along a straight line. At these times of new and full Moon phases, as viewed from Earth, the lunar- and solar-related ocean bulges also line up to produce ***tides*** having the greatest monthly range. These are called ***spring tide***s. Twice monthly, at the first and third quarter Moon

phases, the Sun is pulling on the Earth along a line that is at right angles to the pull of the Moon. At this time the ***tides*** have the lowest monthly range. These are called ***neap tides***.

22. Once formed by astronomical factors, the ***tides*** can be thought of as global-scale ***ocean waves*** moving across the ocean, with ***high tide*** being the ***crest*** of the ***wave*** and ***low tide*** the ***trough*** of the ***wave***. For a ***semidiurnal tide*** at the equator, the wave would have a period of about 12.5 hours and a length that approaches 20,000 km, or half the circumference of the Earth.

23. As ***ocean waves***, the ***tides*** are modified by many ***non-astronomical factors*** including ***friction***, water depth (***bathymetry***), bottom ***topography***, coastline ***geomorphology***, and the weather to produce the observed local **tide**.

24. Local ***tides***, although resulting from a complex interplay of ***astronomical*** and ***non-astronomical*** factors, can be predicted with a high degree of accuracy from detailed analysis of the long-term local ***tide record***.

25. Because of their size and shape, many ocean basins have natural periods that equal ***tidal periods***. This helps to explain why many locations on the U.S. Atlantic Coast have a predominantly ***semidiurnal tide***, while many locations on the Gulf Coast have a predominantly ***diurnal tide***, and many locations on the Pacific Coast have a predominantly ***mixed tide***.

26. Treated as a ***wave***, the local ***tide*** is resolved into various components, called ***partial tides***. These are forecasted individually and added together to predict the future local ***tide***.

27. Although as few as four partial ***tide*** components can account for 70% of the total ***tidal range***, some 60 components are commonly used. More than 100 must be considered to predict the ***tides*** along complex irregular coasts such as that of Alaska.

28. In order to predict the local ***tide***, ***tide stations*** must gather data for a minimum of 18.6 years to experience most of the astronomical configurations of the Earth-Moon-Sun system generating the ***tides***.

    28.1. ***Tidal currents*** and the movement of water are ***currents*** generated in response to the resultant ***pressure gradient*** caused by the changing ***tidal water level***. ***Flood currents*** are net water flow towards the coast that occur in the period between the ***tidal trough*** (***low tide***) and the ***tidal crest*** (***high tide***). ***Ebb currents*** are net water flows away from the coast that occur in the period between the ***tidal crest*** (***high tide***) and the ***tidal trough*** (***low tide***). ***Tidal current velocities*** vary as the ***pressure gradient*** changes.The period between ***flood*** and ***ebb*** with little to no ***tidal current flow*** is referred to as ***slack water*** and is related to overcoming the inertia of the fluid system.

29. Prediction of ***tidal water levels*** and ***currents*** becomes more difficult in shallow embayments and estuaries due to the ***friction***, water depth (bathymetry), bottom

topography, coastline ***geomorphology*** within the semi-enclosed water body. These factors can lead to inertia related to acceleration and deceleration effects; amplification (or shoaling) due to the decrease of the width and depth (coastline convergence) in landward direction; damping of the ***tidal wave*** due to bottom ***friction*** and, partial ***reflection*** at abrupt changes of the cross-section and at the landward end of water body. ***Tidal current velocities*** are often out of phase with ***tidal water levels*** in these systems.

11. The Ocean and Climate Variability

1. The ocean has a significant impact on Earth's weather and climate, and so there is a need to understand and predict short-term changes in ocean conditions as well seasonal, decadal, and longer term changes. A decadal oscillation is a change that occurs with a frequency of a few years to decades. The basin-scale, decadal oscillation in sea surface temperatures, ***thermocline*** depth, and surface atmospheric pressure in the tropical Pacific Ocean is referred to as ***El Niño-Southern Oscillation (ENSO)***. ***ENSO*** affects atmospheric circulation, temperature, and precipitation patterns worldwide. In addition to ***ENSO***, other decadal oscillations in ocean and atmospheric conditions that have a significant impact on regional climate include the Pacific Decadal Oscillation, the North Atlantic Oscillation, and the Indian Ocean Dipole.

2. ***ENSO*** is characterized by three states or phases: ***ENSO neutral***, ***El Niño***, and ***La Niña***. During ***ENSO neutral*** conditions, easterly surface winds in the equatorial Pacific (trade winds) blow from higher surface air pressures in the east toward lower surface pressures in the west. These easterly trade winds push warm surface waters westward. Sea surface temperatures are thus higher, the thermocline is deeper, and rainfall is greater in the western tropical Pacific compared to the eastern tropical Pacific. Productive ***upwelling*** of cool, nutrient-rich waters occurs in the eastern Pacific, along the west coast of South America.

