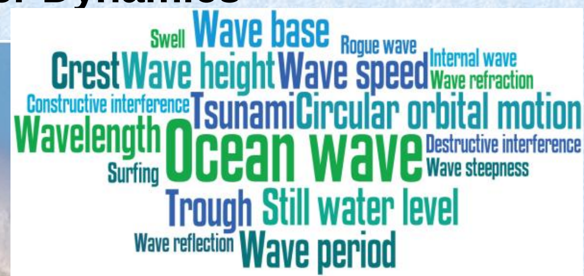
Chapter 8 Lecture

Waves and Water Dynamics



Chapter Overview

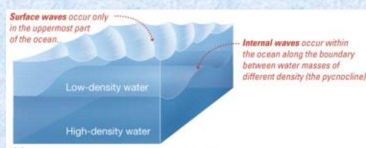
- Most waves are wind-driven.
- Most waves are generated by storms.
- Waves transmit energy across the ocean surface.
- Deep water and surf zone waves have different characteristics.
- Tsunami are special fast, long waves generated by seismic events.

Wave Generation

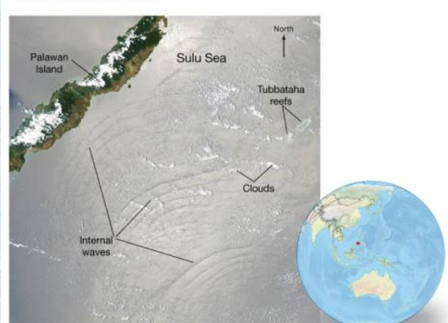
- **Disturbing force** causes waves to form.
- Wind blowing across ocean surface
- Interface of fluids with different densities
  - Air – ocean interface
    - **Ocean waves**
  - Air – air interface
    - **Atmospheric waves**
  - Water – water interface
    - **Internal waves**

Internal Waves

- Associated with pycnocline
- Larger than surface waves
- Caused by tides, turbidity currents, winds, ships
- Possible hazard for submarines



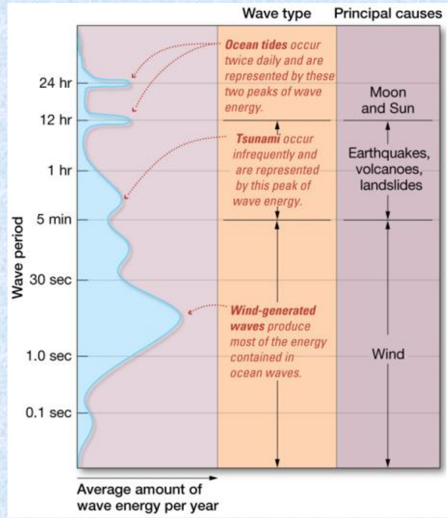
(a) Block diagram showing the differences between surface waves and internal waves.



(b) View from space of internal waves highlighted by sunglint (bright areas) in the Sulu Sea between the Philippines and Malaysia. Image taken April 8, 2003, by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard the Aqua satellite.

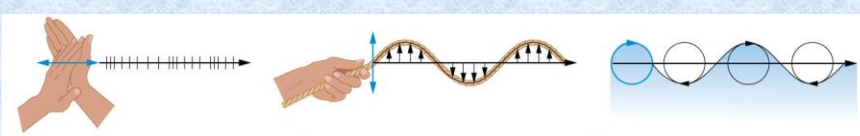
Wave Movement

- Waves transmit energy
- Cyclic motion of particles in ocean
  - Particles may move
    - Up and down
    - Back and forth
    - Around and around



Progressive Waves

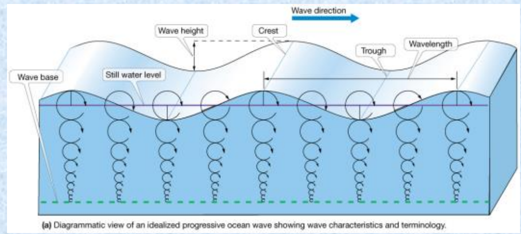
- **Progressive waves** oscillate uniformly and progress without breaking
  - **Longitudinal**
  - **Transverse**
  - **Orbital**



1. LONGITUDINAL WAVE *Hands clapping or thumping a table.* Particles (*blue color*) move back and forth in the direction of energy transmission. These waves transmit energy through all states of matter.
2. TRANSVERSE WAVE *A rope attached to a wall.* Particles (*blue color*) move back and forth at right angles to the direction of energy transmission. These waves transmit energy only through solids.
3. ORBITAL WAVE *The movement of water waves.* Particles (*blue color*) move in a circular path. These waves transmit energy along interface between two fluids of different density (liquids and/or gases).

Wave Terminology

- **Crest**
- **Trough**
- **Still water level**
  - Zero energy level
- **Wave height (H)**
- **Wavelength (L)**
- **Still water level**



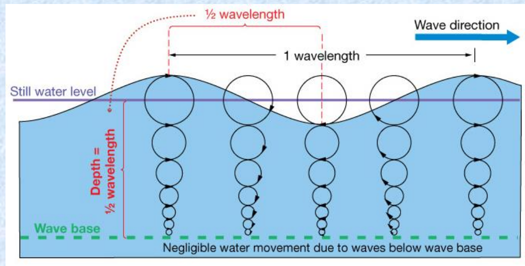
(a) Diagrammatic view of an idealized progressive ocean wave showing wave characteristics and terminology.

