Net lessons for temperature/salinity equations

$$\frac{DT}{Dt} = \kappa_T \nabla^2 T$$ +Source/Sink

$$\frac{DS}{Dt} = \kappa_S \nabla^2 S$$ +Source/Sink

- At any one place (d/dt), the change in temperature is due to 1) advection (movement) of water when there is a temperature gradient, 2) diffusion to/from your cooler/warmer neighbors, and 3) sources/sinks (solar heating, etc)

- If you are following along with a water parcel (D/DT) the advection term is gone, and only diffusion and sources/sinks change your temperature.

Momentum equation: total

$$\frac{Du}{Dt} = -\frac{1}{\rho}\frac{dp}{dx} + A_H\left(\frac{d^2u}{dx^2} + \frac{d^2u}{dy^2}\right) + A_v\frac{d^2u}{dz^2}$$

$$\frac{Dv}{Dt} = -\frac{1}{\rho}\frac{dp}{dy} + A_H\left(\frac{d^2v}{dx^2} + \frac{d^2v}{dy^2}\right) + A_v\frac{d^2v}{dz^2}$$

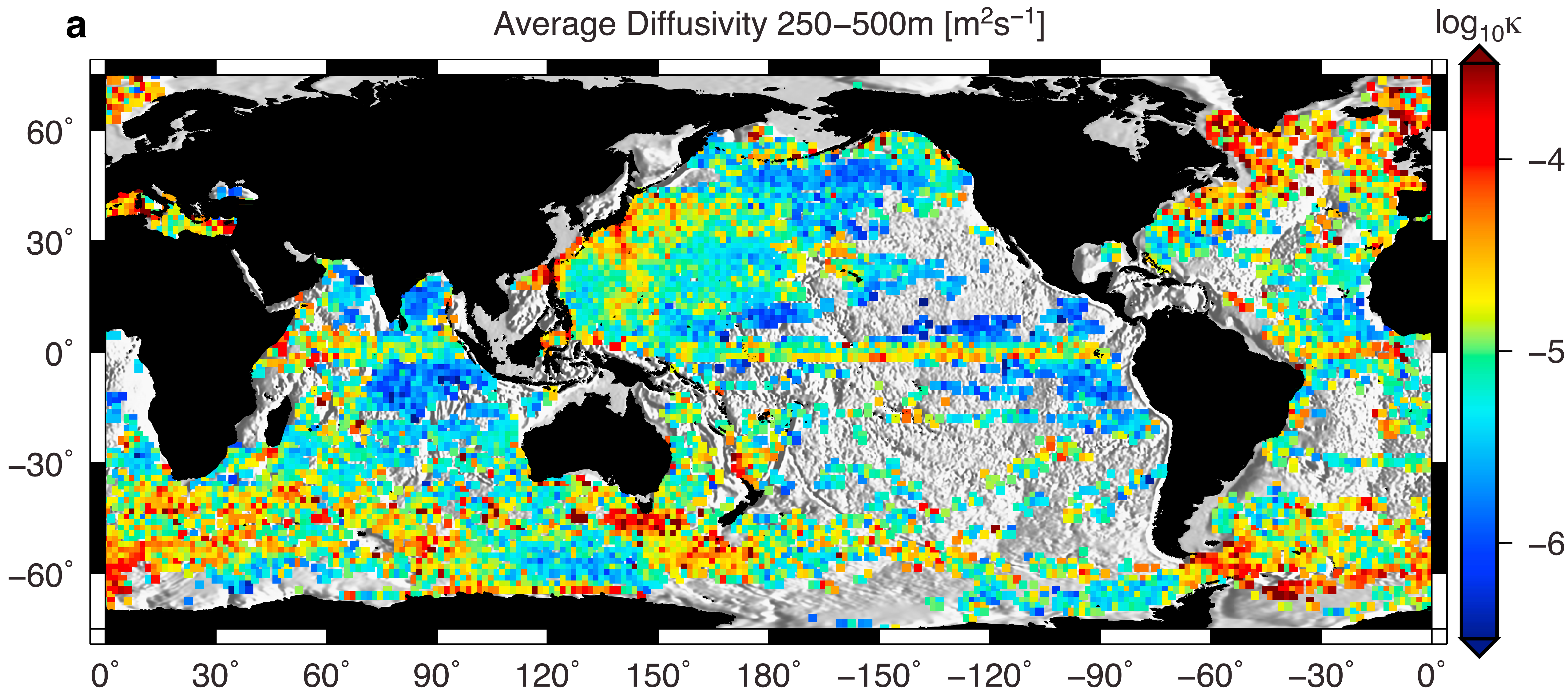
$$\frac{Dw}{Dt} = -\frac{1}{\rho}\frac{dp}{dz} + A_H\left(\frac{d^2w}{dx^2} + \frac{d^2w}{dy^2}\right) + A_v\frac{d^2w}{dz^2} + g$$

Acceleration following a fluid parcel

Pressure differences push water

Redistribution of momentum within the ocean, tends to act gradually, sometimes ignored for some problems. But the surface/bottom stress versions are not!!

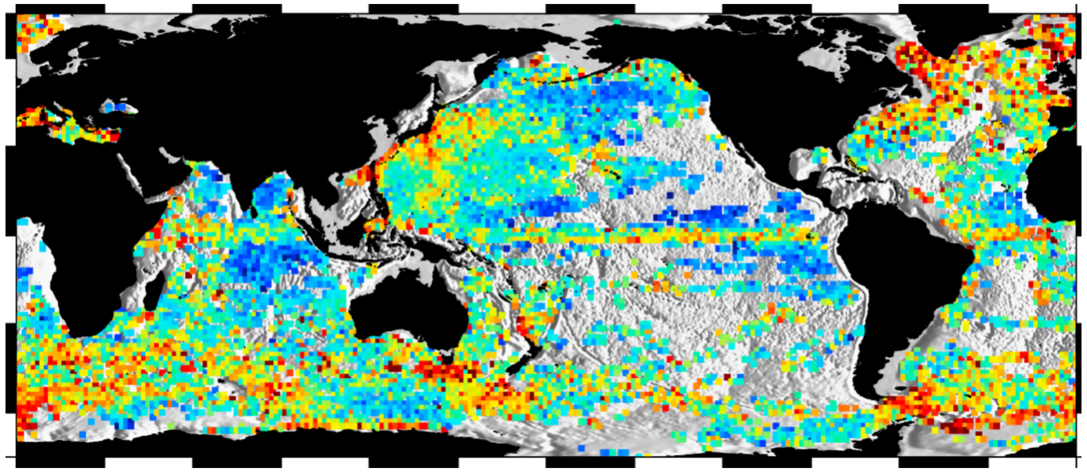
Global patterns of turbulence



The strength of small-scale turbulence varies by a factor of 1000! It has systematic patterns related to physical processes we are starting to understand

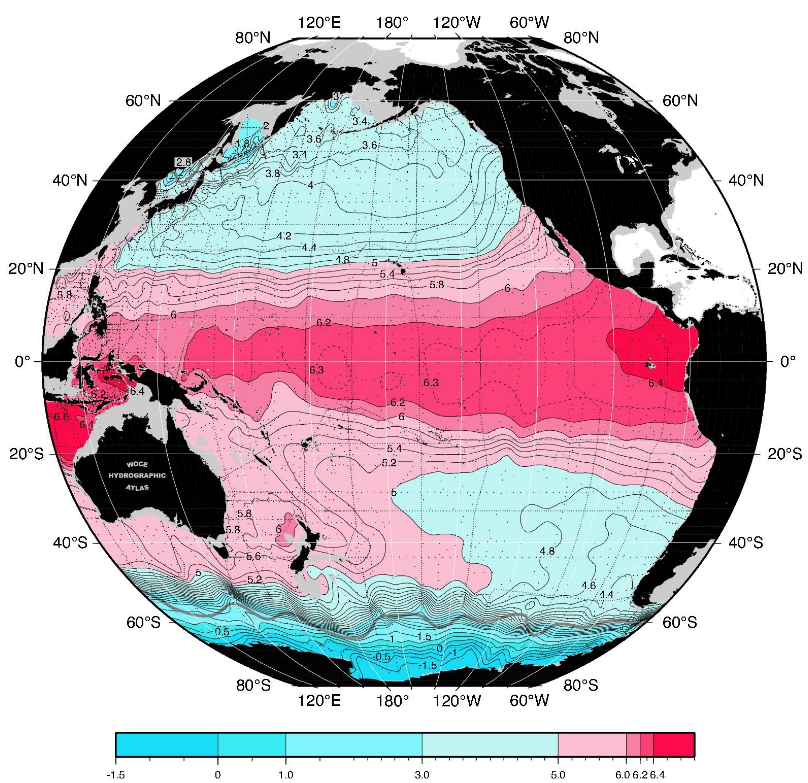
Whalen, Talley and MacKinnon, 2012
Whalen, MacKinnon, Talley, Waterhouse 2015

Convolving patterns

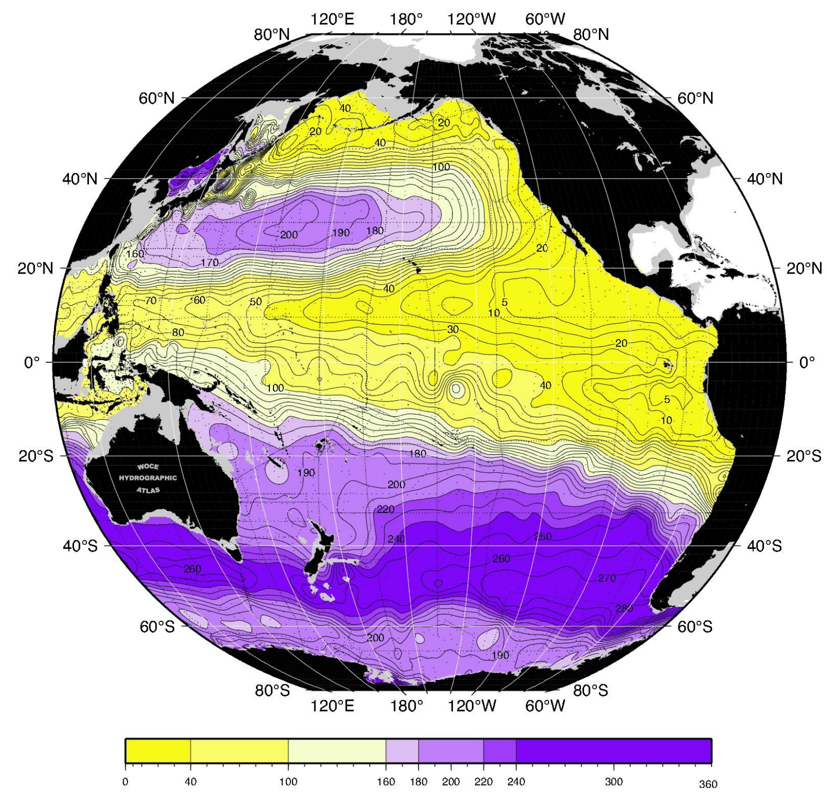


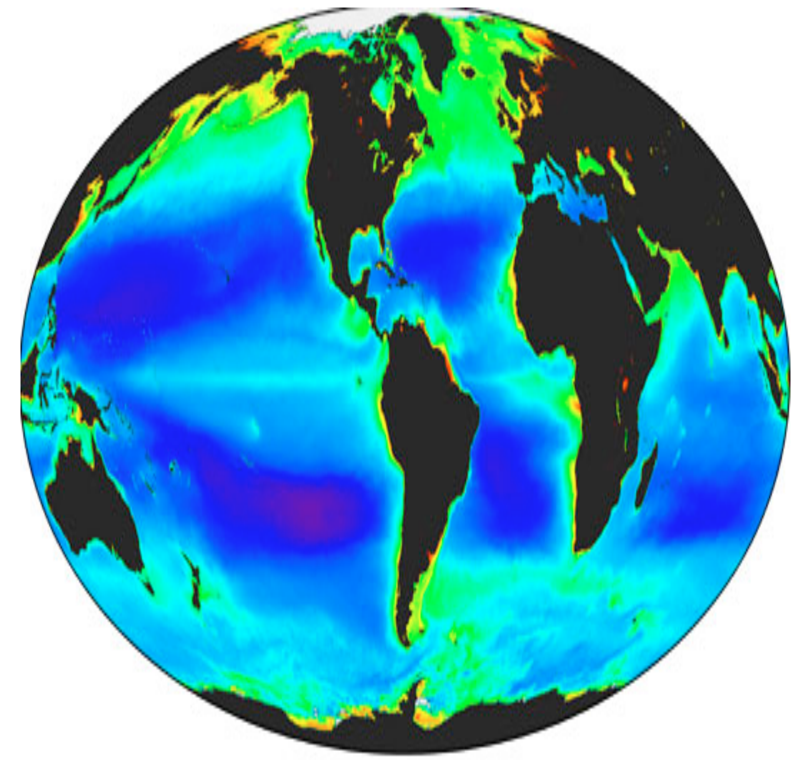
X

Potential temperature (ºC) 27.3 γ^n (kg/m^3)



Oxygen (µmol/kg) 500 m





= ??

Waves

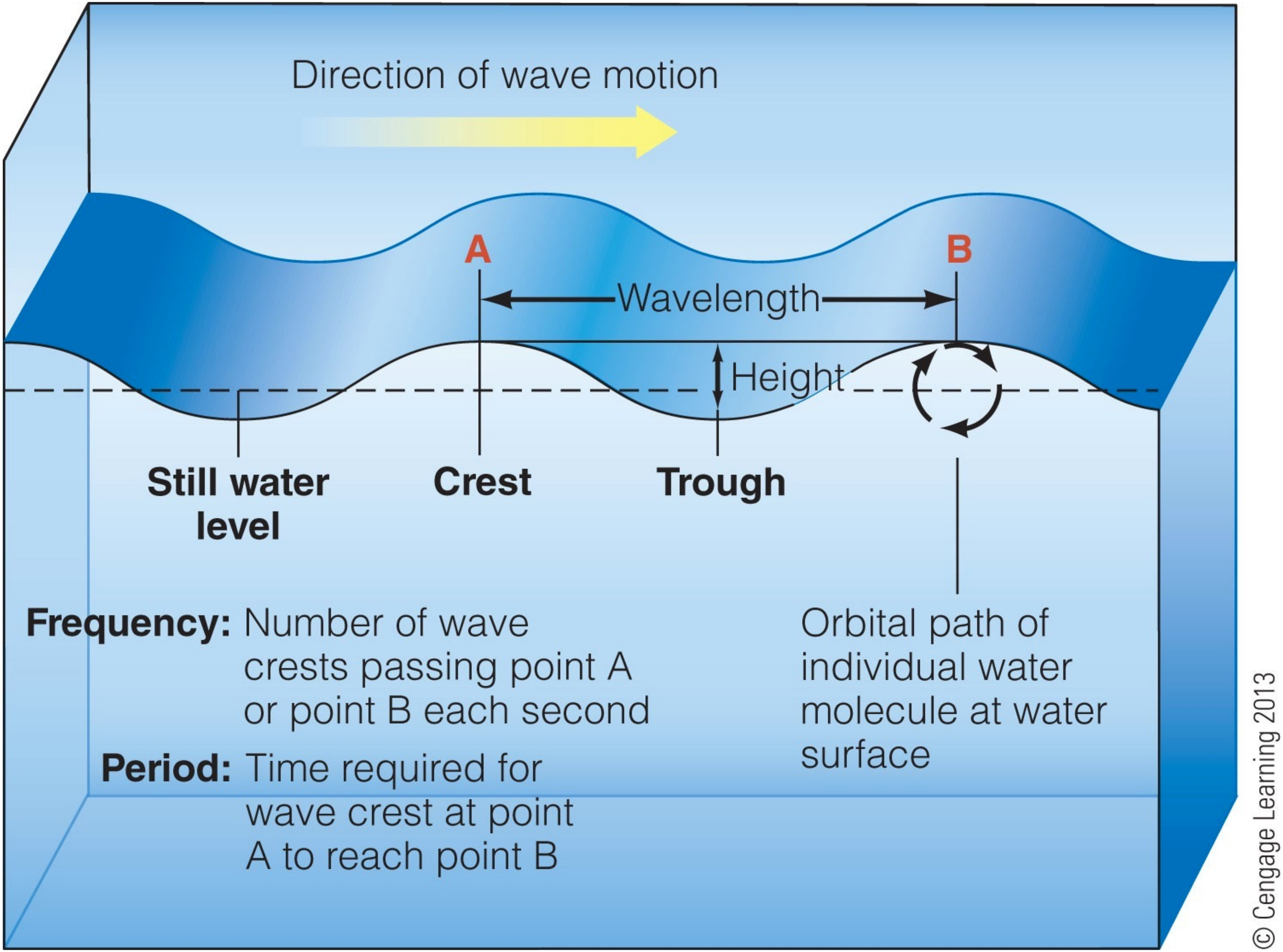
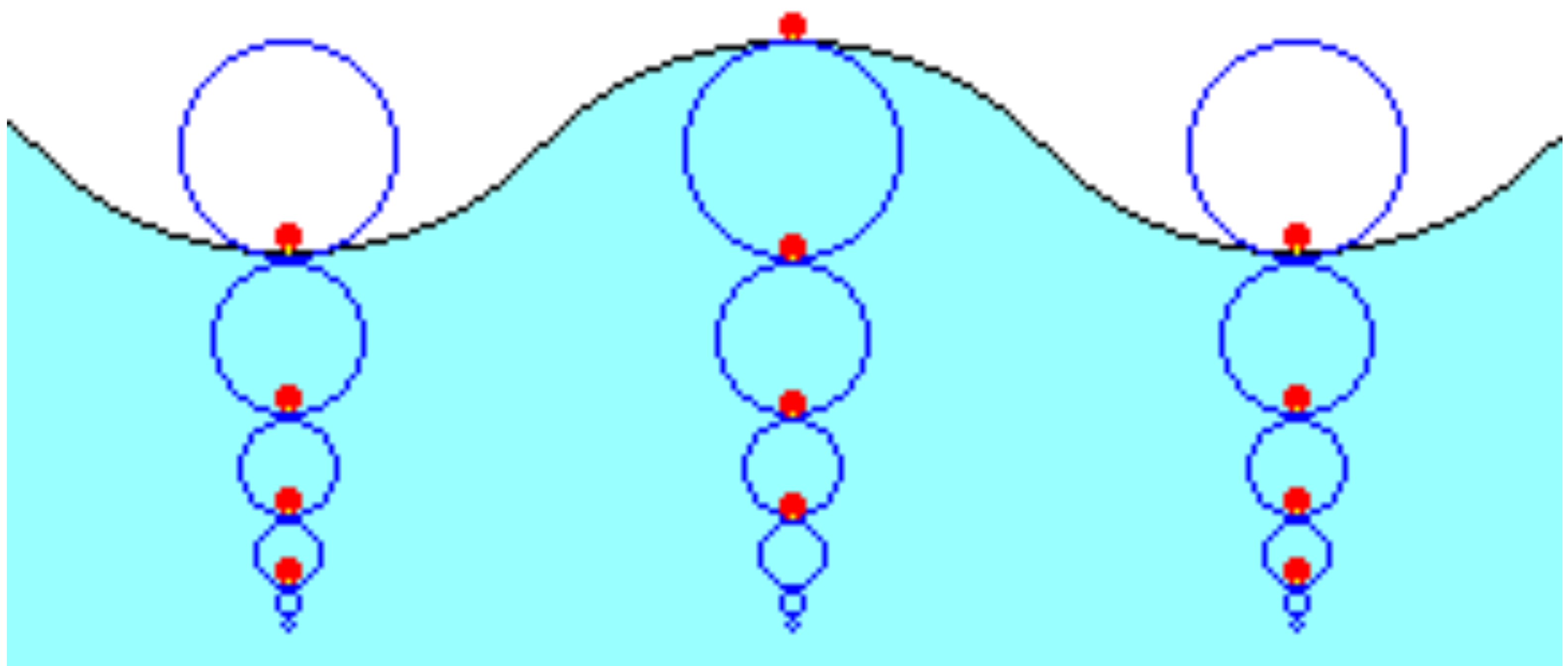


