AMERICAN METEOROLOGICAL SOCIETY



Project Ocean

Deep Ocean and Shallow Water Waves

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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This material is based upon work previously supported by the National Science Foundation and the U.S. Office of Naval Research (under Awards N00014-20-1-2384 and N00014-23-1-2666).

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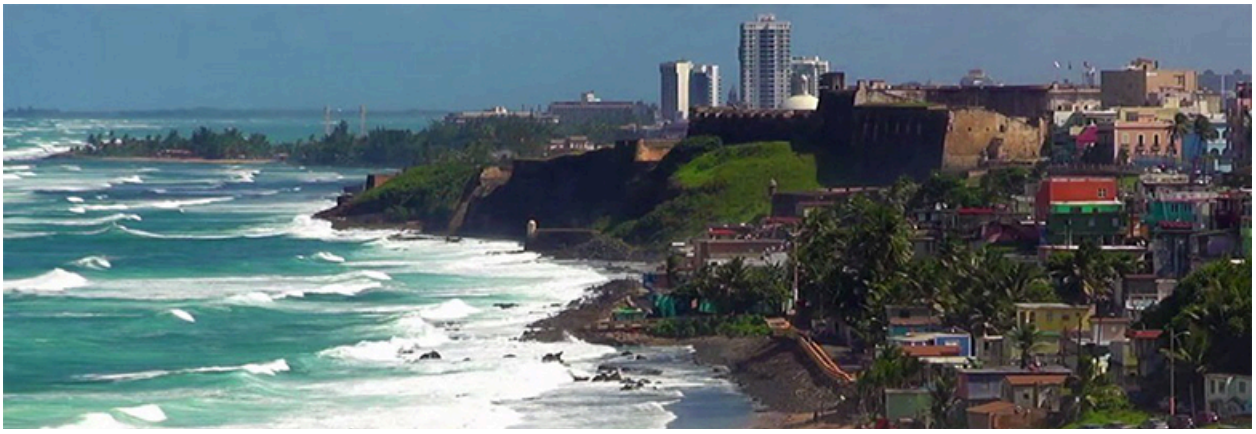


Figure i. Breaking waves on the San Juan, Puerto Rico coast. [NOAA]

“An ocean traveler has even more vividly the impression that the ocean is made of waves than that it is made of water..."

- Sir Arthur Stanley Eddington (1882-1944)

“Like as the waves make towards the pebbl'd shore, so do our minutes, hasten to their end”

- William Shakespeare (1564-1616)

Module: Deep Ocean and Shallow Water Waves
Audience/Grade Level: K-12 Educators

Learning Objectives

After completion of this module participants will be able to:

5. Open Ocean Surface Currents

- Identify the physical laws (e.g., conservation principles) and dominant forces used to describe ocean fluid motion.

8. Open Ocean Waves

- Describe the forces that generate and restore open ocean waves (e.g., wind, gravity, surface tension).
- Distinguish between standing waves and progressive waves.
- Identify and define wave parameters: wave height, wavelength, wave period, and wave speed.
- Distinguish between deep-water waves, transitional waves, and shallow-water waves based on depth.
- Explain the process of wave generation and the concept of a fully developed sea.
- Analyze how wave steepness leads to wave breaking and the formation of whitecaps.
- Define and differentiate between sea, swell, and rogue waves.
- Describe wave interference and how constructive and destructive interference affect wave groups.
- Explain the orbital motion of water particles and how it varies with depth.

9. Shallow-Water Waves

- Define deep, transitional, and shallow-water waves and describe their interaction, if any, with the sea bottom.
- Describe how wave speed, height, and wavelength change as waves approach shallow water.
- Explain the process and significance of wave refraction and wave breaking near shorelines.
- Identify the conditions under which surf zones and breakers are formed.
- Describe tidal waves as planetary-scale shallow-water waves and explain the roles of gravity and inertia.
- Describe the formation and propagation of tsunamis and their impact as shallow-water waves.

STANDARDS:

Project Ocean Fundamental Understandings:

Open Ocean Surface Currents (5.1)
Open Ocean Waves (8.1-8.20)
Shallow-Water Waves (9.1-9.12)

Applicable Ocean Literacy Principles: 1.A, 2.E, 3.A, 7.D, 7.F

Next Generation Science Standards:

Performance Expectations

- 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-PS2-1. Support an argument that the gravitational force exerted by Earth on objects is directed down.
- MS-ESS2-4. Develop a model to describe the cycling of water through Earth's systems driven by energy from the sun and the force of gravity.
- MS-ESS2-6. Develop and use a model to describe how unequal heating and rotation of the Earth cause patterns of atmospheric and oceanic circulation that determine regional climates.

Disciplinary Core Ideas

- PS2.A: Forces and Motion
- ESS2.A: Earth Materials and Systems
- ESS2.C: The Roles of Water in Earth's Surface Processes

Crosscutting Concepts

1. Patterns.
3. Scale, proportion, and quantity.
5. Energy and matter: Flows, cycles, and conservation.

Science and Engineering Practices

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

Engage | Heavy Seas and Big Waves

Whether from personal experience or from watching television and movies, it is hard not to imagine **waves** and **surf** when one thinks about the ocean. And big surf, of course, means surfing! Are the **breaking waves** along the beach that we recognize as surf the same waves that form in the deep ocean? Why and how are waves in shallow water near the coast different from waves in the middle of the open ocean?

Most ocean waves start as **deep-water waves** that originate as disturbances of the still ocean surface by wind. Deep-water waves come in many shapes and sizes and range in **wavelength** from hundreds of meters, like the big ocean waves U.S. Navy ships sometimes encounter at sea (**Figure 1**), down to a fraction of a centimeter for the smallest **ripples**. Waves transfer energy as they propagate outwards from their point of origin without a significant horizontal transport of the water itself. As a wave passes by, the original still water surface is restored by Earth's gravitational attraction or, for the smallest ripples, by surface tension. Waves that have traveled beyond the area of generation are called **free waves** or **swell**. Once formed, these waves may travel very long distances. Because deep-water waves do not interact with the ocean bottom as they travel, their speed, or **celerity**, is independent of the water depth. The patterns of **waves** observed on the ocean surface in the deep ocean are complex and ever-changing. However, general wave patterns can be investigated by reference to the characteristics of **ideal waves**.



Figure 1. The bow of the USS Kitty Hawk (CV-63) in heavy seas with 40+ foot waves somewhere in the South Pacific, circa 2007. [Extracted from Perfect Storm 90 foot waves!!!]

As **deep ocean surface waves** approach shallower waters, they start to interact with the bottom. They can be modeled first as **transitional waves**. And then, as water depths become even shallower as compared to the wavelength of the propagating

ocean wave, they can be modelled as **shallow-water waves**. The physical characteristics of both transitional and shallow-water waves are altered by interaction with the bottom. As shallow-water waves build, they can become too high for their supporting base and eventually break to produce surf. Under the right conditions, this can produce big **breaking waves** at the beach that are good for surfing (**Figure 2**).



Figure 2. Surfing a shallow water wave at a NOAA Marine Sanctuary. [NOAA Sanctuaries].

Wind-driven ocean waves play a crucial role in mixing the upper ocean **water column** and facilitating the exchange of energy, momentum, and constituents, such as gases, between the atmosphere and the ocean. Wave action helps shape the coastline and plays a role in the transport of coastal sediments. Waves also represent a potential source of renewable energy for humans.

