AMERICAN METEOROLOGICAL SOCIETY



Project Ocean

Ocean Tides

TEACHER'S GUIDE

Project Ocean

This guide is one of a series produced by Project Ocean, a U.S. Office of Naval Research-sponsored initiative of the American Meteorological Society (AMS), in recent partnerships with St. Mary's College of Maryland, Washington College, and the United States Naval Academy. Project Ocean is a continuation of past projects focused on creating and training a network of master teachers to provide peer training sessions in pre-college (K-12) physical oceanographic education. To support these teachers in their teacher training, Project Ocean develops and produces course modules and other educational materials.

For further information, and the names of the trained master teachers in your state or region, please contact:

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Figure i. The NOAA San Francisco Tide Station has been operating for 150+ years. [NOAA]

“The winds, the sea, and the moving tides are what they are. If there is wonder and beauty and majesty in them, science will discover these qualities..."

- Rachel Carson (1907-1964)

Module: Ocean Tides
Audience/Grade Level: K-12 Educators

Learning Objectives

After completion of this module participants will be able to:

9. Shallow-Water Waves

- Describe tidal waves as planetary-scale shallow-water waves and explain the roles of gravity and inertia.

10. Ocean Tides

- Explain the astronomical factors that produce tides, including Earth-Moon-Sun gravitational interactions.
- Distinguish between tidal types: semidiurnal, diurnal, and mixed tides.
- Describe the concept of tractive force, the horizontal portion of the tide-generating force, and how it creates tidal bulges on Earth.
- Explain how the Moon's declination and Earth's rotation influence tidal patterns.
- Define a tidal day.
- Differentiate between spring tides and neap tides based on Moon phase alignments.
- Interpret how tidal bulges shift in latitude and how local tides are influenced by non-astronomical factors.
- Explain how tides can be mathematically modeled using partial tide components.
- Describe how tidal currents form and how they vary with changing water levels.
- Distinguish between ebb currents and flood currents.
- Identify the challenges in predicting tides in shallow embayments and estuaries.

STANDARDS:

Project Ocean Fundamental Understandings:
Shallow-Water Waves (9.11)
Ocean Tides (10.1-10.29)

Applicable Ocean Literacy Principles: 1.A, 1.C, 1.D, 2.E, 3.G

Next Generation Science Standards:
Performance Expectations
- K-PS2-1. Plan and conduct an investigation to compare the effects of different strengths or different directions of pushes and pulls on the motion of an object.
- 3-PS2-2. Make observations and/or measurements of an object's motion to provide evidence that a pattern can be used to predict future motion.
- 4-PS4-1. Develop a model of waves to describe patterns in terms of amplitude and wavelength and that waves can cause objects to move.
- 4-ESS2-2. Analyze and interpret data from maps to describe patterns of Earth's features.
- 5-ESS2-1. Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact.
- MS-ESS1-1. Develop and use a model of the Earth-sun-moon system to describe the cyclic patterns of lunar phases, eclipses of the sun and moon, and seasons.
- MS-ESS1-2. Develop and use a model to describe the role of gravity in the motions within galaxies and the solar system.

Disciplinary Core Ideas
- PS2.A: Forces and Motion
- ESS1.B: Earth and the Solar System
- ESS2.A: Earth Materials and Systems
- ESS2.C: The Roles of Water in Earth's Surface Processes

Crosscutting Concepts
1. Patterns.
2. Cause and effect: Mechanism and explanation.
4. Systems and system models.

Science and Engineering Practices
2. Developing and Using Models
4. Analyzing and Interpreting Data
5. Using Mathematics and Computational Thinking

Engage | Nuisance Flooding

Tides are planetary oceanic **waves** generated primarily by the gravitational pull of the Moon and Sun. These waves result in the regular rise and fall of the ocean surface that occurs with periods of approximately 12 or 24 hours each day, depending on the location on Earth. The amplitude of the waves is modulated by the relative positions of the Sun and Moon, and the position of the Moon with respect to Earth's equator.

Tides are measured at coastal locations as local changes in sea (water) level. The difference in height between water levels at **high** and **low tides** is called the **tidal range,** and the time between successive high tides is called the **tidal period**. Local tides result from a complex interplay of astronomical and non-astronomical factors. This results in a tidal range that can vary spatially between locations and temporally at a given location as a function of the relative position of the Earth, Moon, and Sun. Some high tides are higher than others, and some low tides are lower than others depending on the position of the Moon and Sun relative to Earth and non-astronomical factors such as wind and barometric pressure.

During times of higher-than-normal tidal water levels (higher high tides), low-lying coastal areas can become inundated at high tide. This type of tidal flooding is also known as sunny day flooding, high-tide flooding, or **nuisance flooding** (**Figure 1**). This type of flooding occurs naturally, but in a scenario where the **global mean sea level** is rising over time, low-lying areas that were in the past infrequently subject to nuisance flooding or not subject to nuisance flooding at all can become impacted.



Figure 1. Nuisance, or high-tide, flooding at City Dock, downtown Annapolis, MD, near the U.S. Naval Academy, February 2018 [Luis Rodriguez, USNA Oceanography Dept.]

Group Review and Discussion:

1) *Why does the Earth have tides?*
2) *Differentiate between tidal range and tidal period.*
3) *How does an increase in global mean sea level affect the frequency of nuisance flooding?*

Explore | Tides – The Moon and the Sun

Ocean tides are the periodic rise and fall of sea level observed along coasts. While tides are most often viewed from their local impact on water levels and currents, their origins are astronomical. They form as a result of the complex interaction of the gravitational attraction of the Moon and the Sun on the Earth's water surface, with the influence of the Moon being dominant due to its closeness. Many other influences build on these astronomical foundations to produce the tides actually observed at any

specific location. These include such factors as the shape of the ocean bottom, coastline irregularities, and weather. Of the astronomical factors, the influence of the Moon is greater than the Sun because it is closer to the Earth. In a theoretical construct that ignores the effects of land masses, friction, and actual ocean depth, the Moon's gravitational attraction and the inertia of the water contribute to the formation of two bulges, which tend to make the surface of the ocean egg-shaped. One bulge is towards, and the other away from, the Moon. A place on the Earth rotating daily through these two ocean bulges would experience two high and two low tides.

Go to What Causes Tides? to explore the factors in tide generation. Watch the full 3:30-minute video. Note that this video is also available via What Causes Tides? | NOAA SciJinks – All About Weather. This page contains a "What Causes Tides?" poster than you can print for your classroom or personal reference.