Figure 10-2 p299

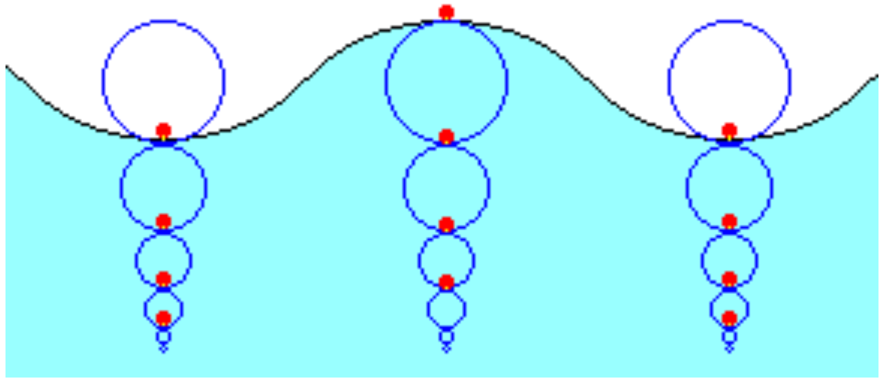
To first order, waves carry INFORMATION, not water itself.



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

Speeds

Particle Speed: speed an individual blob of water moves



Phase speed: the speed the crests move (information)

“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)

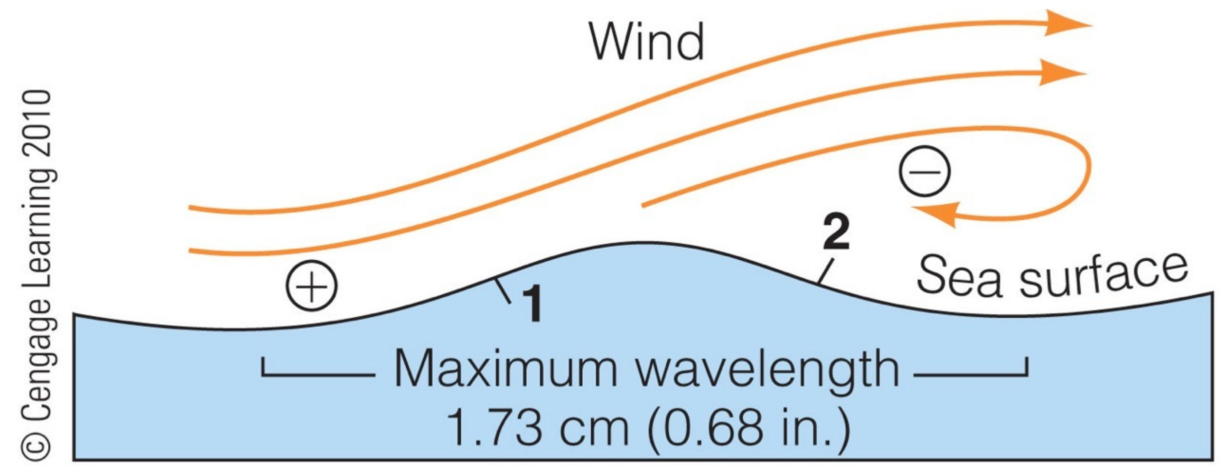
$$c = \sqrt{\frac{g\lambda}{2\pi}}$$

λ =wavelength

What happens when wind blows on the ocean surface?

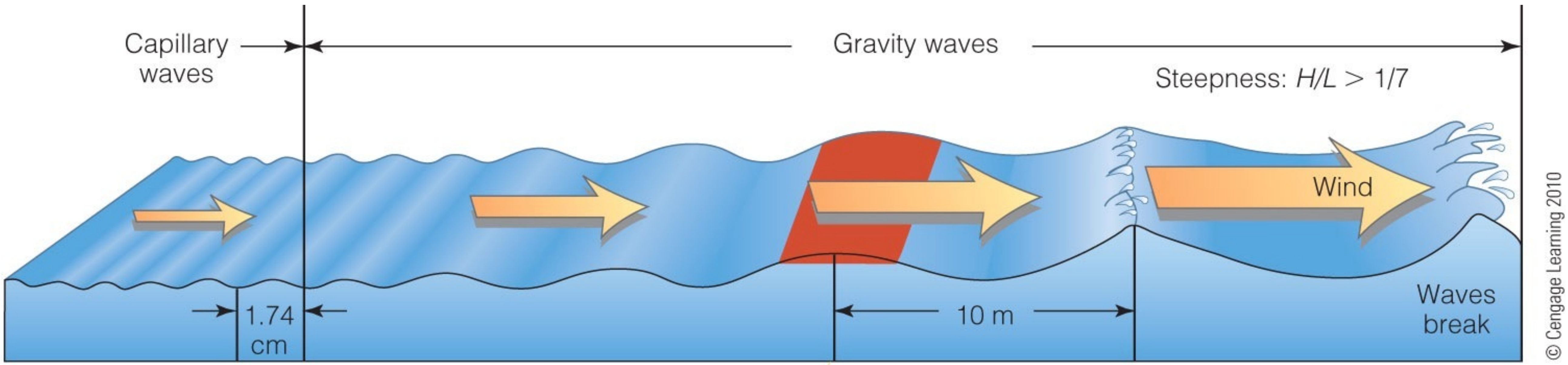
Capillary wave is one in which restoring force is **surface tension,** not gravity.

Tom Garrison



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 p305



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)

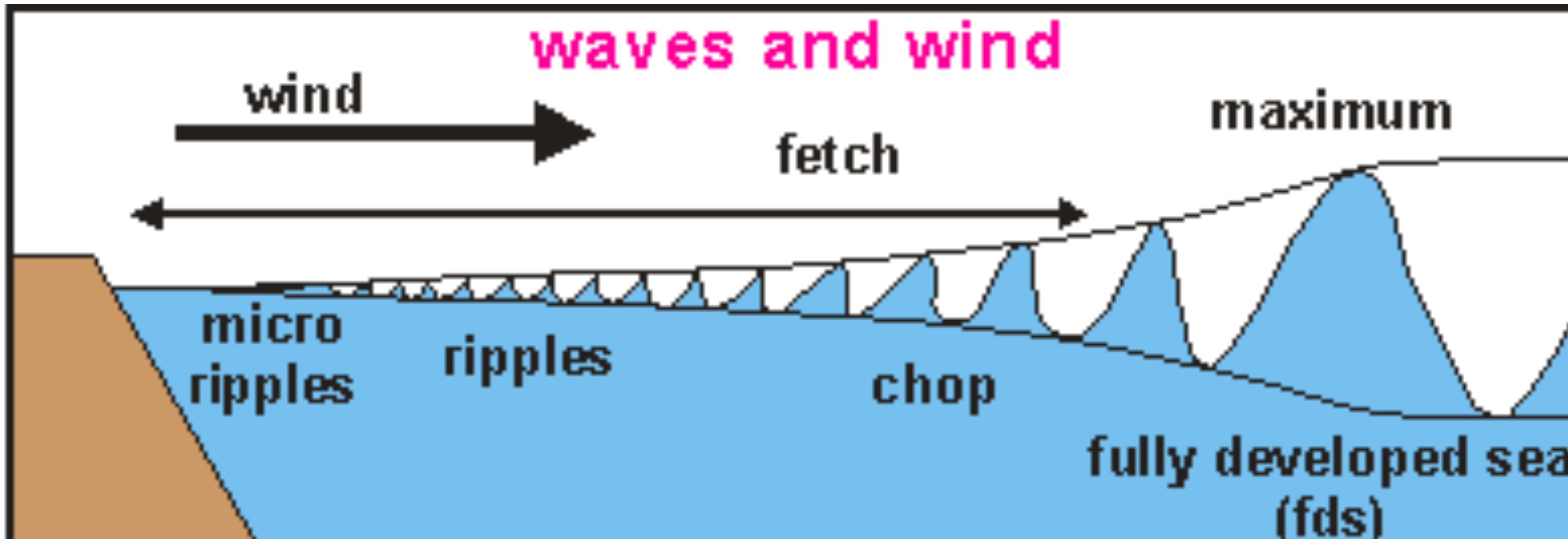
Figure 10-9b p305

Different types of waves

Table 10.1 Disturbing Forces, Wavelength, and Restoring Forces for Ocean Waves

Wave Type	Disturbing Force	Restoring Force	Typical Wavelength
Capillary wave	Usually wind	Cohesion of water molecules	Up to 1.72 cm (0.68 in.)
Wind wave	Wind over ocean	Gravity	60–150 m (200–500 ft)
Seiche	Change in atmospheric pressure, storm surge, tsunami	Gravity	Large, variable; a function of ocean basin size
Seismic sea wave (tsunami)	Faulting of seafloor, volcanic eruption, landslide	Gravity	200 km (125 mi)
Tide	Gravitational attraction, rotation of Earth	Gravity	Half Earth's circumference

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



As waves develop, they offer more surface area for the wind to press against (wind stress). Depending on both fetch and time, the size of the waves increases quadratically to a maximum. The energy imparted to the sea increases with the fourth power of the wind speed! As waves develop, they become more rounded and longer and they travel faster. Their maximum size is reached when they travel almost as fast as the wind. A 60 knot storm lasting for 10 hours makes 15m high waves in open water.

Complications I: dispersion

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

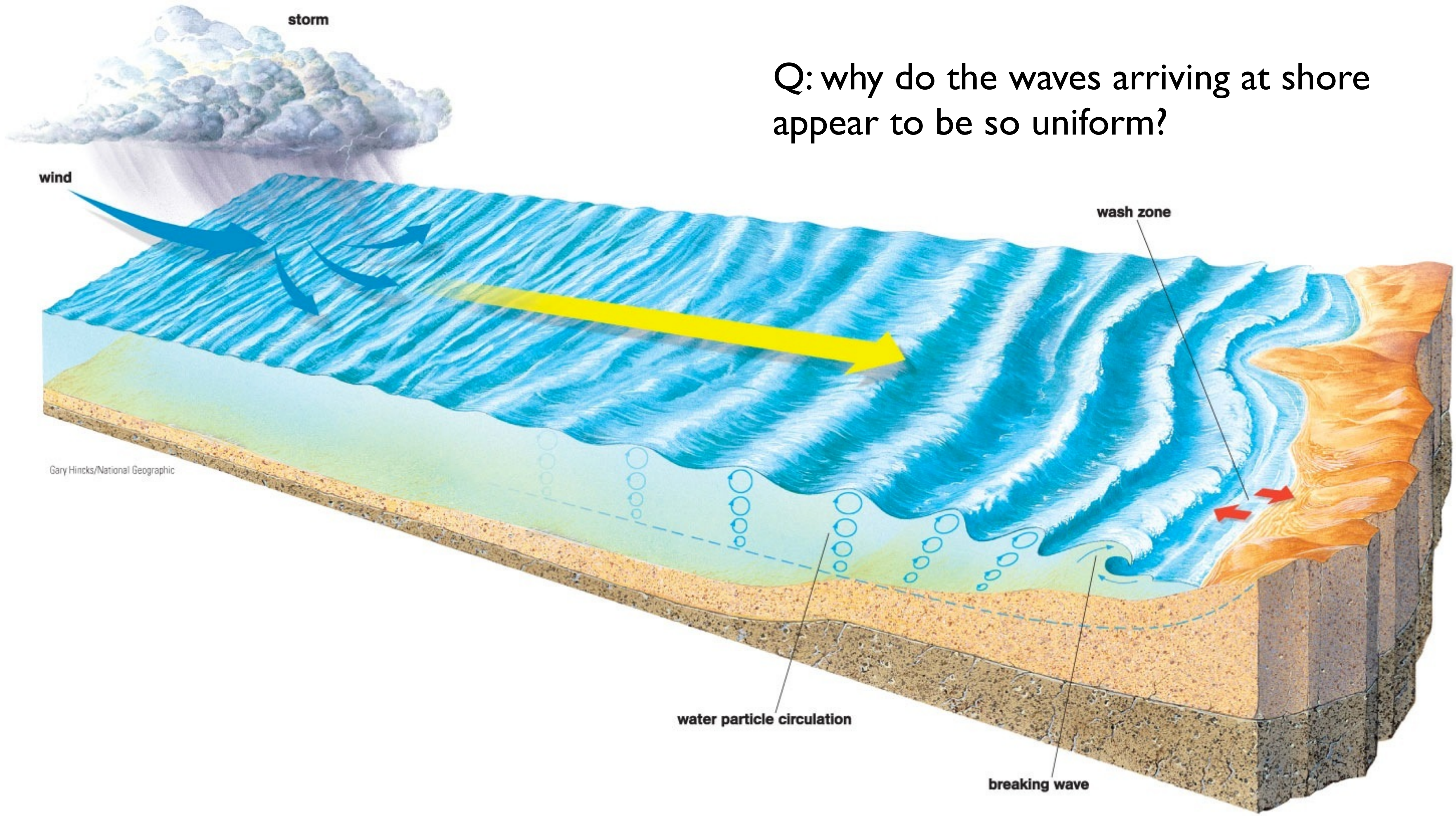
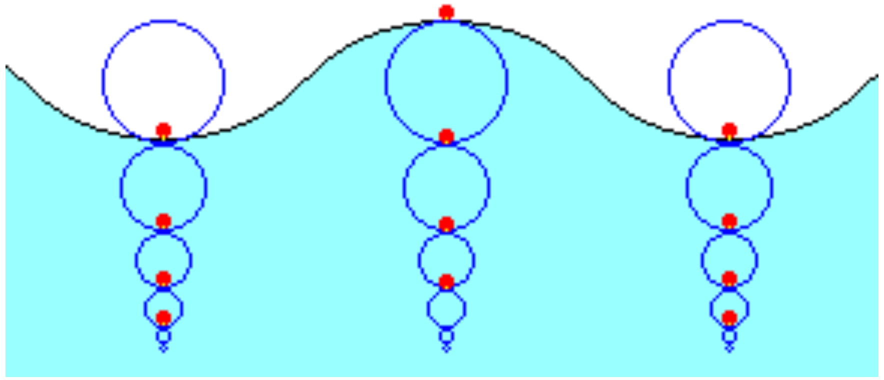


