SIO 210: Waves

- What is a wave?
- Surface gravity waves
- Internal waves

- Reading: DPO 6th Chapter 8, sections 8.1, 8.2, 8.3

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Lecture Oct. 28, 2018

Waves

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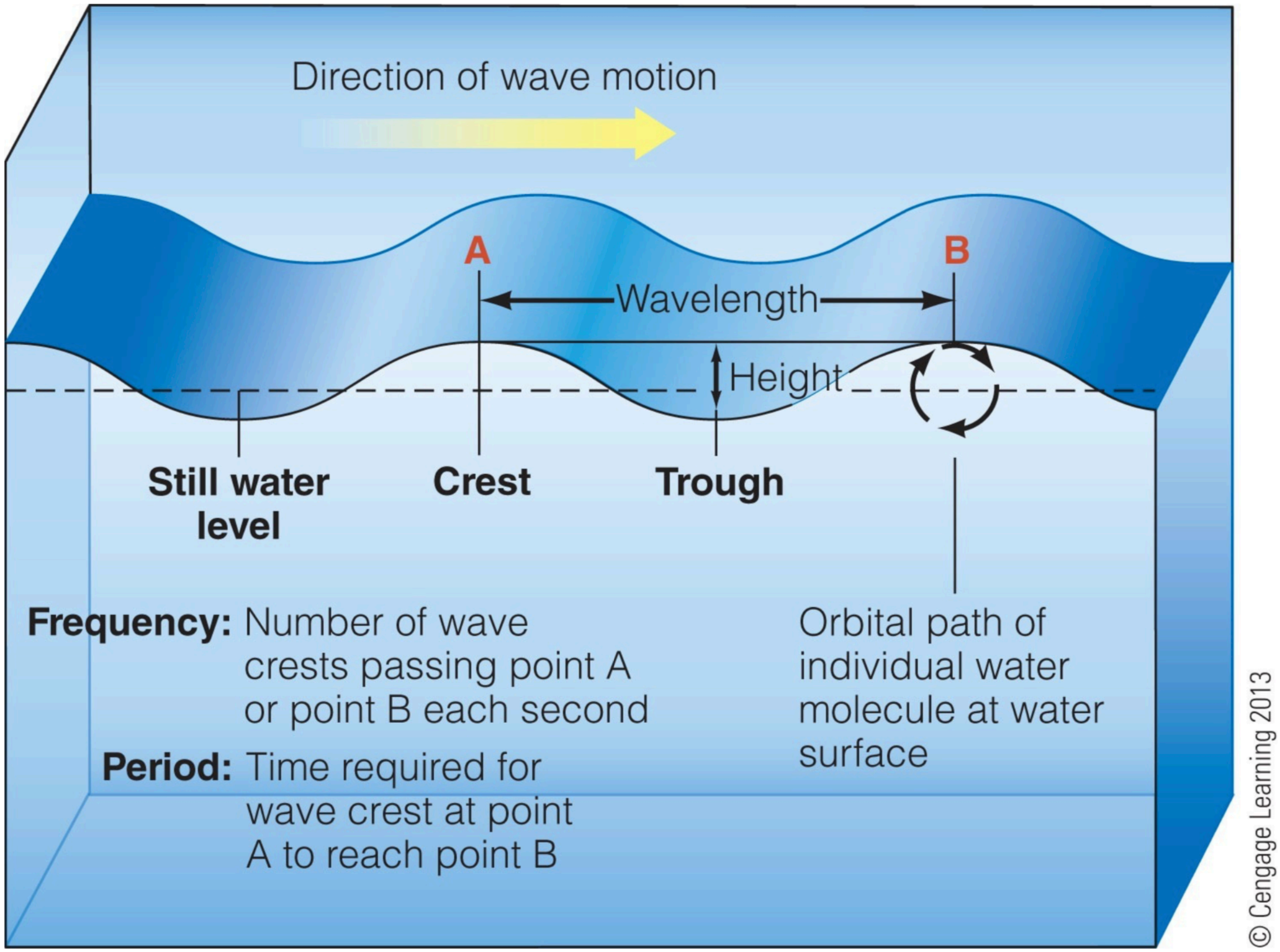
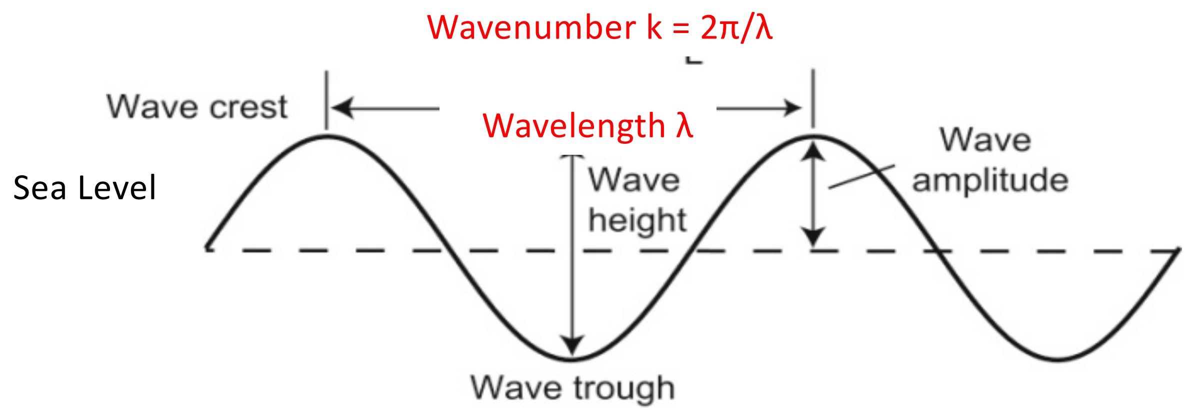


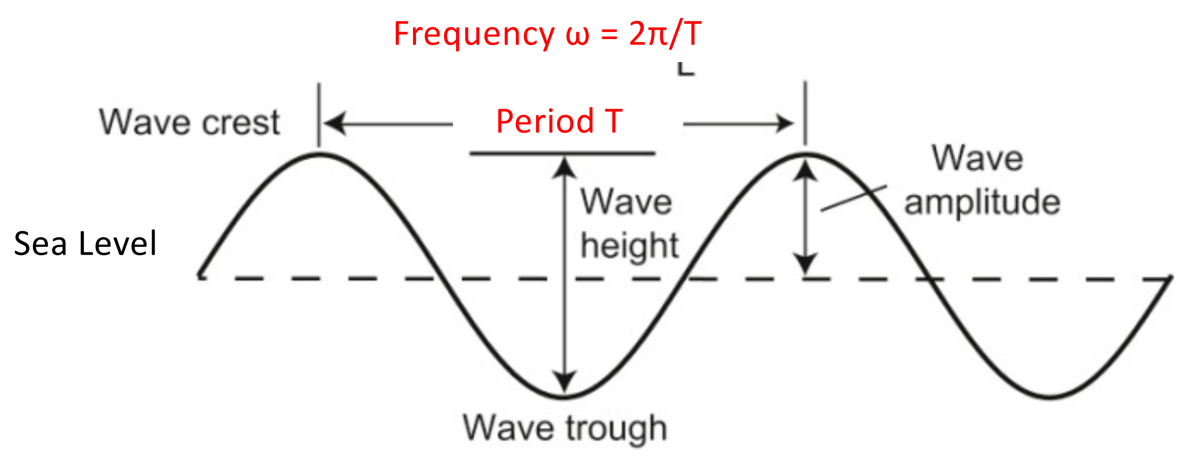
Figure 10-2 p29

Some types of waves and typical speeds

Name	medium	Phase speed	What allows	What generates
sound	air	330 m/s	compressibility	Vibration of vocal chord
sound	water	1500 m/s	compressibility (less than air)	Ships, fish
Seismic P	Solid earth	7-8 km/s	compressibility	Fault rupture
Seismic S	Solid earth	4-5 km/s	‘shearability”	Fault rupture
tsunami	Ocean surface	200 m/s	Gravity and free surface	Submarine earthquake
swell	Ocean surface	Few 10s m/s	Gravity and free surface	wind
capillary	Ocean surface	Cm/s	Surface tension	wind
Internal wave	water	Minutes to hours	Gravity and stratification	Wind, tide
Electromagnetic (EM)	ether	$3x10^8$ m/s		Accelerated charges
Rossby wave	water		Variation of Coriolis parameter or bottom depth	Current instabilities, storms, etc

Definition of wave in space and time





Definition of wave in space and time

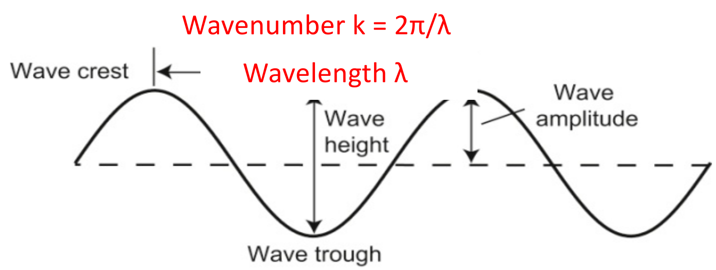
T = period (sec)

f = 1/T = frequency in cps (cycles per second)

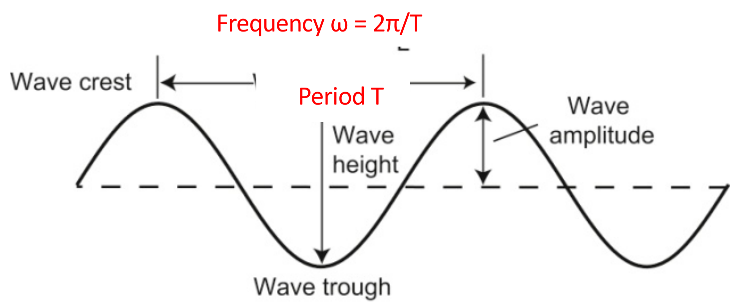
ω = 2π/T = radian frequency (radians per second)

λ = wavelength (m)

k = 2π/λ = wavenumber (radians per meter rpm)



In the textbook, I use L for wavelength instead of λ



Wave definitions (continued)

Phase velocity: velocity of individual crests

$$c_p = \frac{\lambda}{T} = \frac{\omega}{k}$$

Non-dispersive waves: phase velocity the same for all wavelengths
Dispersive waves: phase velocity is not the same for all wavelengths (so waves separate, hence disperse)

Dispersion relation: frequency expressed in terms of the wavenumber

$$\omega = \omega(k)$$

Expressions here given for just one direction.
Can have 3 dimensions, with wave vector $\mathbf{k}$ = (k,l,m) in (x, y ,z) directions, and phase speeds in all three directions $\mathbf{c}_p$= (ω/k, ω/l, ω/m).