In addition to wind-driven waves, there are also other forms of waves in the ocean. **Tsunamis** are seismic sea waves, or ocean pressure waves, generated by submarine earthquakes, volcanic eruptions, or landslides. Ocean **internal waves**, or **internal gravity waves**, can form at the interface of density layers beneath the ocean surface. And planetary-scale **Rossby waves** and **Kelvin waves** occur naturally in the ocean (and atmosphere). Lastly, **tides** as we experience them at the coast are shallow-water ocean waves of global dimensions, generated by the gravitational attraction of the Moon and the Sun.

While optional, we recommend Ocean Waves Basics for an overview of ocean waves (especially the first 8 minutes) before you progress through the rest of the module.

Group Review and Discussion:

1.) *What causes most deep-ocean surface waves to form?*
2.) *Differentiate between deep ocean, transitional, and shallow water waves.*
3.) *Why are waves important to air-sea interactions?*
4.) *What are some other types of waves that form in the ocean?*

Explore | Wind and Ocean Waves

The direction of wave movement mirrors the prevailing surface winds that produce the ocean gyres. On any given day, wind direction may differ considerably from the long-term average due to weather systems (e.g., storms) traveling over the ocean. The changes in wind speed and direction alter wave characteristics, including the direction of wave movement and wave height.

Figure 3 is a global map showing significant wave heights and wave direction provided by Oceanweather, Inc. for 12Z 24 November 2024. The wind field is derived from Oceanweather's Global Ocean Wave Model, which uses wind observations obtained by instrumented buoys and remote sensing of the ocean surface by Earth-orbiting satellites. **Significant wave height** is the average height of the highest one-third of the waves observed in a patch of ocean. Oriented perpendicular to the advancing wave crests, arrows represent the direction of wave movement.

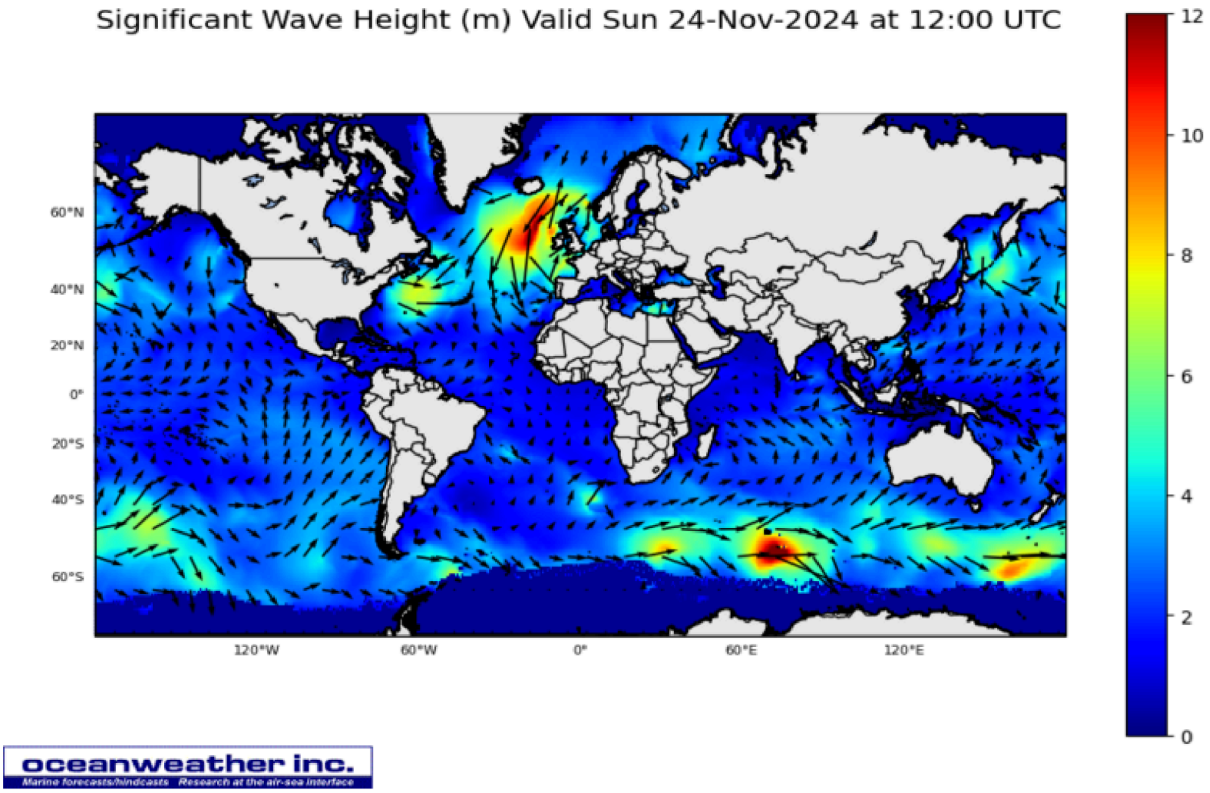


Figure 3. Global view of significant wave heights and wave directions valid for 12Z 24 NOV 2024. [Oceanweather, Inc]

The color-coded background displays significant wave heights. The regions of highest significant wave heights in both the Northern and Southern Hemispheres covered a greater portion of the ocean surface in the latitude belts from 30° to 60°. Since waves are wind-generated, the latitude belts with the highest significant wave heights are associated

with relatively strong surface winds and more storm systems in these regions. Note that waves in the Southern Hemisphere ocean between about 40°S and 60°S are moving generally toward the east, indicating the motion of wind flow toward the east.

Figure 4 is a map of the North Atlantic showing in greater detail the greatest significant wave heights and wave directions for 12Z 24 November 2024 (same time as Figure 3).