Figure 10-11 p306

Speeds

Particle Speed: speed an individual blob of water moves



Phase speed: the speed the crests move (information)

"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

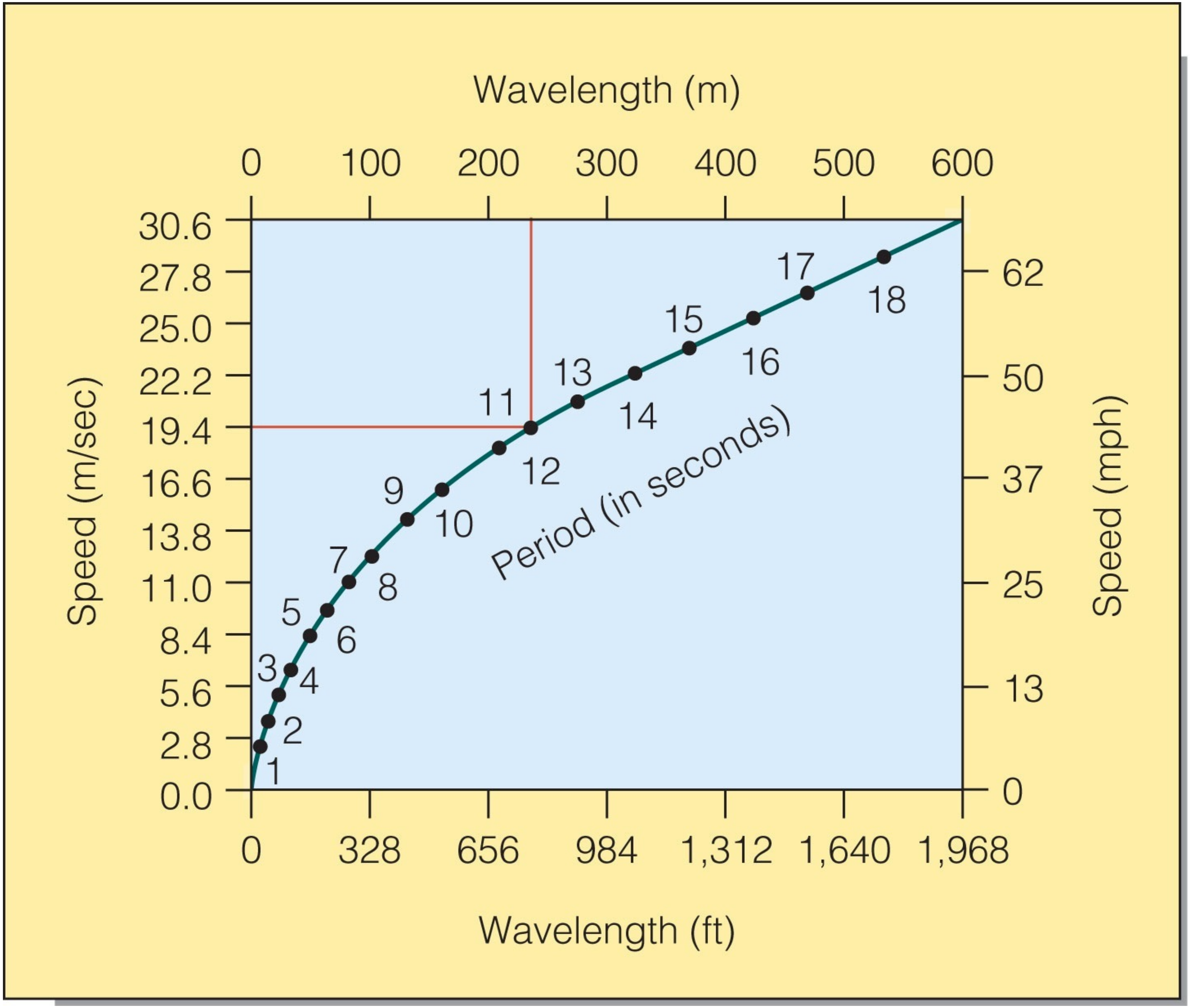
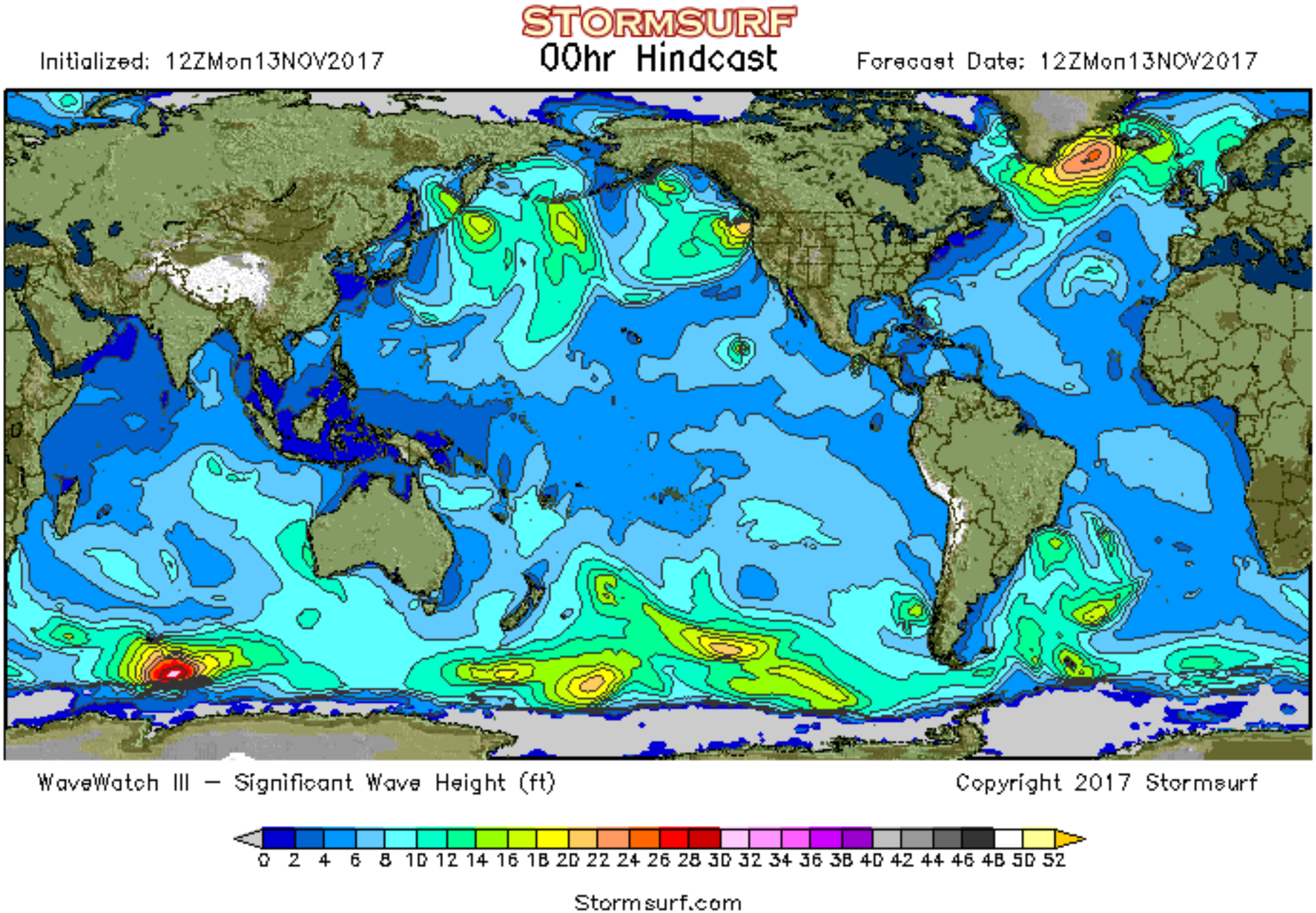
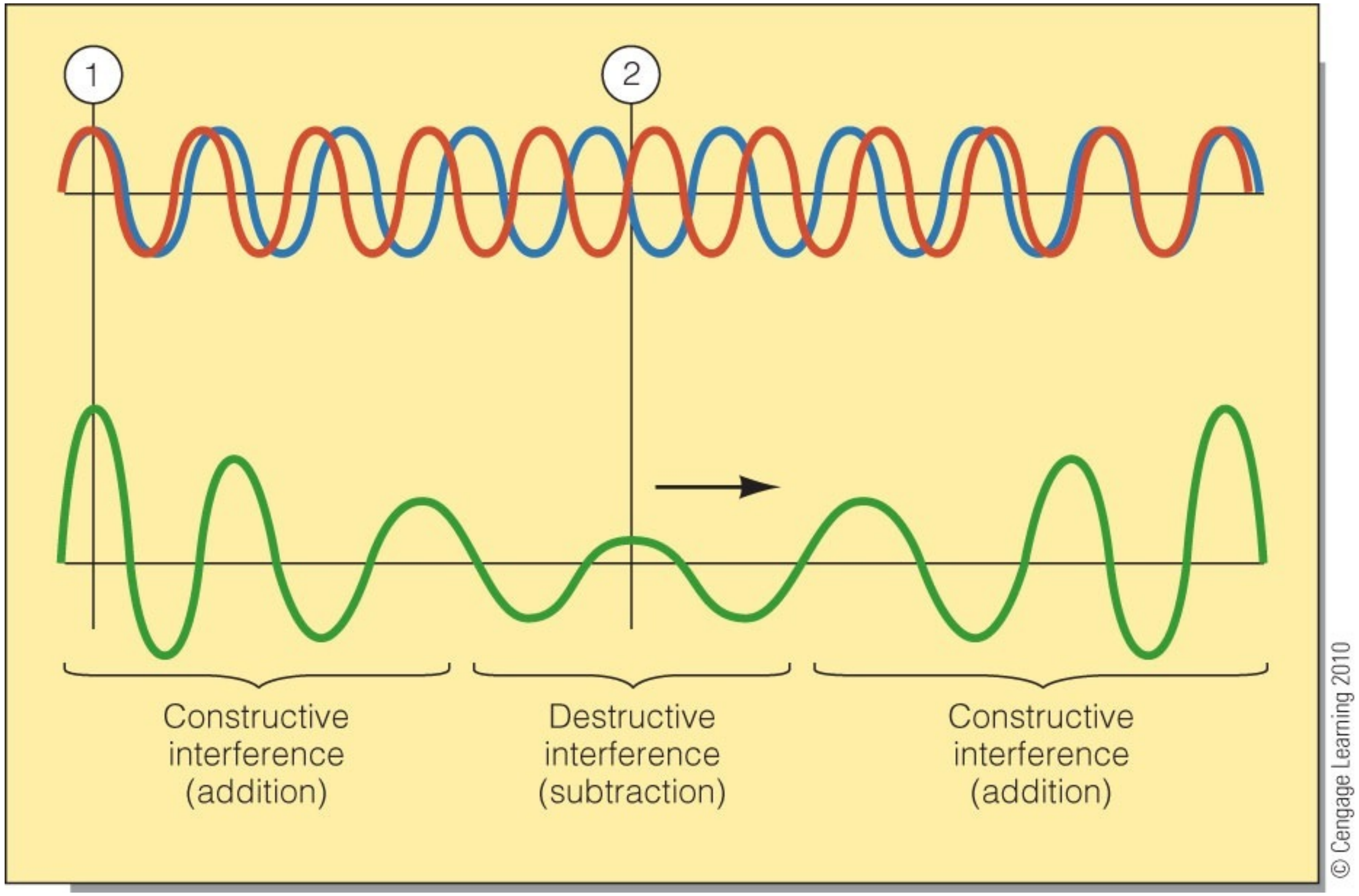


Figure 10-7 p303



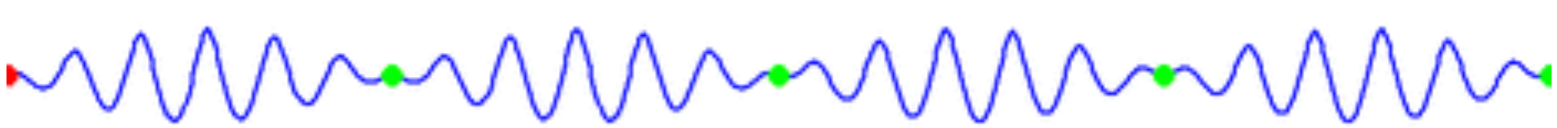
http://www.stormsurfing.com/cgi/display.cgi?a=spac_wind