Wave definitions

Group velocity: velocity that wave energy moves. Visually looks like movement of a wave packet. Wave crests can move through the group; that is, phase velocity and group velocity might not be the same.

$$c_g = \frac{\partial \omega}{\partial k}$$

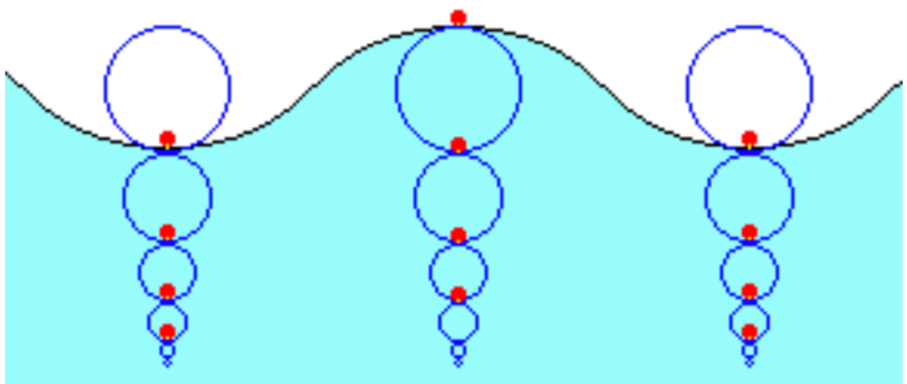
Non-dispersive waves*: group velocity equals phase velocity

Dispersive waves: group velocity not equal to phase velocity

*Non-dispersive: ω = constant * k, so c_p=constant and c_g= constant

Surface gravity waves as example

To first order, waves carry INFORMATION, not water itself.

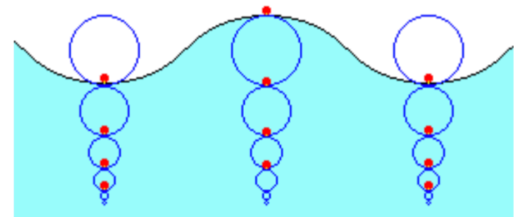


http://faculty.gvsu.edu/videticp/waves.htm

All waves

Speeds

Particle Speed: speed an individual blob of water moves



Phase speed: the speed the crests move (information)

Surface gravity waves example

"Shallow Water Waves" (wavelength long compared to ocean depth)

$$c = \sqrt{gH}$$

g=gravity=9.8m²/s
H= ocean depth

"Deep Water Waves" (wavelength short compared to ocean depth)

$$c = \sqrt{\frac{g\lambda}{2\pi}}$$

λ =wavelength

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Ocean surface gravity waves

What is the restoring force for ocean surface waves? Gravity

Mound up the water with any force and it will fall. This will set up a wave.

What is the medium? Interface between air and water. What's important here is the very large density difference between air and water.

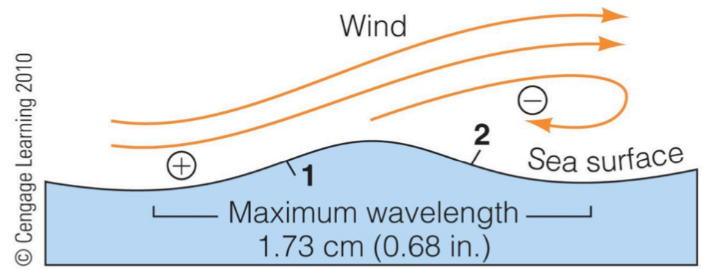
What is the particle motion?
Particles in a surface wave move in ellipses (vertical plane)
Ellipse size gets smaller with increasing depth (exponential decay)

Deep-water waves: ellipses are gone (zero) at ocean bottom or way above ocean bottom. So ellipses are nearly circles that decay in radius with depth.
These are "*short waves*": wavelength is shorter than the ocean depth

Shallow-water waves: ellipses are not zero at the ocean bottom, so the wave feels the ocean bottom.
These are "*long waves*": wavelength is greater than the ocean depth

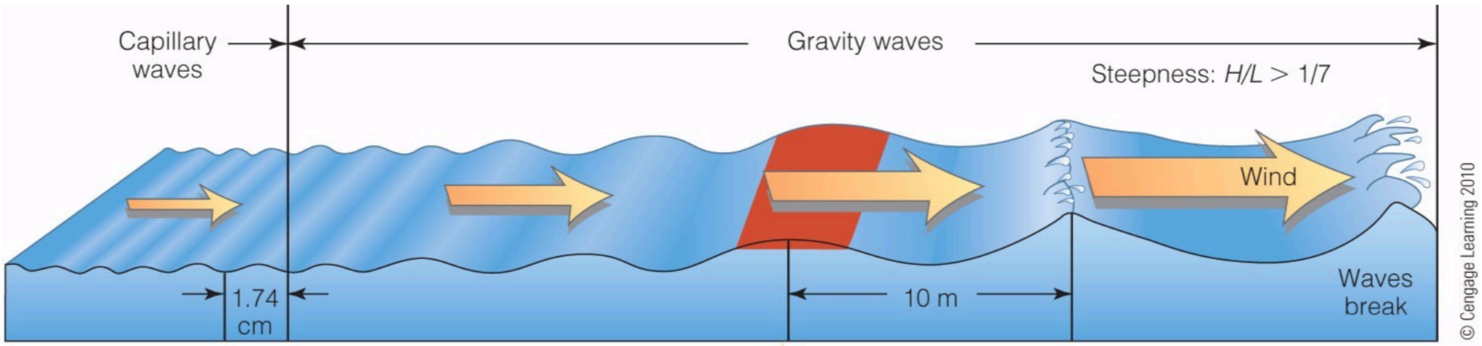
What happens when wind blows on the ocean surface?

Capillary wave is one in which restoring force is **surface tension,** not gravity.



a Wind forces acting on a capillary wave. A capillary wave interrupts the smooth sea surface, deflecting surface wind upward, slowing it, and causing some of the wind's energy to be transferred into the water to drive the capillary wave crest forward (point **1**). The wind may eddy briefly downwind of the tiny crest, creating a slight partial vacuum there (−). Atmospheric pressure (+) pushes the trailing crest forward (downwind) toward the trough (point **2**), adding still more energy to the water surface.

Figure 10-9a p30

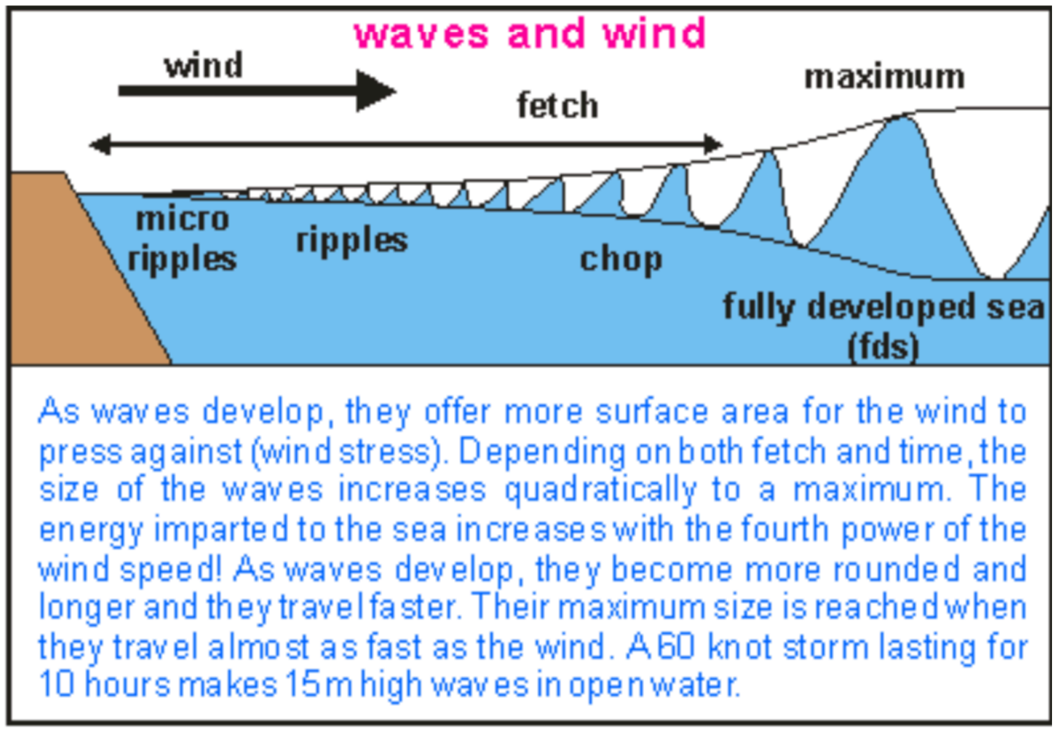


b Capillary waves become gravity waves as their wavelength exceeds 1.74 centimeters. These wind-induced gravity waves (wind waves) continue to grow as long as the wind above them exceeds their speed.