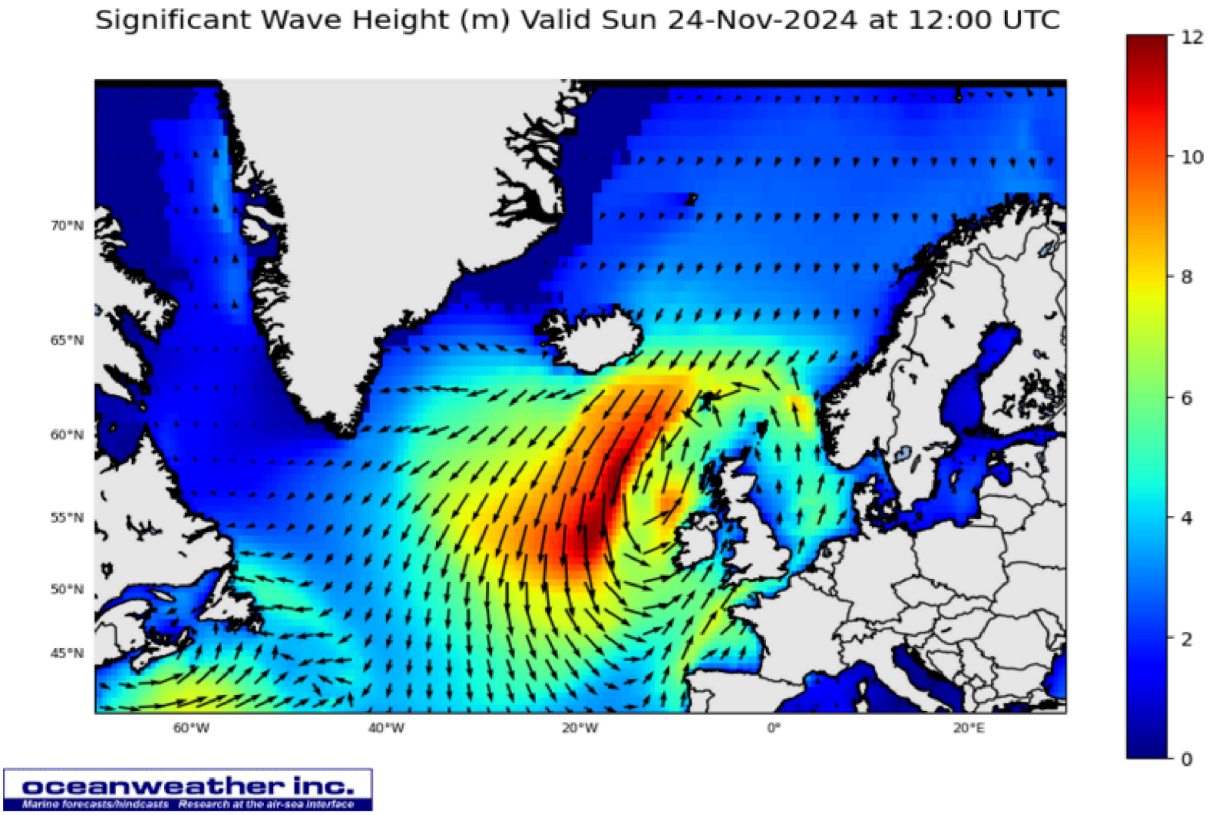


Figure 4. North Atlantic Ocean with the greatest significant wave heights and wave directions for 12Z 24 NOV 2024. [Oceanweather, Inc.]

In Figure 4, note the wave pattern centered at about 56°N, 18°W. The orange and red areas indicate significant wave heights that are higher compared to those in surrounding waters. **Figure 5** displays the marine observations and model data for the North Atlantic Ocean at nearly the same time as Figure 3 and Figure 4. The isobars, lines of equal air pressure, are drawn at a 2-mb interval and labeled so 90 is 990 mb, 00 is 1000 mb, 12 is 1012 mb, etc. Purple and blue lines denote low pressures, while green and yellow denote higher pressures.

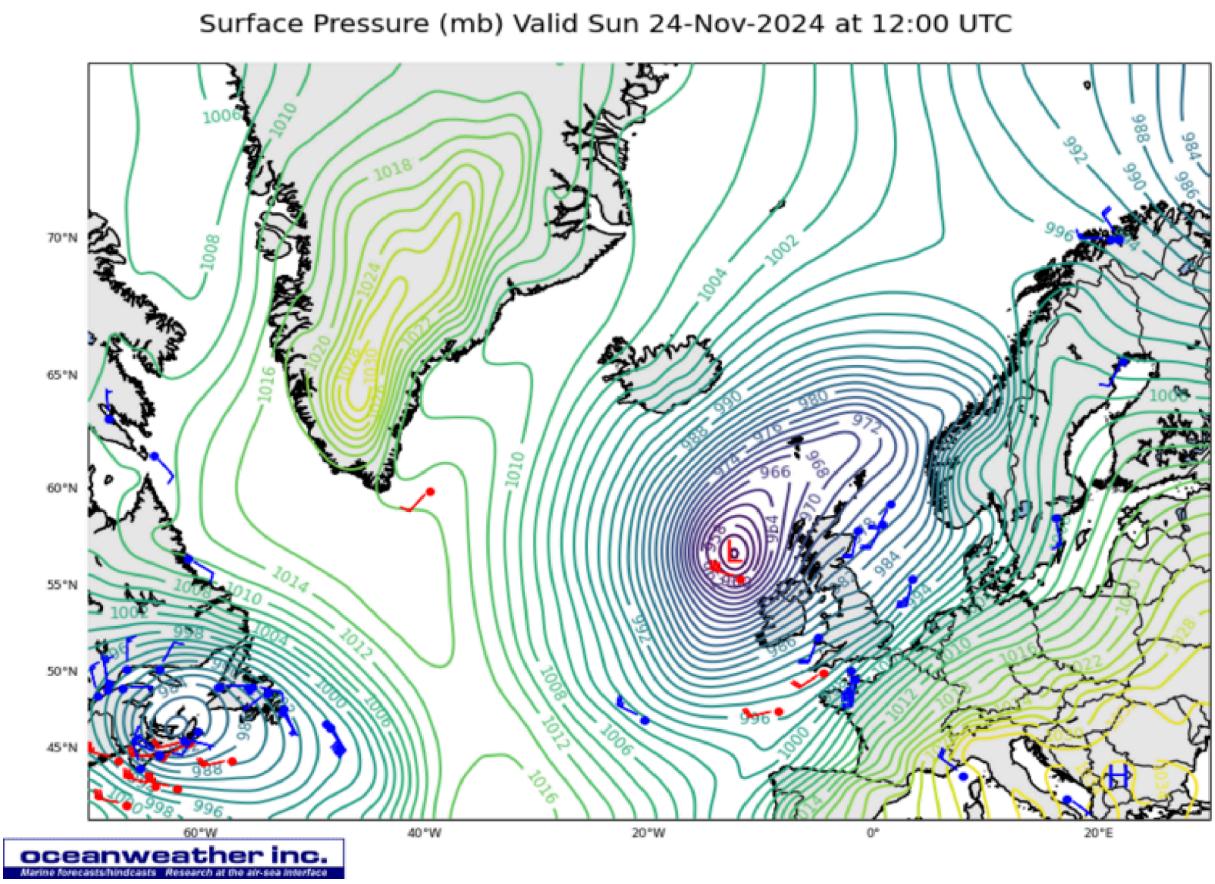


Figure 5. North Atlantic marine observations and model data valid for 12Z 24 NOV 2024. [Oceanweather, Inc.]

The pattern of isobars in Figure 5 reveals an atmospheric low-pressure system (cyclone) centered at about 56°N, 12°W. As is typical with Northern Hemisphere atmospheric low pressure systems, the horizontal wind pattern is indicated by wind barbs plotted around the low pressure center and exhibits counterclockwise motion. Horizontal winds are strongest where isobars are closest together.

Group Review and Discussion:

1.) *Would you expect the highest significant wave height to occur in tropical, midlatitude, or polar latitudes?*
2.) *What is the relationship between isobar spacing on a surface pressure map and underlying significant wave heights?*
3.) *In the case shown, where did the highest significant wave heights occur with respect to the center of the low pressure system?*

Explain | Deep-Water Ocean Waves

Ocean Waves

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) and also internally in the ocean at the interface between **density** layers. Ocean waves are **mechanical (pressure) waves** that involve a combination of both longitudinal and transverse motion. Standing wave forms such as **seiches** also occur in oceanic systems. Wind, gravity, and/or seismic disturbances can alter the potential energy of the water surface, which generates propagating waves in the open ocean. After a wave passes, the water surface is restored by gravity or, for the smallest **ripples** or **capillary waves**, by surface tension of the water itself. For large-scale **planetary waves** like **tides**, the **Coriolis force** also plays a role in the restoration of the ocean surface. Patterns of rising and falling water levels observed on the open ocean surface are complex and constantly changing. Open ocean waves are, for the most part, **progressive waves** that transmit energy outward from an initial disturbance without the physical, horizontal transport of water. Open ocean wave patterns can be investigated through the use of the characteristics of **ideal waves**.

Anatomy of an Ocean Wave

The patterns 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, or celerity (C) (Figure 6)**. Wave characteristics are determined by the factors that generate the wave. 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 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 $2\pi/L$. The time it takes for two successive wave crests (one wavelength) to pass a fixed point is the wave period (T). 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.