Group Review and Discussion:

1) *Does the Sun or Moon exert a greater influence on tide generation? Why?*
2) *If a location on Earth rotates through two ocean surface bulges each day, how many high tides and how many low tides would occur?*
3) *If a location on Earth rotates through one ocean surface bulge each day, how many high tides and how many low tides would occur?*
4) *When does high tide flooding occur?*

Explain **| Ocean Tides**

Overview of Tides

Tides are planetary oceanic waves generated by the gravitational pull of the Moon and Sun. These waves result in the regular rise and fall of the ocean surface that occurs with periods of approximately 12 or 24 hours each day, depending on the location on Earth. The amplitude of the waves is modulated by the relative positions of the Sun and Moon and the position of the Moon with respect to Earth's equator. Tides are measured at coastal locations as local changes in sea (water) level. The difference in height between water levels at high and low tides is called the tidal range, and the time between successive high tides is called the tidal period. Although the effects of the tide are observed along the shore as local changes in water level and current flow generated in response to the resultant **pressure gradient**, tides are actually **progressive waves** developed from the **gravitational** interaction and motions of the Sun, the Moon, and the Earth acting on ocean waters.

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

Equilibrium Theory of Tides: The Tide-Generating Force and Tidal Bulges

Fundamental to the formation of the tides is the gravitational attraction between the Earth, Moon and Sun. Attraction is determined by both the masses of these celestial objects and the distance between their centers of mass. The greater the masses, the greater is the attraction, while the greater the distance, the smaller 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 the Sun.

The magnitude of the gravitational attraction of the Moon (or the Sun) will not be the same at all places on Earth's surface. Not all places on Earth are the same distance away from an attracting celestial body. Places on the Earth nearest to the Moon will experience a greater lunar gravitational attraction than places on the opposite side of the Earth. So, the portion of the Earth's ocean facing the Moon is pulled more strongly by the Moon than is the portion on the more distant opposite side of the Earth (a similar effect on ocean water is produced by the Sun).

The Earth and Moon orbit their common center of gravity called the **barycenter** (3000 miles from Earth's center, or 900 miles below Earth's surface) - see The Earth-Moon Barycenter. As the lunar gravitational force acts to draw the water closer to the Moon, inertia attempts to keep the water in place. If we consider a hypothetical, water-covered Earth in a rotating non-inertial reference frame, the **centrifugal force** acts to balance the lunar gravitational force at the barycenter. The centrifugal force/inertia acts in a direction away from the barycenter. The difference between the lunar gravitational force and the centrifugal force/inertia is the **tide-generating (producing) force**, or **TGF**.

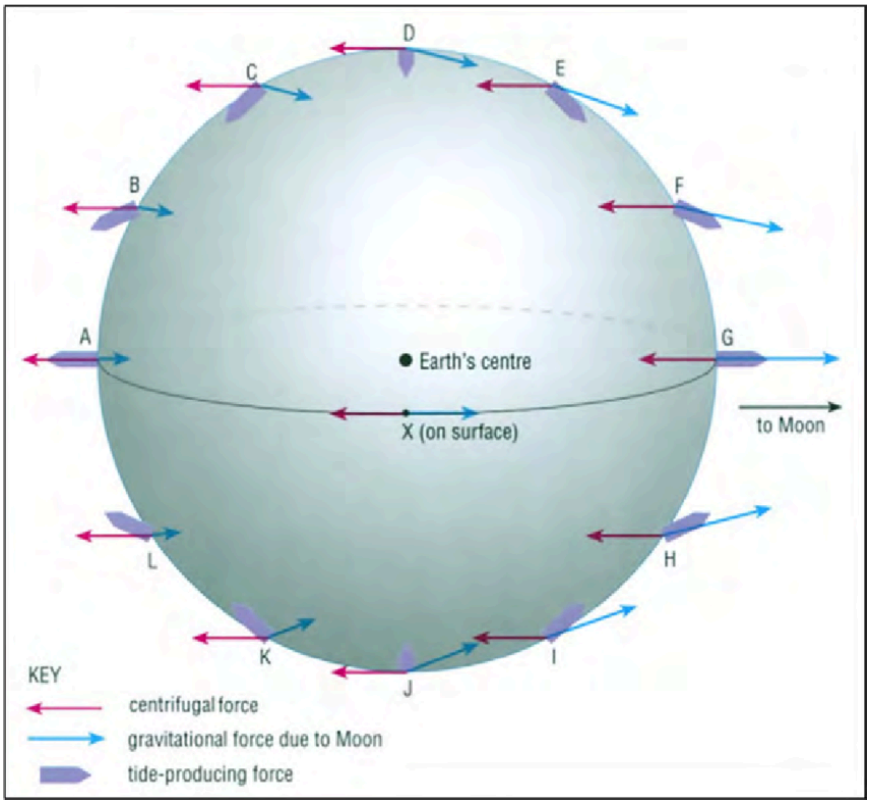


Figure 2. Forces that help generate tides. The thin, light blue arrows at various points (A through L, and X on Earth's surface) show the direction and magnitude of the lunar gravitational force. The thin magenta arrows represent the centrifugal force, and the thicker light purple arrows represent the tide-generating (producing) force, or TGF. [From Silva, Valder & Alves, Daniele & Setti Jr, Paulo T. & Santana, Felipe. (2024), CC BY-SA 4.0 International, https://www.researchgate.net/figure/Tide-generating-forces_fig1_380331610]

The curvature of the Earth also affects the relative distance of any point on Earth from the Moon's center of mass, so the magnitude of the gravitational attraction of the Moon (or the Sun) will not be the same at all places on Earth's surface at any given time. The gravitational force acts along an axis between the surface of the Earth and the Moon's center of mass. Centrifugal/inertial forcing acts perpendicular to the orbital axis (pointing away from the Moon) at the barycenter. The TGF at any point on the surface of the Earth is the resultant vector sum of these two forces. Where the centrifugal force/inertia is greater than the lunar gravitational force, the net tide-generating force (TGF) is away from the Moon. Where the lunar gravitational force is greater than the centrifugal force/inertia, the net TGF is towards the Moon. The net TGF is directed away from the Moon on the side of Earth opposite the Moon and toward the Moon on the side of Earth facing the Moon.