Orbital Wave Characteristics

- **Wave steepness** = H/L
  - If wave steepness > $^{1}/_{7}$, wave breaks
- **Wave period** (T) = time for one wavelength to pass fixed point
- **Wave frequency** = inverse of period or 1/T

Orbital Wave Characteristics

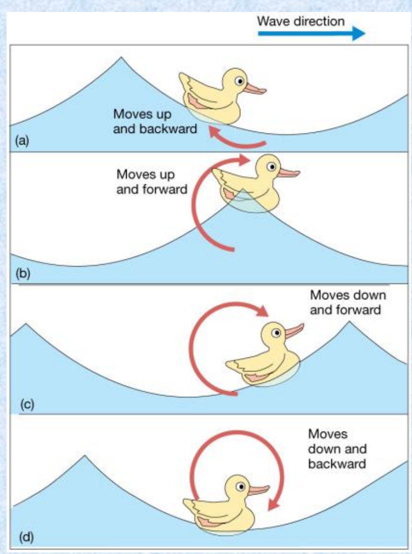
- Diameter of orbital motion decreases with depth of water.
- **Wave base** = ½ L
- Hardly any motion below wave base due to wave activity



(b) Detail showing the decreasing size of orbital motion of water particles in waves with depth. Note that wave base (the depth at which orbital motion ceases) is at a depth of one-half the wavelength, measured from still water level.

Circular Orbital Motion

- Wave particles move in a circle.
- Waveform travels forward.
- Wave energy advances.

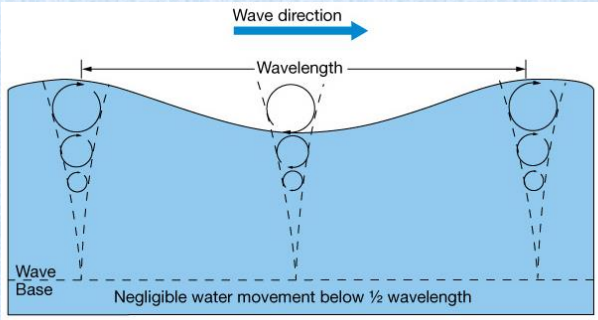


Deep Water Waves

- **Wave base** – depth where orbital movement of water particles stops
- If water depth is greater than wave base (≥½L), wave is a **deep water wave.**

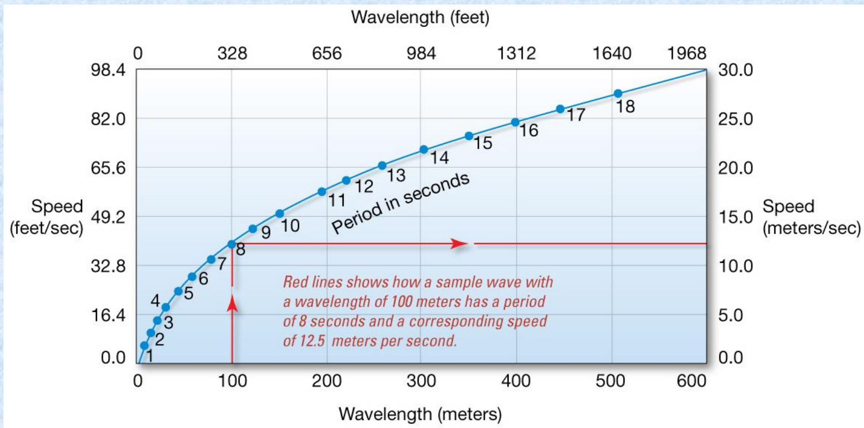
Deep Water Waves

- All wind-generated waves in open ocean
- **Wave speed** = wavelength (L)/period (T)
- Speed called celerity (C)



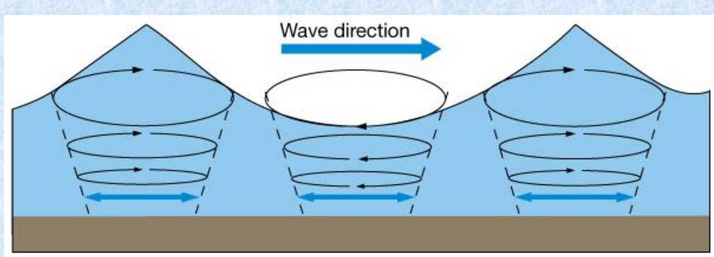
(a) Deep-water wave: Circular orbits diminish in size with increasing depth. Water depth is greater than $^1/_2$ wavelength.

