Surface Waves

NOAA Tech Refresh

20 Jan 2012

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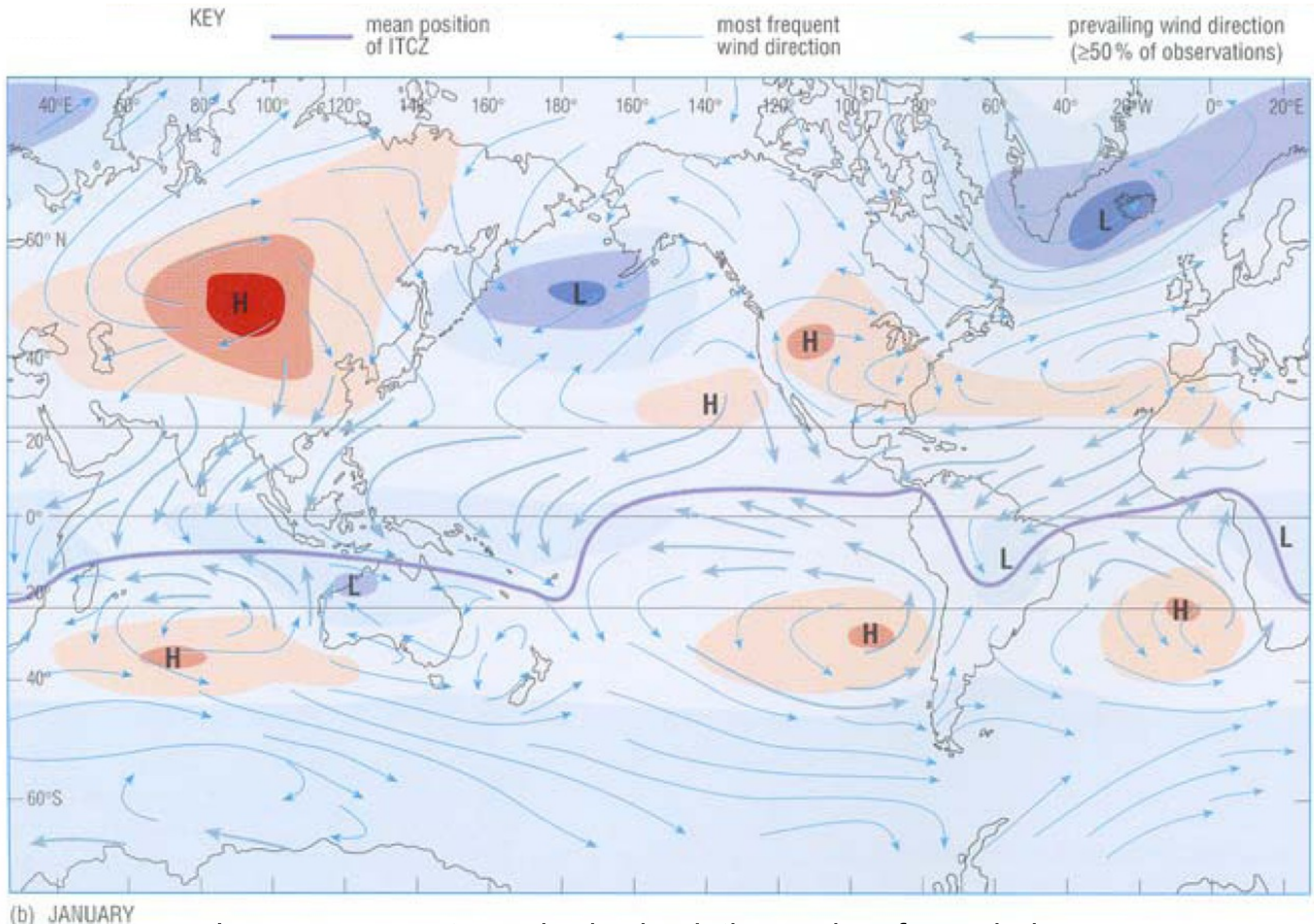
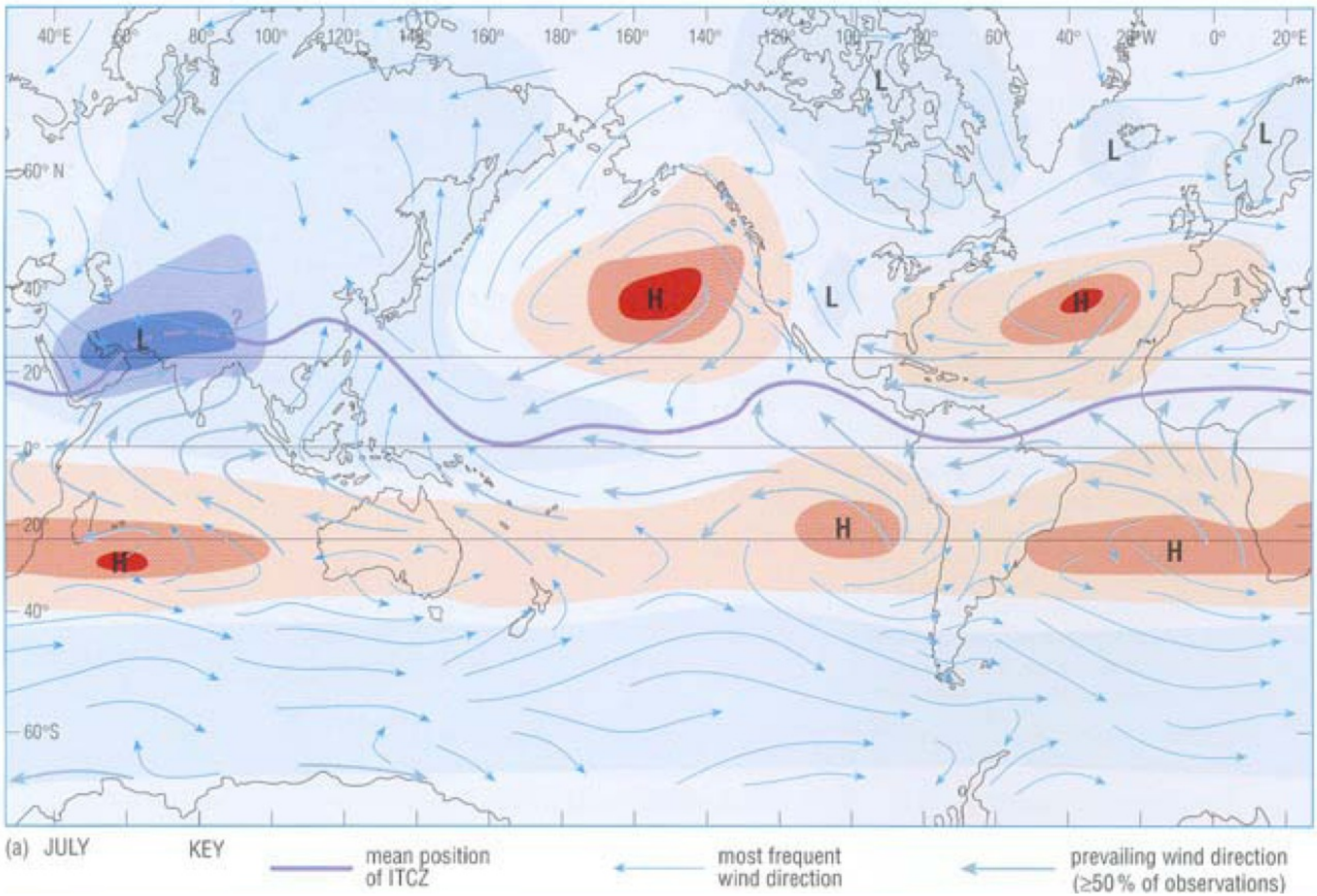
Outline

- Surface winds
  - Wind stress
  - Beaufort scale
  - Buoy measurements
- Surface Gravity Waves
  - Wave characteristics
  - Deep/Shallow water waves
  - Generation
  - Modeling



January mean atmospheric circulation and surface winds

Fig 2.3 Ocean Circulation

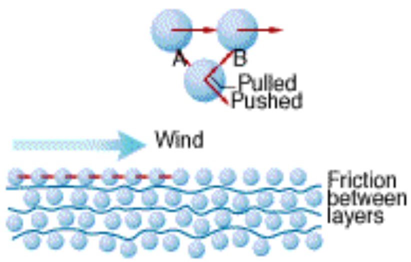


July mean atmospheric circulation and surface winds

Fig 2.3 Ocean Circulation

Wind Forcing at the Ocean Surface

- Wind-forcing can generate *currents and waves*, as wind transfers some of its momentum into the ocean
- Wind acts via friction at the surface: wind stress **τ**



Stresses have units of N/m^2, (force/area), like pressure. Stresses are forces parallel to a surface, pressure is force perpendicular to the surface.