Equilibrium Theory of Tides: The Tractive Force and Tidal Bulges

The vertical component of the TGF at the surface of the Earth is negligible as compared to the Earth's own gravitational pull. It is the horizontal component of the TGF, or the **tractive force**, that would produce the theoretical **tidal bulges** depicted in **Figure 3**. The tractive force acts tangentially to the Earth's surface. The lunar tractive force is about the same strength as other horizontal forces that act on the oceans, such as the wind and pressure gradients. A similar interaction between the Earth and the Sun produces theoretical ocean bulges that line up towards and away from the Sun. The tractive force for a given celestial body varies as a function of its mass divided by the cube of the distance from the Earth (M/r^3). Consequently, even though the Sun is much more massive than the Moon, it is much further away from the Earth, so the Sun has (on average) only 46% of the tractive force as the Moon. In summary, the horizontal component of TGF, the tractive force, acts tangentially across the ocean surface water and in the **Equilibrium Theory of Tides**, creates tidal bulges on opposite sides of the planet.

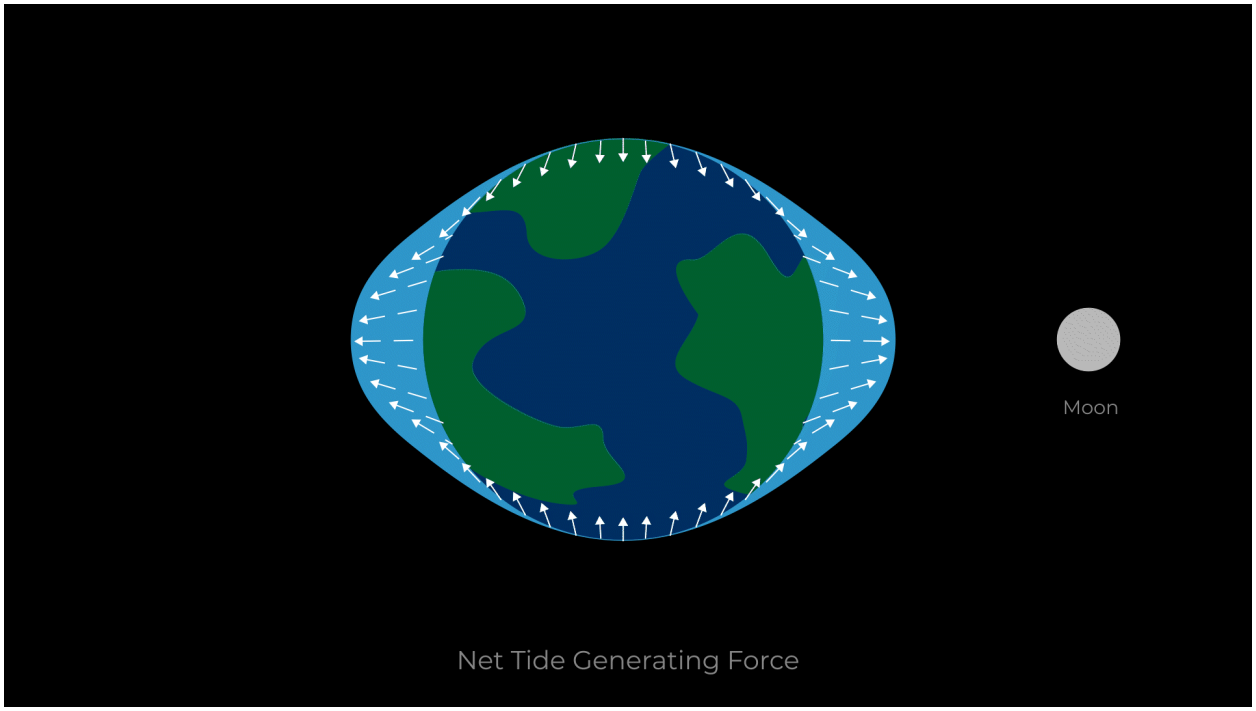


Figure 3. Bulges of water formed on the side of the Earth closest to the Moon and the side farthest away. [NASA/Vi Nguyen, see animations at Tides - NASA Science]

On a theoretical Earth with no friction, no land masses, and a very deep ocean, ocean bulges would remain aligned with the celestial bodies contributing to their formation. A place that is moved by the Earth's rotation through the ocean bulges would experience rising and falling **sea (water) level**. These changes in sea (water) level are the tides

produced under theoretical conditions by astronomical factors acting alone. This simplified explanation of tides is called the Equilibrium Theory of Tides.

Equilibrium Theory of Tides: Tidal Variations

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. The Moon revolves around the barycenter once each **lunar month** (~ 27.3 days). 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**.

It is important to note that water does not "slosh" back and forth due to astronomical gravitational tides. The ocean tidal bulges produced by the Moon remain in the same alignment relative to the Moon, and change their latitudinal and longitudinal positions on Earth from day to day as they follow the Moon during its monthly revolution about the Earth. The Moon's orbit is inclined relative to the Earth's equatorial plane, and this angle of inclination is called the lunar **declination**. During one lunar month, the Moon's latitudinal position 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. **Diurnal (daily) inequality** in the high and low tides is most pronounced when the Moon is at max declination. **Solar declination** affects tides as well. The Sun is at minimum (zero) declination during vernal and autumnal equinoxes, positioned directly above the equator. The Sun is at maximum declination, with its largest angle to the equator, during summer and winter solstices.

Equilibrium Theory of Tides: Semidiurnal, Diurnal, and Mixed Tides

When the Moon is directly over the equator, its associated tidal bulges 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**. 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 tide and one low tide per tidal day. This is known as a diurnal tide. Different tidal patterns would 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 would 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**. When the Moon is above or nearly above the equator, the diurnal inequality in the high and low tides is at a minimum, and the tides are known as **equatorial tides**. 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.