Speed of Deep Water Waves



Shallow-Water Waves

- Water depth (d) is less than 1/20 L
  - Water "feels" seafloor
- C (meters/sec) = 3.13 √ d(meters) or
- C (feet/sec) = 5.67 √d (feet)



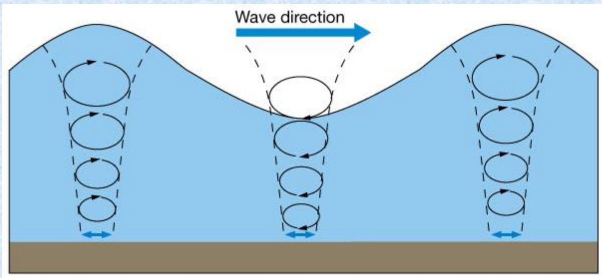
(c) Shallow–water wave: The ocean floor interferes with circular orbital motion, causing the orbits to become progressively flattened. Water depth is less than $^1/_{20}$ wavelength.

Shallow-Water Waves

- Wind-generated waves in shallow nearshore areas
- Tsunami
- Tides
- Particle motion in flat elliptical orbit

Transitional Waves

- Characteristics of both deep- and shallow-water waves
- Celerity depends on both water depth and wavelength



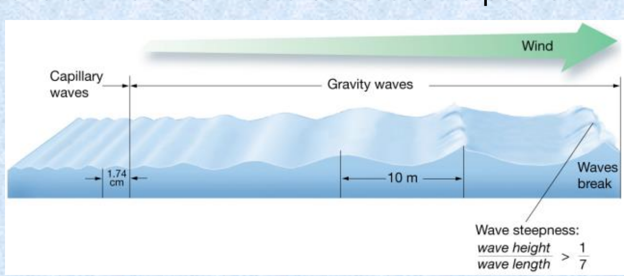
(b) Transitional wave: Intermediate between deep-water and shallow-water waves. Water depth is greater than $^1/_{20}$ wavelength, but less than $^1/_2$ wavelength.

Wind-Generated Wave Development

- **Capillary Waves**
  - Wind generates stress on sea surface
  - V-shaped troughs
  - Wavelengths less than 1.74 cm (0.7 in)
- **Gravity Waves**
  - Increasing wave energy
  - Pointed crests, rounded troughs
  - Wavelengths greater than 1.74 cm

Wind-Generated Wave Development

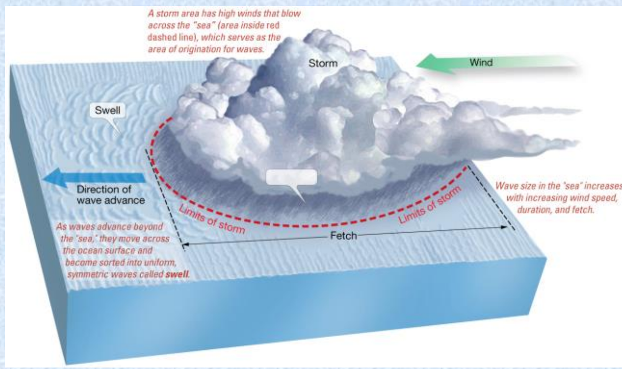
- **Capillary Waves**
  - Ripples
  - Wind generates initial stress on sea surface
- **Gravity Waves**
  - More energy transferred to ocean
  - Trochoidal waveform as crests become pointed



