Key Ideas

- Wind waves form when energy is transferred from wind to water.
- Waves transmit energy, not water mass, across the ocean’s surface.
- The behavior of a wave depends on the relation between the wave’s size and the depth of water through which it is moving.
- Waves can change direction by refraction and diffraction, can interfere with one another, and reflect from solid objects.

Waves: Undulatory Motion of a Water Surface

- Parts of a wave - wave crest, wave trough, wave height (H), wave amplitude, wave length (L), and wave period (T).
- Wave period - basis for classifying waves.
Most Waves: Wind-Generated

- Size and type of wind-generated waves: affected by wind velocity, wind duration, fetch, and original state of the sea surface.
- As wind velocity increases, wavelength, period and height increase, but only if wind duration and fetch are sufficient.
Progressive Waves

- As waves pass, wave form and wave energy move rapidly forward, but not the water.
- Water molecules move in an orbital motion as the wave passes.
- Diameter of orbit increases with increasing wave size and decreases with depth below the water surface.

A Little Math

- Wave speed = wave length/wave period
- \( C = \frac{L}{T} \)
Relationship of Wave Length to Depth of Wave Motion

\[ C = \text{speed of advancing wave front} \]

\[ D = \frac{L}{2} \]

Motion of Water as Wave Passes

Water in the crest of the wave moves in the same direction as the wave, but water in the trough moves in the opposite direction.
Classifying Waves

Waves are classified on the basis of:
• Disturbing force
• Free waves vs. forced waves
• Restoring force
• Wavelength

<table>
<thead>
<tr>
<th>Wave Type</th>
<th>Typical Wavelength</th>
<th>Disturbing Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind wave</td>
<td>60–150 m (200–500 ft)</td>
<td>Wind over ocean</td>
</tr>
<tr>
<td>Seiche</td>
<td>Large, variable; a function of basin size</td>
<td>Change in atmospheric pressure, storm surge, tsunami</td>
</tr>
<tr>
<td>Seismic sea wave (tsunami)</td>
<td>200 km (125 mi)</td>
<td>Faulting of seafloor, volcanic eruption, landslide</td>
</tr>
<tr>
<td>Tide</td>
<td>¼ circumference of Earth</td>
<td>Gravitational attraction, rotation of Earth</td>
</tr>
</tbody>
</table>

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Waves transmit energy across the ocean’s surface.

**Factors Affecting Wind Wave Development**

**Wind strength** - wind must be moving faster than the wave crests for energy transfer to continue

**Wind duration** - winds that blow for a short time will not generate large waves

**Fetch** - the uninterrupted distance over which the wind blows without changing direction
Factors Affecting Wind Waves: Fetch

Properties of Ocean Waves

- Fully developed sea - sea state where the waves generated by the wind are as large as they can be under current conditions of wind velocity and fetch
- Significant wave height - average of the highest 1/3 of the waves present; good indicator of potential for wave damage to ships and for erosion of shorelines.
Table 9.1 The Relationship between Wind Speed and Wave Height

<table>
<thead>
<tr>
<th>Average Wind Speed (knots)</th>
<th>Significant Wave Height (m/s)</th>
<th>Significant Wave Period (s)</th>
<th>Significant Wave Speed (m/s)</th>
<th>Maximum Wave Height (m)</th>
<th>Minimum Fetch (km)</th>
<th>Minimum Wind Duration (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5.1</td>
<td>5.5</td>
<td>8.58</td>
<td>2.19</td>
<td>16</td>
<td>2.4</td>
</tr>
<tr>
<td>20</td>
<td>10.2</td>
<td>7.3</td>
<td>11.39</td>
<td>4.39</td>
<td>110</td>
<td>10</td>
</tr>
<tr>
<td>30</td>
<td>15.3</td>
<td>12.5</td>
<td>19.50</td>
<td>10.43</td>
<td>450</td>
<td>23</td>
</tr>
<tr>
<td>40</td>
<td>20.4</td>
<td>18.0</td>
<td>28.00</td>
<td>25.79</td>
<td>1136</td>
<td>42</td>
</tr>
<tr>
<td>50</td>
<td>25.5</td>
<td>21.0</td>
<td>32.76</td>
<td>30.19</td>
<td>2272</td>
<td>69</td>
</tr>
</tbody>
</table>

1. Minimum fetch and minimum wind duration are distances and times required when wind speed is the only limiting factor in wave development.