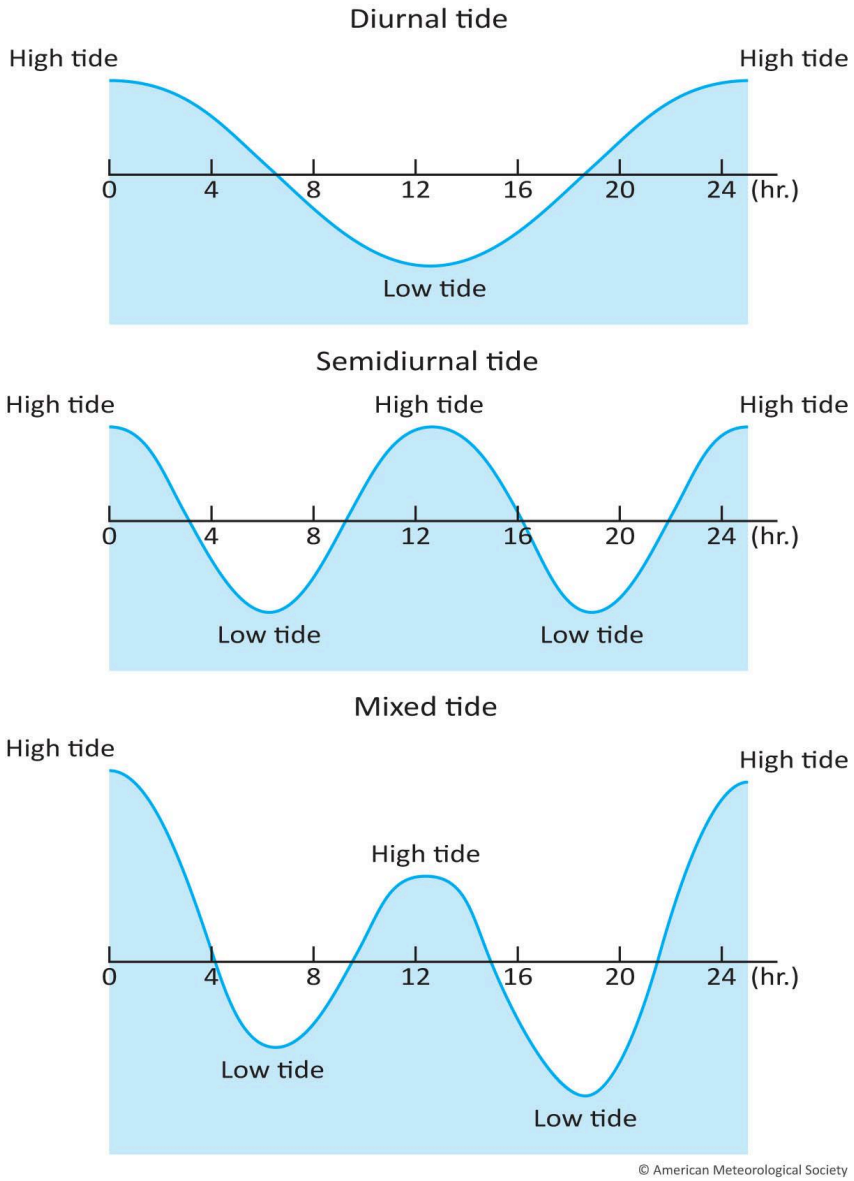


Figure 4. Diurnal, semidiurnal, and mixed tides. [Segar, Kish, and Mills, 2018]

Tides are dominated by the Moon-related ocean bulges, while the Sun-related ocean bulges play a modifying role.

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 tidal bulges also line up to produce tides having the greatest monthly tidal range. These are called **spring tides** (**Figure 5 - top**). 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** (**Figure 5 - bottom**).

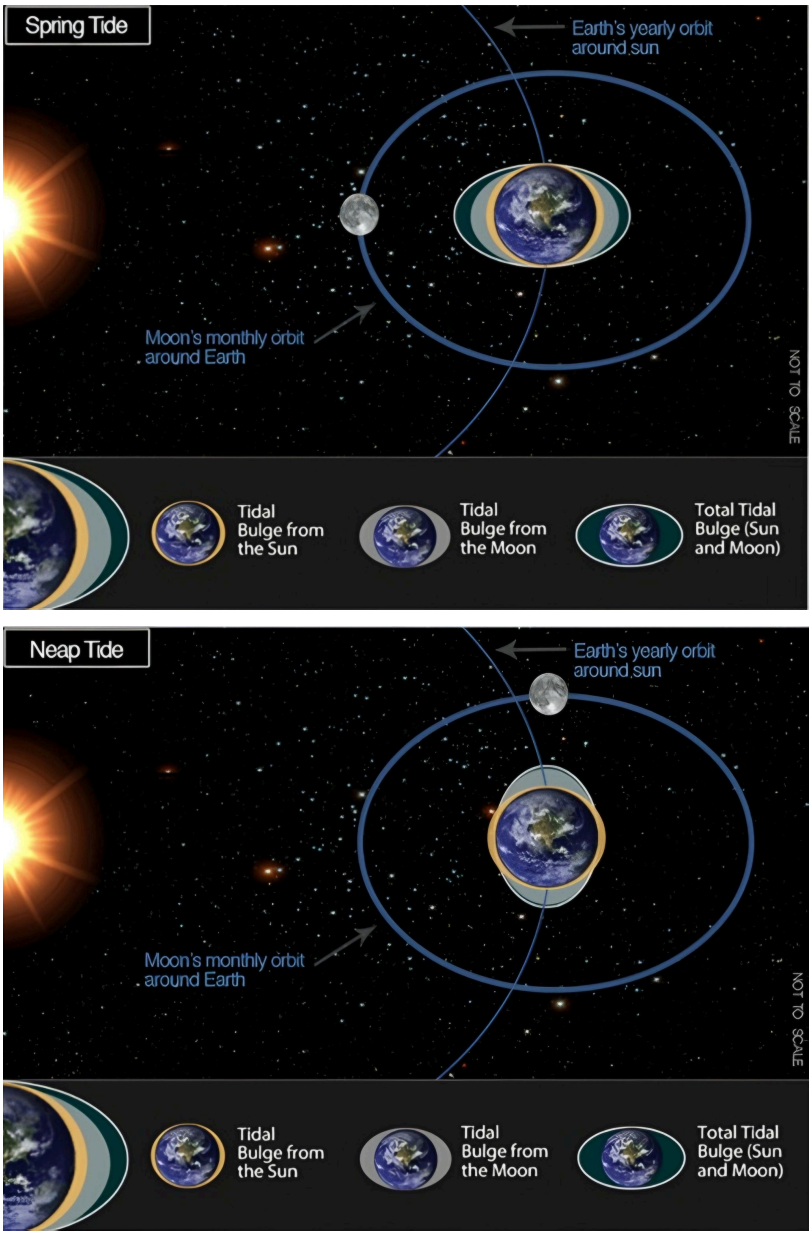


Figure 5. (Top) Spring Tide and (Bottom) Neap Tide. [NOAA's National Ocean Service]

Beyond the Equilibrium Theory of Tides: Dynamic Theory and Predicting Local Tides

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. However, predicting local water level variations due to tides at a point on a coastline is complex and requires moving beyond the Equilibrium Theory of Tides to **Dynamic Tide Theory**. For the Equilibrium Theory of Tides to apply in reality, the ocean basins would need to be >20 km deep at the equator in order for a shallow water wave to keep up with lunar forcing (the average depth of the world ocean is ~3700 m.). The Equilibrium Theory of Tides ignores friction, which is important near rough bathymetry and in coastal areas. The Equilibrium Theory of Tides also ignores the **Coriolis Effect**. Lastly, the Equilibrium Theory of Tides assumes an Earth completely covered by water. Land masses and the shape of ocean basins affect the propagation of the tides. As ocean waves, the tides are modified by many non-astronomical factors, including **friction**, **water depth (bathymetry)**, bottom topography, coastline shape/alignment (**geomorphology)**, and weather. These factors, plus astronomical tides, together produce the **observed local tide**. The observed local tide is the water level referenced to a specific **tidal datum**- the average, over a 19-year period, of water height at a particular stage of the tide (i.e., **mean high water**, **mean low water**, **mean lower low water**, **mean sea level**, **mean tidal level**, etc.).