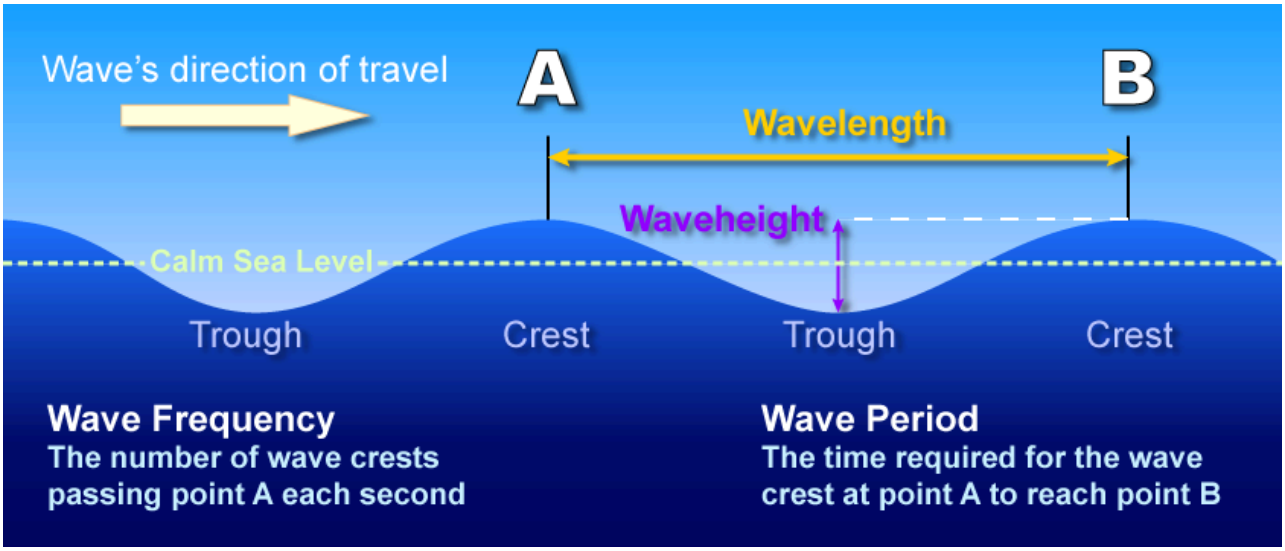


Figure 6. Wave anatomy. [NOAA]

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 (HS)**, the average height of the highest 1/3 of all waves occurring in a particular time period. Waves greater than 2 times larger than significant wave height (HS) are considered **rogue waves**. The **average wave period (TP)** is the average period of the highest 1/3 of all waves occurring in a particular time period. Once a wave forms, its frequency and period remain constant. The wave period can be used to estimate the **angular frequency** of the wave ($\omega = 2\pi/T$. The wave celerity (C) or the distance a wave crest travels per unit time is $= \omega/\kappa$ or can be determined by dividing the wavelength (L) by the wave period (T). Wave celerity, or **wave phase velocity**, is the speed at which an individual wave advances or "propagates".

Ideal open ocean waves can mathematically be approximated and modeled using the **wave equation**. But the characteristics of ocean waves, particularly wave energy, wave height, and wave celerity, change as ocean waves enter shallower waters with depths (h) closer to or less than their wavelength (L). Consequently, ocean waves are categorized by depth as: deep-water waves ($h/L \geq ½$); transitional waves ($1/20 < h/L < ½$), and; shallow-water waves ($h/L \leq 1/20$). Characteristics of deep-water waves can be mathematically approximated and modeled using a simplified deep-water approximation to the wave equation, and characteristics of shallow-water waves are mathematically approximated and modeled using a simplified shallow-water approximation to the wave equation.

Wind Generation of Open Ocean, Deep-Water Waves

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. 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.

Wind is the most common factor that can disturb a still ocean surface, thereby generating **turbulence** and open ocean waves. Wind is continuously acting on the sea surface to form **waves**. Air flowing over the water surface initially generates small ripples, called **capillary waves**, which are small enough to be restored by surface tension. The roughening of the water surface by capillary waves increases the transfer of wind energy to the ocean surface. As ripples evolve into waves with wavelengths of centimeters and greater, the restoring force transitions from surface tension to gravity. **Figure 7** shows much smaller wavelength capillary waves coexisting with longer-wavelength gravity waves.

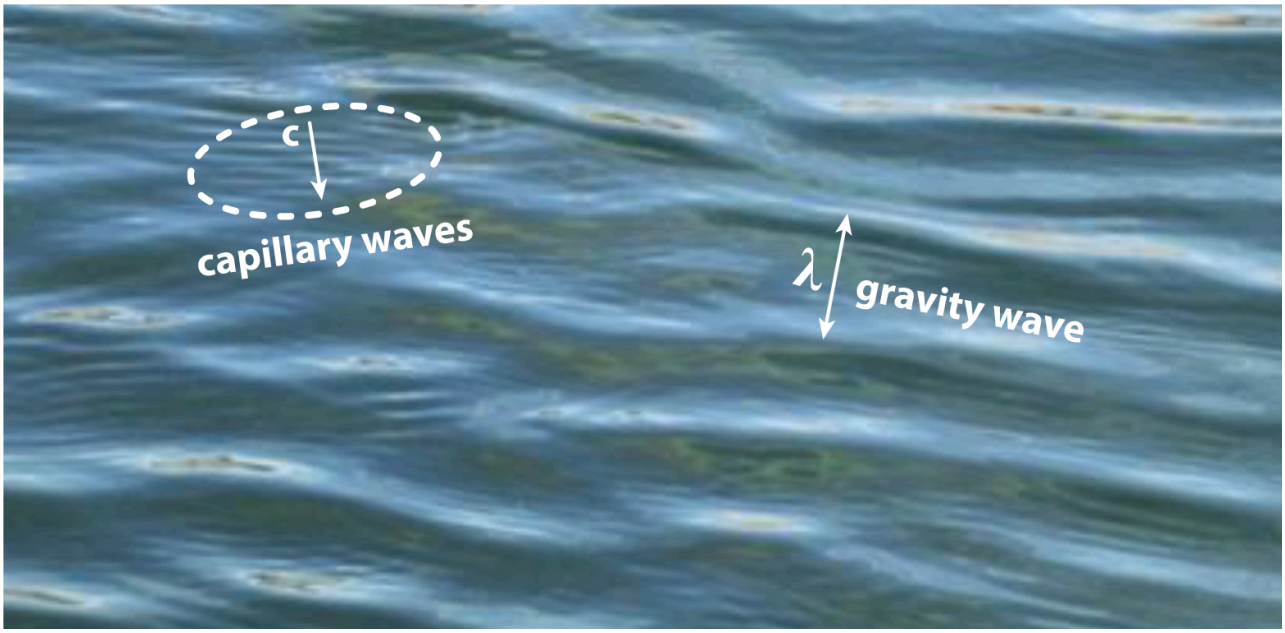


Figure 7. Wind-driven capillary waves and longer-wavelength gravity waves. [Adapted from Naeser, H., 2022]

The size of open ocean waves produced by the wind increases with wind speed, wind duration, and fetch, or the distance over water over which the wind blows unimpeded. The increase in the size of open ocean waves produced by the wind has limits. When the ratio of wave height (H) to wavelength (L), called the wave steepness of an open ocean wave, exceeds 1 to 7, the wave breaks and forms **whitecaps** (**Figure 8**). 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. 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**. Unusually high open ocean waves, or **rogue waves**, may form in areas where waves generated by strong storms encounter oncoming currents.



Figure 8. White-capped waves. [SCCF Recon]

Deep-water waves

Deep-water waves are open-ocean waves that occur in water with a depth greater than one-half the wavelength (**Figure 9**). There is no significant interaction between the orbital motion associated with deep-water waves and the ocean bottom. Thus, wave celerity for a deep-water wave is independent of the water depth. Once a deep-water wave forms, its wave period remains constant. The **phase velocity** of an individual deep-water wave is determined by its wavelength. The greater the wavelength, the greater the wave celerity.