(See figure 10.10)

Figure 10-9b p30

Wind Waves created by
* strong wind
* blowing for a long time (duration)
* over a large distance (fetch)



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Melville (1996)

Breaking waves
(From SIO210 introduction lecture)

Routes to Breaking I

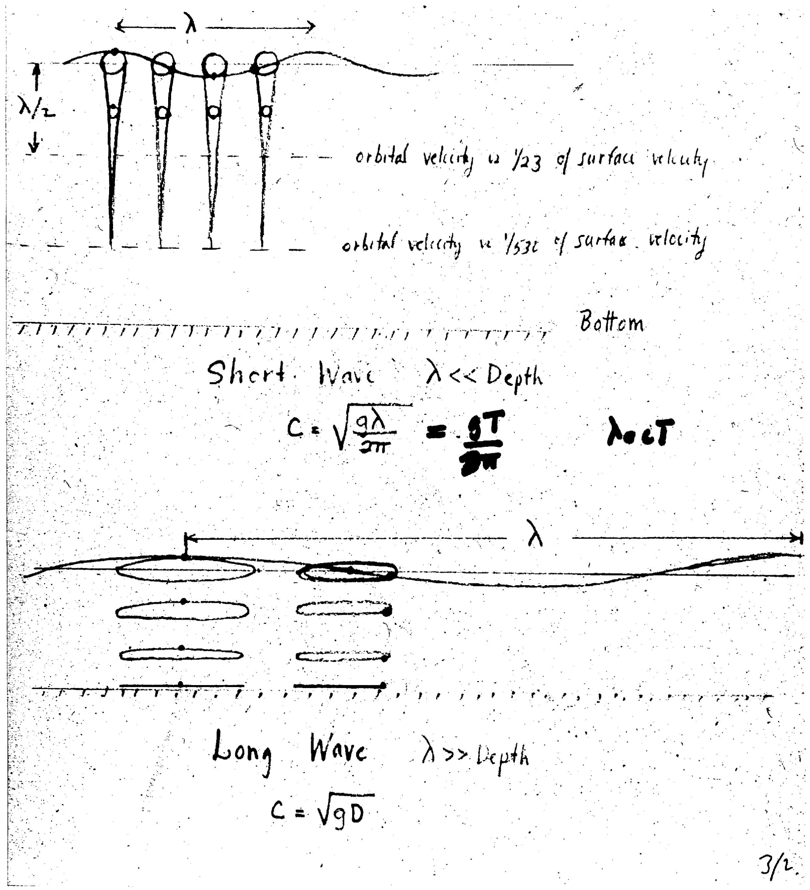
Breaking at larger scales may result from dispersive focusing, geometric focusing, wave-wave and wave-current interactions without wind-forcing being directly involved: a,b.

At sufficiently high winds and small wave scales, each wave may be breaking (c). Note also in (c) the foam streaks aligned with the wind.

T seconds to minutes.

H and L cm to m

Particle motions in surface waves



Drawings from M. Hendershott lecture

Deep water wave (short wave)

λ << Depth

$$c_p = \sqrt{\frac{g}{k}} = \sqrt{\frac{g\lambda}{2\pi}} = \frac{g}{\omega} = \frac{gT}{2\pi}$$

Shallow water wave (long wave)

λ >> Depth = h

$$c_p = \sqrt{gh}$$

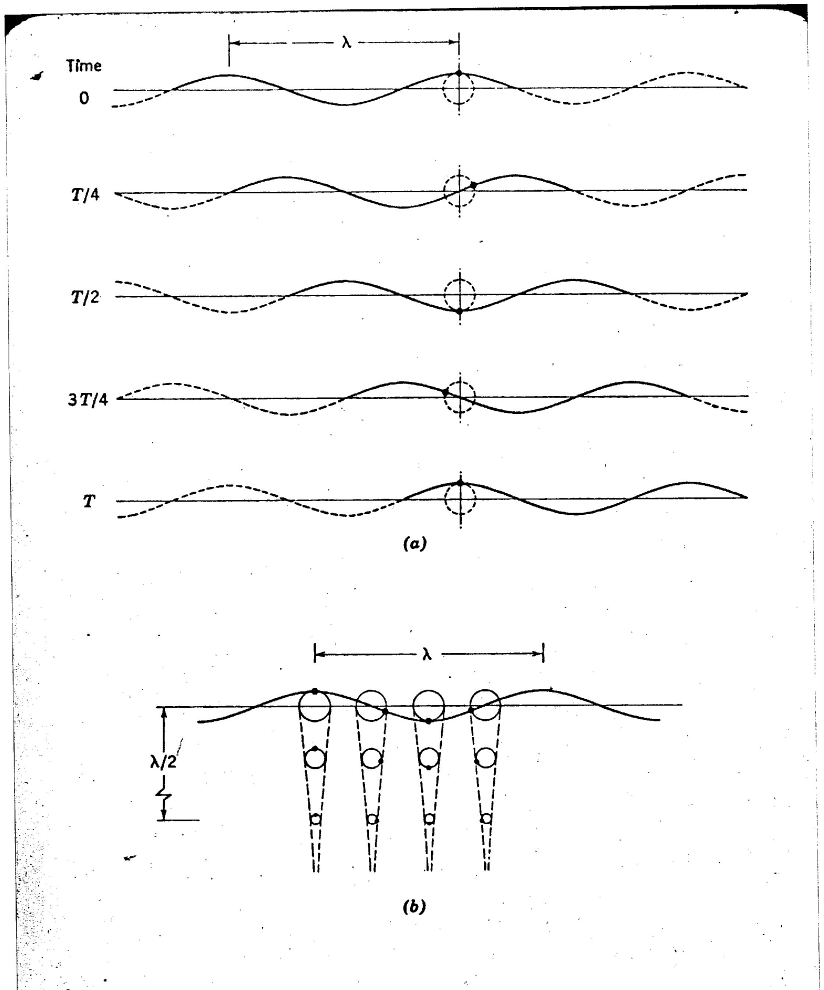
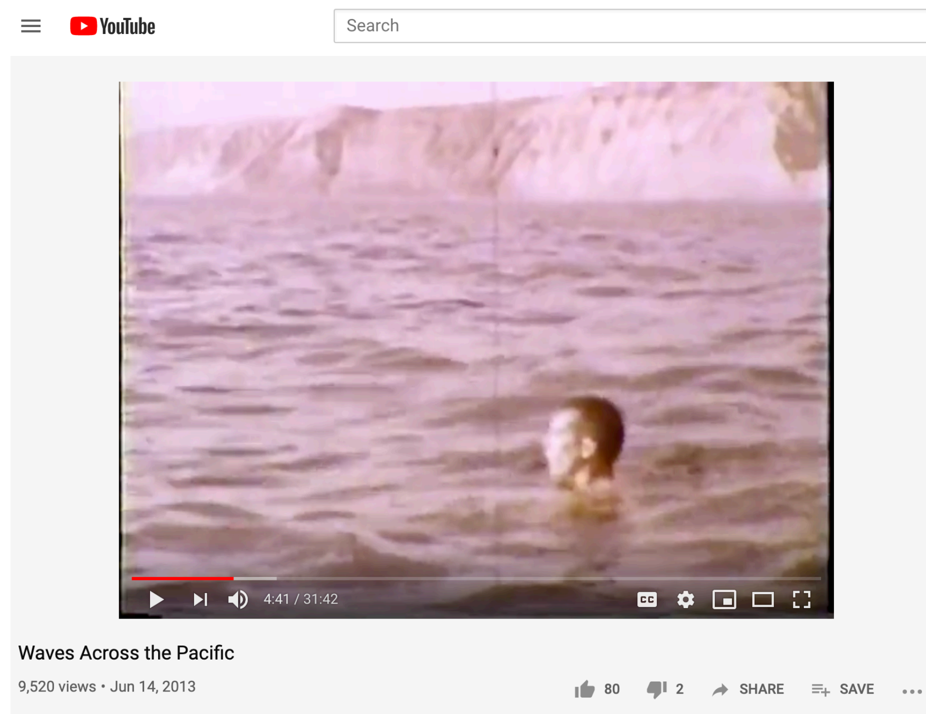


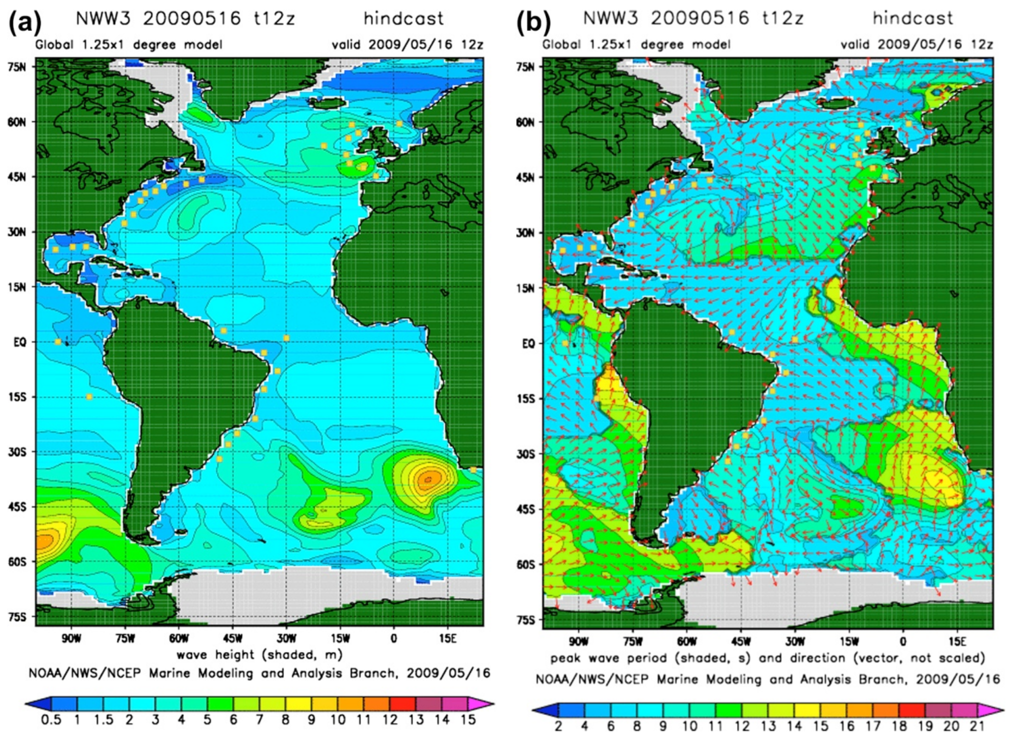
FIG. 7-12. (*a*) Instantaneous sea-surface profiles as a wave passes by. From the first sketch to the last, one wave period T has elapsed. Notice how the water particle marked by the heavy dot is carried forward, downward, backward, and upward so that its path during one wave period is the small circle in each sketch. (*b*) Cross section of a wave showing circular orbits or water particles at depth. Their diameter at a depth of half a wavelength ($\lambda/2$) is 1/23 of their surface diameter. Each water particle (heavy dots) traces out its circular path once every wave period.