Dynamic Theory, Partial Tides, and Predicting Local Tides

Tides establish complex patterns within each ocean basin that often differ greatly from tidal patterns of adjacent ocean basins or other regions of the same ocean basin. 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. Likewise, some places on Earth have a larger **tidal range** than others because of differences in the shape/slope of the ocean floor and local geomorphology. Regions with tidal ranges < 2 m are considered **microtidal**. Regions with tidal ranges between 2 to 4 m are classified as **mesotidal**, and regions with tidal ranges > 4 m are **macrotidal**.

Local tides can be predicted with a high degree of accuracy from a detailed analysis of the long-term local **tide record**. Treated as a wave, the local tide is resolved into

various components, called **partial tides**, or **tidal harmonics**. These are forecasted individually and added together to predict the future local tide. Although as few as four partial tide components can account for 70% of the total tidal range, 37 components are commonly used for U.S. tide predictions. More than 100 must be considered to predict the tides along complex irregular coasts such as that of Alaska. At most locations, a minimum of 30 days of tide gauge data is required to identify the major lunar and solar tidal harmonics. In order to predict the local tide with high accuracy, **tide gauge 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.

Tidal Currents and Real Tides

Tidal currents are horizontal water movements 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.

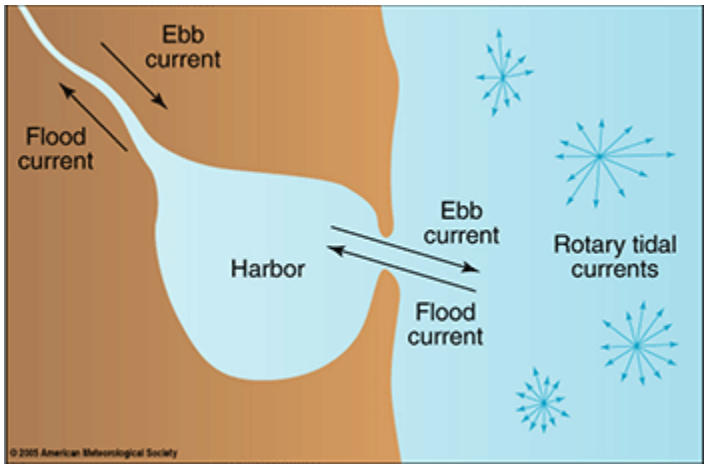


Figure 5. A flood current is a net water flow toward the land, which causes rising water levels, and an ebb current is a net water flow seaward, which causes falling water levels. [Moran, 2011]

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

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 the water body. Tidal current velocities are often significantly out of phase with tidal water levels in these systems. Prediction of tidal water levels is also complicated by the **meteorological tidal component**, particularly wind and barometric pressure variations.

Group Review and Discussion:

1) *What forces generate Earth's tidal bulges?*
2) *Are semi-diurnal tides most likely at tropical or polar locations? Why?*
3) *How do local tides result from a complex interplay of astronomical and non-astronomical factors?*
4) *Differentiate between a spring tide and a neap tide.*
5) *When there is an ebb current, are we approaching high tide or low tide?*

Elaborate | Predicting Ocean Tides – Real Tides, Real Data

Ocean tides are the periodic rise and fall of water levels observed along coasts. Although tides are most often viewed from their local impact, their origins are literally astronomical. They are a result of the complex interaction of the gravitational attraction of the Moon and the Sun on the Earth's water surface. Many other non-astronomical influences build on these astronomical foundations to produce the tides actually observed. These include such factors as the shape of the ocean bottom, coastline irregularities, and weather.

This activity investigates the tides by generating and comparing tidal predictions and observations of changes in local water levels over time using real water level data. The objective is to build an understanding of the factors that influence the water levels in bays, estuaries, harbors, and along beaches and are used to predict the tide.

After completing this activity, you should be able to differentiate between predicted and observed tidal water levels at a given coastal location and also discuss factors that can result in observed tidal water levels being different from predicted tidal levels at a given coastal location.

Activity:
First, go to NOAA Tides and Currents. Select and click on the icon for the state of Maryland, or if you prefer, type Annapolis, MD, in the search window to navigate to an Interactive map showing NOAA Tide and Current monitoring stations in the Annapolis/Maryland area.

Use the Interactive map of NOAA Tide and Current monitoring stations in the Annapolis/Maryland area to zoom in on the Annapolis, MD water level gauging station - Station ID: 8575512. Click on the icon for Annapolis station and you should see a pop-up window with the location and current conditions at Annapolis similar to the one shown in **Figure 6**.