Table 9.2 Universal Sea State Code

<table>
<thead>
<tr>
<th>Sea State Code</th>
<th>Description</th>
<th>Average Wave Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>S30</td>
<td>Sea like a mirror; wind less than one knot</td>
<td>0</td>
</tr>
<tr>
<td>S31</td>
<td>A smooth sea; ripples; no foam; very light winds; 1-3 knots, not felt on face</td>
<td>0-0.3 m</td>
</tr>
<tr>
<td>S32</td>
<td>A slight sea; small waves; winds light to gentle; 4-6 knots, felt on face; light foggy wave</td>
<td>0.3-0.6 m</td>
</tr>
<tr>
<td>S33</td>
<td>A moderate sea; large waves; crests begin to break; winds gentle to moderate; 7-11 knots; light fog fully extent</td>
<td>0.6-1.2 m</td>
</tr>
<tr>
<td>S34</td>
<td>A rough sea; moderate waves; many crests break, whitecaps, some wind-blown spray; winds moderate to strong breeze, 11-27 knots; wind whirls in the rigging</td>
<td>1.2-2.4 m</td>
</tr>
<tr>
<td>S35</td>
<td>A very rough sea; waves heave up, forming foam streaks and spindrift; winds moderate to fresh gale, 28-40 knots; wind affects walking</td>
<td>2.4-4.0 m</td>
</tr>
<tr>
<td>S36</td>
<td>A high sea; sea begins to roll, forming very definite foam streaks and considerable spray; winds a strong gale, 41-47 knots; loose gear and light canvas may be blown about or ripped</td>
<td>4.0-6.1 m</td>
</tr>
<tr>
<td>S37</td>
<td>A very high sea; very high, steep waves with wind-driven overhanging crests; sea surface white due to dense coverage with foam; visibility reduced due to wind-blown spray; winds at whole gale force, 48-55 knots</td>
<td>6.1-9.1 m</td>
</tr>
<tr>
<td>S38</td>
<td>Mountainous seas; very high-rolling breaking waves; sea surface foam-covered; very poor visibility; winds at storm level, 56-63 knots</td>
<td>9.1-13.7 m</td>
</tr>
<tr>
<td>S39</td>
<td>Air filled with foam; sea surface white with spray; winds 64 knots and above</td>
<td>13.7 m and above</td>
</tr>
</tbody>
</table>

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Wave Dispersion

The longer the wave length, the faster the wave speed.

Swell Formation and Dispersion

Wave separation, or dispersion, is a function of wavelength. Waves with the longest wavelength move the fastest and leave the area of wave formation sooner. The smooth undulation of ocean water caused by wave dispersion is called swell.

A wave train.
When waves from different directions meet, they interfere with one another.

Wave interference can be:

**Destructive interference** – two waves that cancel each other out, resulting in reduced or no wave

**Constructive interference** – additive interference that results in waves larger than the original waves

**Rogue waves** - freak waves that occur due to interference and result in a wave crest higher than the theoretical maximum

![Wave Interference Diagram](image)
Wave Interference

Wave Interference

Waves Entering Shallow Water

Waves Entering Shallow Water
Shallow-Water Waves

When waves enter shallow water:
- Wave speed decreases
- Wave length decreases
- Wave period does not change
- Wave height increases

\[ D < \frac{L}{20} \]

Wave Movements

- Wave base - depth to which a surface wave can move water
- Depth greater than wave base - orbits are circular with no interaction between wave and bottom
- Depth shallower than wave base - orbits are elliptical and become increasingly flattened towards the bottom
Deep- and Shallow-Water Motion

What happens when wind waves break against the shore?

Wind Waves Approaching Shore
Waves Entering Shallow Water

- Wave speed decreases as depth decreases.
- Wavelength decreases as depth decreases.
- Wave height increases as depth decreases.
- Troughs become flattened and the wave profile becomes extremely asymmetrical.
- Period remains unchanged. Period is a fundamental property of a wave.
- Refraction is the bending of a wave crest into an area where it travels more slowly.

Wave Steepness

Maximum height for a given wavelength is based on H/L. If H/L > 1/7, wave becomes too steep.
Breaking Waves

**Plunging waves** break violently against the shore, leaving an air-filled tube, or channel, between the crest and foot of the wave. Plunging waves are formed when waves approach a shore over a steeply sloped bottom.

**Spilling waves** occur on gradually sloping ocean bottoms. The crest of a spilling wave slides down the face of the wave as it breaks on shore.

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Breaking Waves

- In shallow water, wave height increases and wave length decreases.
- Wave steepness - wave height /wavelength (H/L)
- When H/L is larger than or equals 1/7 (H/L ≥ 1/7), the wave becomes unstable and breaks.
Spilling, Plunging and Surging Breakers

(a) SPILLING BREAKER

(b) PLUNGING BREAKER

(c) SURGING BREAKER

Storm Surge

- Rise in sea level due to low atmospheric pressure and build-up of water by storm winds
- Water is deeper at the shore area, allowing waves to progress farther inland
- Especially severe when superimposed upon a spring high tide
Wave Refraction, Diffraction, and Reflection

**Wave refraction** - the slowing and bending of waves in shallow water

**Wave diffraction** - propagation of a wave around an obstacle

**Wave reflection** - occurs when waves “bounce back” from an obstacle they encounter. Reflected waves can cause interference with oncoming waves, creating standing waves.
Wave Refraction
Wave Diffraction

Wave height decreases

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Waves that occur at the boundaries of water layers with different densities are called internal waves.