7/1

Hendershott, M. Ocean engineering; goals, environment, technology. John F. Brahtz, editor.New York, Wiley [1968]



“Waves across the Pacific”
(see Youtube)
31 Minutes long
Walter Munk



(a) Significant wave height (m) and (b) peak wave period (s) and direction (vectors) for one day (May 16, 2009). *Source: From NOAA Wavewatch III (2009).*

DPO Fig. 8.3

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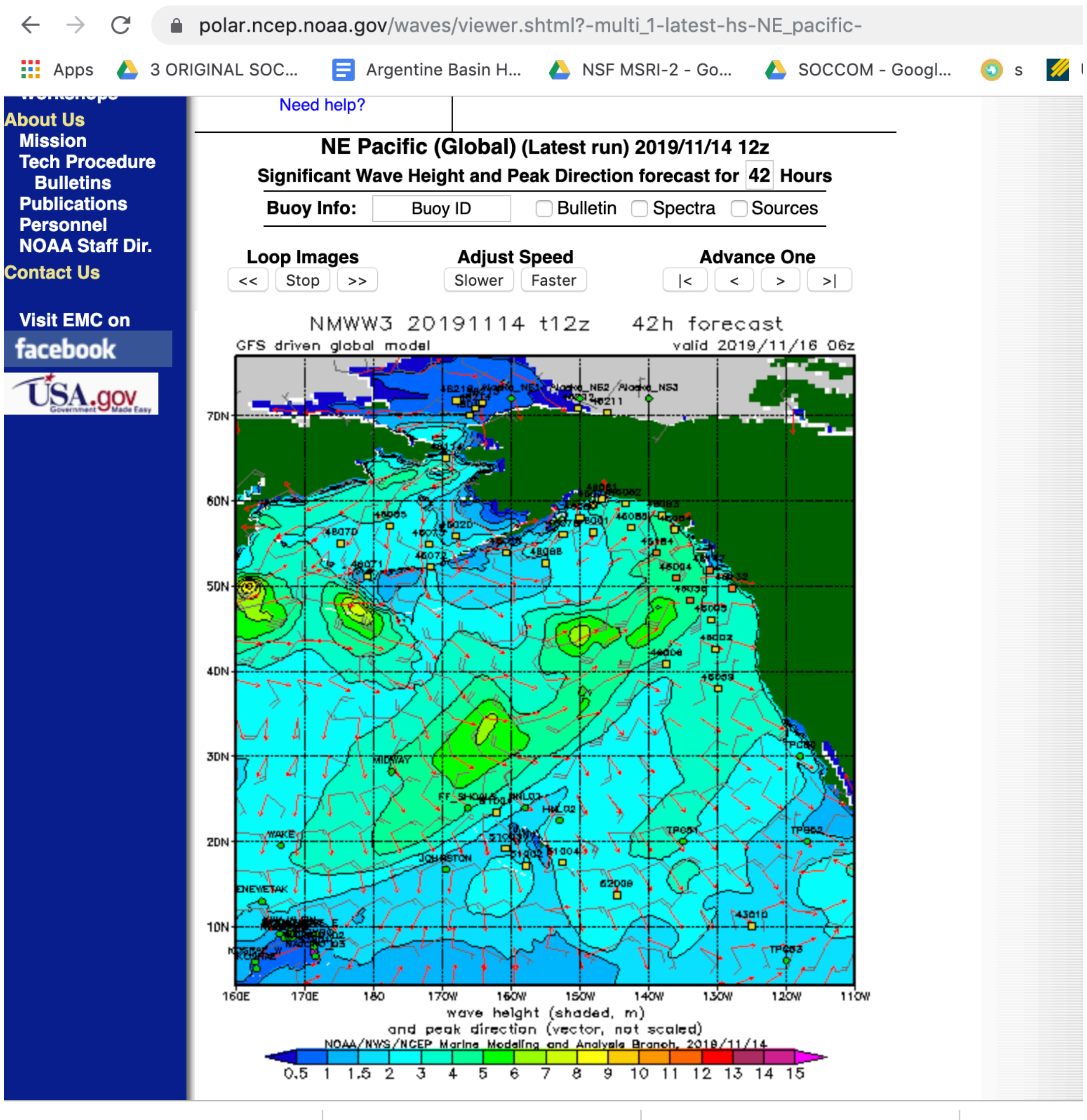
NOAA Wavewatch Model III

http://polar.ncep.noaa.gov/waves

Go to website to see animated version



Complications I: dispersion

Q: why do the waves arriving at shore appear to be so uniform?

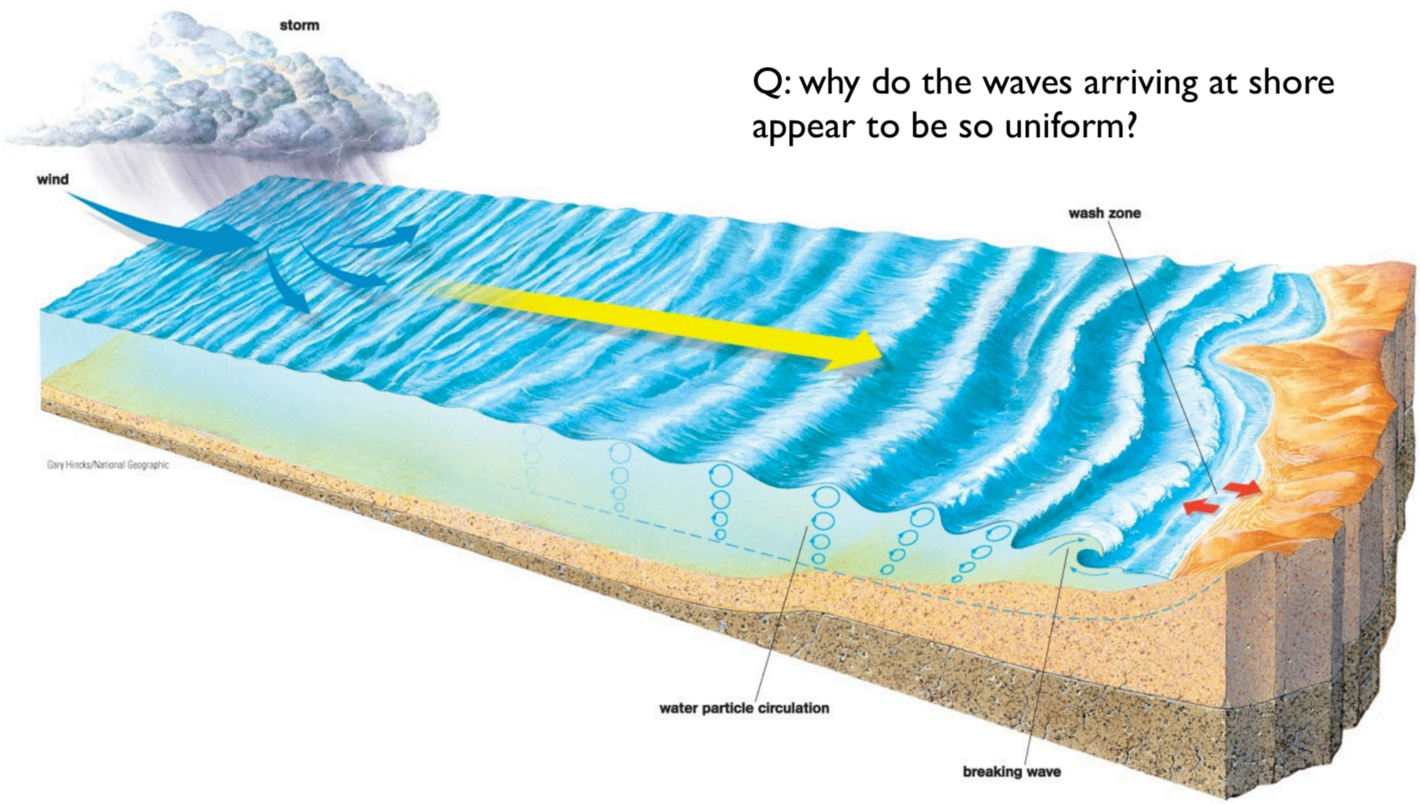
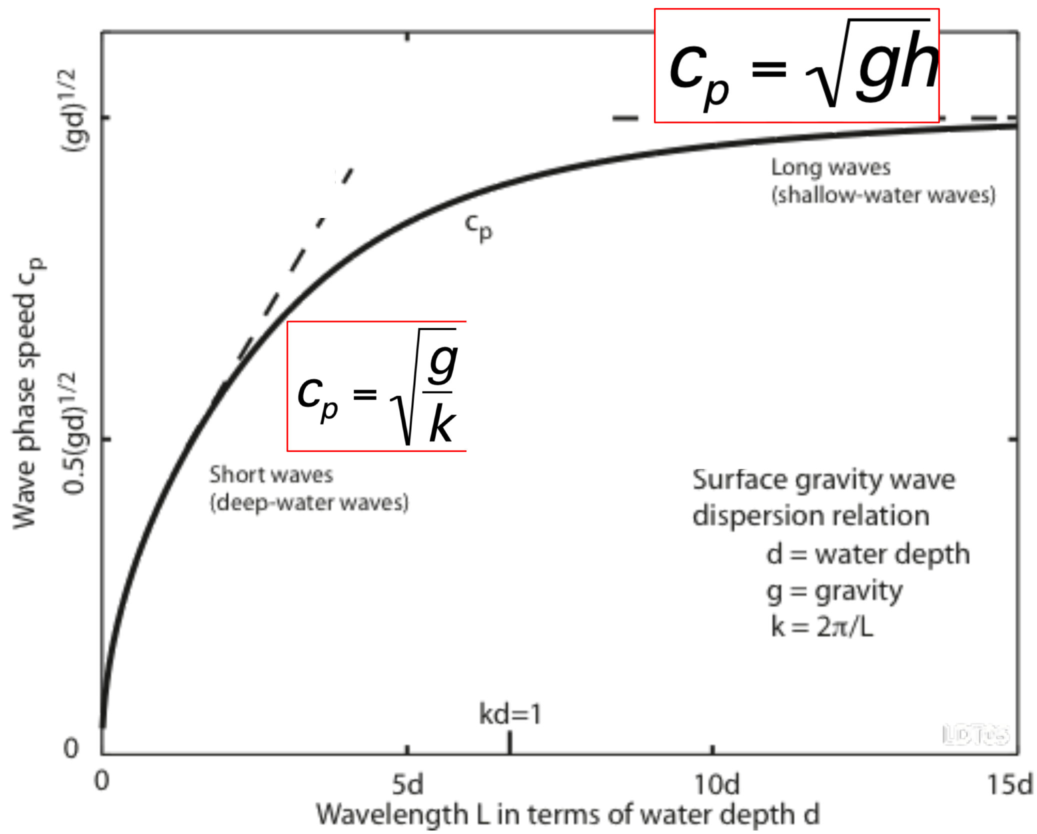