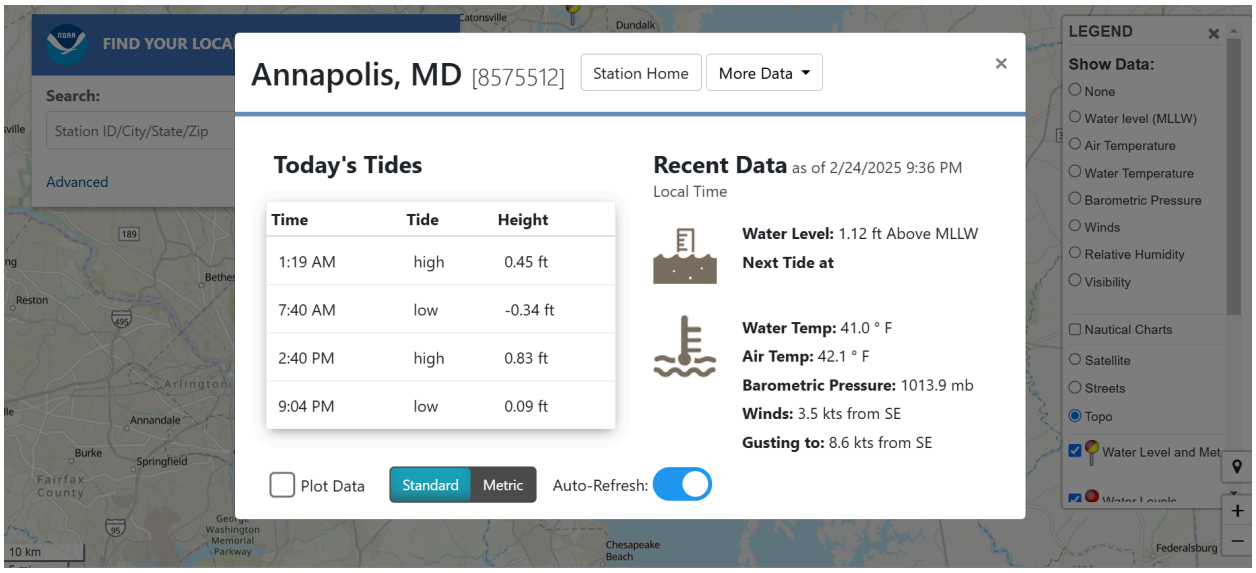


Figure 6. Example of current water levels, tidal predictions, and conditions at Annapolis, MD water level gauging station - Station ID: 8575512 using the NOAA Tide and Current interactive map for Maryland.

In the pop-up window for the Annapolis, MD water level gauging station - Station ID:8575512, you will notice a couple of options in the lower left corner. Click to select 'Metric.' In the left-hand side of the pop-up window you will see the predicted high tide and low tide water levels for the two most current tidal cycles. These predicted tidal levels are based on harmonic analysis of 37 partial tides.

1. Based on the predicted high tide and low tide water levels for the two most current tidal cycles at the Annapolis, MD station, Annapolis experiences a predominately _____ tide.
   a. diurnal
   b. semi-diurnal
   c. mixed

2. The tidal period is about _____ (HH hours, MM minutes).
   a. 11 HH 30 MM
   b. 12 HH 10 MM
   c. 13 HH 25 MM

d. 13 HH 50 MM

In the pop-up window for the Annapolis station, you will notice a couple of options in the lower left corner. Click to select ‘Metric,’ and click to check the box that says plot data. The pop-up window should expand to show plots of water levels (predicted and observed), water temperature, and meteorological conditions (wind direction, wind speed, air temperature, and barometric pressure) over the last two tidal cycles. This represents a great quick look at water levels in Annapolis. But there is much more information that can be gained from this gauging station.

In the upper middle portion of the pop-up box for the Annapolis station, you will notice a pull-down menu that says ‘More Data’. Use that menu to select ‘Data Inventory’. This will open up a new browser window that will show the types of data that have been collected at Annapolis and the time period over which these data have been collected.

3. According to the data record, the NOAA Annapolis, MD station has been collecting hourly water level data (Verified Hourly Height Water Level) since _____.
   a. 1900
   b. 1928
   c. 1946
   d. 1952

Go back to the browser tab pop-up window for Annapolis, MD. From the ‘More Data’ pull-down menu in the upper middle portion of the pop-up window for the station, select ‘Sea Level Trends’. This will open up a new browser window that will display the relative sea level trend at the Annapolis station over the complete data record.

4. Over the complete water level data record collected at the NOAA Annapolis station, the relative sea level has been rising at a rate of about _____ mm/yr.
   a. 0.8
   b. 1.7
   c. 2.5
   d. 3.9

Go back to the browser tab pop-up window for Annapolis. In the upper middle portion of the pop-up window, click on the box that says ‘Station Home’. This will take you to Annapolis Station. Take a moment and review the information available on this page.

At the top of the NOAA station homepage, you will see a pull-down menu that says ‘Tides/Water Levels’. Use this pull-down menu to select ‘Water Levels’. This will take you to a page showing a plot of predicted and observed water levels for the two most recent tidal cycles. The options window below the water level plots allows you to select plots or data over a desired time period.

Figure 7 shows predicted and verified observed water levels at the Annapolis station from 9-11 May 2021. Looking at the difference between the observed and predicted tidal water levels over the same time period, it is clear that the observed water levels are different from the predicted tidal water levels.