- Force/Area depends on the square of the wind speed u, and it points in the same direction as the wind:

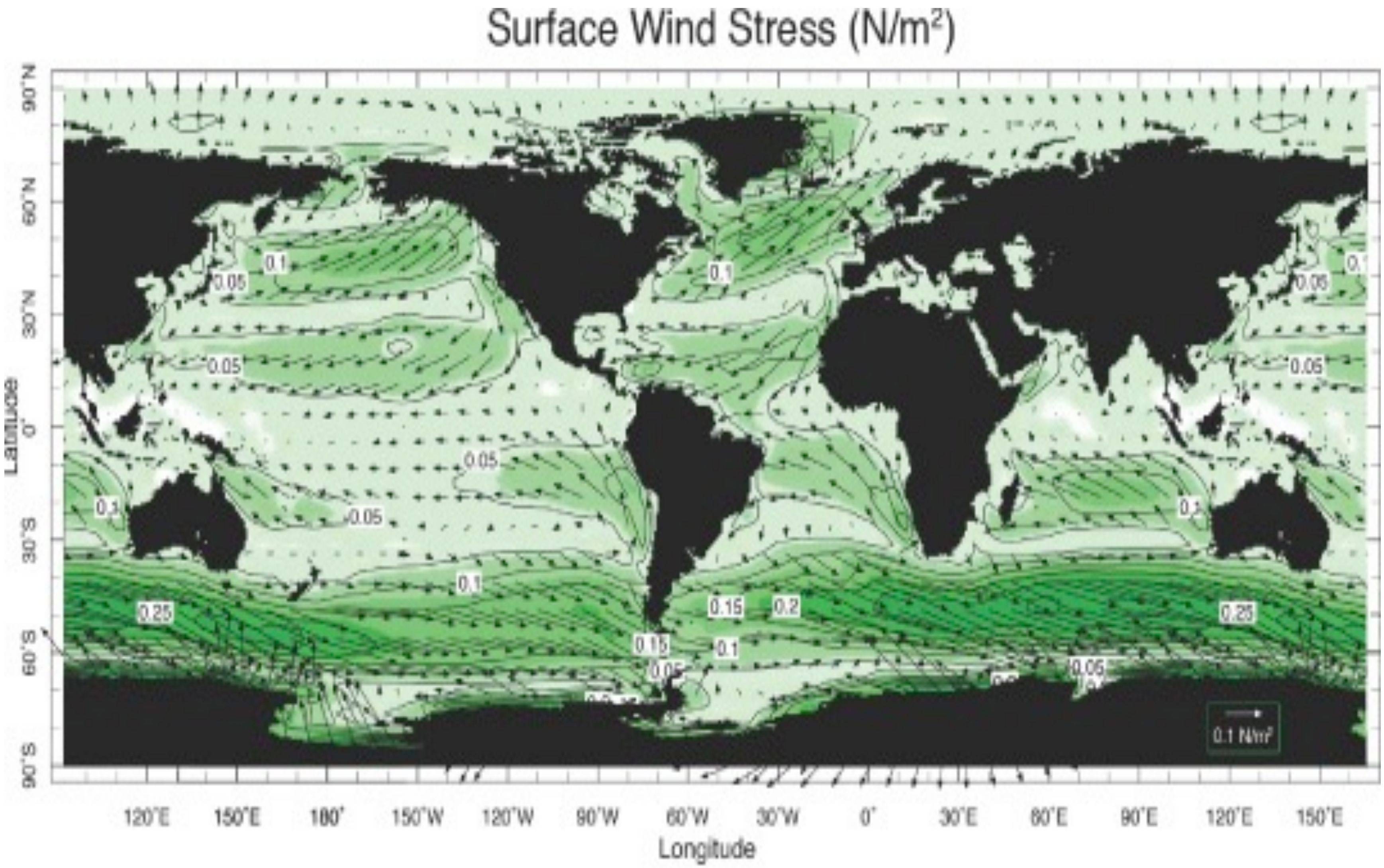
$$\tau \propto u^2$$

$$\vec{\tau} = \rho_a C_D |\vec{u}| \vec{u}$$

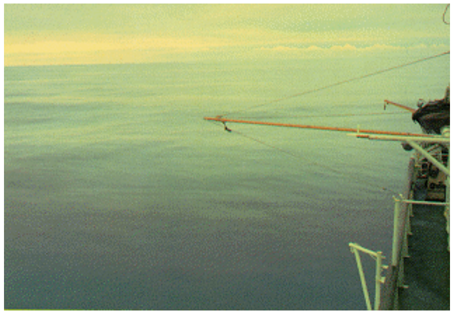
C_D = drag coefficient $\approx 1.4 \times 10^{-3}$

ρ_a = density of air $\approx 1.3\, kg/m^3$

Example: 20kt wind ≈ 10 m/s → 0.18 N/m^2 = 1.8 dyne/cm^2



Surface Wind Stress (N/m²)
Latitude
90°N
60°N
30°N
0°
30°S
60°S
90°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
30°W
0°
30°E
60°E
90°E
120°E
150°E
Longitude
0.1 N/m²



0, <1 knot

1, 1-3 knots

2, 4-6 knots

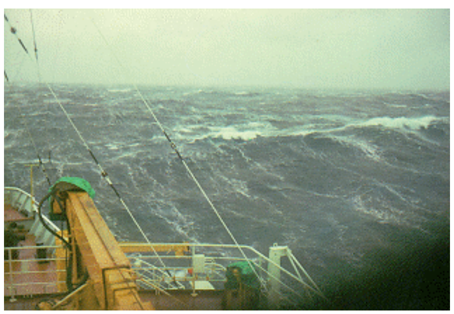
3, 7-10 knots

4, 11-17 knots

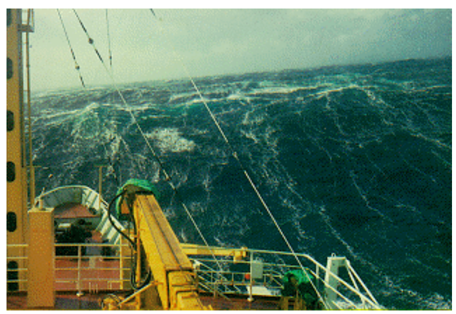
5, 17-21 knots

6, 22-27 knots

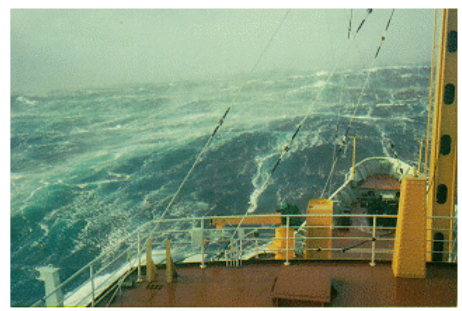
7, 28-33 knots



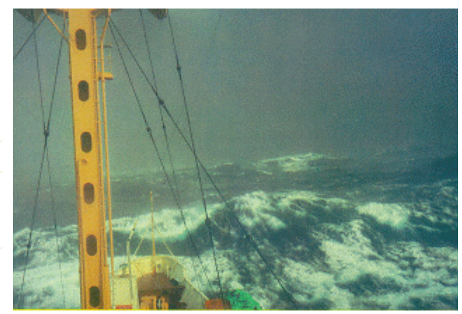
8, 33-40 knots



9, 41-47 knots



10, 48-55 knots



11, 56-63 knots

Beaufort scale, after http://www.geology.wmich.edu/Kominz/windwater.html

Beaufort scale still provides climatological data

Look at buoy winds off oregon coast.