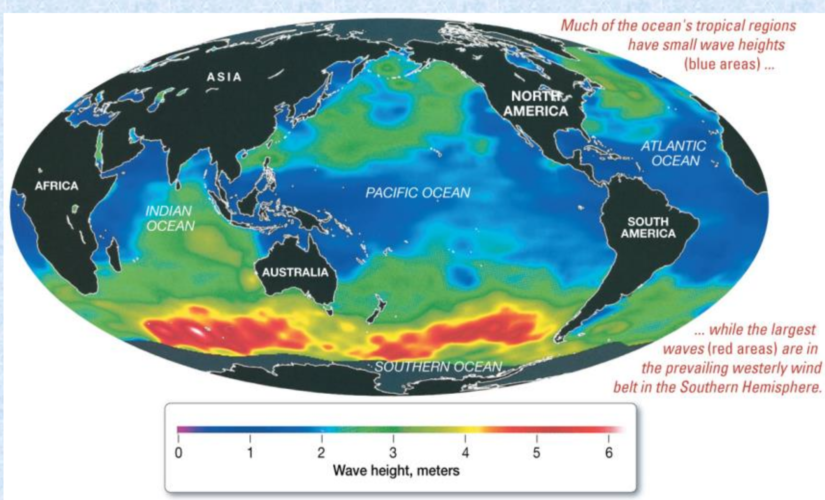
Factors Affecting Wave Energy

- **Sea**
  - Region where wind-driven waves are generated
  - Forced waves

- Wind speed
- Wind duration
- Fetch – distance over which wind blows

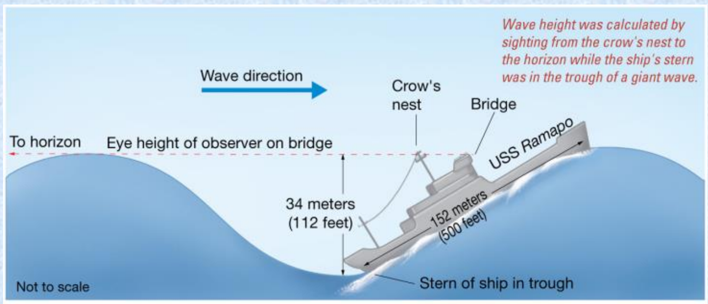


TOPEX/Poseidon satellite Wave Heights



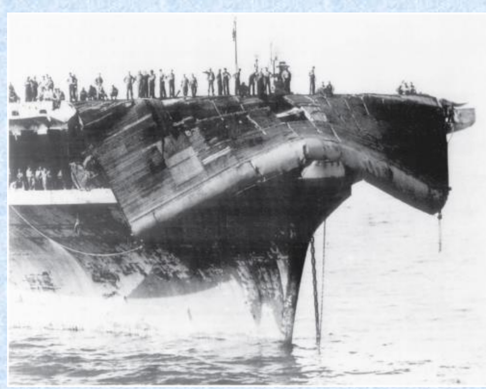
Maximum Wave Height

- *USS Ramapo* (1933): 152-meters (500 feet) long ship caught in Pacific typhoon
- Waves 34 meters (112 feet) high
- Previously thought waves could not exceed 60 feet



Wave Damage

- *USS Ramapo* undamaged
- Other craft not as lucky, e.g. aircraft carrier *Bennington* (1945)
- Ships damaged or disappear annually due to high storm waves



Wave Energy

- **Fully developed sea**
  - Equilibrium condition
  - Waves can grow no further
- **Swell**
  - Uniform, symmetrical waves that travel outward from storm area
  - Long crests
  - Transport energy long distances

Fully Developed Sea

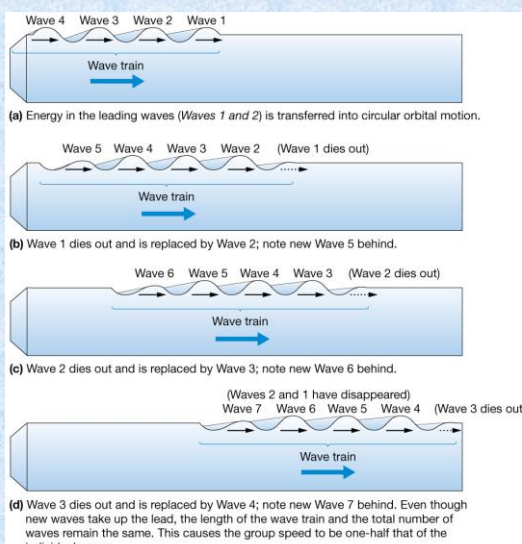
TABLE 8.2 CONDITIONS NECESSARY TO PRODUCE A FULLY DEVELOPED SEA AT VARIOUS WIND SPEEDS AND THE CHARACTERISTICS OF THE RESULTING WAVES

These conditions . . .			. . . produce these waves			
Wind speed in km/hr (mi/hr)	Fetch in km (mi)	Duration in hours	Average height in m (ft)	Average wave-length in m (ft)	Average period in seconds	Highest 10% of waves in m (ft)
20 (12)	24 (15)	2.8	0.3 (1.0)	10.6 (34.8)	3.2	0.8 (2.5)
30 (19)	77 (48)	7.0	0.9 (2.9)	22.2 (72.8)	4.6	2.1 (6.9)
40 (25)	176 (109)	11.5	1.8 (5.9)	39.7 (130.2)	6.2	3.9 (12.8)
50 (31)	380 (236)	18.5	3.2 (10.5)	61.8 (202.7)	7.7	6.8 (22.3)
60 (37)	660 (409)	27.5	5.1 (16.7)	89.2 (292.6)	9.1	10.5 (34.4)
70 (43)	1093 (678)	37.5	7.4 (24.3)	121.4 (398.2)	10.8	15.3 (50.2)
80 (50)	1682 (1043)	50.0	10.3 (33.8)	158.6 (520.2)	12.4	21.4 (70.2)
90 (56)	2446 (1517)	65.2	13.9 (45.6)	201.6 (661.2)	13.9	28.4 (93.2)

Swells

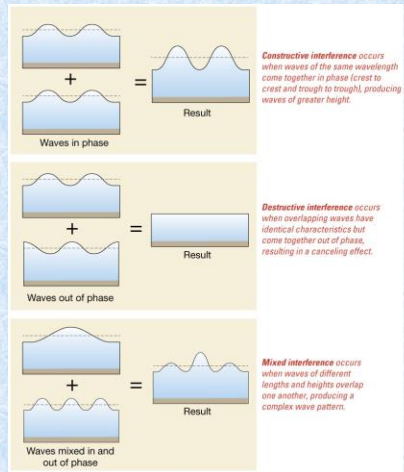
- Longer wavelength waves travel faster and outdistance other waves.
  - **Wave train –** a group of waves with similar characteristics
  - **Wave dispersion –** sorting of waves by wavelengths
  - **Decay distance –** distance over which waves change from choppy sea to uniform swell
- Wave train speed is ½ speed of individual wave.