Figure 10-11 p306

Surface wave dispersion relation

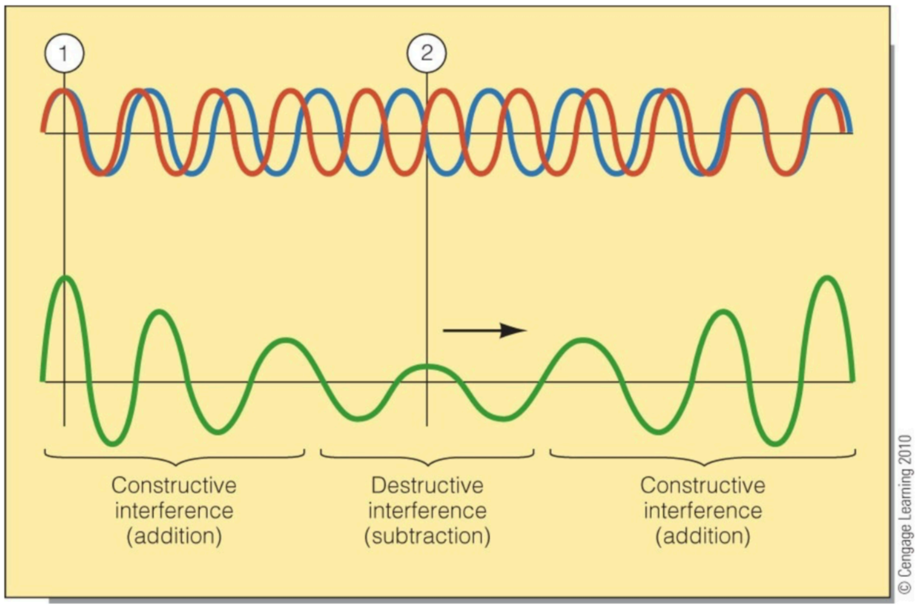


High phase speed

Long waves move faster than short waves

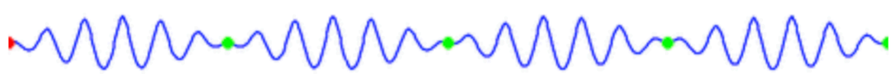
Low phase speed

Complications 2: Constructive and destructive interference between waves of different wavelengths/frequencies leads to wave GROUPS



a Two overlapping waves of different wavelength are shown, one in blue and one in red. Note that the wave shown in blue has a slightly longer wavelength.

The red dot moves with the phase velocity, and the green dots propagate with the group velocity.



http://en.wikipedia.org/wiki/Dispersion_(water_waves)

Figure 10-15a p311

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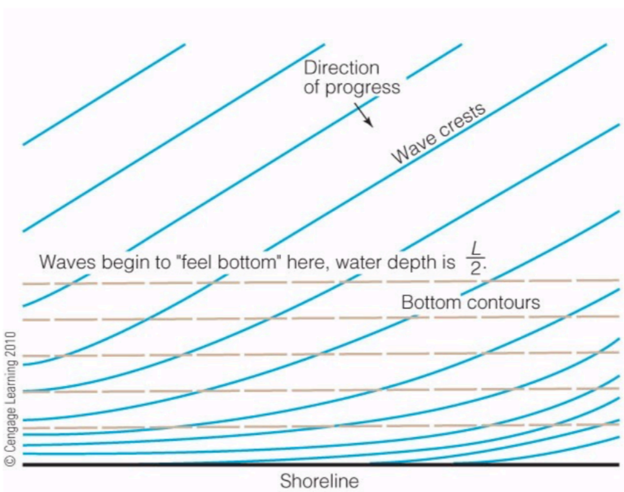
Refraction

(A consequence of dispersion: variation in wave speed)

"Shallow Water Waves" (wavelength long compared to ocean depth)

$$c = \sqrt{gH}$$

g=gravity=9.8m^2/s
H= ocean depth



a Diagram showing the elements that produce refraction.

b Wave refraction around Maili Point, O'ahu, Hawai'i. Note how the wave crests bend almost 90° as they move around the point.

Figure 10-19 p314

Depth H changes as waves come in to shore

So wave speed changes

So offshore part of wave moves at different speed (faster) than onshore part (slower)

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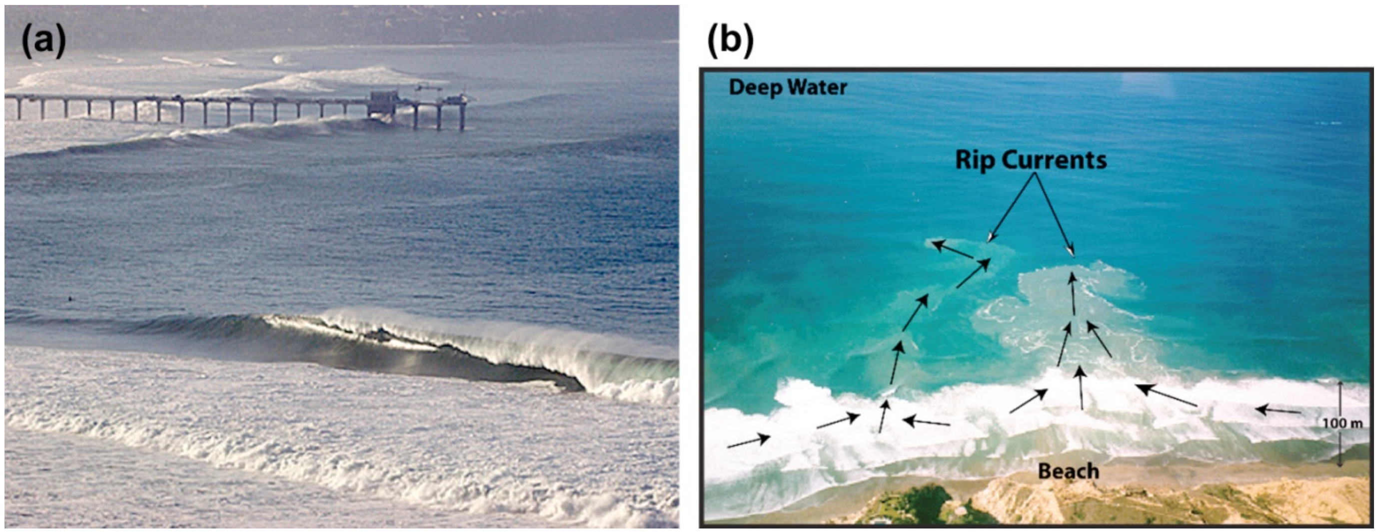
Refracting surface waves at SIO pier



DPO Fig. 8.4

(a) Surf zone, looking toward the south at the Scripps Pier, La Jolla, CA. *Source: From CDIP (2009). (b) Rip currents, complex pattern of swell, and alongshore flow near the head of a submarine canyon near La Jolla, CA, Photo courtesy of Steve Elgar (2009).*