http://www.wrh.noaa.gov/pqr/

Outline

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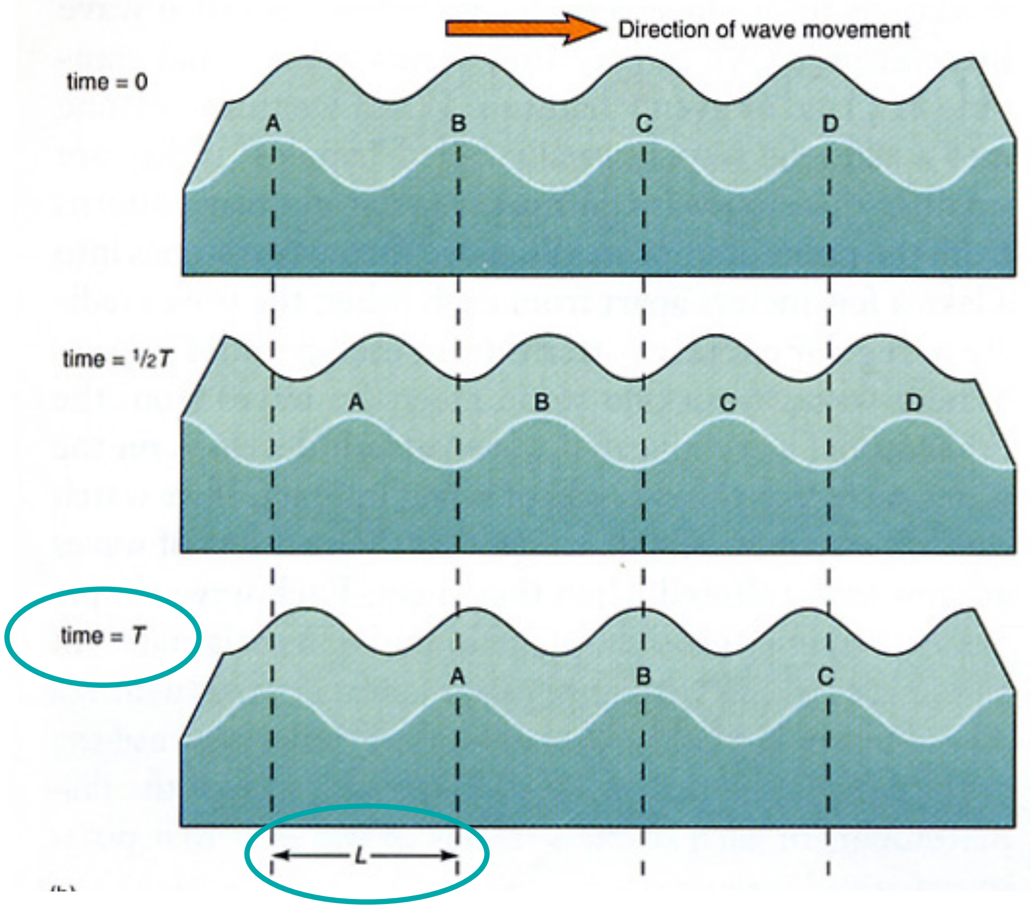
  - Wind stress
  - Beaufort scale
  - Buoy measurements
- **Surface Gravity Waves**
  - **Wave characteristics**
  - **Deep/Shallow water waves**
  - **Generation**
  - **Modeling**

Wave Propagation



Segar

- Wave Period **T**:
  time between arrival of successive wave crests at a given place
- Wave Length **L**:
  distance between successive wave crests
- Wave (phase) speed **c**:
  $\mathbf{c_p = L / T}$

By definition, the definition of c_p is valid for all waves.

Structure/Terminology for a surface wave on the ocean

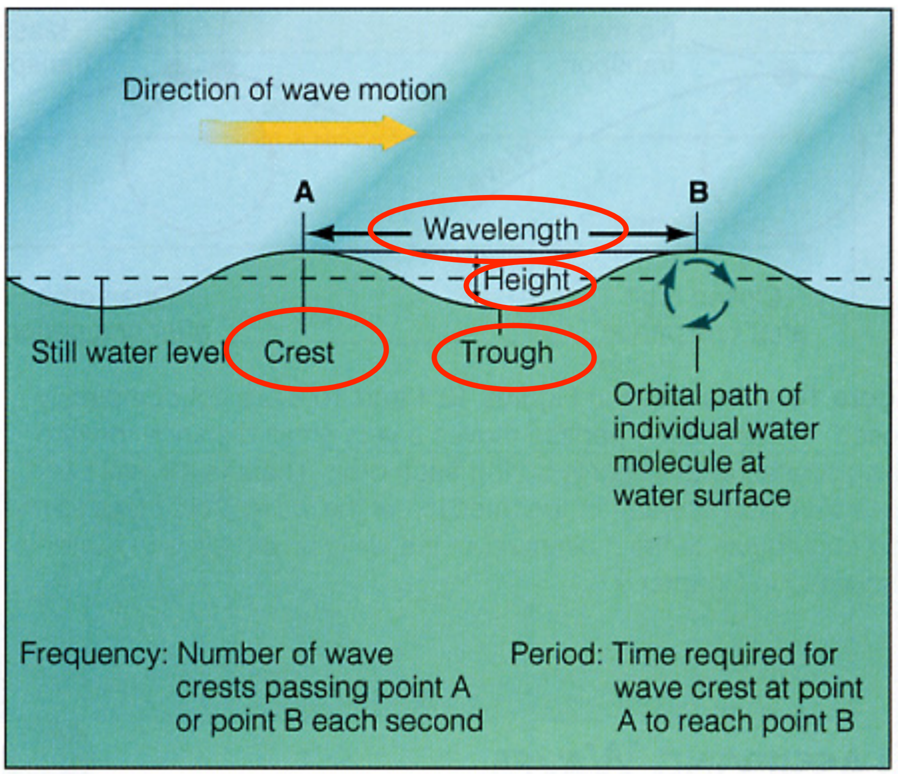


Figure 10.2 The anatomy of a progressive wave.

Garrison

- Crest: highest point on the wave
- Trough: lowest point on the wave
- Height **H**: vertical distance between crest and trough
- (Amplitude A: half of Height)
- Wavelength **L**: distance between adjacent wave crests

Other definitions

- L often written λ
- Wave number, $k = 2\pi/L$
- Radial frequency, $\sigma = 2\pi/T$ (also ω)
- Frequency, $f = 1/T$

Ocean Waves

- Disturbance: sea surface is displaced
  - winds
  - vertical displacement
  - produce pressure disturbance
- Restoring Force:
  - gravity
  - surface tension
  - Earth's rotation
- Propagation:
  - pressure gradients due to different water heights
- Dissipation
  - bottom friction
  - wave breaking

The ocean is a medium for a wide variety of waves with different sources and restoring forces.