Wave Train Movement



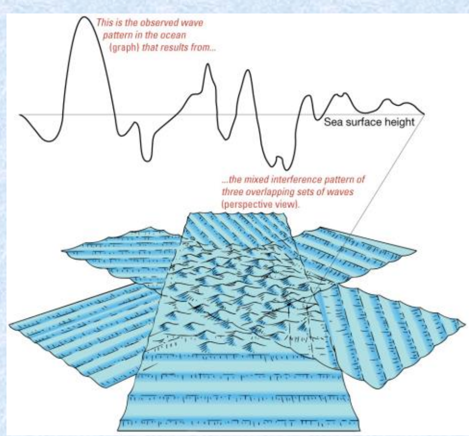
Wave Interference Patterns

- Collision of two or more wave systems
- **Constructive interference**
  - In-phase wave trains with about the same wavelengths
- **Destructive interference**
  - Out-of-phase wave trains with about the same wavelengths



Wave Interference Patterns

- **Mixed interference**
  - Two swells with different wavelengths and different wave heights



Rogue Waves

- Massive, spontaneous, solitary ocean waves
- Reach abnormal heights, enormous destructive power
- Luxury liner *Michelangelo* damaged in 1966
- Basis of *The Perfect Storm*

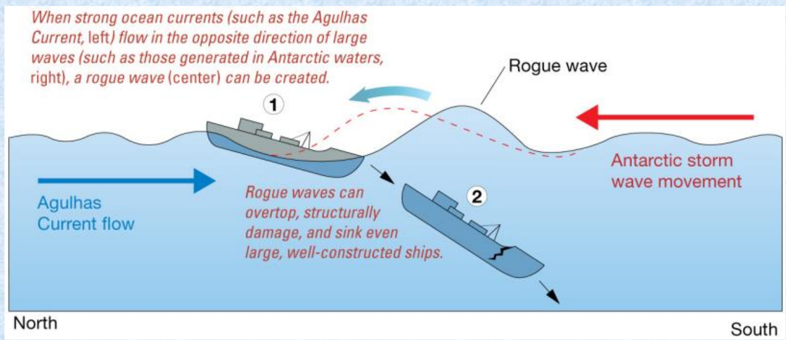
Rogue Waves

(a) View of the bow of the *Michelangelo* as it crashes through storm waves in the North Atlantic.

(b) View from inside a cabin through the torn superstructure of the *Michelangelo* after it was hit by a rogue wave. Note the missing section of bow on the right side of the ship *(red oval)*.

Rogue Waves

- Difficult to forecast
- Occur more near weather fronts and downwind of islands
- Strong ocean currents amplify opposing swells



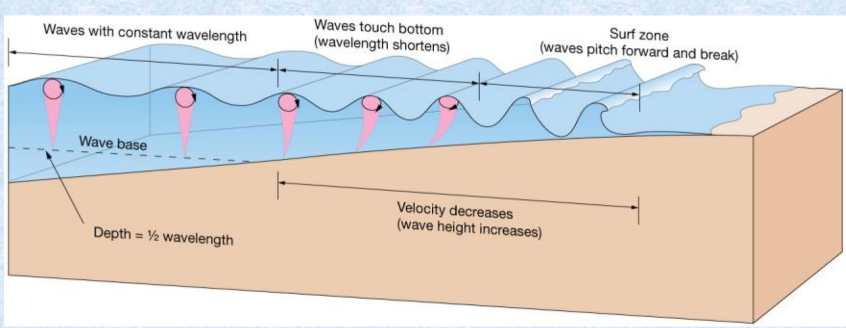
Waves in Surf Zone

- **Surf zone** – zone of breaking waves near shore
- **Shoaling water** – water becoming gradually more shallow
- When deep water waves encounter shoaling water less than ½ their wavelength, they become transitional waves.

Waves Approaching Shore

- As a deep-water wave becomes a shallow-water wave:
  - Wave speed decreases
  - Wavelength decreases
  - Wave height increases
  - Wave steepness (height/wavelength) increases
  - When steepness $\geq {}^{1}/_{7}$, wave breaks

Waves Approaching Shore



Breakers in Surf Zone

- Surf as swell from distant storms
  - Waves break close to shore
  - Uniform breakers
- Surf generated by local winds
  - Choppy, high energy, unstable water
- Shallow water waves

Spilling Breakers

- Gently sloping sea floor
- Wave energy expended over longer distance
- Water slides down front slope of wave

(a) Spilling breaker, resulting from a gradual beach slope.

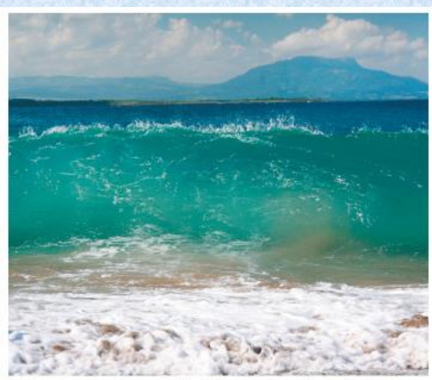
Plunging Breakers

- Moderately steep sea floor
- Wave energy expended over shorter distance
- Curling wave crest

(b) Plunging breaker, resulting from a steep beach slope; these are the best waves for surfing.