3. During the ***El Niño*** phase, the easterly trade winds in the Pacific weaken or reverse, and warmer water moves from the western tropical Pacific to the east. Sea surface temperatures are above average and the thermocline is deeper in the central and eastern tropical Pacific. Rainfall increases over the tropical Pacific and is reduced over Indonesia. Coastal upwelling in the eastern Pacific is reduced or ceases.

4. During the ***La Niña*** phase, the easterly trade winds are stronger than average. Sea surface temperatures are below average and the thermocline is shallower in the central and eastern tropical Pacific. Rainfall increases over Indonesia and is reduced in the central and eastern tropical Pacific. Coastal upwelling in the eastern Pacific is enhanced.

5. The shifts in evaporation and precipitation patterns and the locations of high and low pressure systems in the tropical Pacific associated with the various ***ENSO*** phases can have an impact on planetary-scale winds, including jet streams. These planetary-scale winds guide the movement of air masses and storm systems, affecting surface air temperatures and precipitation patterns around the world. The impact of ***ENSO*** conditions on regional climate in areas far distant from the tropical Pacific is an example

of a teleconnection. Teleconnections are significant relationships or links between weather phenomena at widely separated locations on earth, often impacting climate patterns that span thousands of miles. Some teleconnection patterns oscillate, with atmospheric mass/pressure shifting back and forth between two distant locations - as is the case when an ***El Niño*** phase transitions to a ***La Niña*** phase.

6. In the U.S., teleconnections during an ***El Niño*** phase result in winters that are typically wetter across the southern states and drier than usual in the Pacific Northwest and Midwest. ***La Niña*** winters typically feature drier weather in the southern states and wetter conditions in the Pacific Northwest and Midwest. The Atlantic hurricane season tends to be more active and hurricanes more destructive during ***La Niña*** due to reduced vertical wind shear over the Atlantic Ocean and more favorable conditions for storm formation and intensification. During ***El Niño***, increased wind shear typically suppresses hurricane activity in the Atlantic.

12. Changes in the Ocean

1. Global average temperatures have risen approximately 1.1°C since the preindustrial era (1880), primarily due to the steep rise in greenhouse gases. The year 2024 is the warmest year since record-keeping began in 1880, and the past 10 years have been the hottest on record.

2. Sea level is rising globally, and the rate of sea level rise is increasing. Between 2006 and 2023, global mean sea level rose at a rate of 3.2 mm per yr, which is more than twice as fast as the rate for most of the 20th century, 1.4 mm per yr.

3. Sea level rise since 1900 is approximately 20 cm (8 in). This is the largest rise in about 2800 years, the time of the previous meltwater pulse since the Last Glacial Maximum about 20,000 years ago. There have been several meltwater pulses lasting several centuries followed by periods of little rise.

4. Globally, melting land ice was the major contributor to sea level rise in the early 21st century and is expected to remain the primary factor for decades to come. Land ice includes the expansive Greenland and Antarctic polar ice sheets, as well as mountain glaciers. The Greenland Ice Sheet is smaller than the Antarctic Ice Sheet, but is in a more temperate climate and makes a greater annual contribution to meltwater that causes sea level rise. Ocean thermal expansion due to increasing ocean temperatures is also a significant contributor to global sea level rise. Land water storage is another factor; sea level is impacted by changes in surface water and groundwater storage and runoff.

5. On a regional and local level, sea level trends may be higher or lower than the global average. In many coastal regions, sea level is rising at a rate higher than the global average due to local factors such as ground subsidence, changing ocean currents, extraction of water and other natural resources, and the uneven distribution of glacial meltwater. In other regions, sea level is decreasing due to factors such as isostatic adjustment of the land surface due to glacier melt.

6. While sea ice extent and distribution is strongly influenced by climate variability and change, melting of sea ice does not increase sea level. It does, however, contribute to warming at higher latitudes through the ice albedo feedback loop. Sea ice melt also influences regional and global climate and ocean currents.

7. Scientists measure sea level by using tide gauges, pressure sensors on the seafloor, and aircraft and satellite-based radar and laser altimeters. For more than 30 years, a series of satellite-based radar altimeters (the TOPEX/Poseidon, Jason-1, Jason-2, Jason-3, and Sentinel-6 Michael Fraelich missions) has monitored sea level by transmitting microwave pulses and timing the arrival of the reflected pulses.

8. Intergovernmental Panel on Climate Change reports discuss changes in global temperatures, sea level, and other variables associated with various Representative Concentration Pathways (RCPs), which are scenarios for future greenhouse gas concentrations. For all RCPs, including stabilization of emissions, sea level rise is projected to persist into the next century and beyond. Under the Intermediate Scenario, for example, mid-range sea-level rise by 2100 is projected to be about 4 ft.