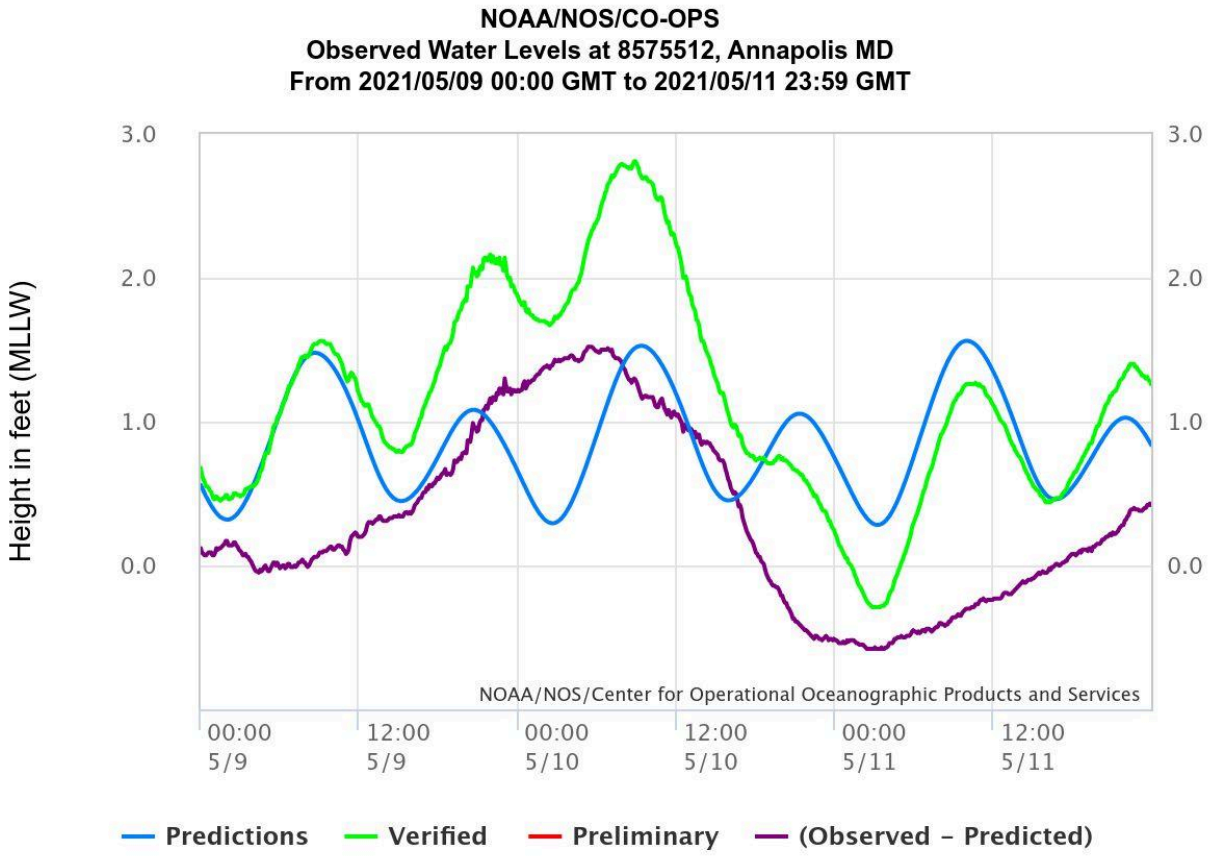


Figure 7. Predicted (blue) and verified (observed) (green) water levels at the Annapolis, MD water level gauging station from 09-11 May 2021 referenced to Mean Lower Low Water (MLLW), the lowest of the low tides per day averaged over a 19-year period. Also shown is the difference between the observed and predicted water levels (purple) over the same time period. [NOAA/NOS/CO-OPS]

5. From 9-11 May 2021, the observed water levels at the Annapolis, MD station were different from the predicted tidal water levels by as much as _____ ft.

a. 0.2
b. 0.8
c. 1.0
d. 1.4

6. What is a factor that could result in observed water levels being different from the predicted tidal water levels in Annapolis, MD?
   a. changes in air pressure
   b. changes in wind speed and/or direction
   c. Both of the above are possible reasons

Navigate back to the NOAA Annapolis, MD station homepage. To the ‘Tides/Water Levels’ pull-down menu, click on the tab that says ‘Meteorological Obs.’ This will take you to a page showing plots of meteorological observations at the station over the two most recent tidal cycles. The options window below the data plots allows you to select plots or data over a desired time period.

Figure 8 shows barometric pressure measured at the Annapolis, MD water level gauging station - Station ID: 8575512 from 9-11 May 2021. Compare these data to the predicted and verified observed water levels at the Annapolis, MD water level gauging station - Station ID: 8575512 from 9-11 May 2021 (Figure 7).

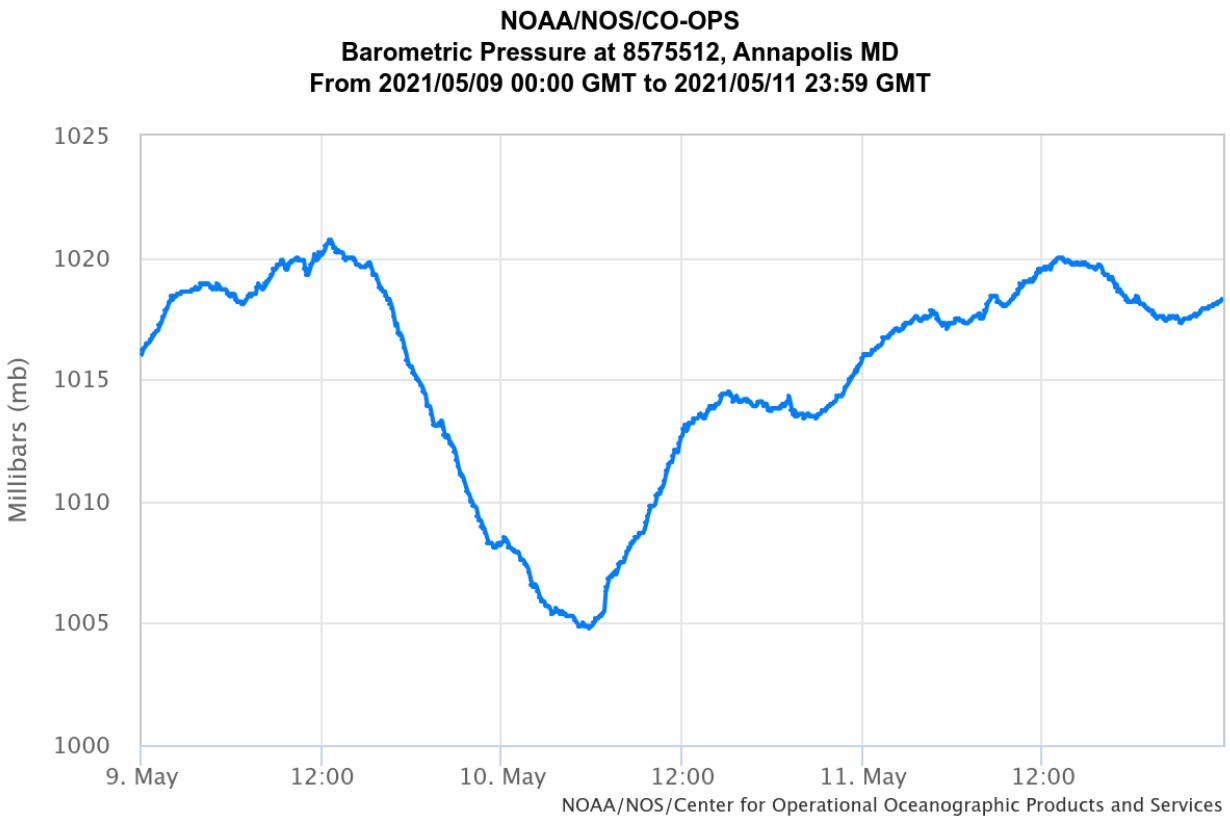


Figure 8. Barometric pressure (blue) measured at the Annapolis, MD water level gauging station - Station ID: 8575512 from 09-11 May 2021. [NOAA/NOS/CO-OPS]

7. Observed water levels appear to be _____ than predicted tidal water levels when barometric pressure is lower.
   a. higher
   b. lower

Figure 9 shows wind speed and direction measured at the Annapolis, MD station from 9-11 May 2021 and the general alignment of Annapolis and the Chesapeake Bay. Compare these data to the predicted and verified observed water levels at the station from 9-11 May 2021 (Figure 7).