Surging Breakers

- Steepest sea floor
- Energy spread over shortest distance
- Waves break on the shore

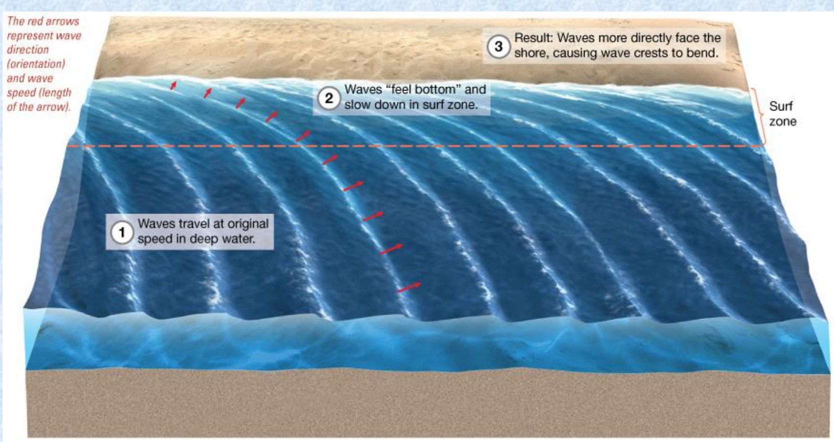


(c) Surging breaker, resulting from an abrupt beach slope.

Wave Refraction

- Waves rarely approach shore at a perfect 90-degree angle.
- As waves approach shore, they bend so wave crests are nearly parallel to shore.
- Wave speed is proportional to the depth of water (shallow-water wave).
- Different segments of the wave crest travel at different speeds.

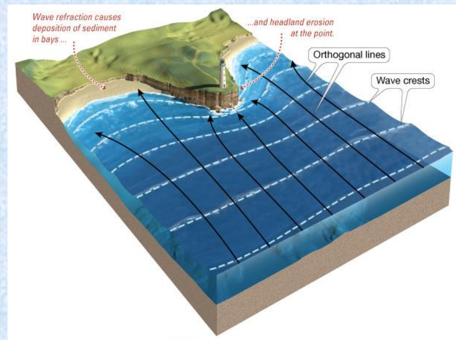
Wave Refraction



(a) Aerial view of wave refraction along a straight shoreline.

Wave Refraction

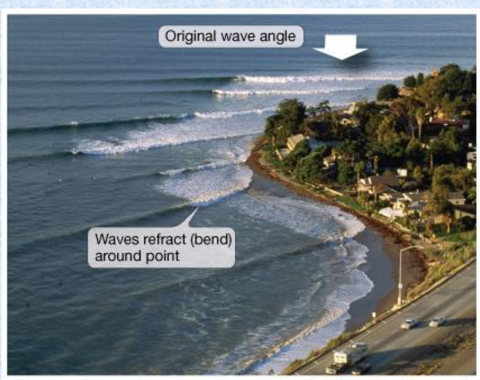
- Wave energy unevenly distributed on shore
- **Orthogonal lines** or wave rays – drawn perpendicular to wave crests
  - More energy released on headlands
  - Energy more dissipated in bays



(b) Perspective view of wave refraction along an irregular shoreline.

Wave Refraction

- Gradually erodes headlands
- Sediment accumulates in bays



(c) Photo of wave refraction at Rincon Point, California (looking west).

Wave Refraction

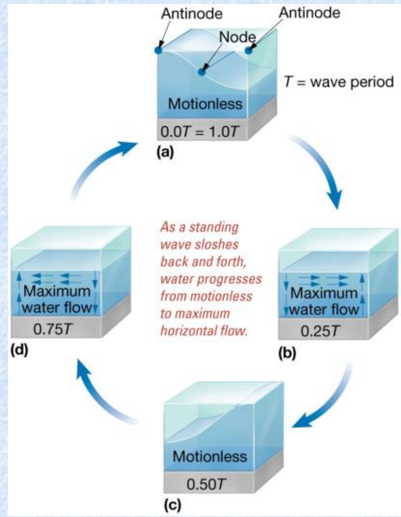
- Waves and wave energy bounced back from barrier
- Reflected wave can interfere with next incoming wave.
- With constructive interference, can create dangerous plunging breakers

Standing Waves

- Two waves with same wavelength moving in opposite directions
- Water particles move vertically and horizontally.
- Water sloshes back and forth.

Standing Waves

- Nodes have no vertical movement
- Antinodes are alternating crests and troughs.



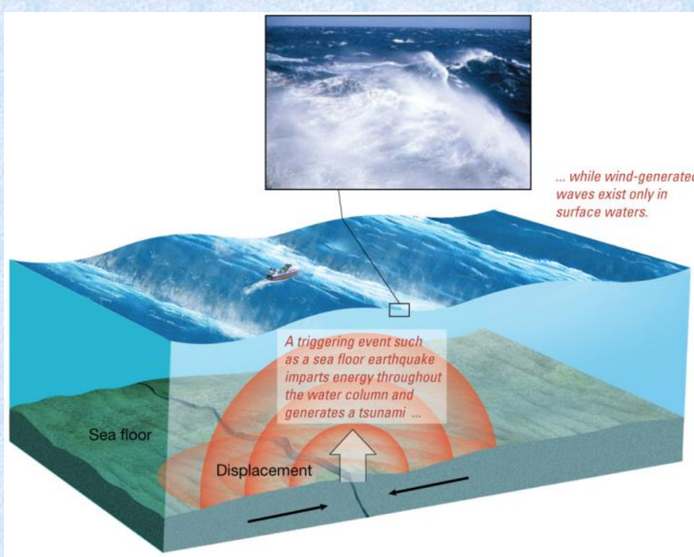
Tsunami

- Seismic sea waves
- Originate from sudden sea floor topography changes
  - Earthquakes – *most common cause*
  - Underwater landslides
  - Underwater volcano collapse
  - Underwater volcanic eruption
  - Meteorite impact – **splash waves**