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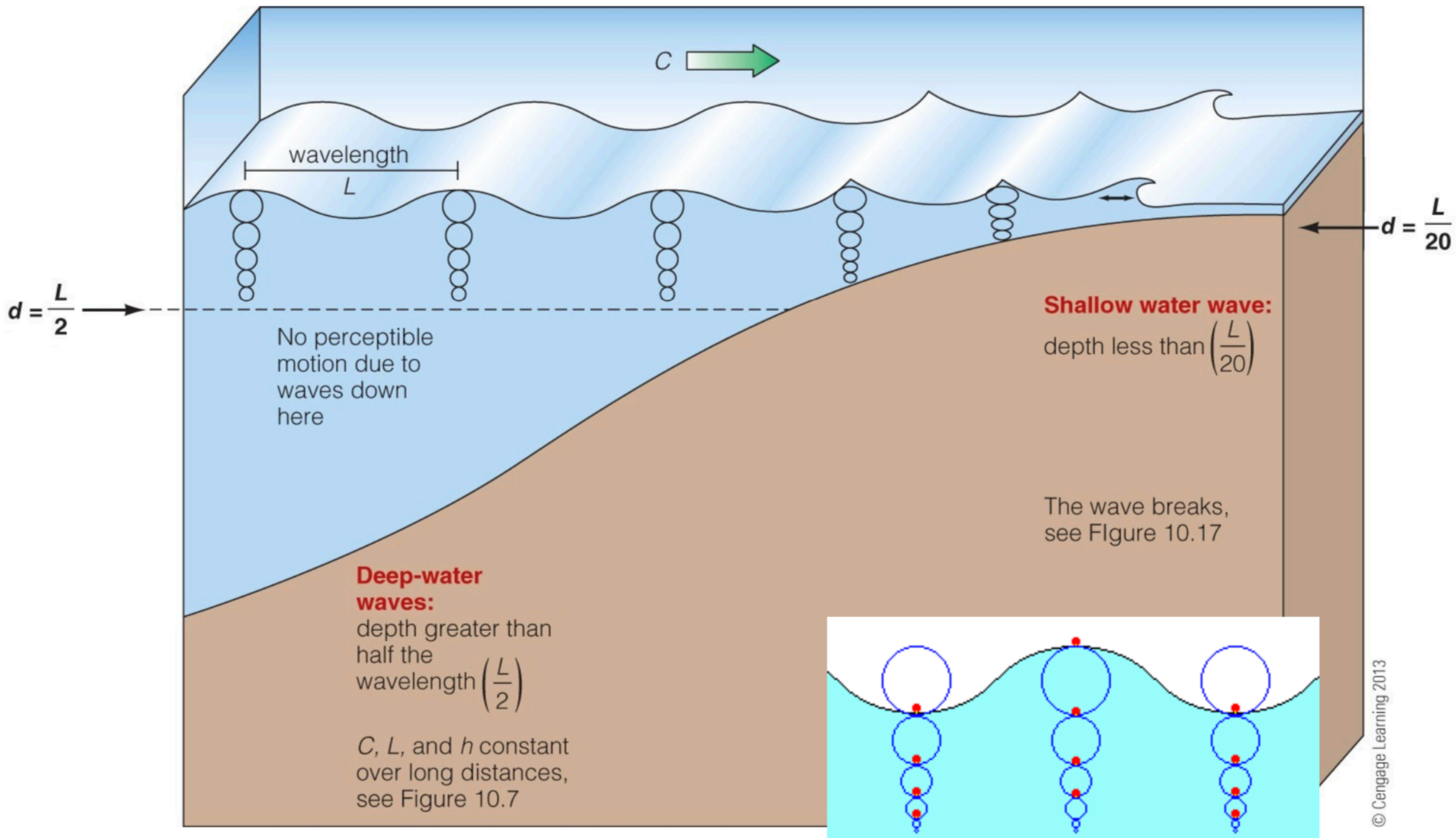
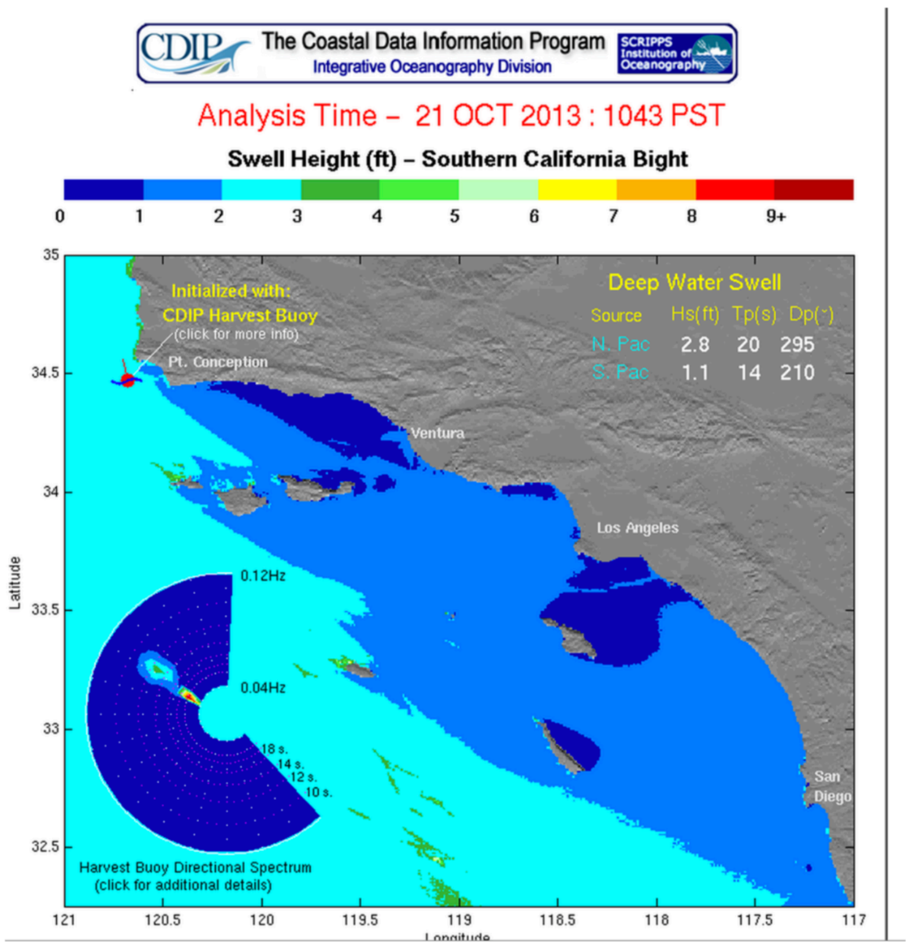
What happens when waves get to shore?



Particle speed exceeds wave speed, waves break

Figure 10-6 p302

The Coastal Data Information Program: creating wave prediction models by integrating data from a network of wave measuring buoys



http://cdip.ucsd.edu/

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Storm surge

Picture from internet

Caused by both wind and atmospheric pressure.

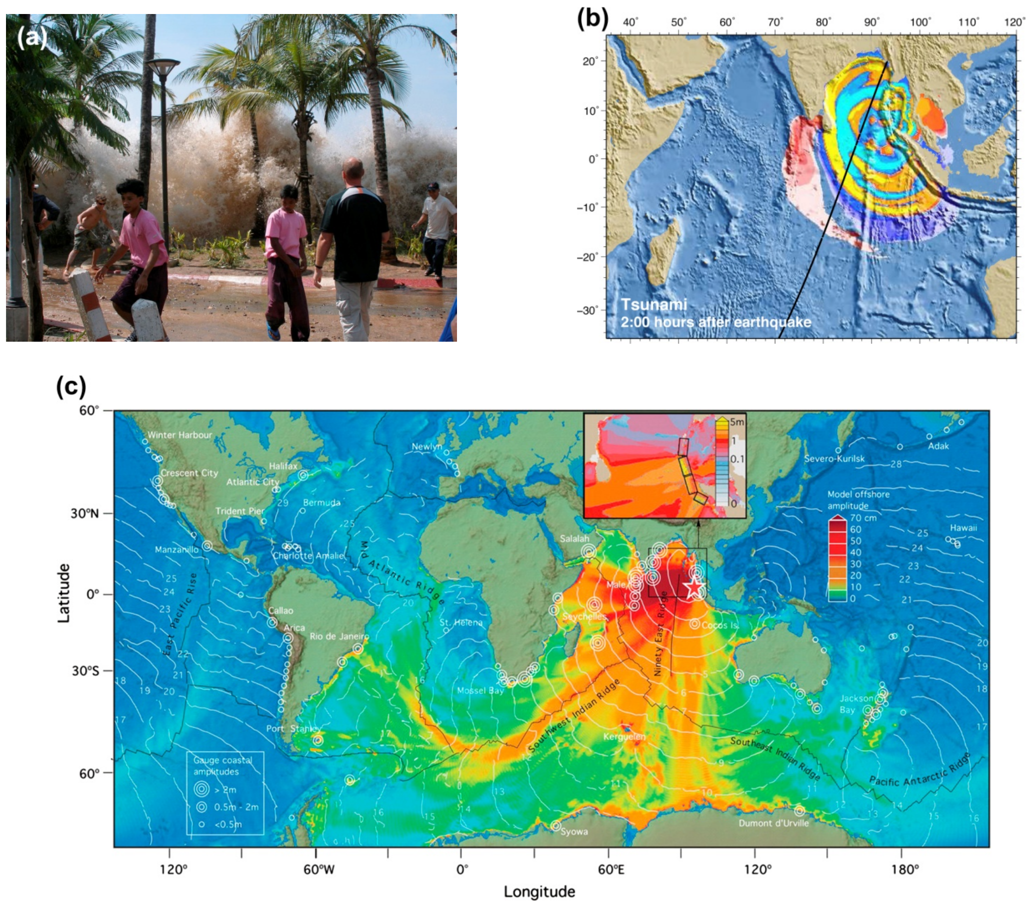
When pressure is low, water rises.

High winds can create enormous waves

Storm surge results, can be very large in some cases, such as hurricanes.

(9 meters from Hurricane Katrina in the Gulf of Mexico)

Tsunami: very long surface gravity wave



Sumatra Tsunami (December 26, 2004). (a) Tsunami wave approaching the beach in Thailand. *Source: From Rydevik (2004).* (b) Simulated surface height two hours after earthquake. *Source: From Smith et al. (2005).* (c) Global reach: simulated maximum sea-surface height and arrival time (hours after earthquake) of wave front. Figure 8.7c can also be
found in the color insert. *Source: From Titov et al. (2005).*

DPO FIGURE 8.7

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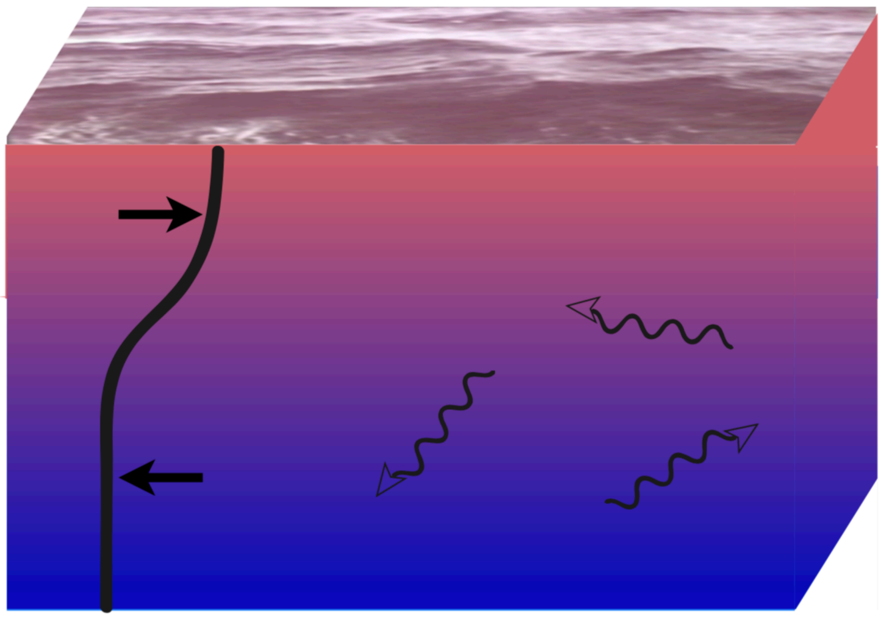
Internal waves