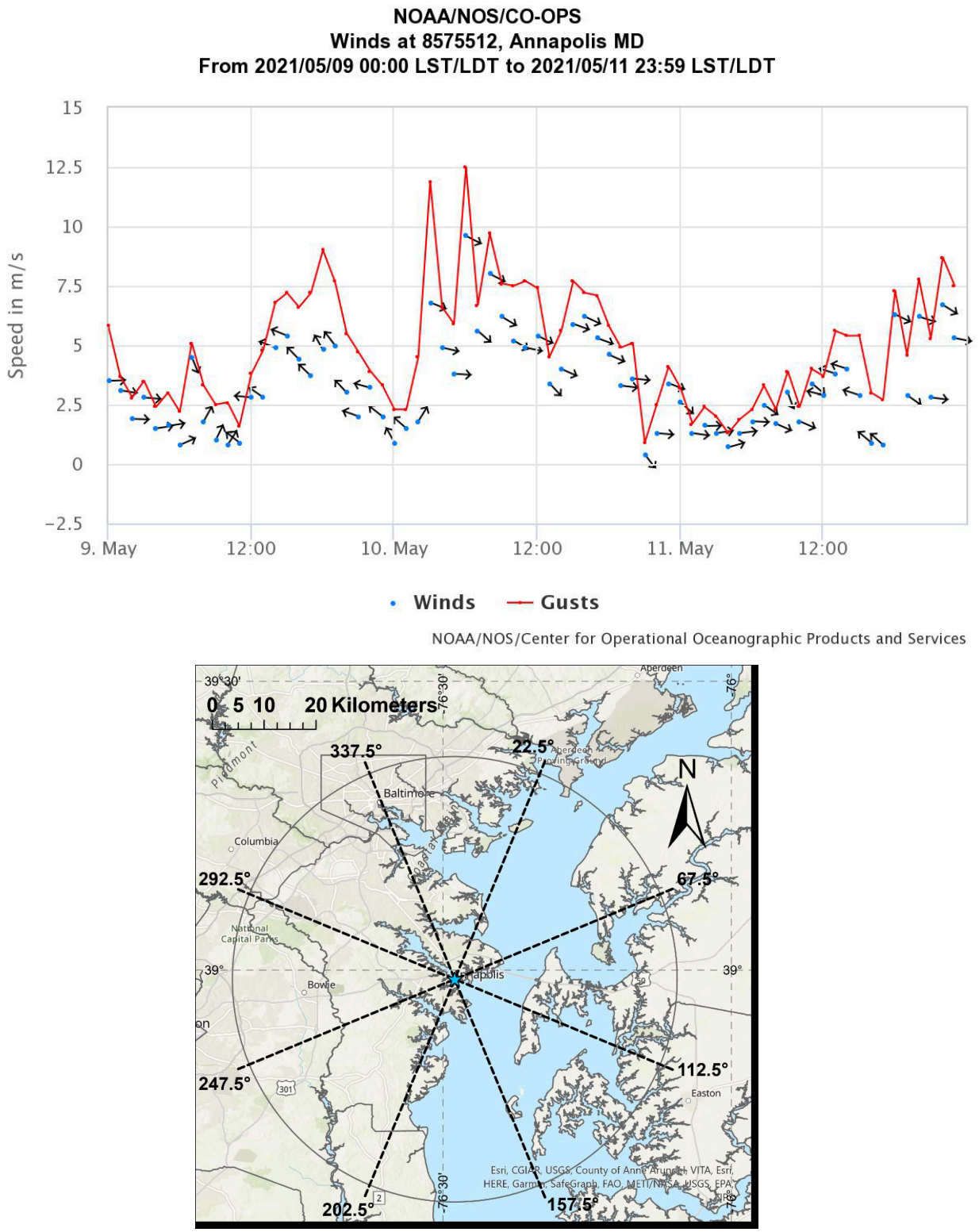


Figure 9. (Top) Wind speed and direction (red) measured at the Annapolis, MD water level gauging station - Station ID: 8575512 from 09-11 May 2021. [NOAA/NOS/CO-OPS] (Bottom) alignment the Annapolis, MD water level gauging station - Station ID: 8575512 and the Chesapeake Bay. [from Davies et al., 2021]

8. Observed water levels appear to be _____ than predicted tidal water levels when preceded by winds from the south to southeast, and observed water levels appear to be _____ than predicted tidal water levels when preceded by winds from the west to northwest.
   a. higher … higher
   b. higher … lower
   c. lower … higher
   d. lower … lower

Group Review and Discussion:

1) *As a group, discuss how and why changes in barometric pressure could cause differences between observed water levels and predicted tidal water levels at a specific location like Annapolis, MD.*
2) *As a group, discuss how and why wind speed and direction relative to the coast could cause differences between observed water levels and predicted tidal water levels at a specific location like Annapolis, MD.*
3) *Discuss other non-astronomical factors besides wind direction, speed, and barometric pressure that could result in differences between predicted and observed water levels at a given coastal location.*
4) *Currently, Annapolis experiences some degree of nuisance flooding, or high tide flooding, about 30-40 times per year (Dahl et al., 2017). Review the rate of relative sea level rise recorded at the Annapolis water level gauging station - Station ID: 8575512 and predict how this might affect the frequency and intensity of nuisance flooding in Annapolis in the future.*

Evaluate | Ocean Tides

9. Nuisance flooding is more likely to occur with _____ in global mean sea level.
   a. a decrease
   b. an increase

10. The tide-generating (producing force) results from the difference in which two forces?
   a. Coriolis Effect and the centrifugal force
   b. lunar gravitational force and the centrifugal force
   c. pressure gradient force and the Coriolis Effect
   d. pressure gradient force and the lunar gravitational force

11. The diurnal inequality is the difference in _____ between successive high (or low) tides.
    a. heights
    b. periods

12. When the positions of the Sun, Moon, and Earth are along a straight line, this generates a _____ tide.
    a. neap
    b. spring

13. The Bay of Fundy, which experiences a maximum tidal range of about 16 m, would be considered
    a. microtidal
    b. mesotidal
    c. macrotidal

14. Due to the complex interplay of astronomical and non-astronomical factors in tide generation, it takes a minimum of about _____ years of data collection for a tidal station to be able to issue water level predictions with the highest accuracy.
    a. 5
    b. 11
    c. 19
    d. 32

Extension **| Moonlight Serenade**

Go to Learning Lesson: Moonlight Serenade | National Oceanic and Atmospheric Administration to access the SpringNeap Tide Wheel. Download the Black Background and White Background, print, and then put these together as instructed.

Additional Resources

General Information:
National Oceanic and Atmospheric Administration (NOAA), 2021: Tides and Water Levels. Accessed 28 May 2021, https://oceanservice.noaa.gov/education/tutorial_tides/.

Demos and Activities:
University of Hawai‘i, College of Education, Curriculum Research & Development Group (CRDG), 2021: Exploring Our Fluid Earth: Tides. Accessed, 11 July 2021, https://manoa.hawaii.edu/exploringourfluidearth/physical/tides.

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