Waves and Water Dynamics

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Table of Contents

1 Introduction

Aside from pure oceanography, wave motion and wave physics are key to understanding micro-, macro-, and planetary-sized wave motion. Keep in mind that waves can form in various settings. For example, along an air–water interface, the movement of air across the ocean surface creates ocean waves. Along an air–air interface, the movement of different air masses creates atmospheric waves, which are often represented by ripple-like clouds. Along a water–water interface, the movement of water of different densities creates internal waves.

Please note that this handout is by no means comprehensive and only contains basic concepts and formulas. To find further relevant information, please read full official textbooks and use Google! Handouts are for quick review!

2 Classical Waves

We will begin by examining basic wave structure, formation, classification, and interaction.

2.1 Wave Formation and Maintenance

- As the wind blows over the ocean's surface, it pushes down on and parallel to it, causing water to build up into minute wavelets known as **capillary waves**, sometimes known as ripples. These capillary waves feature modest, circular troughs with wavelengths of less than 1.74 cm (0.7 inch). The word is derived from capillarity, a phenomenon caused by water's surface tension.

- The sea surface becomes rougher as capillary wave generation rises. More wind is "caught" by the water, allowing the wind and ocean surface to interact more efficiently. Gravity waves form when more energy is delivered to the ocean. These are symmetric waves with wavelengths more than 1.74 cm (0.7 inch). The length of gravity waves is generally 15 to 35 times their height. Wave height grows faster than wavelength as more energy is gained. Trochoidal waveforms are formed when the crests become pointy and the troughs become rounded.

- In oceanography, the **sea** refers to the location where wind-driven waves are formed. It is distinguished by choppiness and waves that move in many directions. Because of the constantly changing wind speed and direction, the waves have a range of periods and wavelengths (most of which are short).

- Wave height is dependent on wind speed, wind duration, and fetch,The **fetch** is the distance over which the wind blows in one direction.

- **Wave steepness** is the ratio of wave height to wave length. When wave steepness reaches a critical value of 1/7, open ocean breakers—called whitecaps—form (i.e. a wave brakes). Waves cannot grow infinitely because an equilibrium condition, called a fully developed sea, has been achieved. Waves can grow no further in a fully developed sea because they lose as much energy breaking as whitecaps under the force of gravity as they receive from the wind.

- As waves generated in a sea area move toward its margins, wind speeds diminish and the waves eventually move faster than the wind. When this occurs, wave steepness decreases and waves become long-crested waves called swells, which are uniform, symmetrical waves that have traveled out of their area of origination.
- Waves with longer wavelengths travel faster and thus leave the sea area first. They are followed by slower, shorter wave trains, or groups of waves. The progression from long, fast waves to short, slow waves illustrates the principle of wave dispersion—the sorting of waves by their wavelength. Waves of many wavelengths are present in the generating area. Wave speed depends on wavelength in deep water, however, so the longer waves "outrun" the shorter ones.
- The distance over which waves change from a choppy "sea" to uniform swell is called the **decay distance**, which can be up to several hundred kilometers.

2.2 Wave-wave Interactions

When swells from different storms run together, the waves clash, or interfere with one another, giving rise to interference patterns.

- Constructive interference occurs when wave trains having the same wavelength come together in phase, meaning crest to crest and trough to trough. If the displacements from each wave are added together, the interference pattern results in a wave with the same wavelength as the two overlapping wave systems but with a wave height equal to the sum of the individual wave heights.
- Destructive interference occurs when wave trains having the same wavelength come together out of phase, meaning the crest from one wave coincides with the trough from a second wave. If the waves have identical heights, the sum of the crest of one and the trough of another is zero, so the energies of these waves cancel each other.
- In most ocean areas, it is likely that two or more swells of different heights and lengths will come together and produce a mixture of constructive and destructive interference. In this scenario, a more complex mixed interference pattern develops. Rogue waves are massive, solitary, spontaneous ocean waves that can reach enor- mous height and often occur at times when normal ocean waves are not unusually large. In a sea of 2-meter (6.5-foot) waves, for example, a 20-meter (65-foot) rogue wave may suddenly appear. There are many fake rogue wave videos on YouTube, but this one is real: rogue wave example link. You can see how this would cause smaller ships (especially wooden) to sink, leading to tales of monstrous waves and lost boats due to sea monsters. The main cause of rogue waves is theorized to be an extraordinary case of constructive wave interference where multiple waves overlap in-phase to produce an extremely large wave.

2.3 Wave-shore Interactions

- Most waves generated in the sea area by storm winds move across the ocean as swell. These waves then release their energy along the margins of continents in the surf zone, which is the zone of breaking waves.