- Continuous stratification allows a range of wave modes
- Higher modes propagate in all directions
- Phase speed orthogonal to group speed

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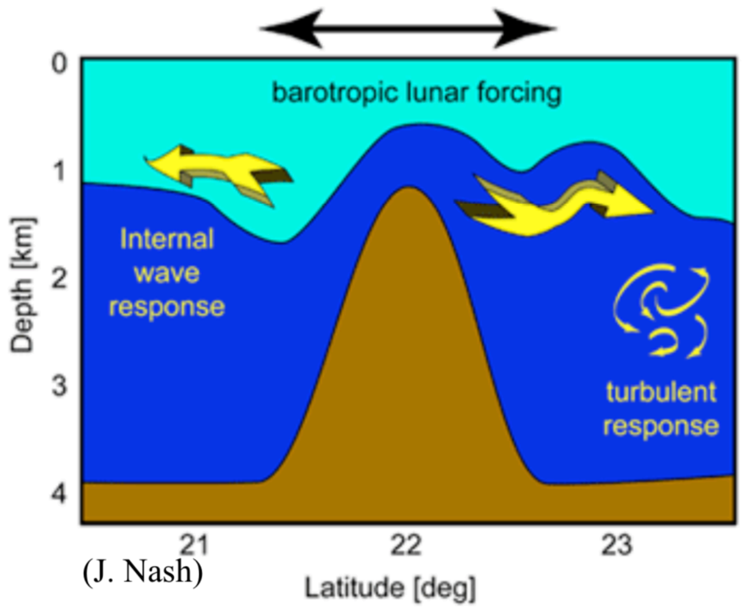
Internal waves generated by tidal flow over topography



(J. Nash)

Internal Tide: An internal wave with a tidal frequency, usually once in 12.4 hours = M2

At UCSD, we see internal tides propagating onshore from the edge of the continental shelf

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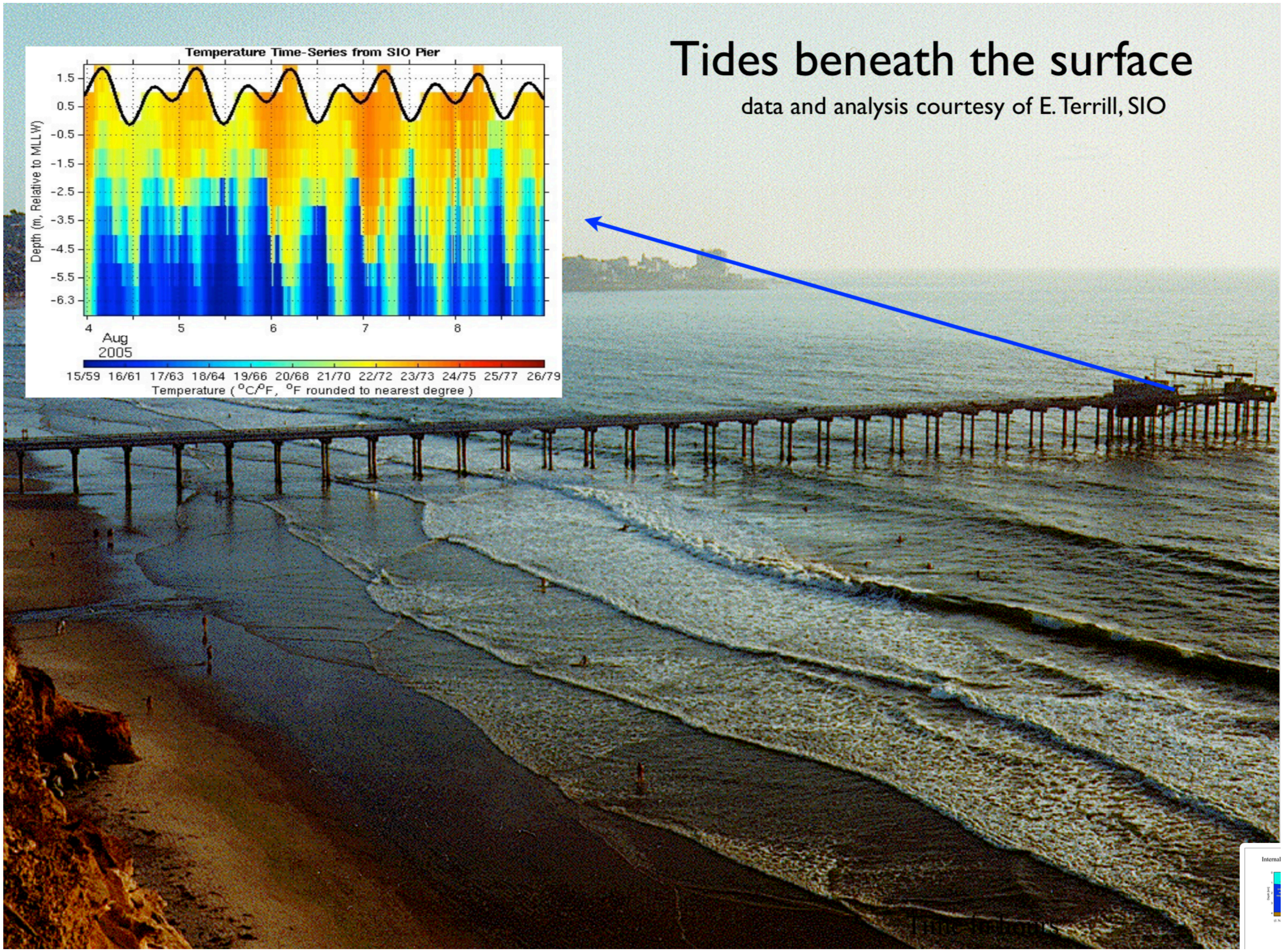
Tides beneath the surface

data and analysis courtesy of E. Terrill, SIO



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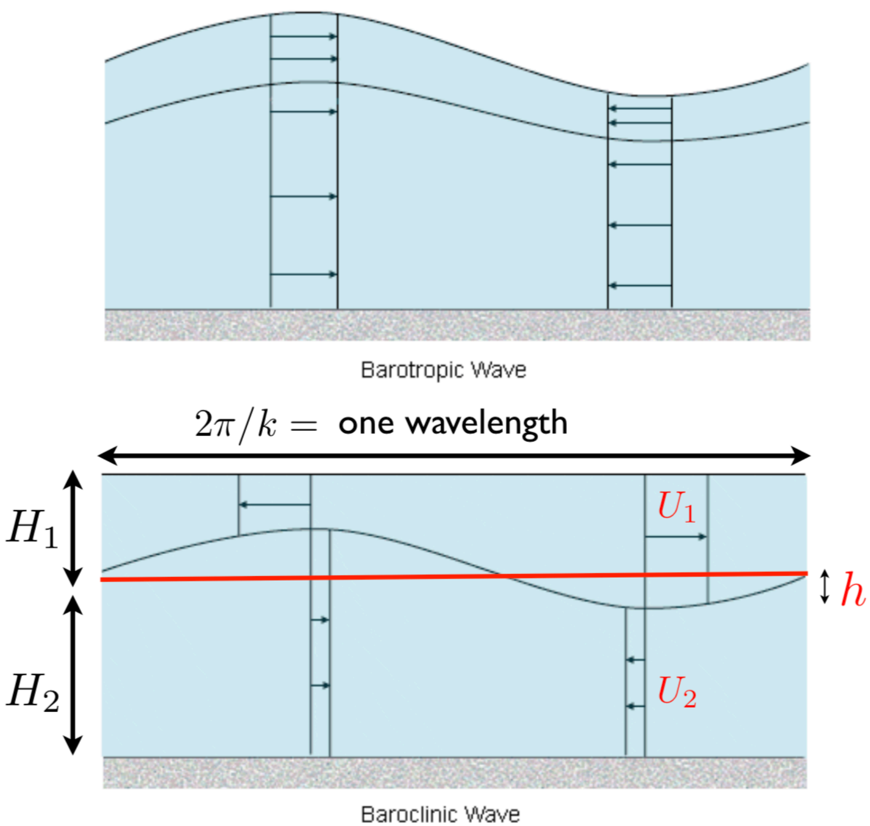
Simple interfacial internal wave