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

Complications 3: Stokes drift

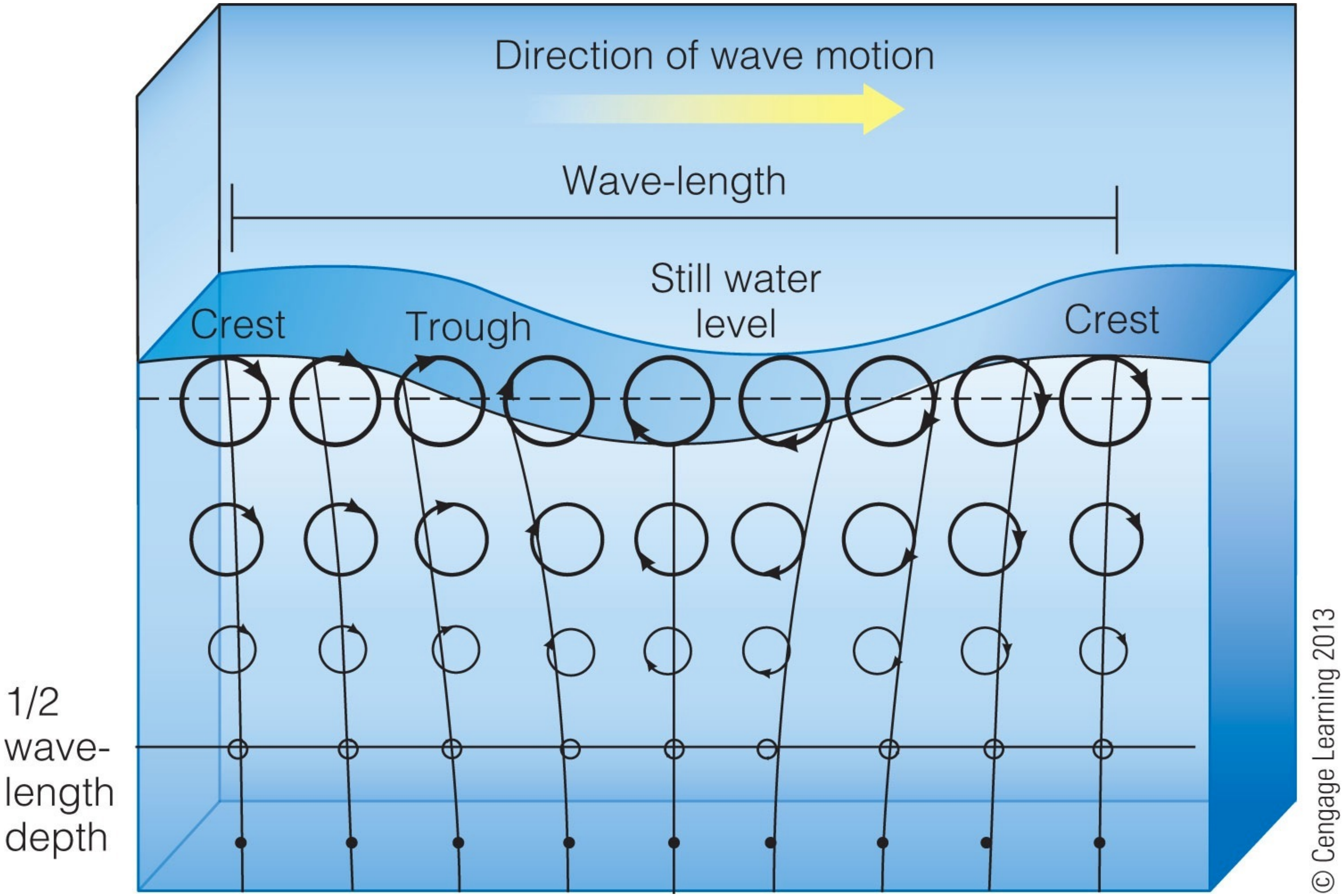
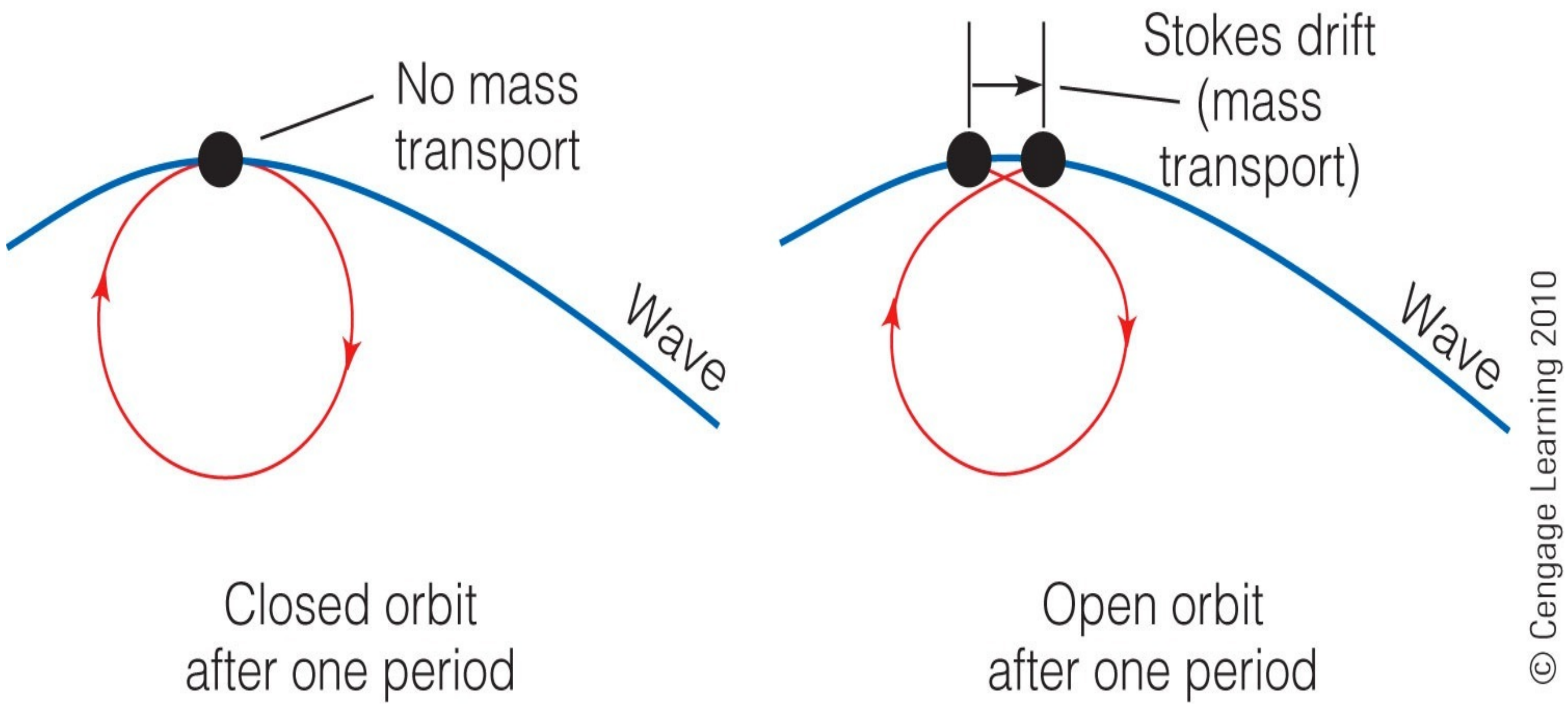
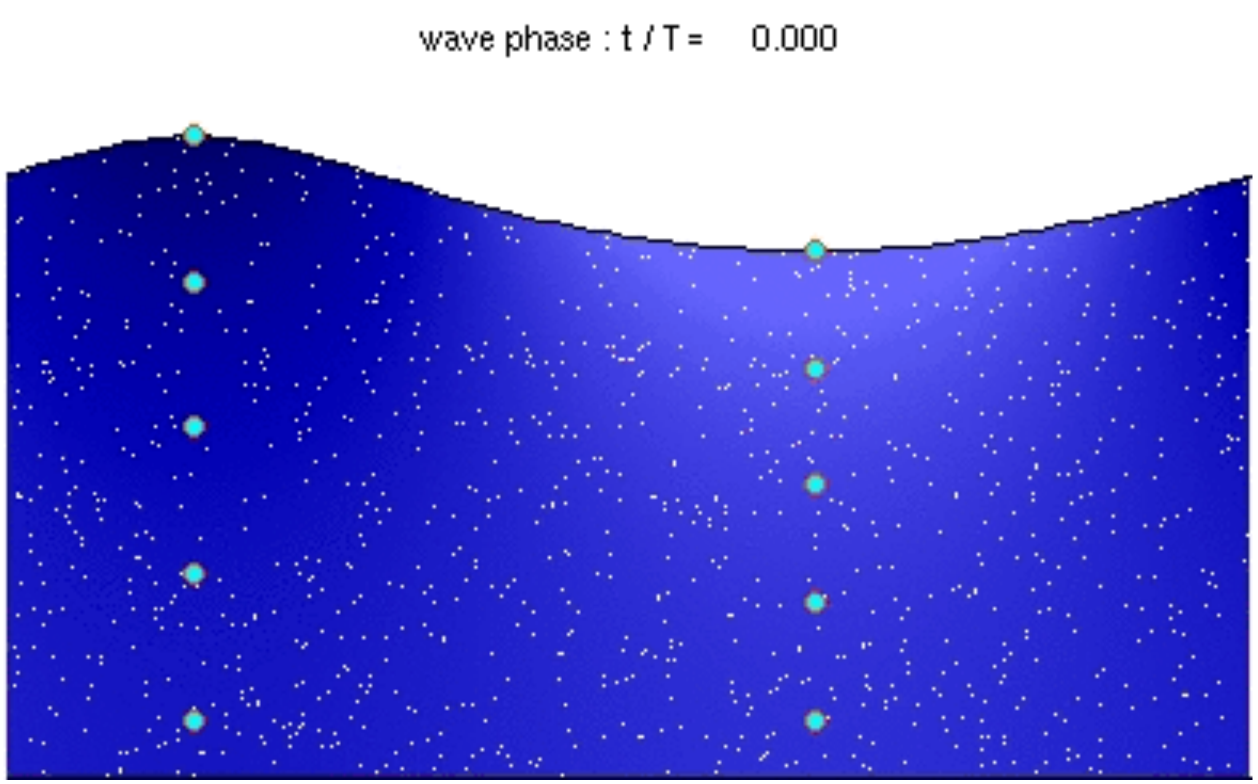


Figure 10-3 p299

Stokes Drift





http://en.wikipedia.org/wiki/Stokes_drift

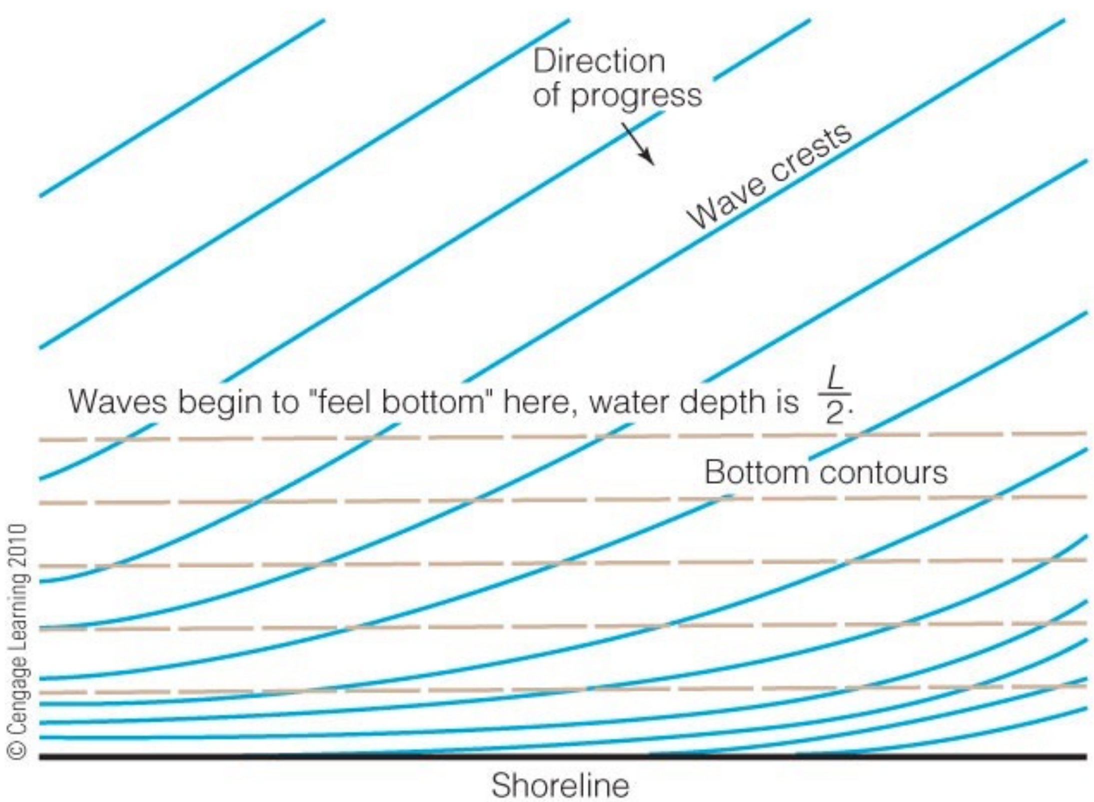
Figure 10-4 p299

Refraction

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

$$c = \sqrt{gH}$$

g=gravity=9.8m²/s
H= ocean depth

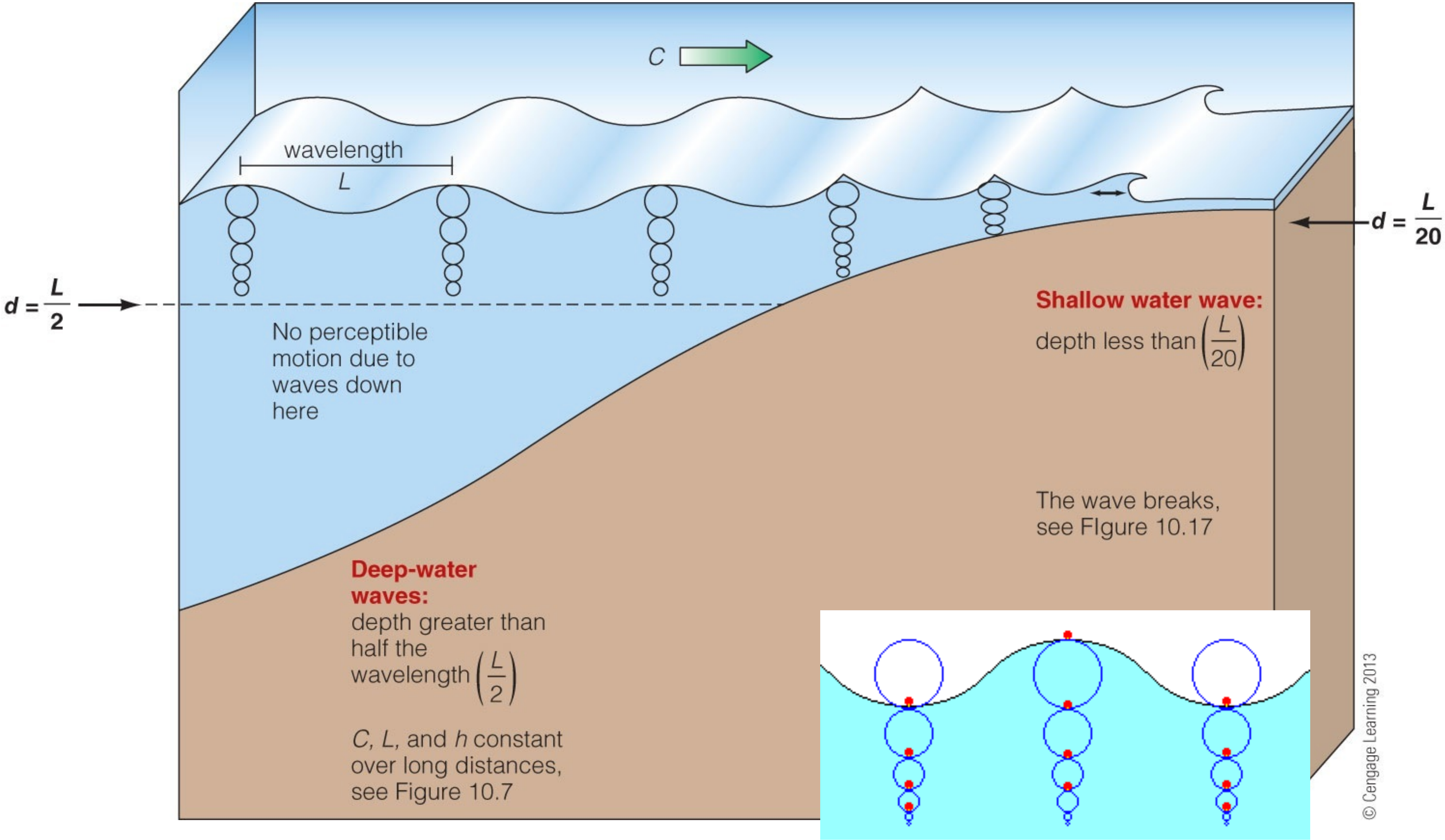


a Diagram showing the elements that produce refraction.

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

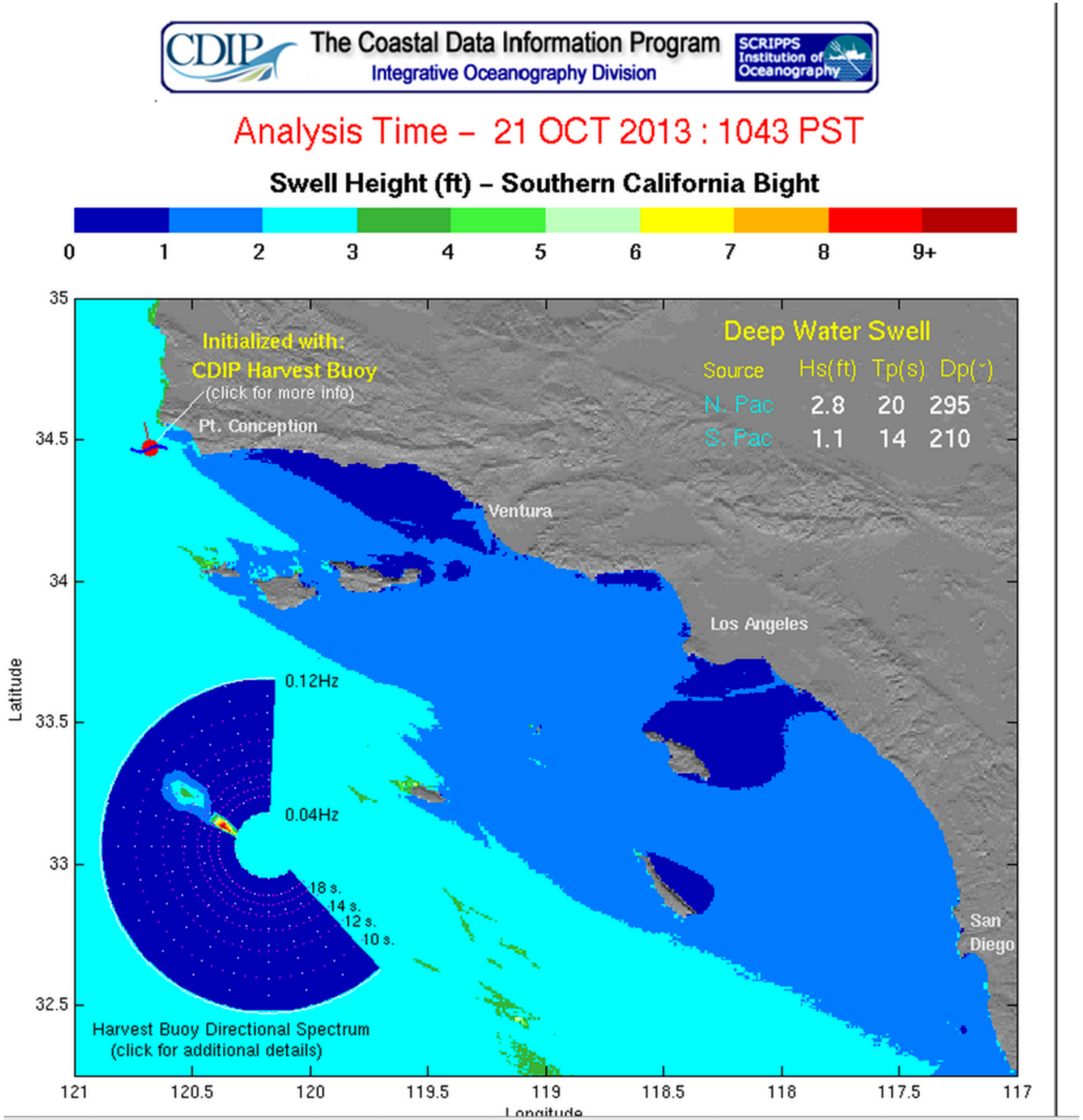
What happens when waves get to shore?



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/

J. Fluid Mech. (2017), *vol.* 823, *pp.* 316–328.
doi:10.1017/jfm.2017.314

Surfing surface gravity waves

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(Received 23 November 2016; revised 21 April 2017; accepted 9 May 2017; first published online 16 June 2017)

A simple criterion for water particles to surf an underlying surface gravity wave is presented. It is found that particles travelling near the phase speed of the wave, in a geometrically confined region on the forward face of the crest, increase in speed. The criterion is derived using the equation of John (*Commun. Pure Appl. Maths*, vol. 6, 1953, pp. 497–503) for the motion of a zero-stress free surface under the action of gravity. As an example, a breaking water wave is theoretically and numerically examined. Implications for upper-ocean processes, for both shallow- and deep-water waves, are discussed.