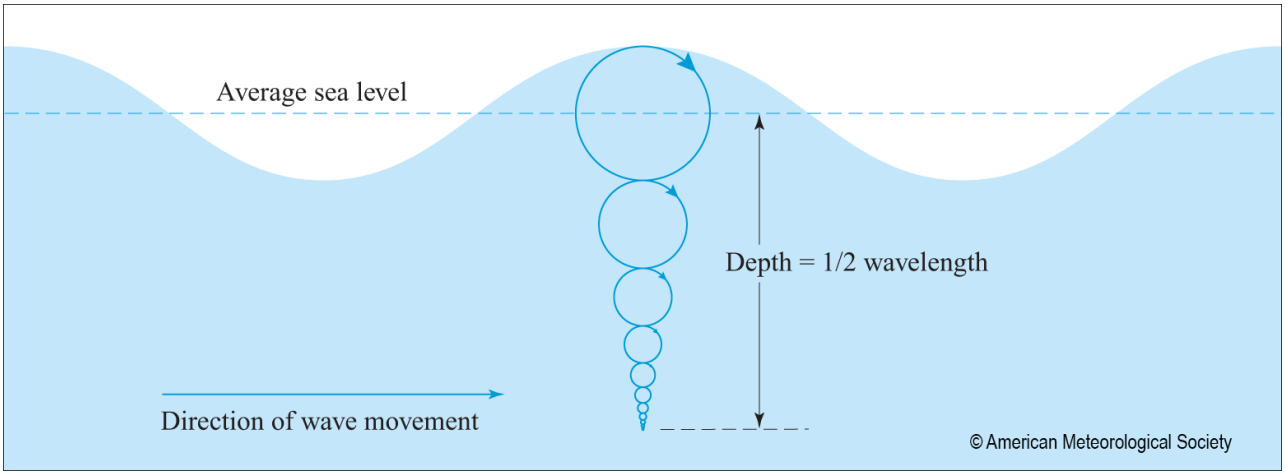


Figure 9. Diagram of a deep-water wave. [Moran, 2011]

Because waves of long wavelengths travel faster than smaller waves, swell leaving the same area of generation eventually sorts itself into groups of similar waves traveling together, called **wave trains** or **wave groups**. When different wave trains interact, they work together either to form an area of higher wave heights (constructive interference), or an area of calmer waves (destructive interference). The speed of these wave groups, called group speed, is about one-half the speed of the individual waves. At times, an individual wave can be observed passing through a wave group before disappearing into the wave-free region.

Transitional waves and Shallow-Water waves

When shoaling waves begin to interact with the seafloor, they are referred to as **transitional waves**. These waves are present in water with a ratio of water depth to wavelength that is less than ½ and greater than 1/20. When the ratio becomes equal to 1/20, the waves are referred to as shallow-water waves.

Shallow-water waves are ocean waves occurring at the sea surface that are affected by the ocean bottom (**Figure 10**). These waves are created by the same mechanisms as **deep-water waves,** and the general physics are the same as for deep-water waves. But as waves enter shallow water, interaction with the bottom alters the wave.

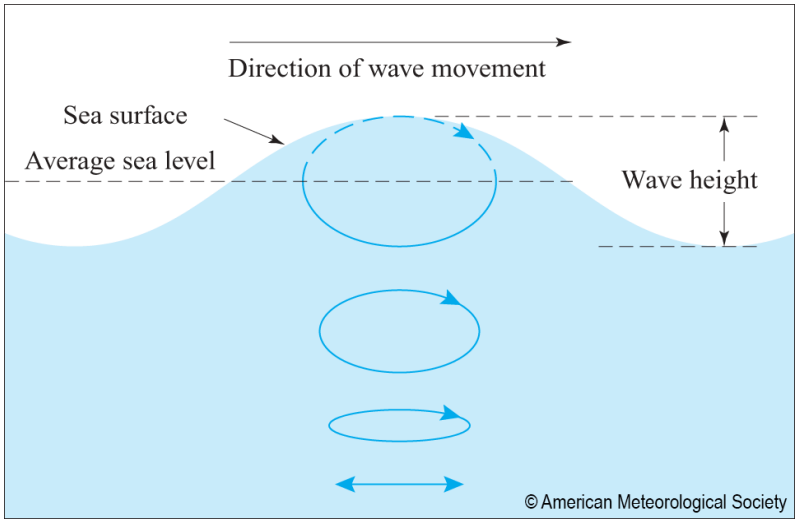


Figure 10. Diagram of a shallow-water wave, which interacts with the ocean bottom. [Moran, 2011]

Shallow-water waves are waves in water where the ratio of water depth (h) to wavelength (L) is less than or equal to 1/20. As a deep-water wave approaches shore and becomes a transitional wave, circular orbits near the ocean surface become more elliptical and start to flatten and weaken with depth due to compression along the bottom. This effect becomes more pronounced as water depth shallows and transitional waves become shallow-water waves. Shallow-water waves have highly elliptical orbits near the surface that quickly flatten, narrow, and weaken with depth. Transitional waves are mathematically modelled using the **full wave equation**. In contrast, true shallow-water waves can be mathematically approximated and modeled using the simplified shallow-water approximation to the wave equation.

Shallow-Water Waves and the Coast

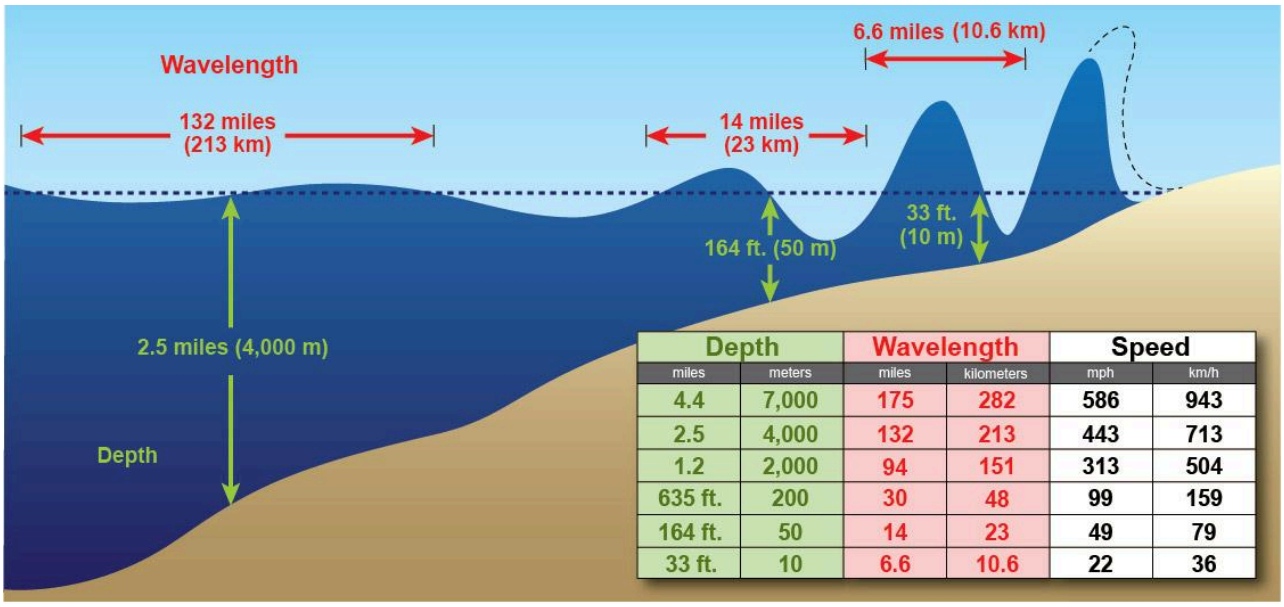
For shallow-water waves, as depth decreases, wave celerity decreases, wavelength shortens, and wave height increases. Eventually, shallow-water waves become so high and unstable that they break. The breaking of shallow-water waves is dependent on a number of factors, such as the slope of the ocean bottom, but it is the relationship between wave height (H) and mean water depth (h) that is most important. Generally, the greater the ratio between wave height (H) and water depth (h), the more likely the wave will break. In shallow water along shorelines with a gently sloping seafloor, waves break when their wave height (H) is approximately 78% of water depth (h). A band of nearly continuous **breaking waves**, or breakers, along the shore is called surf. Breaking waves dissipate energy and are an important mechanism that contributes to mixing and the exchange of energy and material across the air-sea interface.