after Gill,
Atmosphere-Ocean Dynamics

$$\mathbf{h = -h_0 cos(kx - \omega t)}$$

$$\mathbf{U_1 = \frac{\omega h_0}{H_1 k} cos(kx - \omega t)}$$

$$\mathbf{U_2 = -\frac{\omega h_0}{H_2 k} cos(kx - \omega t)}$$

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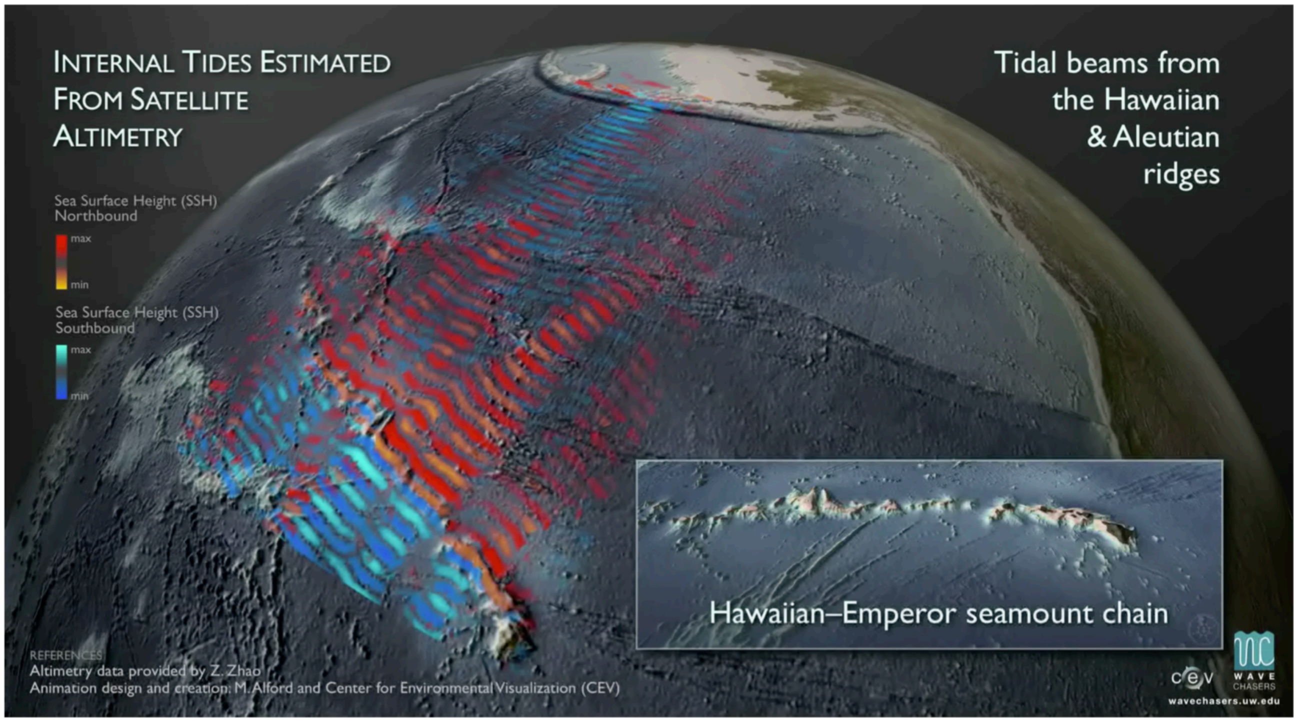
Long-distance internal waves



[Zhao and Alford]

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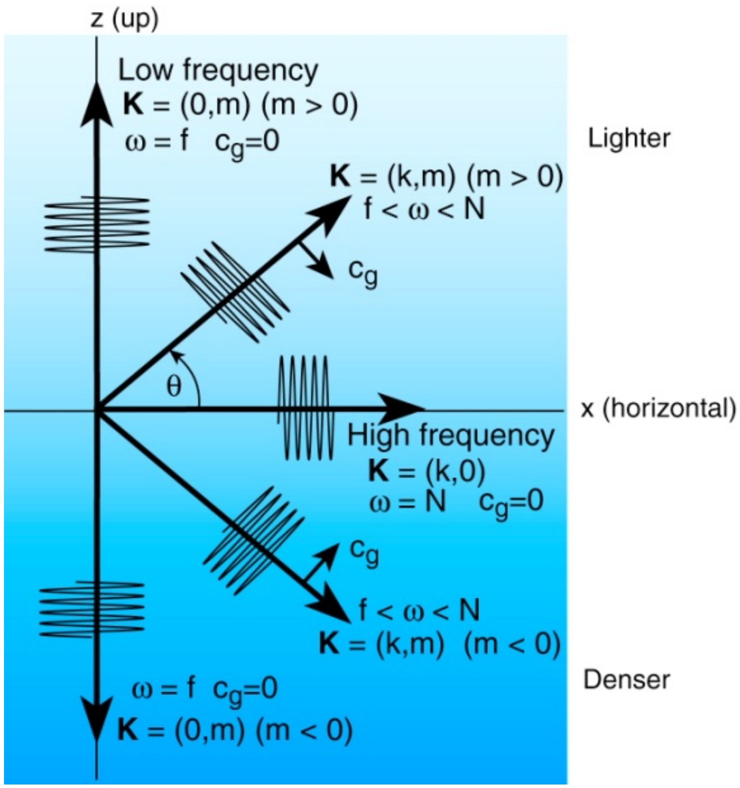
Internal waves: continuous stratification



$$N^2 = -\frac{g}{\rho}\frac{\partial\rho}{\partial z}$$

$$f \leq \omega \leq N$$

Schematic of properties of internal waves. The direction of phase propagation is given by the wavevector (k, m) (heavy arrows). The phase velocity (c_p) is in the direction of the wavevector. The group velocity (c_g) is exactly perpendicular to the wavevector (shorter, lighter arrows).

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Brunt-Vaisala frequency (from PPSW lecture 2)

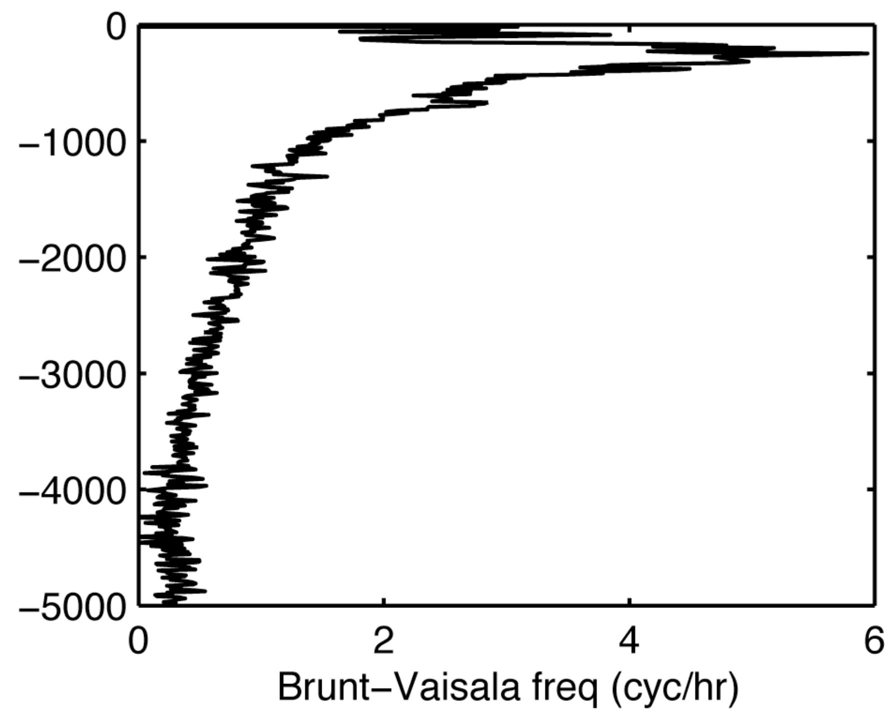
Values of Brunt-Vaisala frequency:

0.2 to 6 cycles per hour

These are the frequencies of “internal waves”

Compare with frequency of surface waves, which is around 50-500 cycles per hour (1 per minute to 1 per second)

Internal waves are much slower than surface waves since the internal water interface is much less stratified than the sea-air interface, which provide the restoring force for the waves.



A BVF profile in the NE Pacific

Internal wave observations

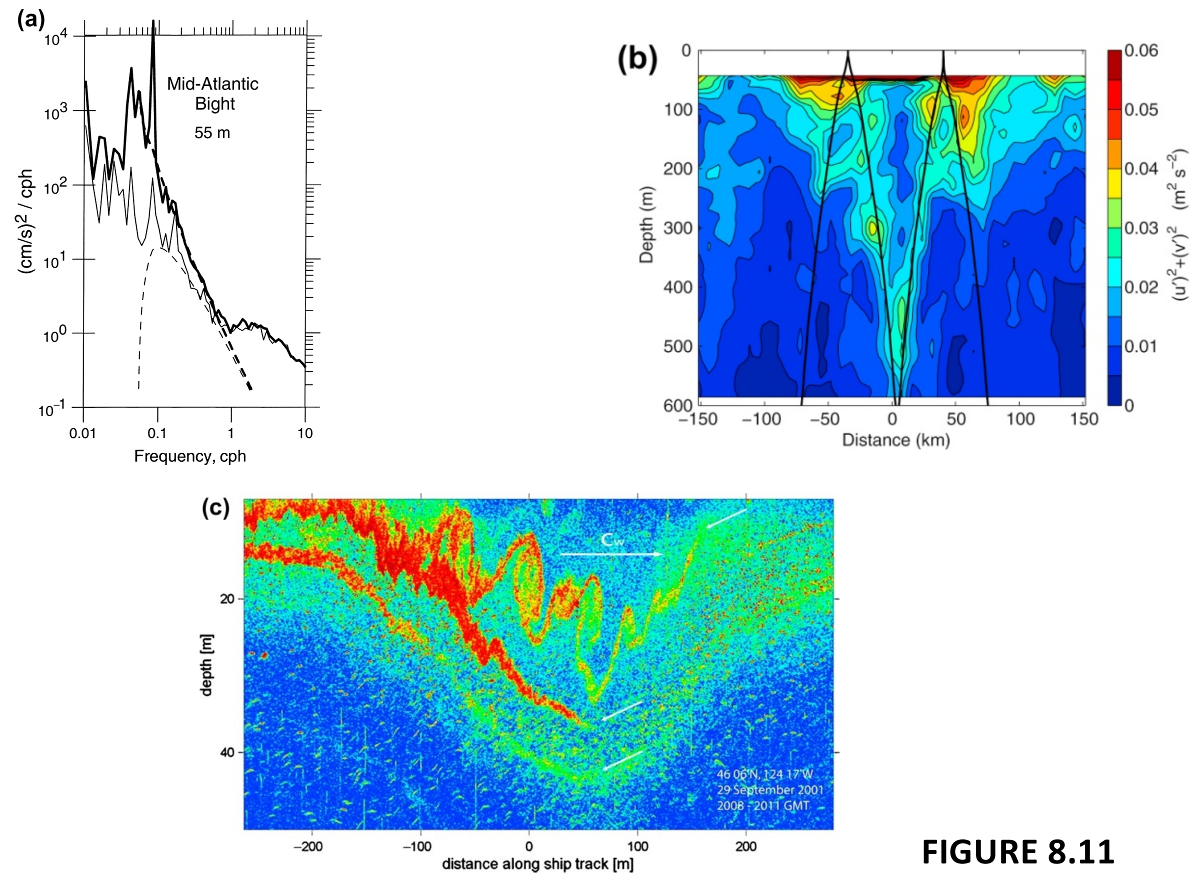


FIGURE 8.11

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