Key words: air/sea interactions, surface gravity waves, wave breaking


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Tsunamis

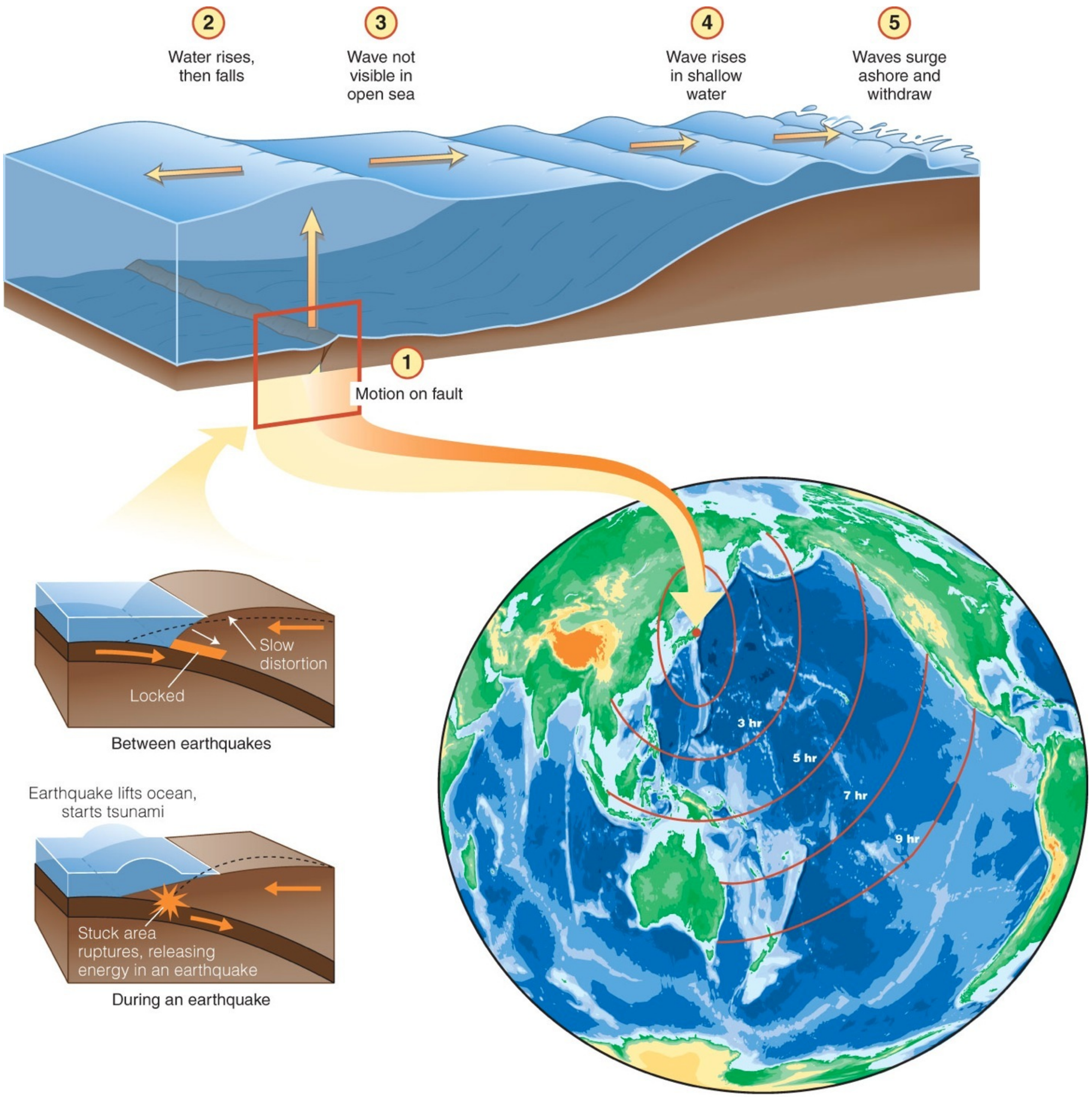


Figure 10-28 p321

Are tsunamis "shallow" or "deep" water waves?

Shallow water waves are FAST!

g = 9.8 m/s2

H = 4000 m

→ c ~ 200 m/s ~ 450 mph!

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

$$c = \sqrt{gH}$$

g=gravity=9.8m²/s

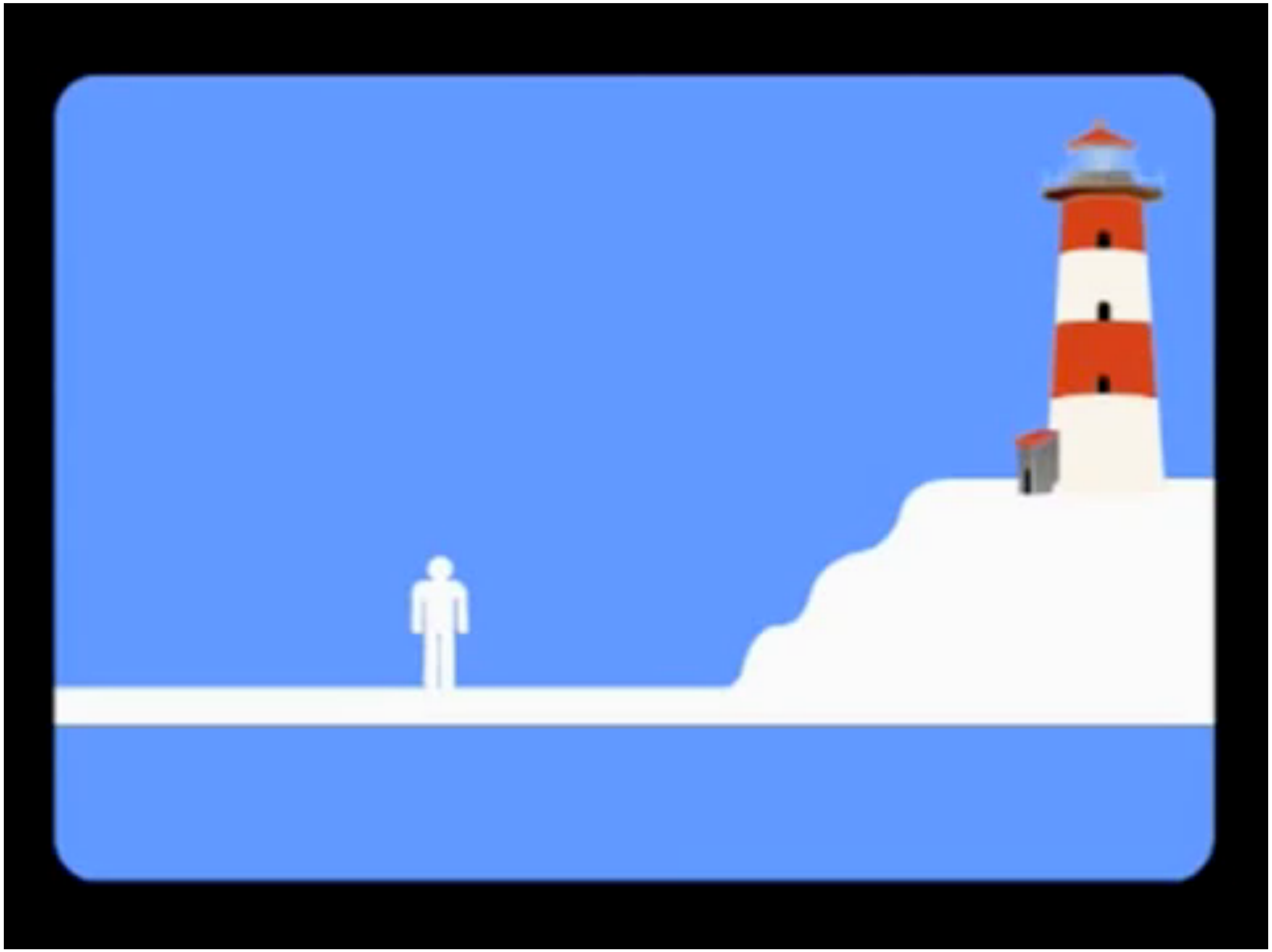
H= ocean depth

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

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

λ =wavelength

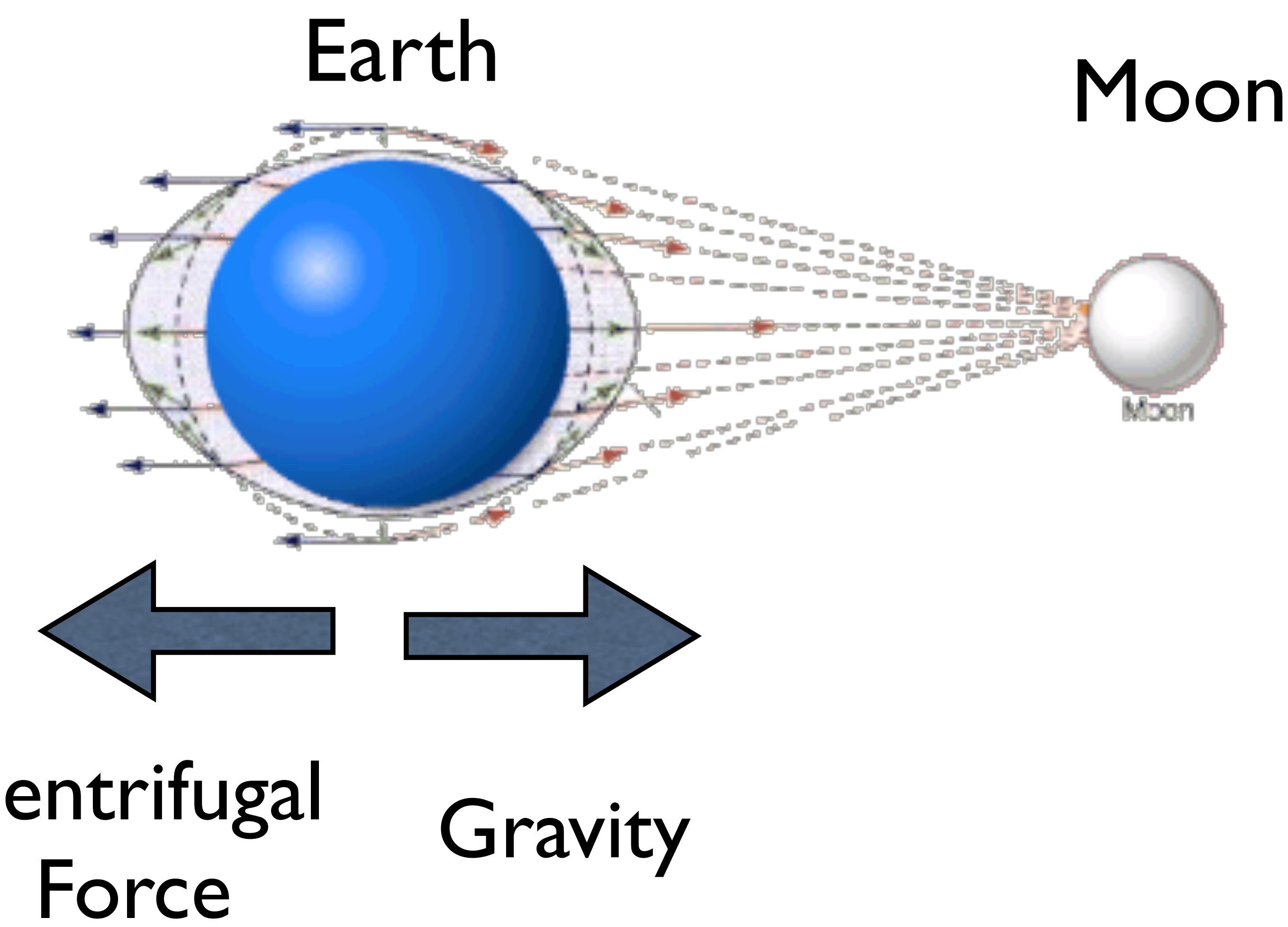
Tsunamis!