Relative amount of energy

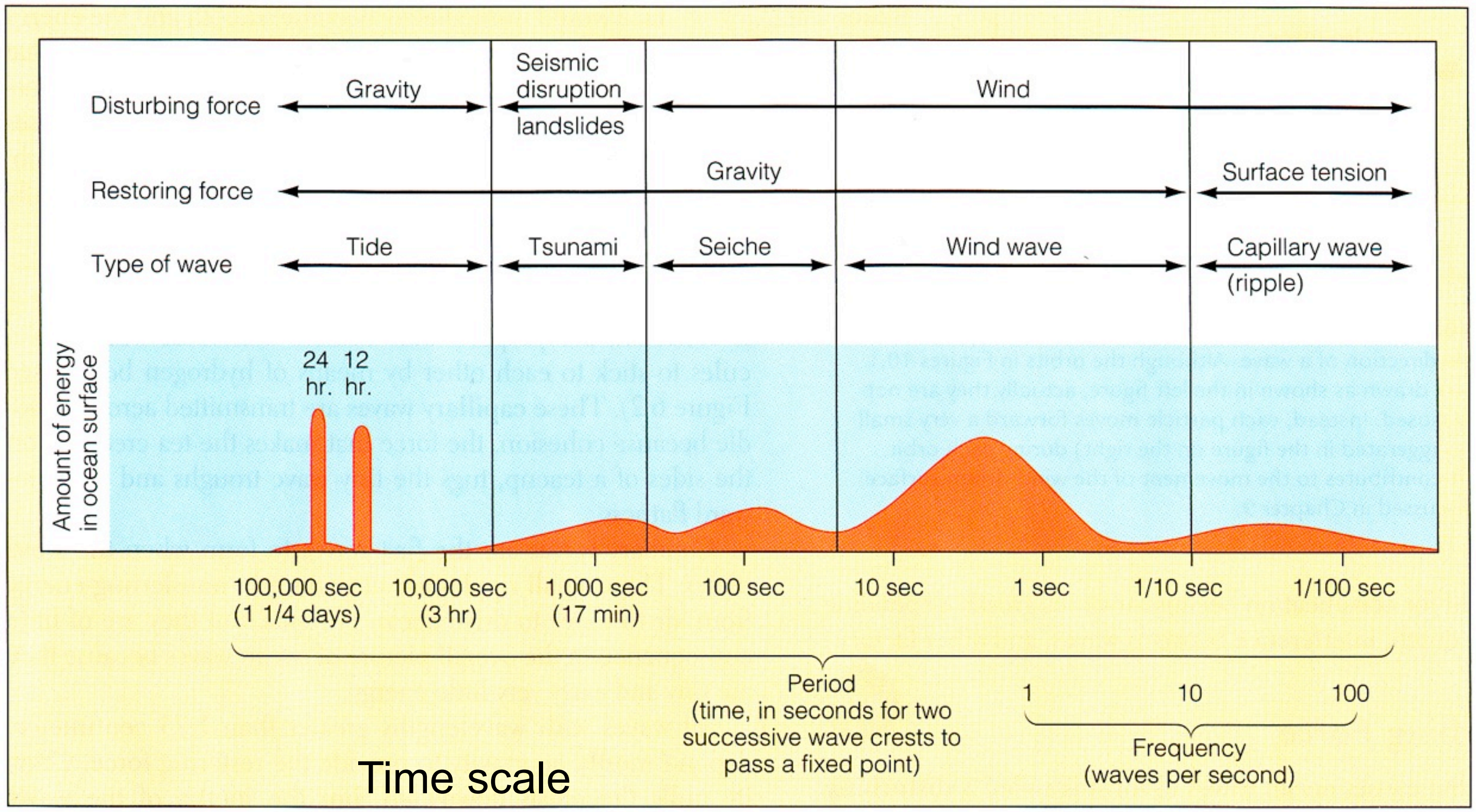
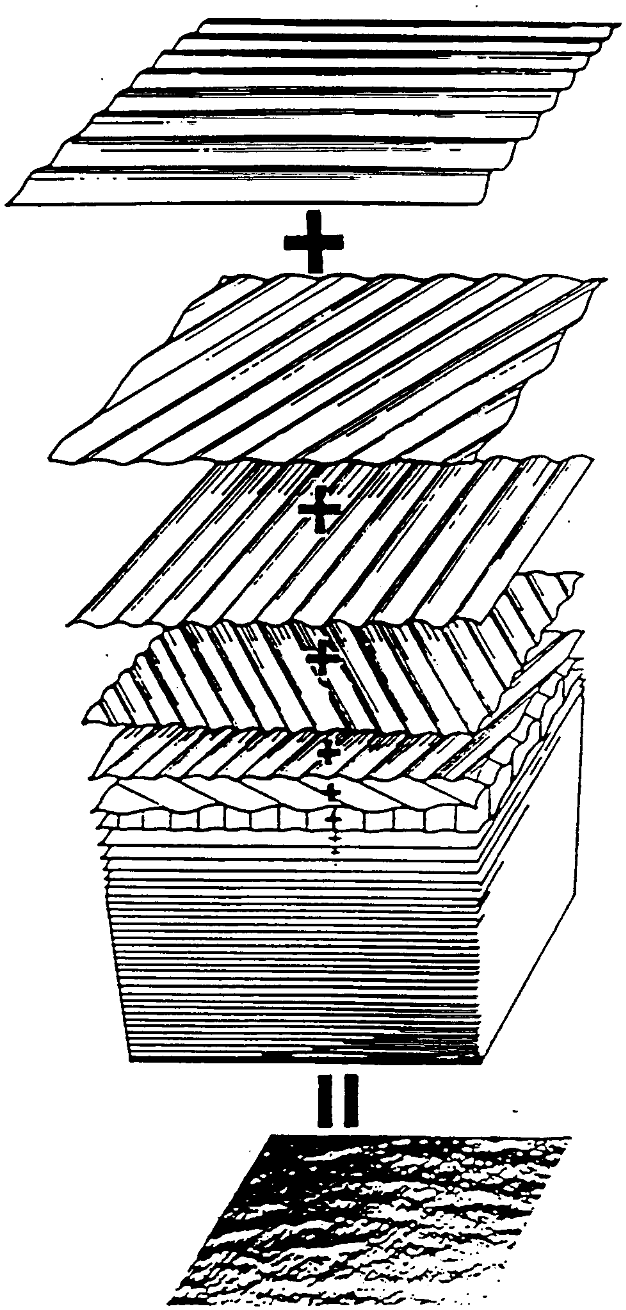


FIGURE 10.5 Wave energy in the ocean as a function of the wave period. As the graph shows, most wave energy is typically concentrated in wind waves. However, large tsunami, rare events in the ocean, can transmit more energy than all wind waves for a brief time. Tides are waves—their energy is concentrated at periods of 12 and 24 hours.

Note, what this figure refers to as wind waves includes locally generated wind waves and ocean swell.



Under linear theory, the sea surface can be represented by the sum of many simple sinusoidal wave trains of different periods and amplitudes moving in different directions.

From Pierson et al. (1955)

General dispersion relation for linear gravity waves

$$C_p = \sigma/k = L/T = \sqrt{\frac{gL}{2\pi}\tanh\left(\frac{2\pi d}{L}\right)}$$

- Derived from linearized conservation of momentum and volume with surface and bottom boundary conditions
- Good for any wavelength/depth combination
- C_p is (phase) speed
- g is gravitational acceleration (9.8 m/s^2)
- L is wavelength
- π is 3.14159…
- Depth, d
- Two limiting cases to consider

Deepwater (shortwave) dispersion relation

$$C_p = \sigma/k = L/T = \sqrt{\frac{gL}{2\pi}}$$

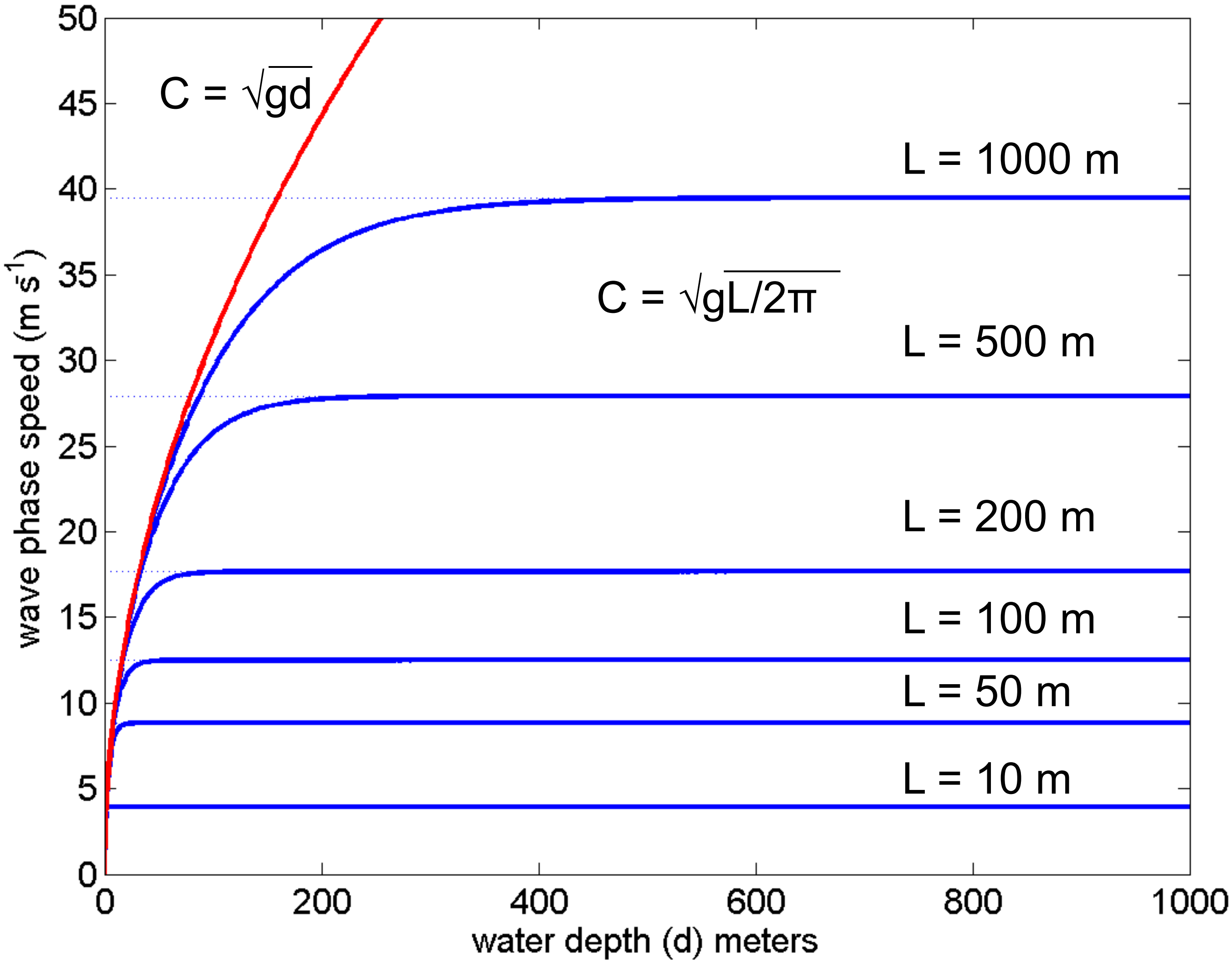
- Good for $2\pi d/L \gg 1$ ($kd \gg 1$), d> L/2
- Longer waves travel faster (dispersive)
- Know any one of c_p, T, L can get the others

Shallow water (long wave) dispersion relation

$$C_p = \sigma/k = L/T = \sqrt{gd}$$

- Good for $2\pi d/L << 1$ ($kd << 1$) or $d < L/20$
- c_p and d alone do not determine T and L
- c_p does not depend on wavelength so all wavelengths travel at same speed (non-dispersive)

General (blue) and shallow water (red) dispersion relation plotted for several different wavelengths, L



What is the motion of the water under waves?