Shallow-water waves and breaking waves erode and transport sediment, thereby altering the bottom. The newly altered bottom, in turn, affects the next wave to come

along. Shallow-water waves play an important role in shaping the coastline. With a gently sloping sea bottom, waves approaching a shoreline at anything other than a right angle are bent, or refracted, so their crests turn to a more parallel alignment with the shore. Refraction focuses wave energy on a headland and disperses wave energy along a bay coastline. Both deep-water and shallow-water waves represent a potential source of renewable energy for humans.

Unique Water Types

There are mechanisms other than wind that generate ocean waves. **Tsunamis** are seismic ocean waves, or 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 celerity and wavelength and a rapid, potentially dangerous, increase in wave height (**Figure 11**). Meteotsunamis are tsunamis driven by air-pressure disturbances often associated with fast-moving weather events.



Depth		Wavelength		Speed	
miles	meters	miles	kilometers	mph	km/h
4.4	7,000	175	282	586	943
2.5	4,000	132	213	443	713
1.2	2,000	94	151	313	504
635 ft.	200	30	48	99	159
164 ft.	50	14	23	49	79
33 ft.	10	6.6	10.6	22	36

Figure 11. Cross-section of a theoretical tsunami as its long waves move through the ocean and compress as they approach the coast. [NOAA]

Internal waves, or internal gravity waves, form at internal ocean boundaries. Significant differences in density at the intersection of two moving water masses or rapid changes in density between layers in a highly stratified ocean water column creates these oscillations. Internal waves can propagate both horizontally or vertically, depending on the mechanism linked to their creation and the degree of density stratification. They move at significantly slower phase velocities as compared to wind-driven surface ocean waves and can travel long distances with large wave heights. They can also reflect off land-ocean boundaries.

Planetary-scale waves also exist in the ocean. Two examples are **Rossby waves** and **Kelvin waves**. Rossby waves are planetary-scale waves that naturally occur in the ocean (and atmosphere) as a result of conservation of potential vorticity on a rotating Earth. Kelvin waves are planetary-scale waves that naturally occur in the ocean (and atmosphere) and balance the Coriolis Force against a boundary like a coastline. 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 is the trough.

Group Review and Discussion:

1.) *Define wave height, wavelength, and wave frequency.*
2.) *Distinguish between forced waves (sea) and free waves (swell).*
3.) *Relate wave trains, wave groups, and group speed.*
4.) *How are ocean waves categorized by depth?*
5.) *What happens to ocean waves when they approach the coast?*

Elaborate | Ocean Waves: Real Data, Real Waves

Ocean waves come in many shapes and sizes. Most start as deep-water waves caused by disturbances of the still ocean surface by wind. The atmosphere and ocean are dynamic environments. This results in complex, ever-changing wave fields on the ocean surface. No two wave conditions are alike. This can be observed by examining real data on actual waves collected from ocean wave monitoring platforms, such as moored buoys. Real ocean wave data can be used to characterize ocean wave patterns using the general characteristics of ideal waves. Such characterization can aid in predicting wave conditions to promote safety of navigation and potential coastal hazards. In this activity, real ocean wave data will be used to characterize the wave conditions at a specific location in the ocean. This activity will also investigate how episodic changes in wind forcing conditions (wind direction and speed) can cause wave conditions to change.

Materials:

- *Computer(s) or laptop(s) with internet connection and access to the National Oceanographic and Atmospheric Administration (NOAA), National Data Buoy Center (https://www.ndbc.noaa.gov/)*
- *Calculator*
- *Pen or Pencil*

Activity - Real Data, Real Waves:

Access the National Oceanographic and Atmospheric Administration (NOAA), National Data Buoy Center webpage at https://www.ndbc.noaa.gov/.

Use the Interactive map on the NOAA, National Data Buoy Center (NDBC) webpage to zoom in to NDBC Moored Buoy Station 44008 southeast of Nantucket, MA. Click on the icon for NDBC Moored Buoy Station 44008 and you should see a pop-up box with the location and current conditions at NDBC Station 44008 similar to the one shown in **Figure 12**.

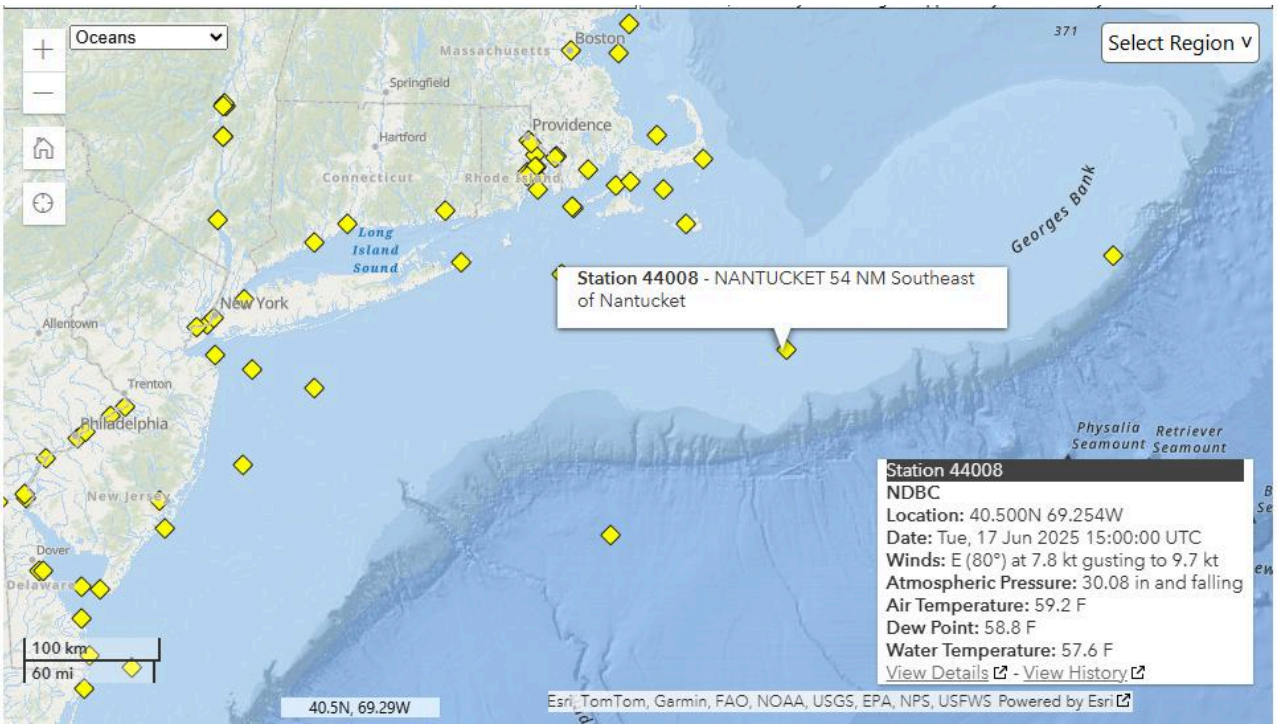


Figure 12. Interactive map showing location and general conditions on 17 June 2025 at National Oceanographic and Atmospheric Administration (NOAA), National Data Buoy Center, Moored Buoy Station 44008 located 54 NM SE of Nantucket, MA. (NBDC).