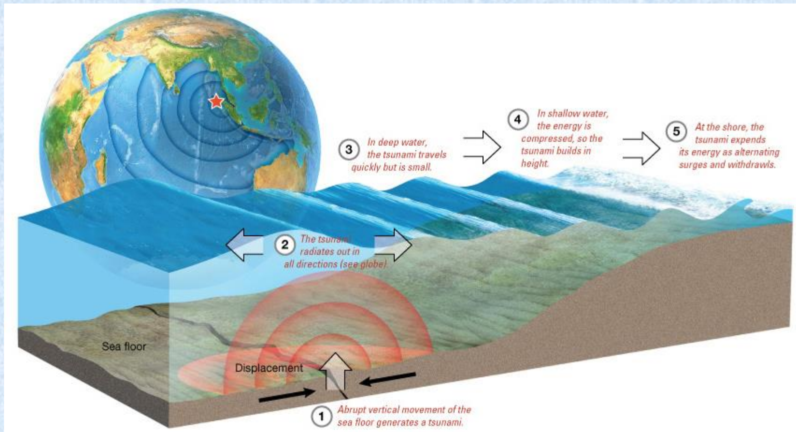
Tsunami Characteristics

- Long wavelengths (> 200 km or 125 miles)
- Behaves as a shallow-water wave
  - Encompasses entire water column, regardless of ocean depth
  - Can pass undetected under boats in open ocean
- Speed proportional to water depth
  - Very fast in open ocean

Tsunami vs. Wind-Generated Waves



Tsunami Generation and Propagation



(a) How a tsunami is generated, propagated, and surges to extreme heights at the shore.

Tsunami Destruction

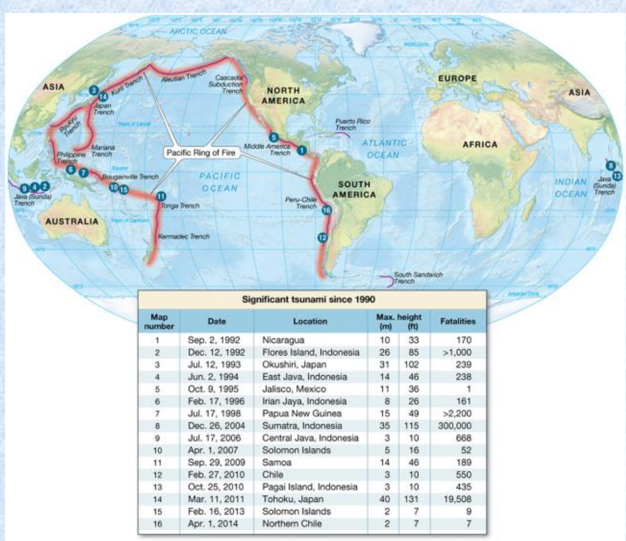
- Sea level can rise up to 40 meters (131 feet) when a tsunami reaches shore.

(b) Sequence of photos of the 2004 Indian Ocean Tsunami inundating the Chedi Resort in Phuket, Thailand, on December 26, 2004.

Tsunami

- Most occur in Pacific Ocean
  - More earthquakes and volcanic eruptions
- Damaging to coastal areas
- Loss of human lives
- Example: Hilo, Hawaii in 1946
  - $25 million damage
  - 159 deaths

Historical Large Tsunami



Significant tsunami since 1990

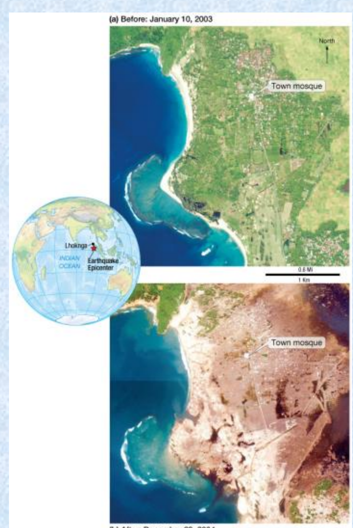
Map number	Date	Location	Max. height (m)	Max. height (ft)	Fatalities
1	Sep. 2, 1992	Nicaragua	10	33	170
2	Dec. 12, 1992	Flores Island, Indonesia	26	85	>1,000
3	Jul. 12, 1993	Okushiri, Japan	31	102	239
4	Jun. 2, 1994	East Java, Indonesia	14	46	238
5	Oct. 9, 1995	Jalisco, Mexico	11	36	1
6	Feb. 17, 1996	Irian Jaya, Indonesia	8	26	161
7	Jul. 17, 1998	Papua New Guinea	15	49	>2,200
8	Dec. 26, 2004	Sumatra, Indonesia	35	115	300,000
9	Jul. 17, 2006	Central Java, Indonesia	3	10	668
10	Apr. 1, 2007	Solomon Islands	5	16	52
11	Sep. 29, 2009	Samoa	14	46	189
12	Feb. 27, 2010	Chile	3	10	550
13	Oct. 25, 2010	Pagai Island, Indonesia	3	10	435
14	Mar. 11, 2011	Tohoku, Japan	40	131	19,508
15	Feb. 16, 2013	Solomon Islands	2	7	9
16	Apr. 1, 2014	Northern Chile	2	7	7