- If the surf is swell that has traveled from distant storms, breakers will develop relatively near shore, in shallow water. The horizontal motion characteristic of shallow-water waves moves water alternately toward and away from the shore as an oscillation. The surf will be characterized by parallel lines of relatively uniform breakers.
- If the surf consists of waves generated by local winds, the waves may not have been sorted into swell. The surf may be mostly unstable, deep-water, high-energy waves with steepness already near the 1:7 ratio. In this case, the waves will break shortly after coming into contact with the ocean bottom some distance from shore, and the surf will be rough, choppy, and irregular.
- When the water depth is about 1.3 times the wave height, the crest of the wave breaks, producing surf.
- When the water depth becomes less than 1/20 the wavelength, waves in the surf zone begin to behave like shallow-water waves. Particle motion is greatly impeded by the bottom, and a significant transport of water toward the shoreline occurs.
  There are three main types of breakers.
- A **spilling breaker**, a turbulent mass of air and water, runs down the front slope of the wave as it breaks. Spilling breakers result from a gently sloped ocean bottom, which gradually extracts energy from the wave over an extended distance and produces breakers with low overall energy.
- A **plunging breaker** has a curling crest that moves over an air pocket. The curling crest occurs because the particles in the crest literally outrun the wave, and there is nothing beneath them to support their motion. Plunging breakers form on moderately steep beach slopes and are the best waves for surfing
- When the ocean bottom has an abrupt slope, the wave energy is compressed into a shorter distance, and the wave will surge forward, creating a **surging breaker**.
- The refraction of waves along an irregular shoreline distributes wave energy unevenly along the shore.
- A vertical barrier, such as a seawall or a rock ledge, can reflect waves back into the ocean with little loss of energy—a process called **wave reflection**.

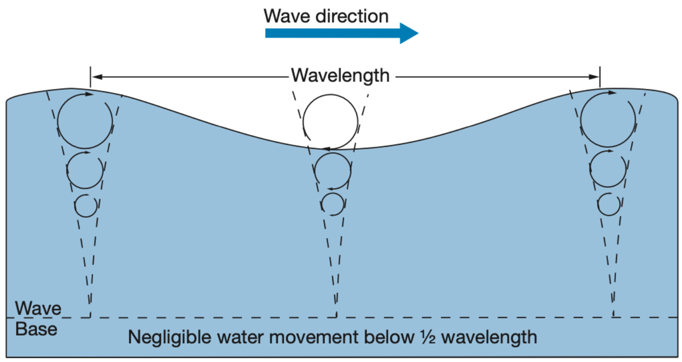
> **Example** (2018 U.S. Earth Science Olympiad #44)
>
> Identify all of the following statements that are correct.
>
> (A) Waves are caused by an interaction between the hydrosphere and atmosphere
> (B) Wave energy originates from different absorption of the sun's energy in the

atmosphere
(C) Waves slow down and become taller in shallower water
(D) Waves slow down and become taller in deeper water
(E) The motion of a water molecule on the surface of the ocean as a wave passes is circular
(F) The motion of a water molecule on the surface of the ocean as a wave passes is linear back and forth

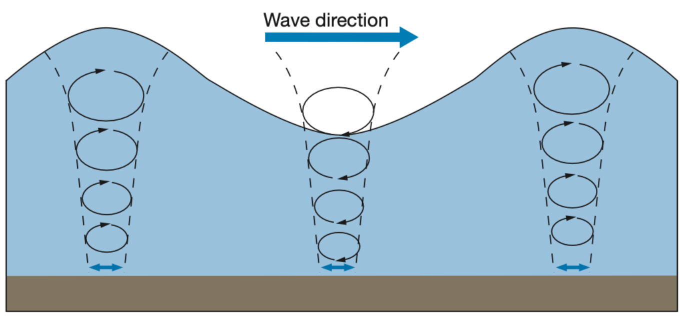
Solution: Answers (A), (B), (C), and (E) are correct. Please note that questions have drastically increased in difficulty since 2018, and this question is not reflective of the difficulty of the current national-level exam.

3 Calculation-based Wave Physics

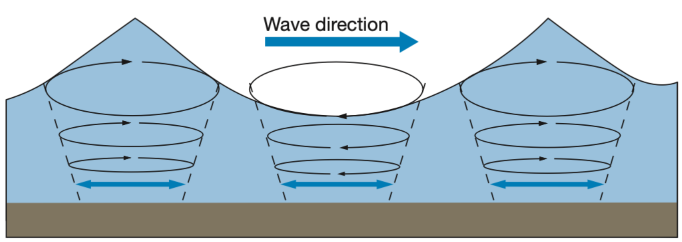
You should be able to apply basic wave formulas and solve simple questions by plugging and chugging! Image from Trujillo.



(a) Deep-water wave: Circular orbits diminish in size with increasing depth. Water depth is greater than $^1/_2$ wavelength.



(b) Transitional wave: Intermediate between deep-water and shallow-water waves. Water depth is greater than $^1/_{20}$ wavelength, but less than $^1/_2$ wavelength.



(c) Shallow–water wave: The ocean floor interferes with circular orbital motion, causing the orbits to become progressively flattened. Water depth is less than $^1/_{20}$ wavelength.