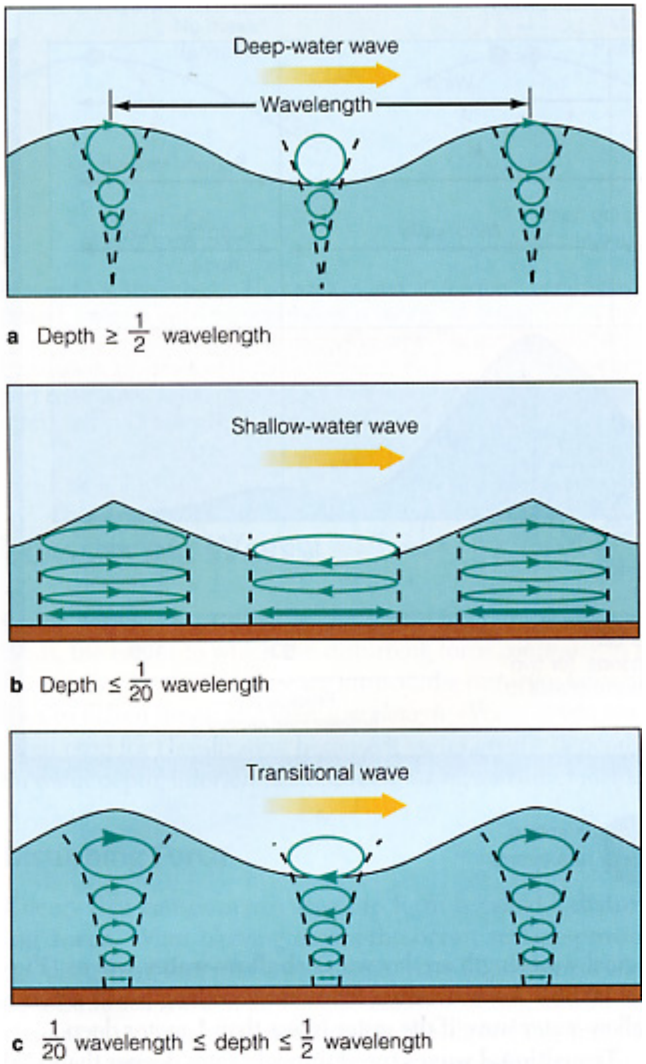
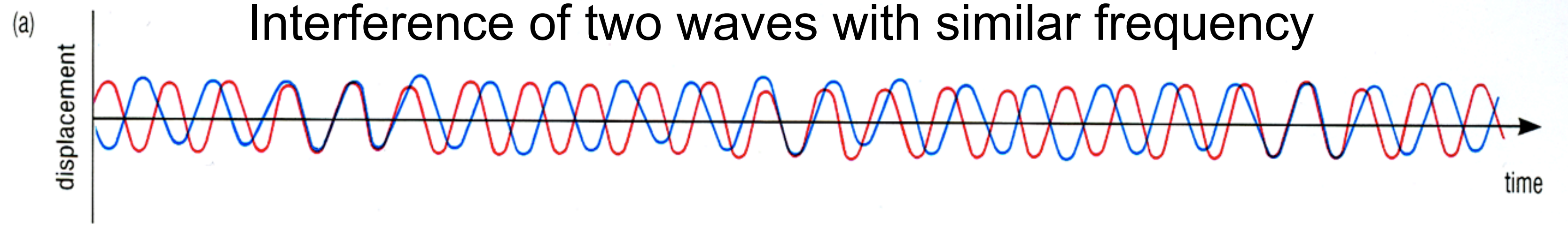


Figure 10.6 Progressive waves: (**a**) a deep-water wave; (**b**) a shallow-water wave; (**c**) a transitional wave. These diagrams are not to scale.

- Deep water wave:
  - nearly circular paths, shrink exponentially with depth
  - crests move with wave direction
  - wave motion ½ at L/9, essentially zero at depth of L/2
- Shallow water wave:
  - more along-wave motion than vertical
  - more flattened toward the bottom
- Transitional water depths:
  - intermediate

Interference of two waves with similar frequency



"seventh wave" phenomenon

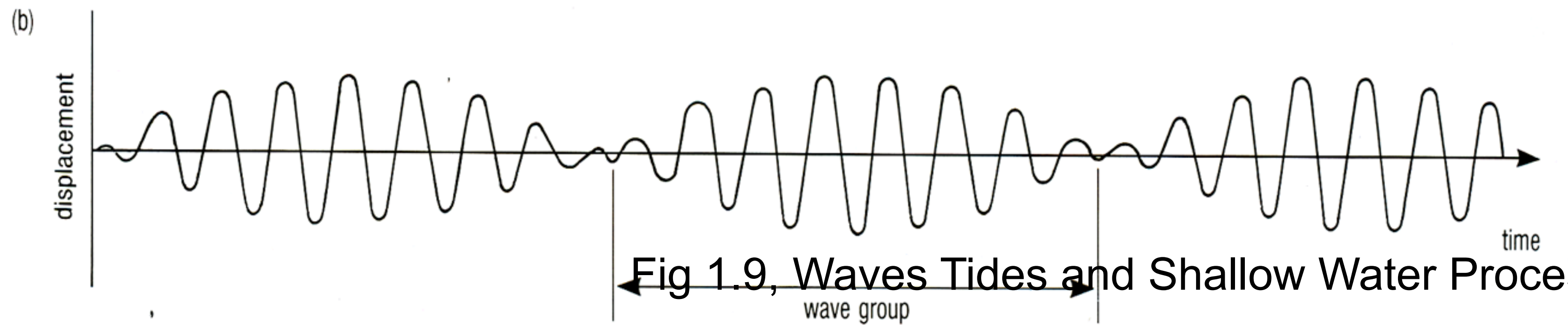


Fig 1.9, Waves Tides and Shallow Water Processes

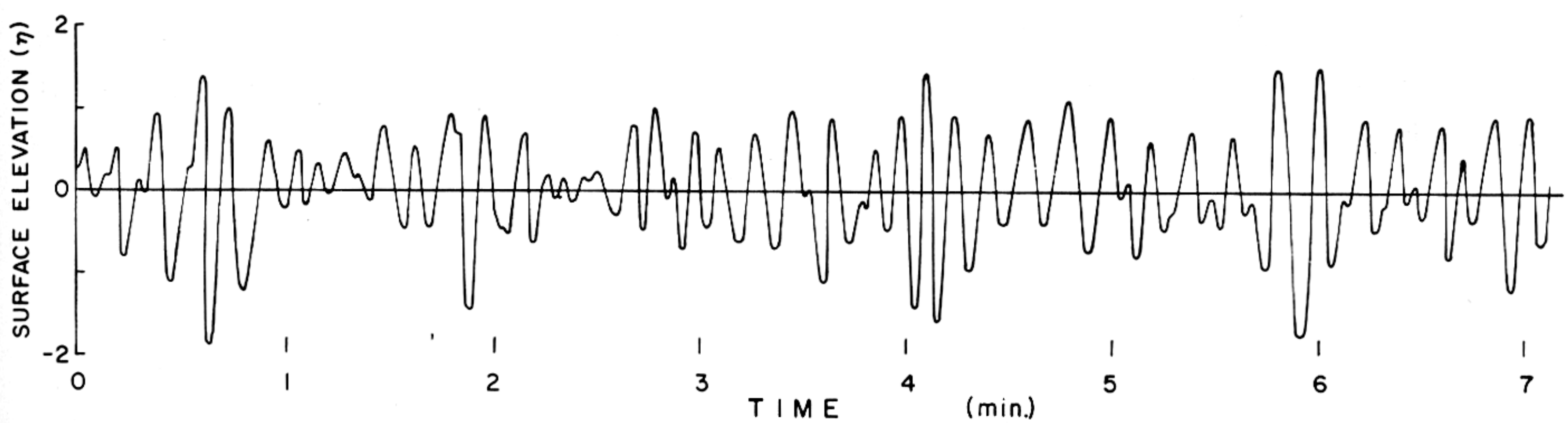


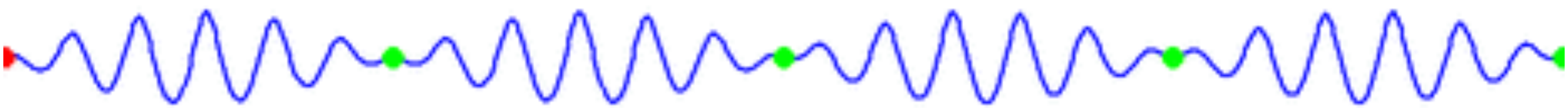
FIG. 12.10 *Character of real wave train (profile) to compare with ideal sine waves of Figs. 12.2 and 12.3. (Note that the vertical scale is much exaggerated as before.)*