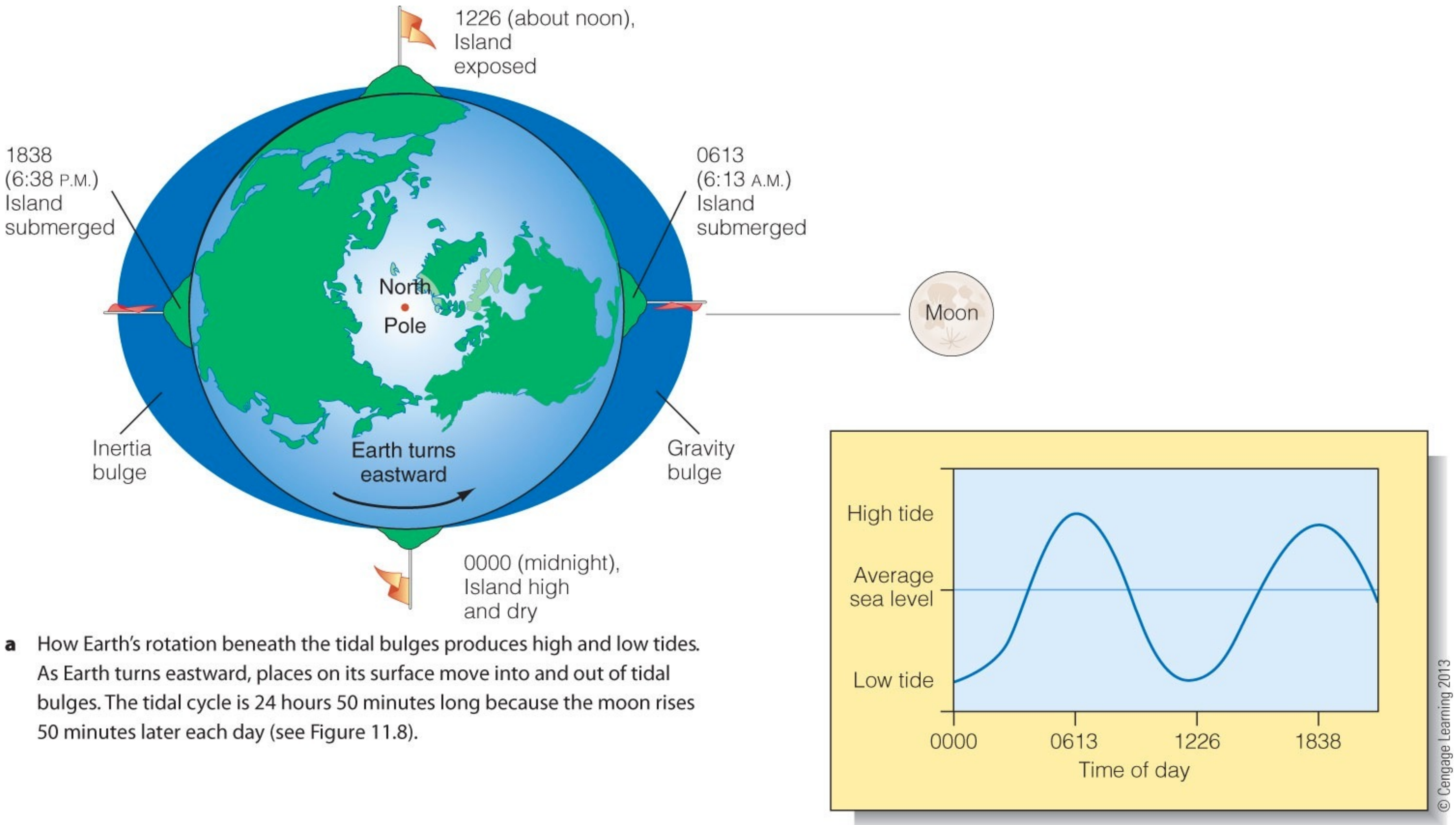


https://www.youtube.com/watch?v=tUN_UTY0GNo

Tides I: basics

2 tidal bulges





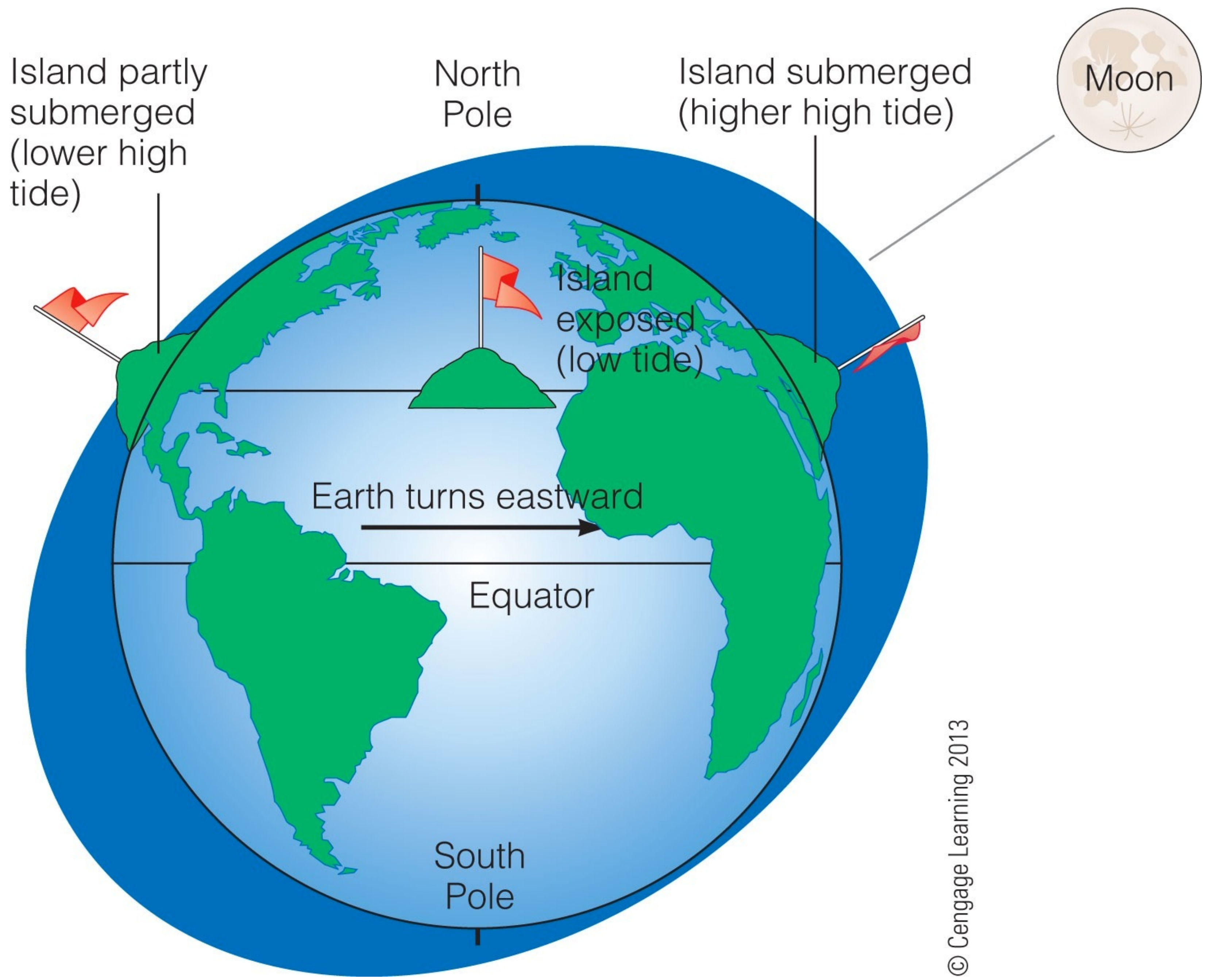
a How Earth's rotation beneath the tidal bulges produces high and low tides. As Earth turns eastward, places on its surface move into and out of tidal bulges. The tidal cycle is 24 hours 50 minutes long because the moon rises 50 minutes later each day (see Figure 11.8).

b Graph of the tides at the island in **(a)**.

Figure 11-7 p335

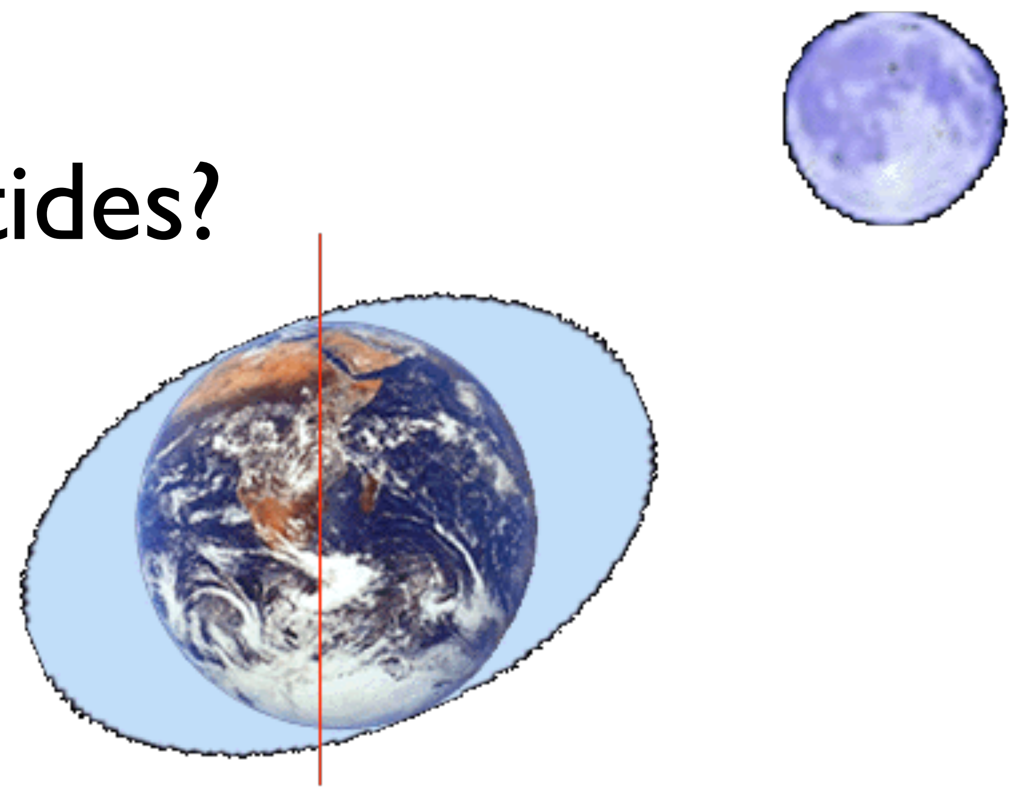
Tides continued

Why are there diurnal (1/day) tides?

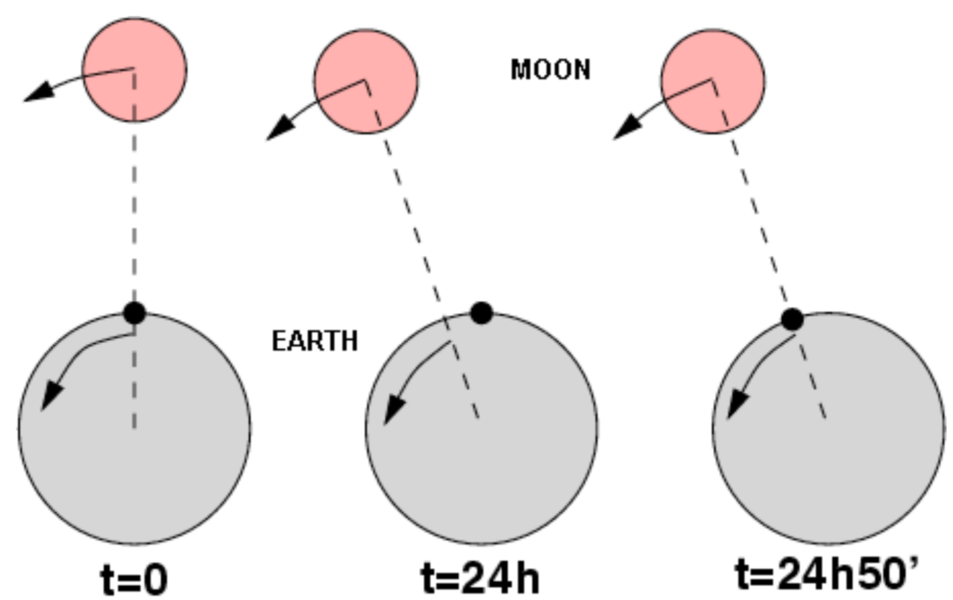


Tides continued

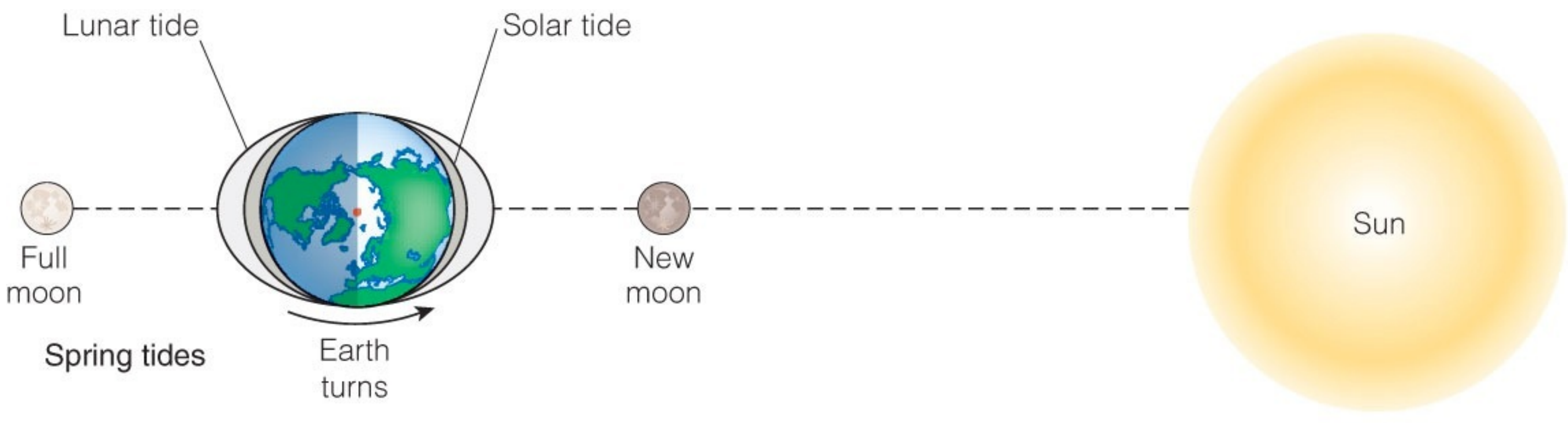
Why are there diurnal (1/day) tides?



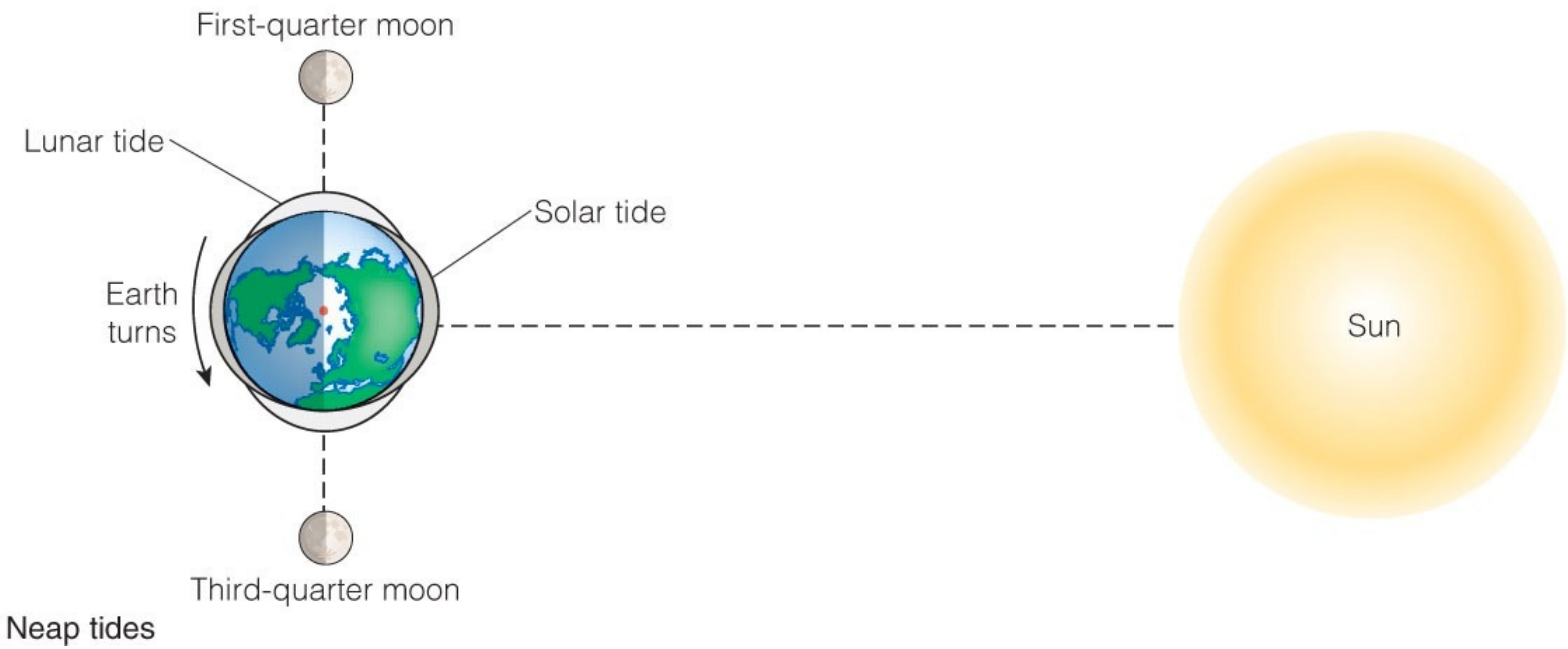
Why isn't the tide every 12 hours?



Spring and Neap tides



a At the new and full moons, the solar and lunar tides reinforce each other, making spring tides the highest high and lowest low tides.



b At the first- and third-quarter moons, the sun, Earth, and moon form a right angle, creating neap tides, the lowest high and the highest low tides.

Figure 11-11 p337

Can the tide "keep up" with the forcing? (no)

1) Pesky continents in the way

2) Even without that, there are wave speed issues.

"Shallow Water Wave speed " (wavelength long compared to ocean depth)

$$c = \sqrt{gH}$$ ~ 200 m/s

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

How does this compare to speed with which earth's rotation sweeps you past the tidal "bumps"?