3.1 Shallow Water Waves

- Waves in which depth (d) is less than 1/20 of the wavelength (L/20) are called shallow-water waves.
- $S(m/s) = 3.13\sqrt{d(\text{meters})}$ where S is wave speed

3.2 Deep Water Waves

- Use this if the water depth (d) is greater than the wave base (L/2).
- $S = \frac{L}{T}$
- By filling in the constants with numbers, the equation for wave speed of deep-water waves varies only with wavelength and becomes:

- $S(m/s) = 1.25\sqrt{L(\text{meters})}$

Example (2019 USESO Camp Exam Hydrosphere #14)

Which of the following statements regarding ocean waves is/are true?

(A) Long waves move faster than waves that are short in length
(B) Tall waves move slower than waves that are short in height
(C) In constant depths, shallow-water waves, transitional waves, and deep waves are differentiated based on wavelength.
(D) In theory, a wave with a steepness of 0.1 will break.
(E) Given the frequency of a wave, one can calculate its period

Solution: Based on the information given in the handout, answers (A), (C), and (E) are correct.

4 Advanced Water Physics

4.1 Sverdrup Transport

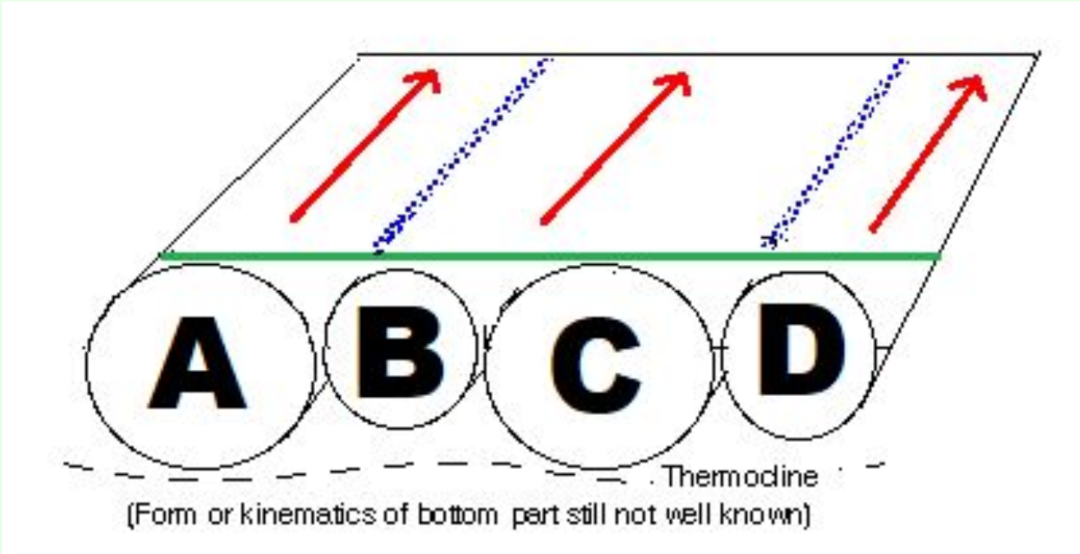
- The Sverdrup transport is the net meridional transport diagnosed in both the subtropical and subpolar gyres, resulting from planetary vorticity changes that balance Ekman pumping or Ekman suction.

4.2 Langmuir Circulation

- Langmuir circulation consists of a series of shallow, slow, counter-rotating vortices at the ocean's surface aligned with the wind.

- The driving force of these circulations is an interaction of the mean flow with wave averaged flows of the surface waves. Stokes drift velocity of the waves stretches and tilts the vorticity of the flow near the surface.

Example (2020 USESO Training Camp Hydrosphere Exam #1)



When wind blows steadily over the sea surface, a circulation pattern consisting of shallow rotating vortices known as Langmuir circulation can form.

A simplified diagram of Langmuir circulation is shown, where the green line is the water surface and the red arrows represent wind direction. A cross section of the rotating vortices is shown through the circles labeled A, B, C, and D (the direction of rotation of the vortices is not shown). Langmuir circulation often leads to lines of accumulated plankton, seaweed and other material on the sea surface known as windrows, shown by the blue lines.

Given this information, which of the following is/are true?

(A) Windrows indicate areas of surface divergence
(B) The vortices labeled A and B rotate in opposite directions
(C) The vortices labeled A and C both rotate clockwise from the point of view of the diagram
(D) Water moves downward between the vortices labeled B and C
(E) The vortices labeled B and C both rotate clockwise from the point of view of the diagram

Solution: A quick glance should immediately indicate that (B) is true. As for the other answer choices, we will take a look on a case-by-case basis. (A) is not true because windrows logically form by convergence of mass. This implies that (C) is true. (D) does not make sense as that is where the water is upwelled to the surface, and (E) cannot be true by (B). Thus the answer is (B) and (C).

5 Closing

Waves and water dynamics are some of the most fundamental aspects of the hydrosphere. Hopefully, this handout helped you review. Good luck on future exams!

-Michael :)