Click on the 'View Details' hyperlink in the pop-up box for NDBC Moored Buoy Station 44008. This will take you to the web page for the NOAA NDBC Station 44008 moored data buoy located 54 NM Southeast of Nantucket, MA (https://www.ndbc.noaa.gov/station_page.php?station=44008).

1. The water depth at NDBC Moored Buoy Station 44008 is about _____ m.
   a. 18
   b. 36
   c. 73
   d. 135

2. At this site, any waves with wavelengths less than about _____ m would be considered deep-water waves.
   a. 3.7
   b. 18
   c. 22.5

d. 36.5

Navigate to the ‘Conditions at 44008…’ table. From the pull-down menu ‘Unit of Measure:’, select ‘Metric’ and from the pull-down menu ‘Time Zone:’, select ‘Station Local Time’ and then press ‘Select’. **Table 1** below uses data from 11 am (15 UTC) 17 June 2025.

Table 1: Example buoy data

Date	Time	Wind Direction (WDIR, ordinal, °)	Wind Speed (WSPD, m/s)	Atmospheric Pressure (PRES, mb)	Air Temperature (ATMP, °C)	Water Temperature (WTMP, °C)
6/17/25	11 am (15 UTC)	E, 80 deg. true	4.0 m/s	1018.7	15.1	14.2

Fill in **Table 2** below using the current conditions:

Table 2: Current buoy data

Date	Time	Wind Direction (WDIR, ordinal, °)	Wind Speed (WSPD, m/s)	Atmospheric Pressure (PRES, mb)	Air Temperature (ATMP, °C)	Water Temperature (WTMP, °C)

Scroll down on the NDBC page to the ‘Wave Summary for 44008…’ . This lists values for swell and for wind waves, or forced waves, or seas.

3. Swell data are for waves that originated from _____ the NDBC Site 44008 area.
   a. outside
   b. within

4. Wind wave data are for waves that originated from _____ the NDBC Site 44008 area.
   a. outside
   b. within

Table 3 below is completed with Wave Summary.

Table 3: Example wave conditions

Date	Time	Significant Wave Height (WVHT, m)	Average Wave Period (APD, sec)	Wave Steepness (STEEPNESS)
6/17/25	11 am EDT (15 UTC)	1.2	5.2	STEEP

Complete **Table 4** using the current wave conditions.

Table 4: Current wave conditions

Date	Time	Significant Wave Height (WVHT, m)	Average Wave Period (APD, sec)	Wave Steepness (STEEPNESS)

For the wave condition tables above, **Significant Wave Height (WVHT)** and **Average Wave Period (APD)** are estimated for the highest 1/3 of all waves occurring in the previous 20-minute time period. Assuming the waves at NDBC Station 44008 are deep-water waves, the approximation below can be used to estimate the mean wavelength (L_0) for the highest 1/3 of all waves occurring in the previous 20- minutes:

$$L_0 = \frac{g \cdot (APD)^2}{2\pi}$$

Where:

- L_0 is the **deep-water wavelength** in meters,
- $g = 9.8 m/s^2$ is the **acceleration due to gravity**,
- ADP is the **average wave period** in seconds,

$\pi \approx 3.1416$.conditions as of 11 am EDT (15 UTC) on 17 June 2025.

5. Based on Table 3 data, at about 11 am (15 UTC) on 17 June 2005, the estimated **mean deep-water wavelength (L_0)** for the highest 1/3 of all waves occurring in the previous 20-minutes was _____ m.
   a. 8.1
   b. 42.2
   c. 94.4
   d. 120.2

Calculate estimated mean wavelength based on Table 4 data and compare it to your answer for #5.

6. Recall that waves break when the ratio of wave height to wavelength exceeds 1/7 or 0.14. Based on the estimated mean wavelength (L_0) for the highest 1/3 of all waves occurring in the previous 20 minutes, if the wavelength stays constant, waves would need to reach a height of _____ m at this location before they become unstable and start to break.
   a. 6.1

b. 12.2
c. 24.3
d. 30.2

Assuming the waves at NDBC Station 44008 are deep-water waves, the approximation below can be used to estimate the mean celerity (C_0) for the highest 1/3 of all waves occurring in the previous 20 minutes:

$$C_0 = \sqrt{\frac{g \cdot L_0}{2\pi}}$$

Where:

- C_0 is the **deep-water wave speed** in meters per second (m/s)
- $g = 9.8 m/s^2$ is the **acceleration due to gravity**,
- L_0 is the **deep-water wavelength** in meters,
- $\pi \approx 3.1416$

7. Based on the 17 June 2025 data recorded at NOAA NDBC Station 44008 and the estimated mean wavelength (L_0) for the highest 1/3 of all waves occurring in the previous 20 minutes, the mean celerity (C_0) for the highest 1/3 of all waves occurring in the previous 20 minutes was _____ m/s.
   a. 2.1
   b. 4.1
   c. 6.1
   d. 8.1

Episodic changes in wind forcing conditions (wind direction and speed) due to storms can cause wave conditions to change rapidly at a given location. Tropical Storm Elsa passed to the west of NDBC Station 44008 on Friday, 09 July 2021 (**Figure 13**). **Table 5** shows wave data and meteorology data from NDBC Station 44066 for the period from 12:00 am on 09 July 2021 to 12:00 pm on 10 July 2021 (local time).

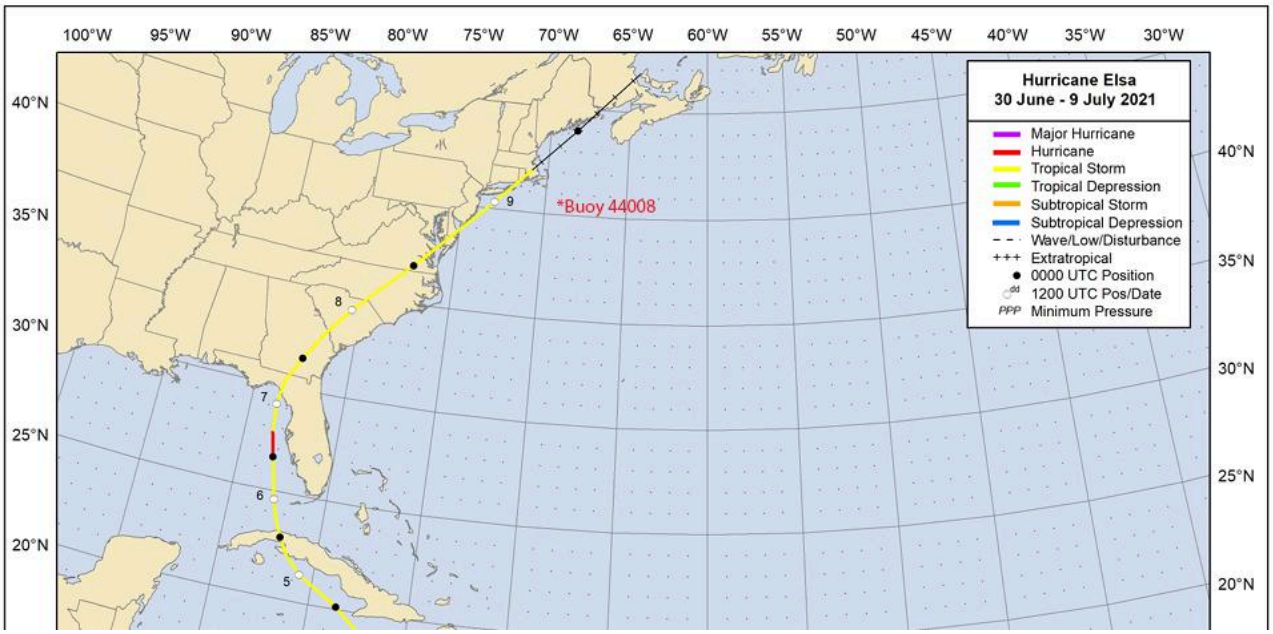


Figure 13. Track of Hurricane Elsa (2021) and position of Buoy 44008. [NOAA NHC]