~ 400 m/s

Conclusion? Can't keep up, tidal patterns are not so simple…

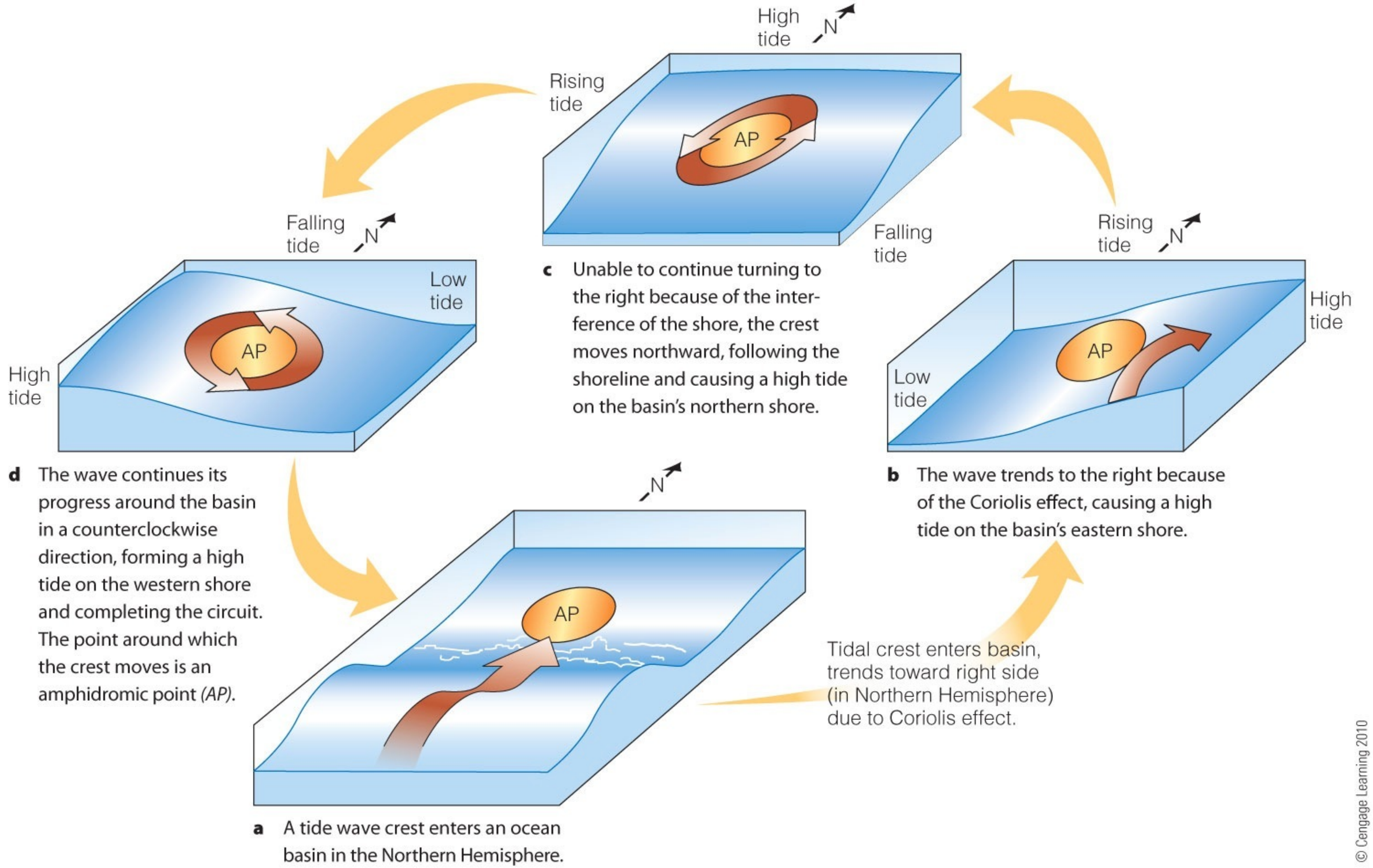


Figure 11-14 p341

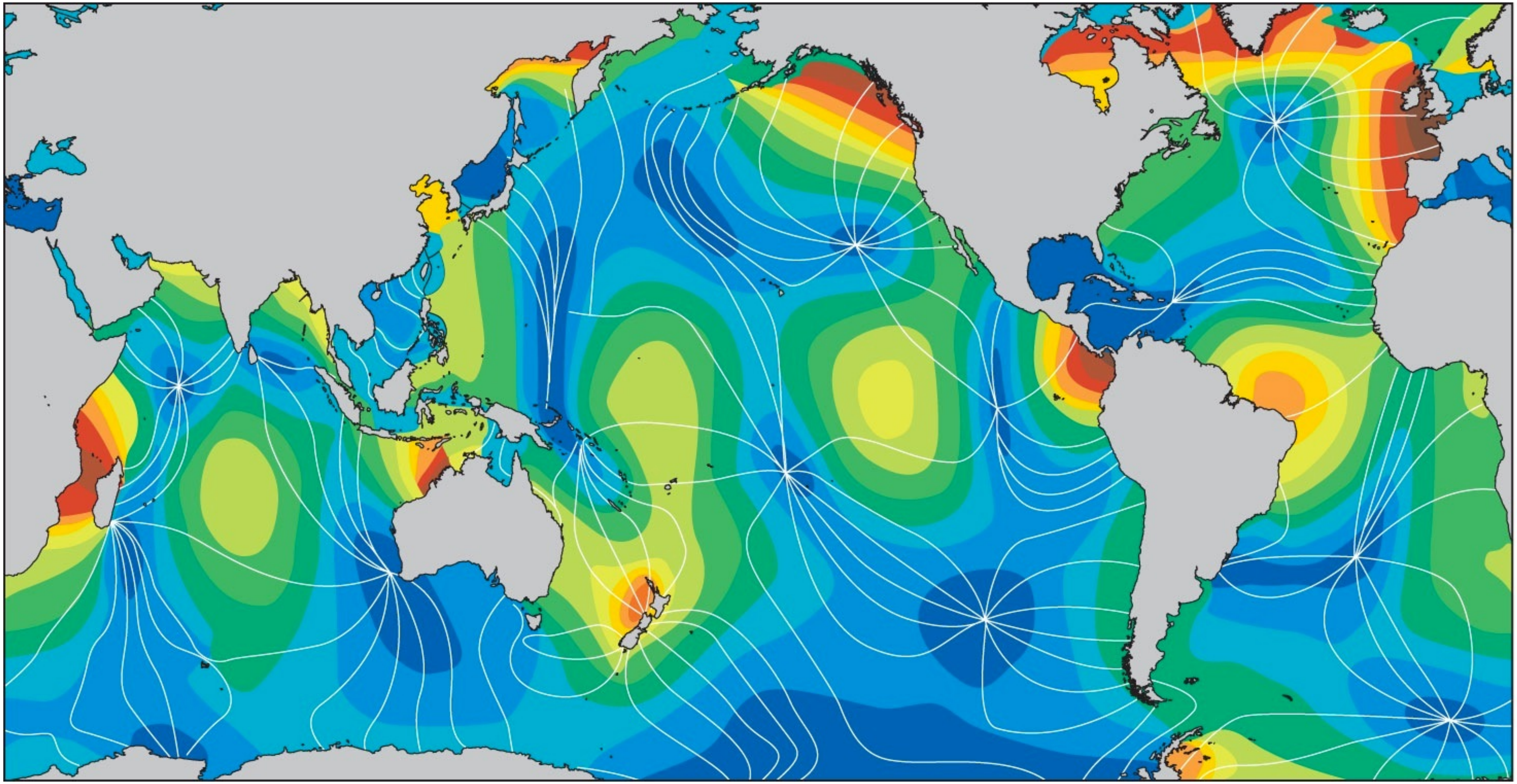
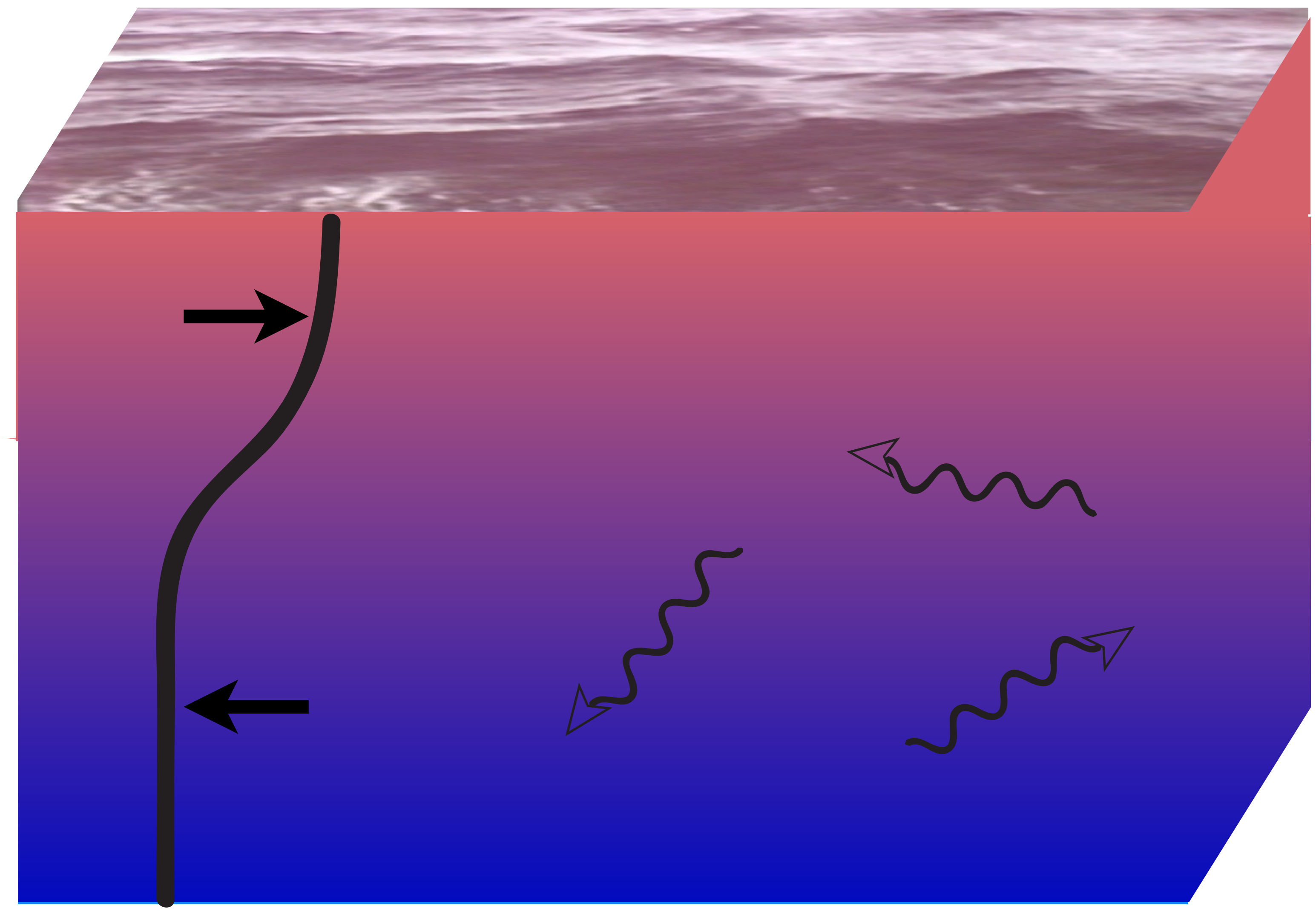


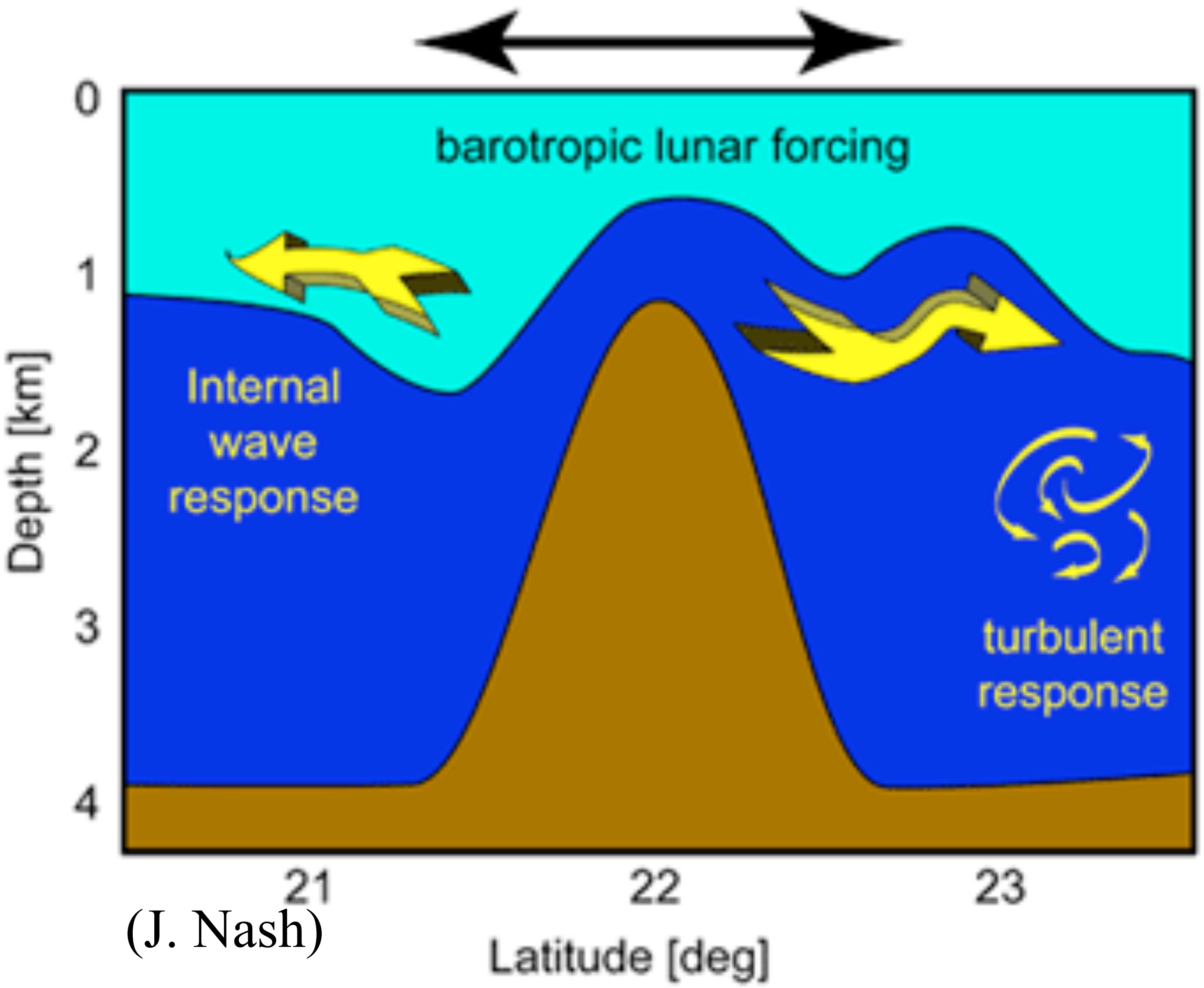
Figure 11-15 p341

Waves



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

Internal waves generated by tidal flow over topography



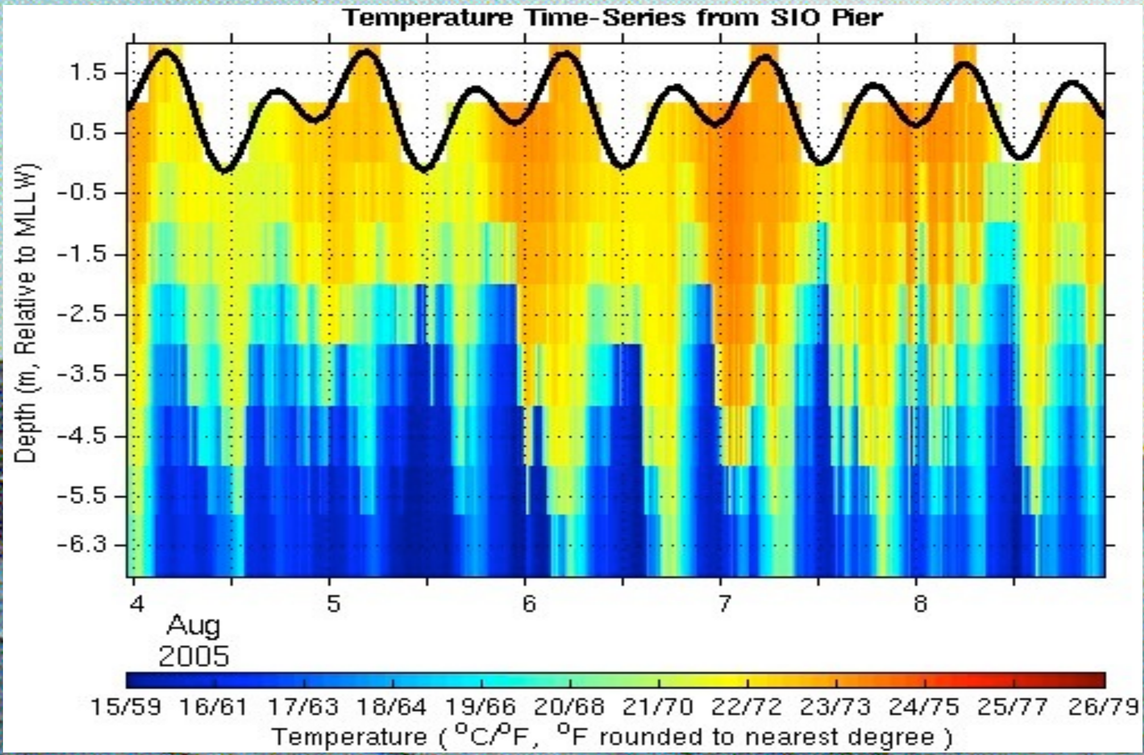
(J. Nash)

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

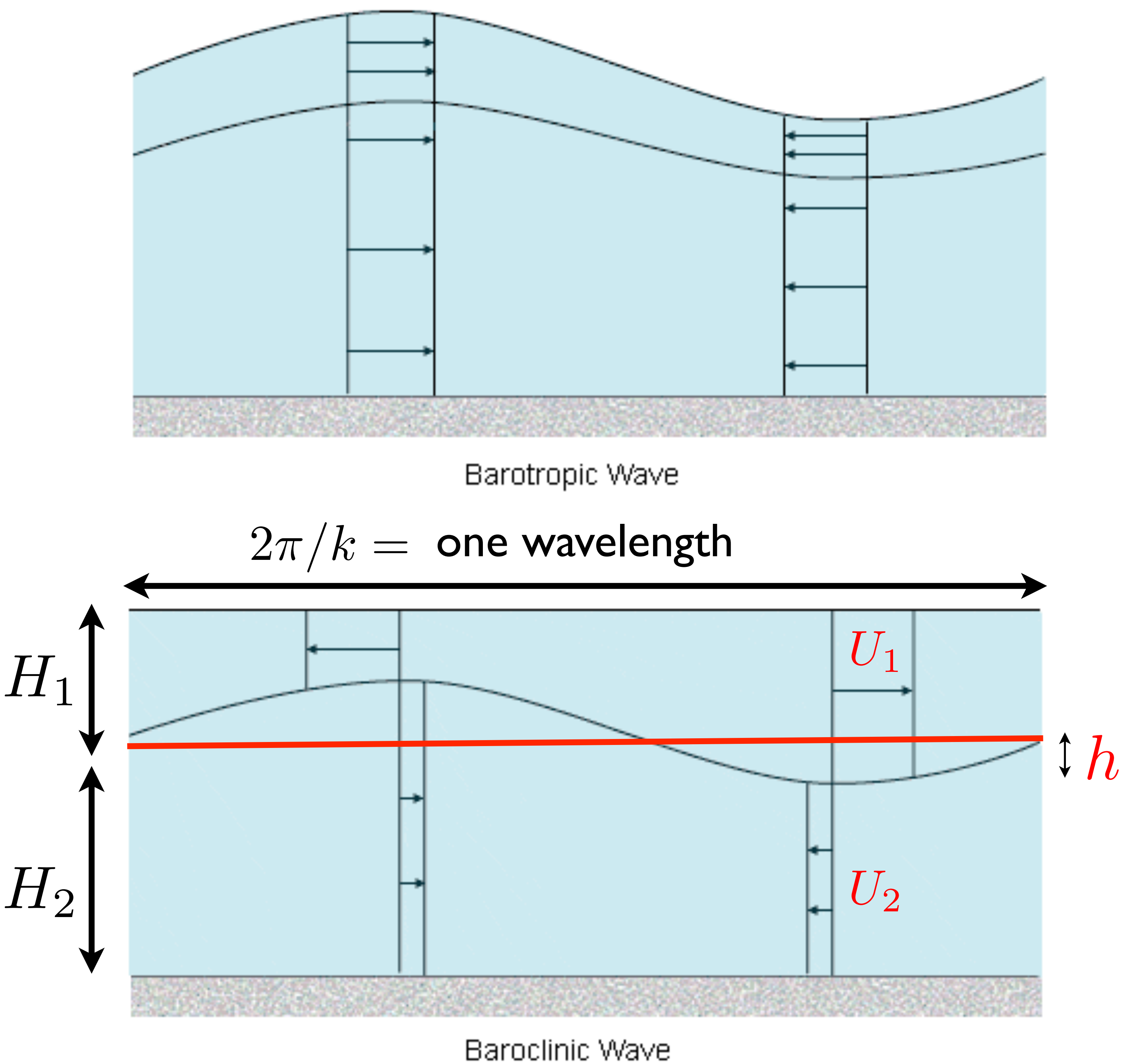
At UCSD, we see internal tides propagating onshore from the edge of the continental shelf