Pond and Pickard (1983)

Group speed (c_g) and phase speed (c_p)

- c_p is the speed at which individual wave crests advance
- c_g is the speed at a wave group advances and the speed at which energy is transmitted by a wave
- For a dispersive wave, $c_g \neq c_p$
- c_p is determined by the definition $c_p = \sigma/k$
- $c_g = \partial\sigma/\partial k$ and is determined by the dispersion relation
- For deepwater waves $c_g = c_p/2$
- For shallow water waves (which are non-dispersive) $c_g = c_p$

Individual wave crests move faster than the group and advance through the wave group



Cp, phase speed = σ/k
Cg, group speed = ∂σ/∂k

Image courtesy of Wikipedia

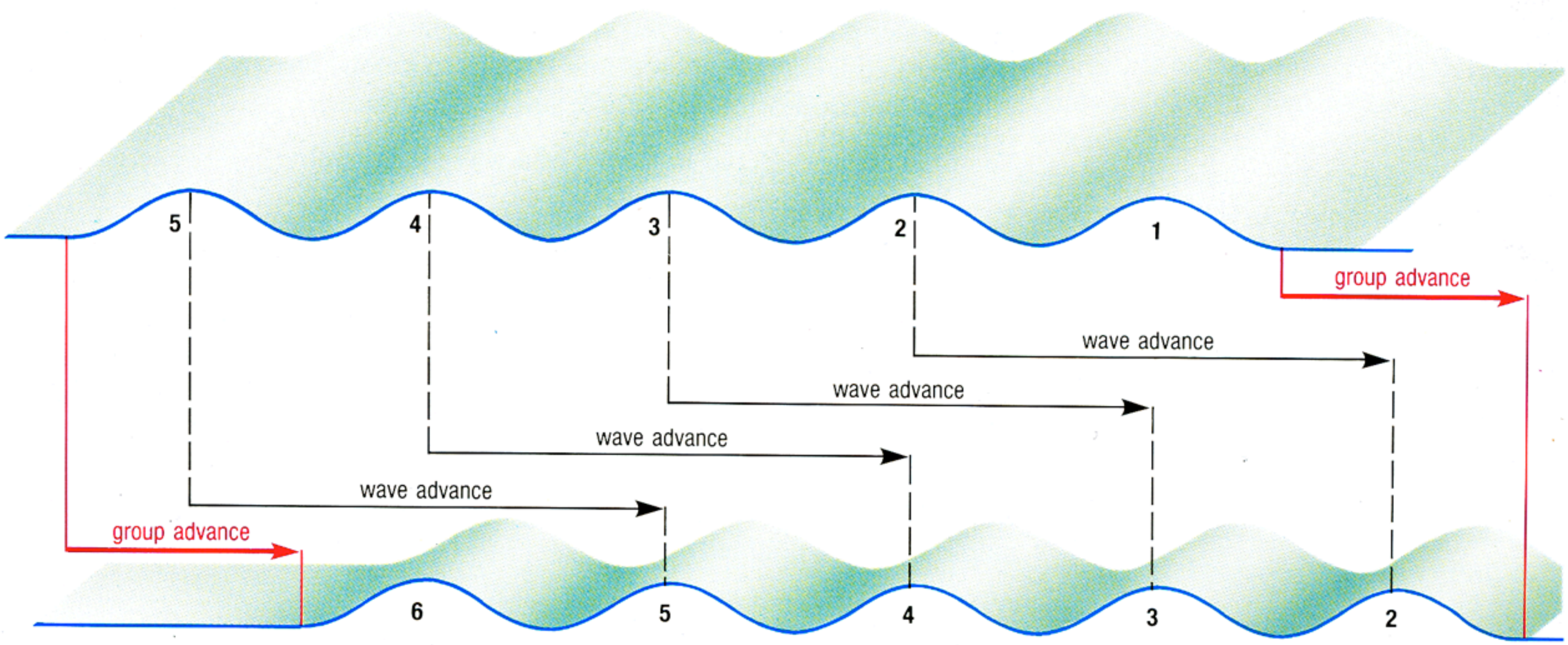


Fig 1.10 WTS

Group speed for deepwater waves

$$\sigma = \sqrt{gk}$$

$$c_g = \frac{\partial \sigma}{\partial k} = \frac{1}{2}\left(g/k\right)^{1/2}$$

$$\frac{c_g}{c_p} = \frac{1}{2}\left(g/k\right)^{1/2}\left(k/g\right)^{1/2} = \frac{1}{2}$$