Table 5: Select NDBC Station 44008 data from Friday, 9 July 2021

Date	Time	WDIR (degT)	WSP (m/s)	WVHT (m)	APD (sec)	PRES (T hPa)	ATMP (degC)	WTMP (degC)
7/9/21	7:40 am (1140 UTC)	144	7.2	0.97	4.33	1014.7	18.8	14.6
7/9/21	8:40 am (1240 UTC)	143	8.6	1.16	4.15	1013.4	19.4	15.1
7/9/21	9:40 am (1340 UTC)	150	9.8	1.4	4.29	1012.5	20.1	16.3
7/9/21	10:40 am (1440 UTC)	153	11.6	1.8	4.59	1011.5	20.9	16.5
7/9/21	11:40 am (1540 UTC)	167	12.9	2.48	5.22	1010.3	21.2	15.7
7/9/21	12:40 pm (1640 UTC)	173	12.4	3.26	6.04	1009.4	21.1	15.6
7/9/21	1:40 pm (1740 UTC)	180	12.9	3.75	6.47	1008.9	21.1	15.7
7/9/21	2:40 pm (1840 UTC)	191	14	3.86	6.74	1008.6	21.1	15.3

WDIR: Wind direction (the direction the wind is coming from in degrees clockwise from true N) during the same period used for WSPD.
WSPD: Wind speed (m/s) averaged over an eight-minute period for buoys and a two-minute period for land stations.
WVHT: Significant Wave Height is the average height (meters) of the highest one-third of the

waves during a 20 minute sampling period.
APD: Average Wave Period is the average period (seconds) of the highest one-third of the wave observed during a 20 minute sampling period.
PRES: Sea level pressure (mb).
ATMP: Air temperature (Celsius).
WTMP: Sea surface temperature (Celsius).

Examine the data in Table 5. In **Table 6** note the highest Significant Wave Height (WVHT) and longest Average Wave Period (APD) recorded at NDBC Station 44066 from 12:00 AM on 09 July 2021 to 12:00 PM on 10 July 2021 (local time). Estimate the average wind speed and direction in the 6 hours prior to the highest Significant Wave Height (WVHT) and longest Average Wave Period (APD) recorded at NDBC Station 44066 from 12:00 am on 09 July 2021 to 12:00 pm on 10 July 2021 (local time) and add them to the table below.

Table 6: Inferred wave conditions

Date	Time	Highest Significant Wave Height (WVHT, m)	Longest Average Wave Period (APD, sec)	6-hour Averaged Wind Direction (WDIR, °)	6-hour Averaged Wind Speed (WSPD, m/s)

8. Compare the data in Table 6 to the track of Tropical Storm Elsa (Figure 13). The trends in wave data during the morning hours of 9 July 2021 _____ the projected track.
   a. do not fit
   b. fit

Compare the data during the passage of Tropical Storm Elsa in Table 6 to the conditions at NDBC Station 44008 on 17 June 2025.

9. Significant Wave Height (WVHT, m) was _____ during the passage of Elsa.
   a. lower
   b. about the same
   c. higher

10. Average Wave Period (APD, s) was _____ during the passage of Elsa.
    a. shorter
    b. about the same
    c. longer

11. Six-hour Averaged Wind Speed (WSPD, m/s) was _____ during the passage of Elsa.
    a. lower
    b. about the same
    c. higher

Group Review and Discussion:

1.) *How did atmospheric and ocean conditions change with the nearby passage of a tropical storm?*
2.) *Based on the data you have examined from NDBC Station 44008, discuss which factors appear to be the most important in determining wave height of open ocean, deep-water waves?*

Evaluate | Deep Ocean and Shallow Water Waves

12. Deep water waves primarily transport:
    a. energy
    b. mass

13. Wavelength is measured as the:
    a. horizontal distance from crest to trough
    b. horizontal distance from crest to crest
    c. vertical distance from crest to trough
    d. vertical distance from crest to crest

14. Wave height is measured as the:
    a. horizontal distance from crest to trough
    b. horizontal distance from crest to crest
    c. vertical distance from crest to trough
    d. vertical distance from crest to crest

15. The speed or celerity of deep water waves _____ on the water depth.
    a. depends on
    b. does not depend on

16. A shallow-water wave is a wave traveling through water with a depth less than _____ the wavelength of the wave.
    a. 1/20
    b. 1/5
    c. 1/3
    d. 1/2

17. A tsunami is a _____ water wave
    a. deep
    b. shallow
    c. transitional

18. The restoring force of a capillary wave is:
    a. Coriolis Force
    b. gravity
    c. surface tension of water

19. The nearby passage of a storm causes _____ in significant wave height.
    a. a decrease
    b. an increase
    c. no change

20. Swell comes from the impact of wind on water:
    a. from a distant area
    b. in the immediate vicinity

Extend | Additional Explorations

Group Demonstration: Wave Races
(Modified from: Karp-Boss, L., E. Boss, H. Weller, J. Loftin, and J. Albright, 2009: Teaching Physical Concepts in Oceanography, An Inquiry-Based Approach - Activity 5.1: Wave Speed and Water Depth. The Oceanography Society, 52 pp)

Wave Characteristics
This 13-question hands-on activity helps identify the principal characteristics of deep- and shallow-water waves.

Additional Resources

General Information:

National Oceanic and Atmospheric Administration (NOAA), National Weather Service, 2021: JetStream Max: Wind, Swell and Rogue Waves. Accessed 27 May 2021, https://www.weather.gov/jetstream/wave_max.

National Oceanic and Atmospheric Administration (NOAA), National Ocean Service, 2021: Waves. Accessed 09 July 2021, https://oceanservice.noaa.gov/education/tutorial_currents/03coastal1.html.

Demos and Activities:

University of Hawai‘i, College of Education, Curriculum Research & Development Group (CRDG), 2021: Exploring Our Fluid Earth: Introduction to Waves. Accessed, 27 May 2021, https://manoa.hawaii.edu/exploringourfluidearth/physical/waves/introduction-waves.

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University of Hawai‘i, College of Education, Curriculum Research & Development Group (CRDG), 2021: Exploring Our Fluid Earth: Wave Energy and Wave Changes with Depth. Accessed, 27 May 2021, https://manoa.hawaii.edu/exploringourfluidearth/physical/waves/wave-energy-and-wave-changes-depth.

U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, 2020: Renewable Ocean Energy. Accessed 09 July 2021, https://app.box.com/s/4zq4upah39un6dy2tbb0x1mav4lac98w.

Acknowledgements

During the preparation of this work the author(s) used ChatGPT-4o in order to copyedit text and understand some of the key concepts. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.