Tides beneath the surface

data and analysis courtesy of E. Terrill, SIO



Simple interfacial internal wave



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

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

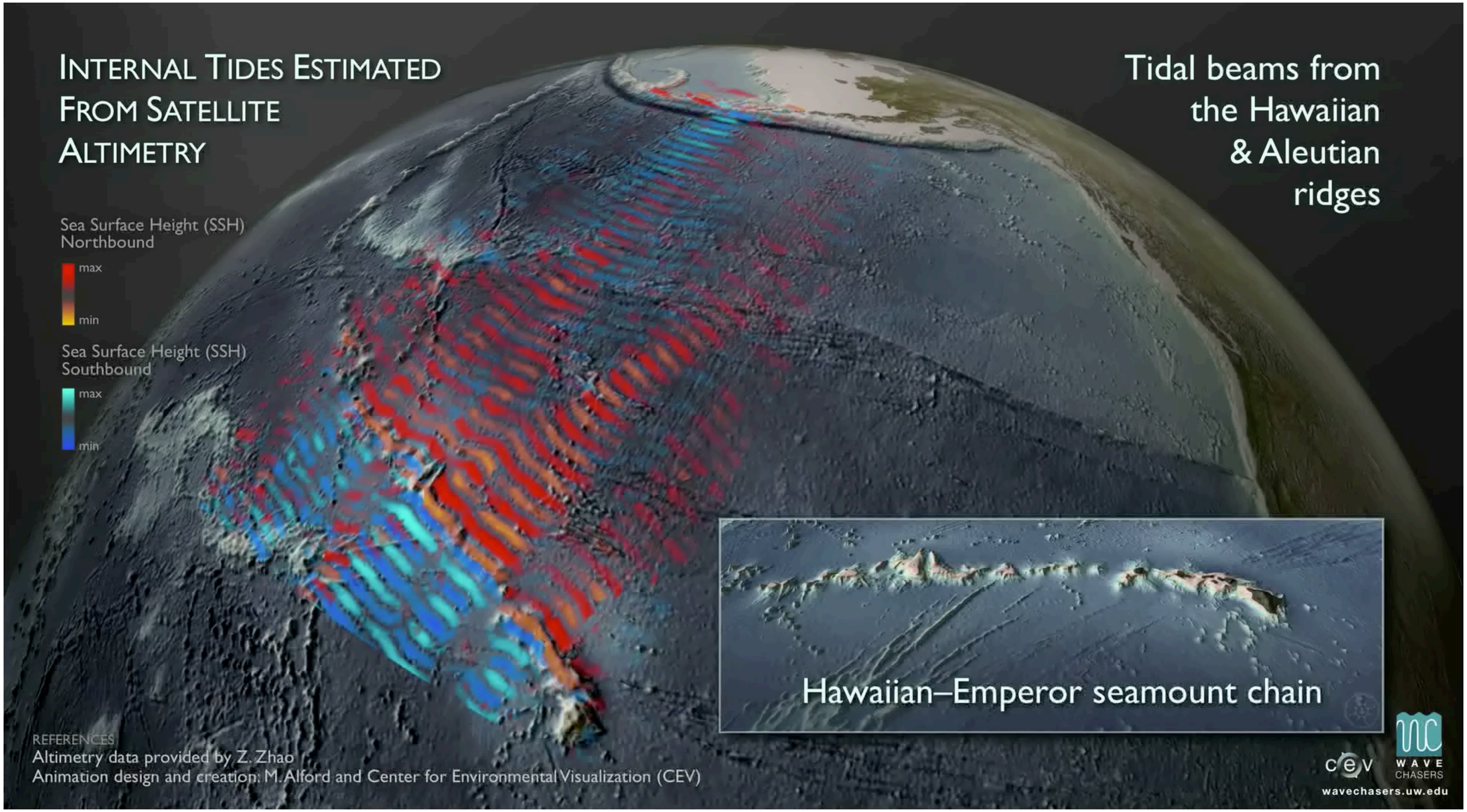
$$\mathbf{U_2 = -\frac{\omega h_0}{H_2 k} cos(kx - \omega t)}$$

after Gill,
Atmosphere-Ocean Dynamics


July 25, 2013
11:07 am

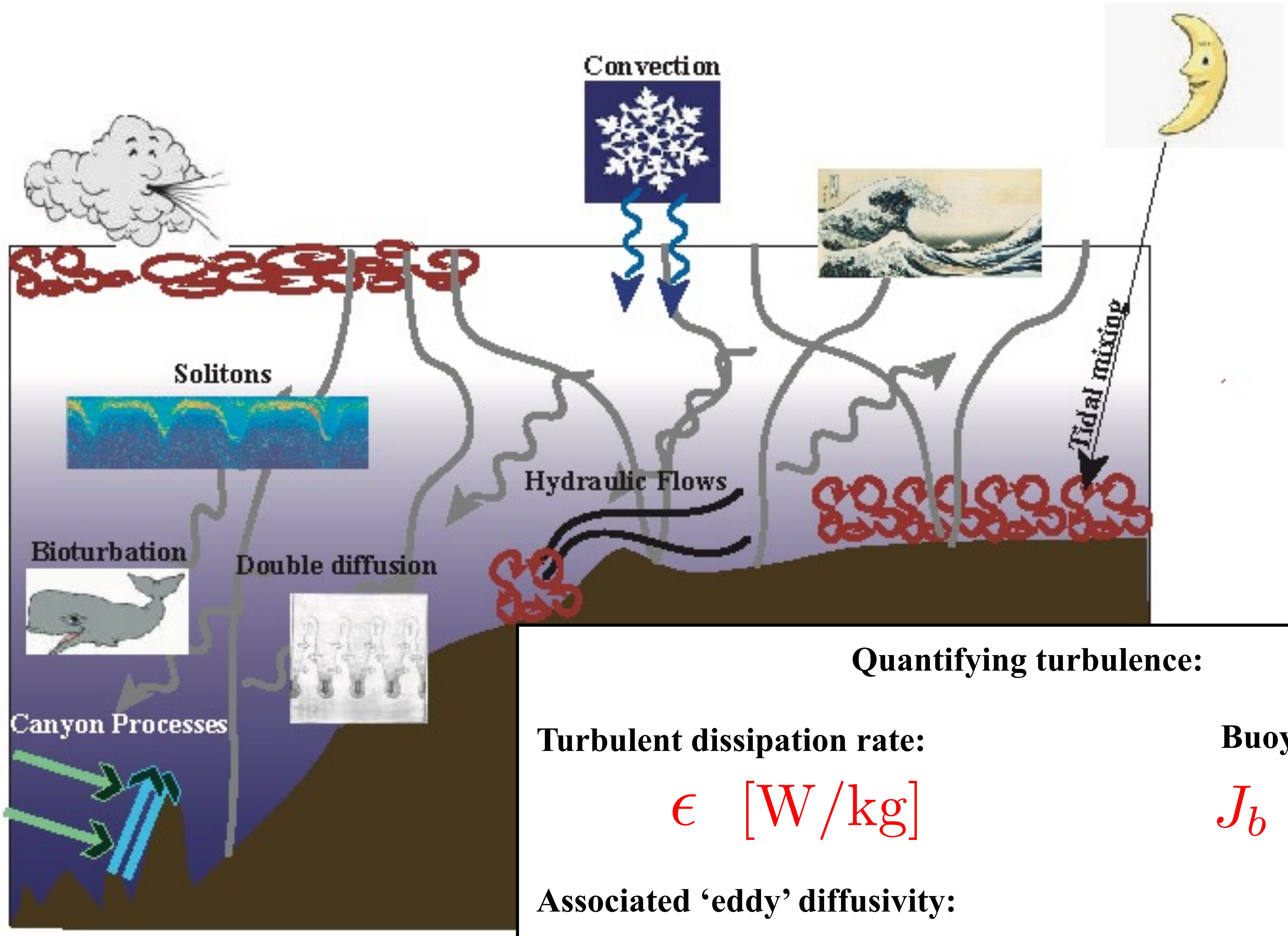

11:31 am

Long-distance internal waves



[Zhao and Alford]

Diapycnal (vertical) Mixing Mechanisms



Quantifying turbulence:

Turbulent dissipation rate:

$$\epsilon \quad [\mathrm{W/kg}]$$

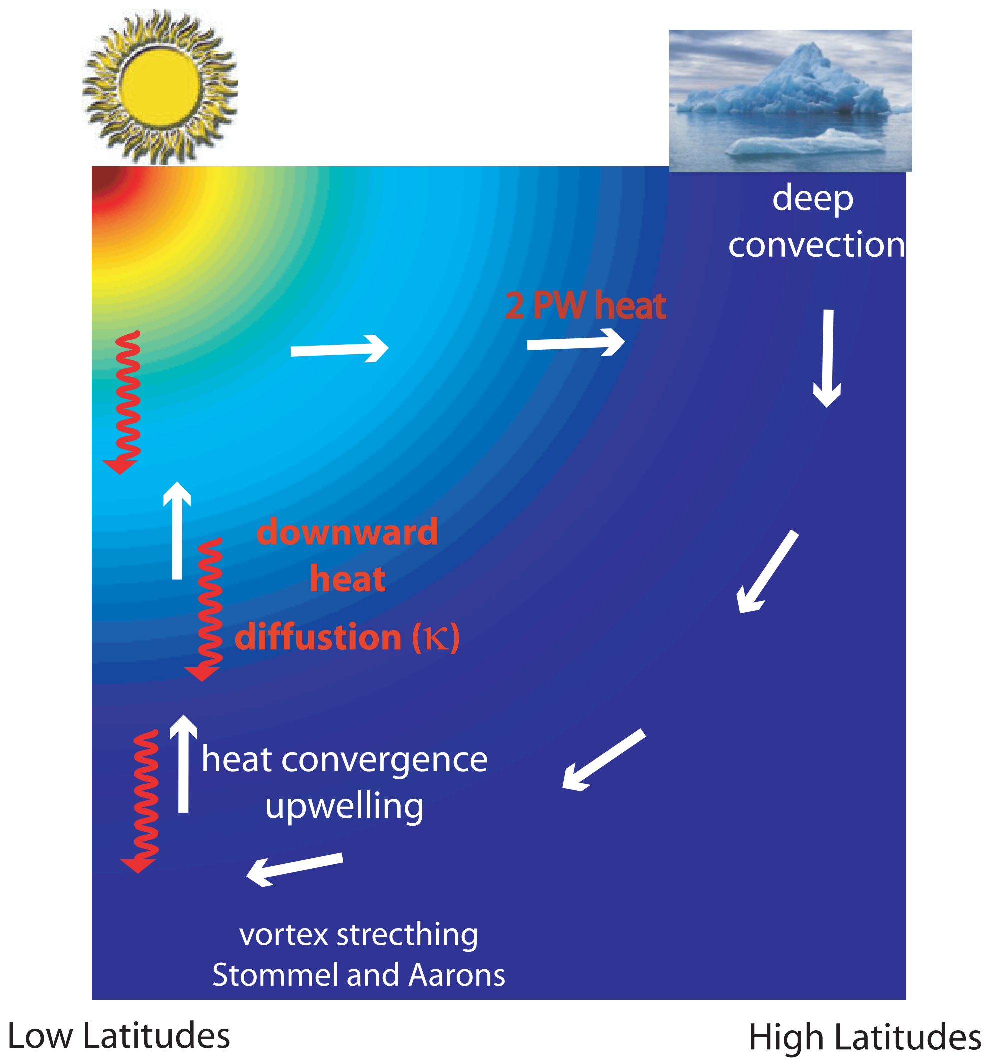
Buoyancy Flux:

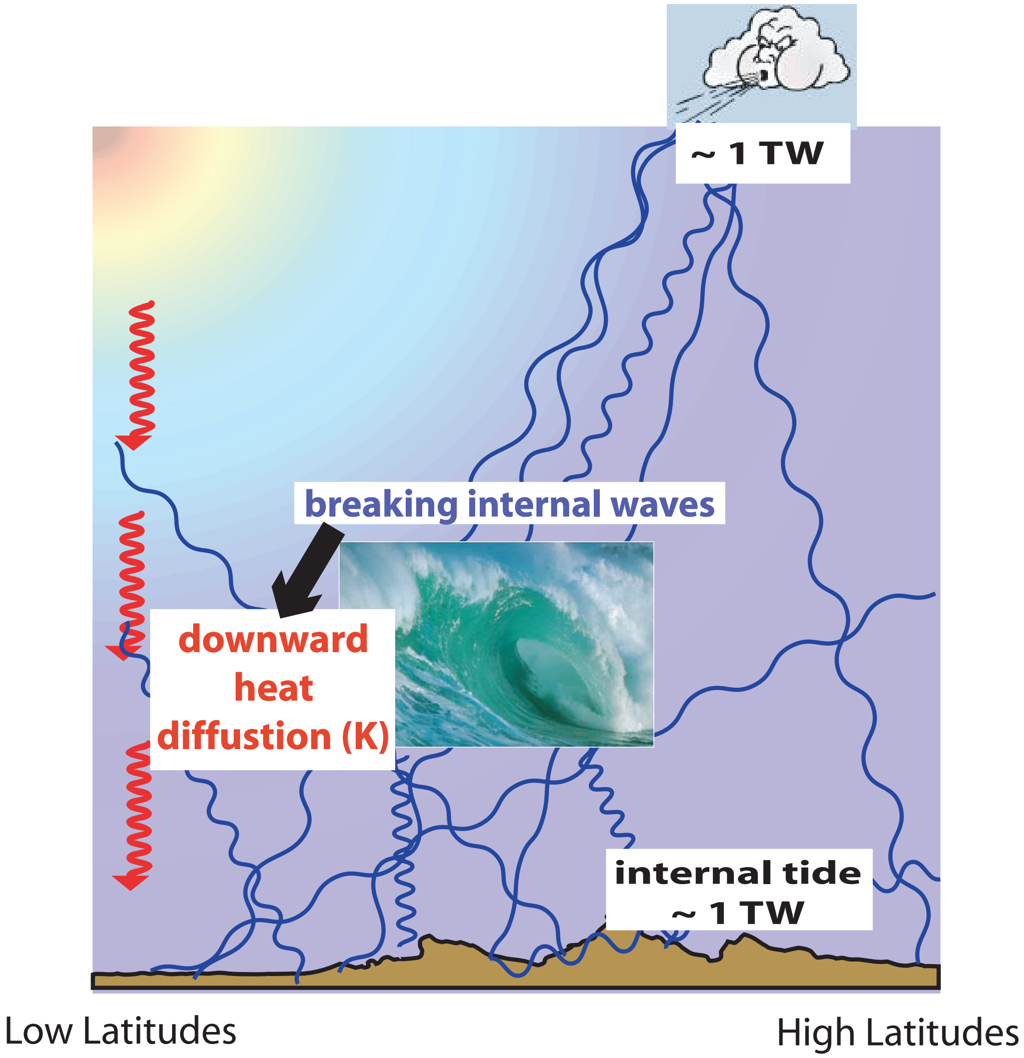
$$J_b = 0.2\epsilon$$

Associated 'eddy' diffusivity:

$$K_\rho = 0.2\frac{\epsilon}{N^2} \qquad [\mathrm{m^2/s}]$$

Turbulent mixing makes the ocean go round





- Determines large scale vertical transport of heat, C02, nutrients, etc.
- Drives meridional overturning circulation by creating potential energy.