Group speed for shallow water waves

$$\sigma = k\sqrt{gd}$$

$$c_g = \frac{\partial \sigma}{\partial k} = (gd)^{1/2}$$

$$c_p = (gd)^{1/2} \longrightarrow \frac{c_g}{c_p} = 1$$

Growth of Wind Waves

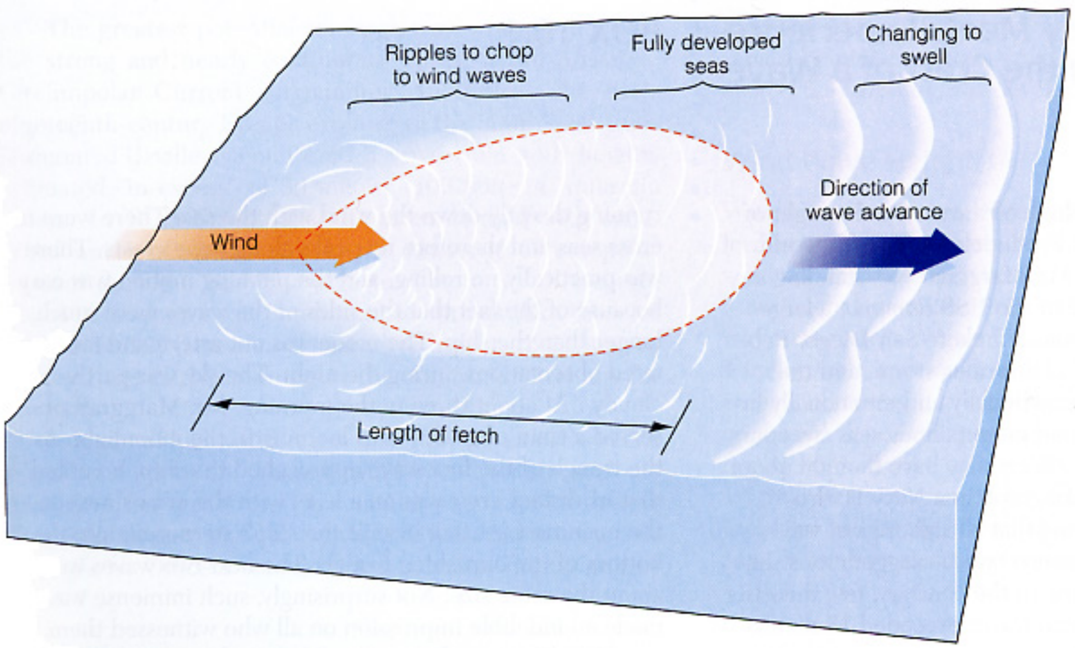
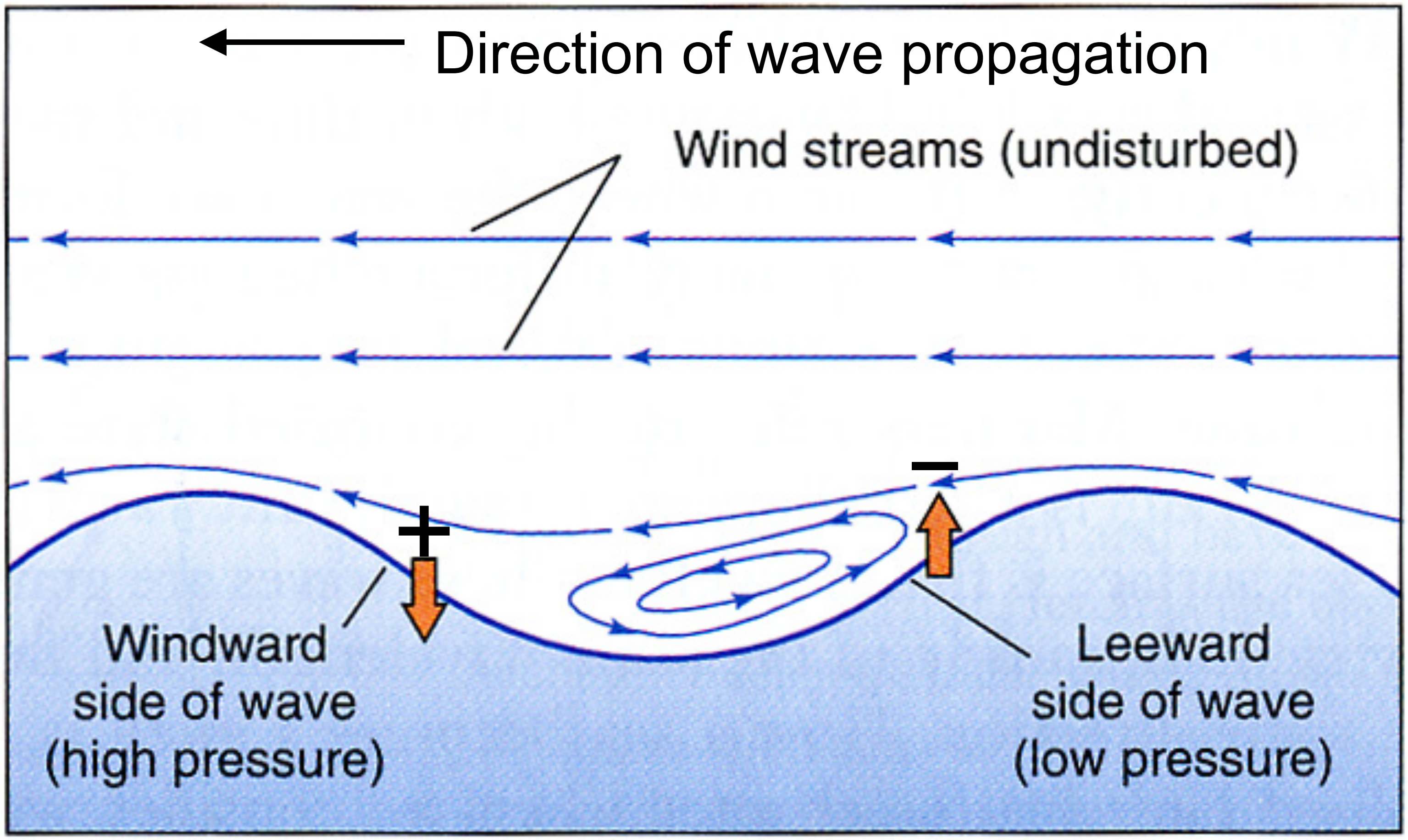


Figure 10.11 The fetch, the uninterrupted distance over which the wind blows without significant change in direction. Wave size increases with increased wind speed, duration, and fetch. A strong wind must blow continuously for three days for the largest waves to fully develop.

Note: a detailed examination of wave generation is beyond the scope of this class.

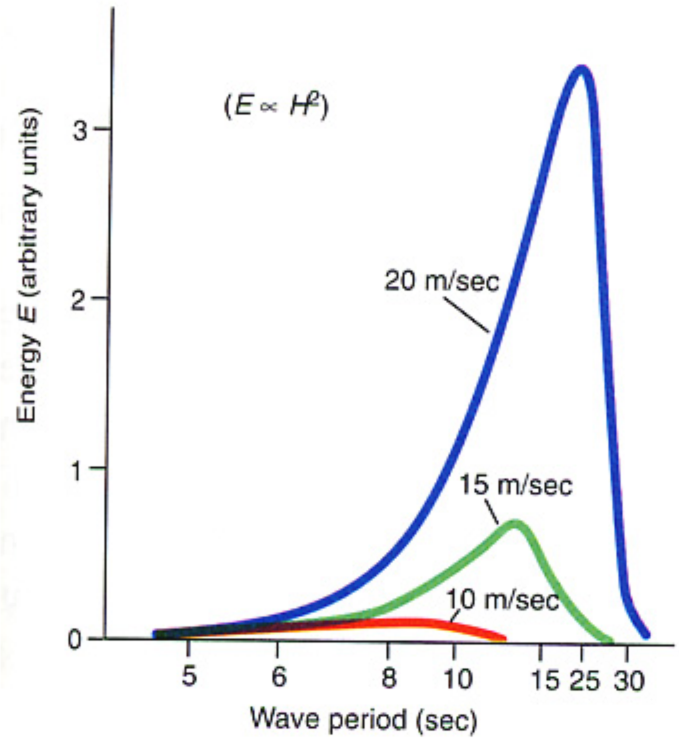
- Wind factors controlling wave growth:
  - strength
  - duration
  - fetch (distance over which the wind blows unimpeded across the water)

Jeffreys' sheltering model of wave generation

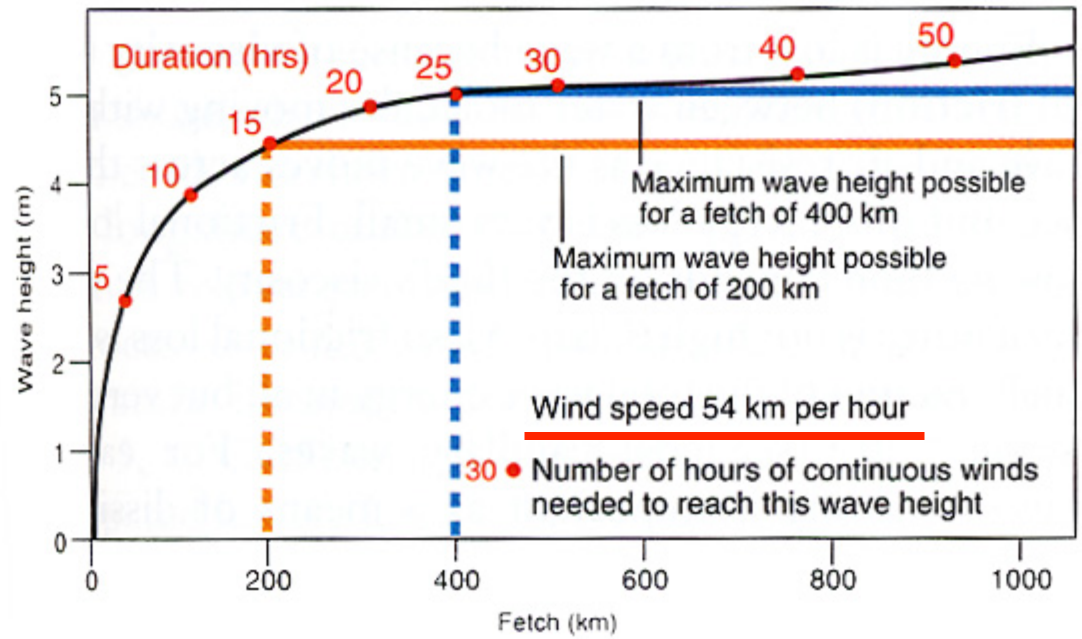


Fully-Developed Sea

Ocean waves so energetic that input from wind equals losses to wave breaking.