Indian Ocean Tsunami

- December 26, 2004
  - Magnitude 9.2 earthquake off coast of Sumatra
  - 1200 km seafloor displaced between two tectonic plates
  - Deadliest tsunami in history
  - Coastal villages completely wiped out

Jason-1 Satellite Detection of Indian Ocean Tsunami

- Detected by Jason-1 satellite
- Traveled more than 5000 km (3000 mi)
- Wavelength about 500 km (300 mi)
- 230,000–300,000 people in 11 countries killed
- Lack of warning system in Indian Ocean

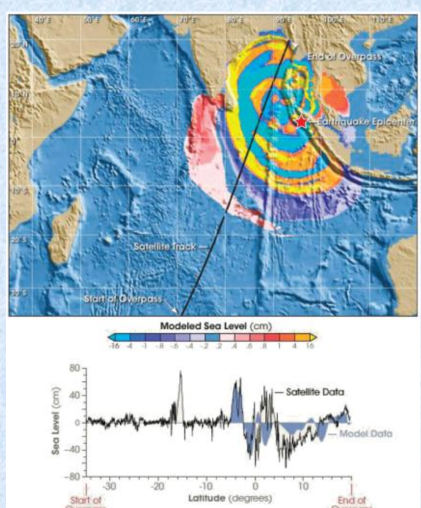


Japan Tsunami

- March 11, 2011 – Tohoku Earthquake
  - Magnitude 9.0 earthquake in Japan Trench
  - Felt throughout Pacific basin
- Most expensive tsunami in history
- Initial surge 15 meters (49 ft)
  - Topped harbor-protecting tsunami walls
  - Amplified by local topography
- Killed 19,508 people
- Disrupted power at Fukushima Daiichi nuclear power plant
  - Reactors exploded
  - Radioactivity problem initiated

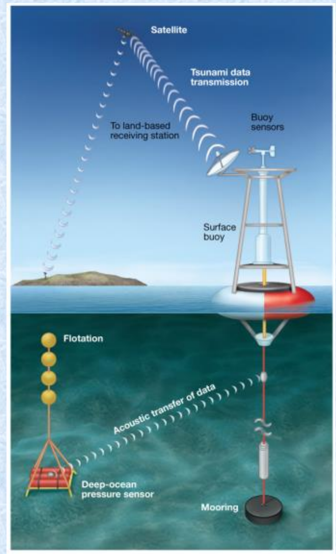
Tsunami Warning System

- **Pacific Tsunami Warning Center (PTWC)** – Honolulu, HI
  - Uses seismic wave recordings to forecast tsunami
- **Deep Ocean Assessment and Reporting of Tsunami (DART)**
  - System of buoys
  - Detects pulse of tsunami passing



Tsunami Watches and Warnings

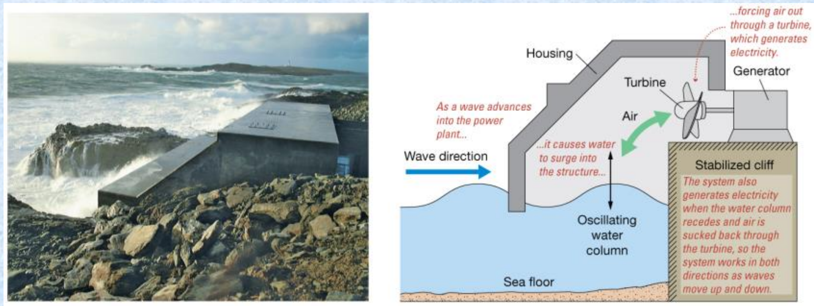
- **Tsunami Watch** – issued when potential for tsunami exists
- **Tsunami Warning** – unusual wave activity verified
  - Evacuate people
  - Move ships from harbors



Waves as Source of Energy

- Lots of energy associated with waves
- Mostly with large storm waves
  - How to protect power plants
  - How to produce power consistently
- Environmental issues
  - Building power plants close to shore
  - Interfering with life and sediment movement

Wave Power Plant



(a) Photo of the exterior of LIMPET 500, the world's first commercial wave power plant.

(b) Schematic view of the interior of a wave power plant showing how it generates electricity from waves.

Wave Power Plant

- First commercial wave power plant began operating in 2000.
- **LIMPET 500** – Land Installed Marine Powered Energy Transformer
  - Coast of Scotland
  - 500 kilowatts of power under peak operating capacity

Wave Farms

- Portugal – 2008
  - Ocean Power Delivery
  - First wave farm
- About 50 wave power development projects globally

Global Wave Energy Resources