**Internal waves**

- Form within the water column along the pycnocline due to density differences.
- Internal waves display all the properties of surface progressive waves including reflection, refraction, interference, breaking, etc.
- Any disturbance to the pycnocline can generate internal waves, including: flow of water related to the tides, flow of water masses past each other, storms, or submarine landslides.
Standing Waves or Seiches

- Water surface “seesaws” back and forth
- Node - imaginary line on the surface where water does not oscillate
- Antinodes - where maximum displacement of the surface occurs as it oscillates; usually located at the edge of the basin

Seiches

Water rocking back and forth at a specific resonant frequency in a confined area is a seiche.

Seiches are also called standing waves.

The node is the position in a standing wave where water moves sideways, but does not rise or fall.

How does a seiche form?
Standing Waves or Seiches
Standing Waves

- Geometry of basin controls the period of a standing wave
- Standing waves can be generated by storm surges or earthquakes
- Resonance amplifies water disturbance at the nodes and occurs when the period of the basin is similar to the period of the force producing the standing wave.
Tsunami and Seismic Sea Waves

Tsunami are long-wavelength, shallow-water, progressive waves caused by the rapid displacement of ocean water. Tsunami generated by the vertical movement of earth along faults are seismic sea waves. What else can generate tsunami?

- landslides
- icebergs falling from glaciers
- volcanic eruptions
- other displacements of the water surface - asteroid impact

Tsunamis

- Previously called tidal waves, but not related to tides
- Consist of long-period waves characterized by very long wavelength (up to 100 km) and high speed (up to 760 km/hr) in the deep ocean
- Because of their large wavelength, tsunamis are shallow-water to intermediate-water waves as they travel across the ocean basin
- Become a danger when reaching coastal areas where wave height can reach 10 m
- Tsunamis originate from earthquakes, volcanic explosions, or landslides
A tsunami, in 1946, was generated by a rupture along a submerged fault. The tsunami traveled at speeds of 212 meters per second.

**Tsunami Speed**

Because tsunami have extremely long wavelengths, they always behave as shallow water waves.

The speed of a tsunami can be calculated using the same formula used for other shallow-water waves:

\[ C = \sqrt{gd} \]

- \( g = 9.8 \text{ m/s}^2 \) (the acceleration due to gravity)
- \( d = \text{depth (a typical Pacific abyssal depth is 4,600 meters)} \)
Tsunami

Ten of the tsunami that have struck since 1990.
Generation of a Tsunami

Sumatra-Andaman Island Earthquake

- Magnitude 9.0
- Sunday, Dec. 26, at 7:58 a.m. local time
- 30 km off the west coast of northern Sumatra
- 250 km SSE of Banda Aceh
- Fourth largest in the world since 1964 Prince William Sound, Alaska, quake
- More casualties than any other tsunami in recorded history
Tsunamis are often no taller than normal wind waves, but they are much more dangerous.

Wind waves come and go without flooding higher areas.

Tsunamis run quickly over the land as a wall of water.

Even a tsunami that looks small can be dangerous!

Any time you feel a large earthquake, or see a disturbance in the ocean that might be a tsunami, head to high ground or inland.
Most Damaging Tsunamis Worldwide

<table>
<thead>
<tr>
<th>Decade Year</th>
<th>Location Name</th>
<th>Number of Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>1815</td>
<td>S. JAVA SEA</td>
<td>1536</td>
</tr>
<tr>
<td>1822</td>
<td>N. CHILE</td>
<td>1536</td>
</tr>
<tr>
<td>1823</td>
<td>SW KYUSHU ISLAND, JAPAN</td>
<td>1536</td>
</tr>
<tr>
<td>1877</td>
<td>RYUKYU TRIBUNE</td>
<td>1536</td>
</tr>
<tr>
<td>1877</td>
<td>MORO GULF, PHILIPPINES</td>
<td>1536</td>
</tr>
<tr>
<td>1877</td>
<td>SORAKO, KAGAMA, JAPAN</td>
<td>1536</td>
</tr>
<tr>
<td>1895</td>
<td>NANKAI, JAPAN</td>
<td>1536</td>
</tr>
<tr>
<td>1923</td>
<td>SW KYUSHU ISLAND, JAPAN</td>
<td>1536</td>
</tr>
<tr>
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</tbody>
</table>

Note: Statistics quoted below 20th Century are approximate.

Tsunami Warning Network

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Summary

Parts of an ocean wave