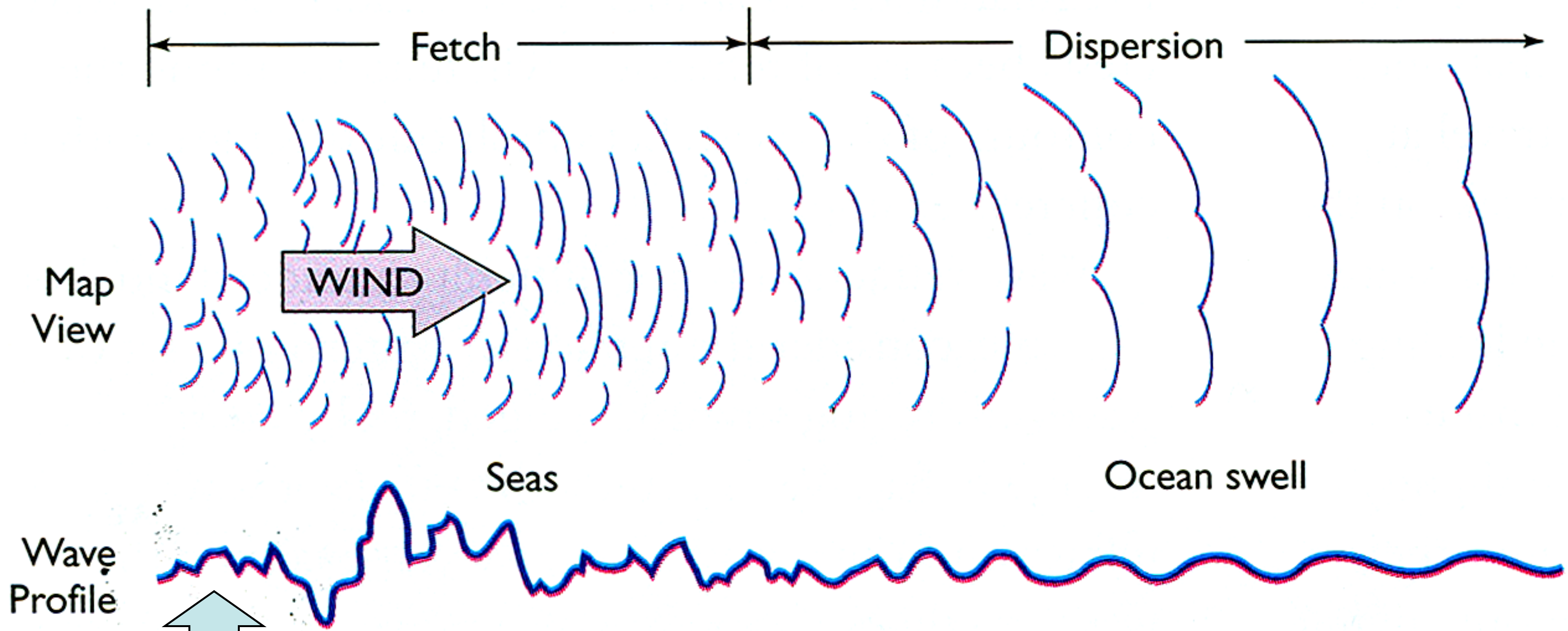


Compare to 16.7, IPO



- Stronger winds = more energy, longer T
  Duration to fully developed is about ½ to 1 day or so (depends on wind speed and fetch)

Deep-water wave transformations



(a) DEEP-WATER WAVE TRANSFORMATIONS

wave generation and growth

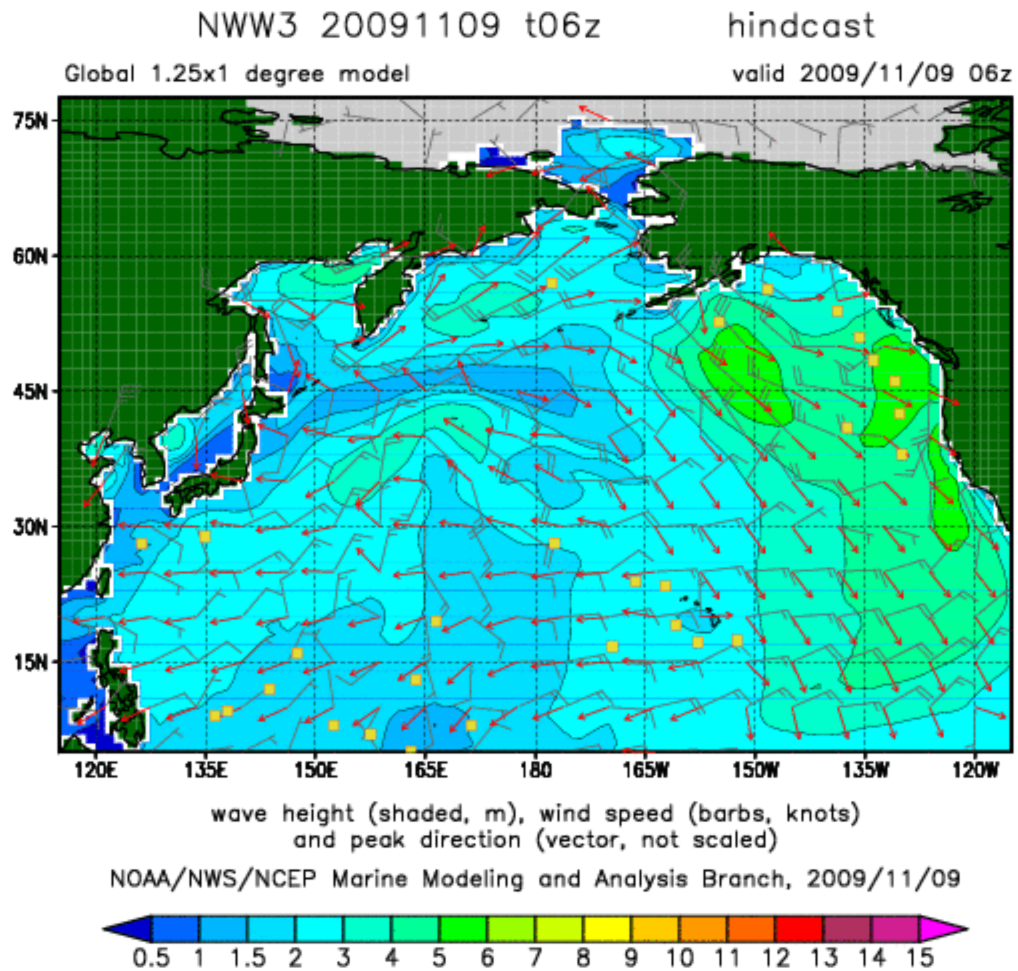
fully developed seas

wave dispersion

Remember: longer waves move faster

- **<u>Wind factors controlling wave growth:</u>**
  - strength
  - duration
  - fetch (distance over which the wind blows unimpeded across the water)

In practice, wave forecasts are based on heavily empirical formulas informed by meteorological models of winds

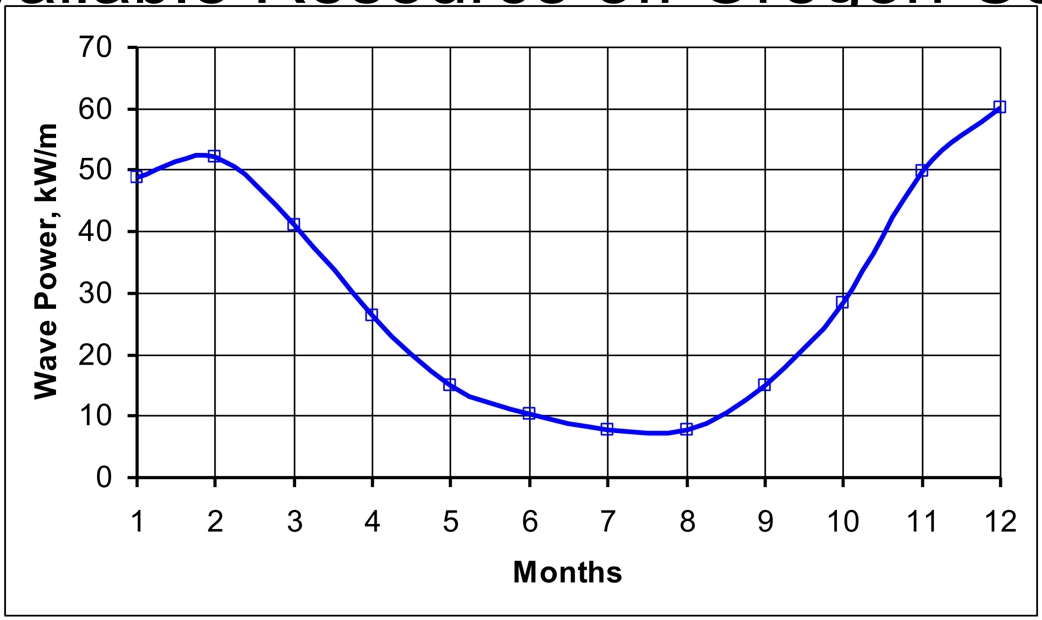


Model assumptions OK for spatial scales larger than 1-10 km

Can reach this link from NOAA WW3 page
https://www.fnmoc.navy.mil/ww3_cgi/index.html

Power from Ocean Waves
Available Resource off Oregon Coast

Seasonal variation – Good match for the NW load demand



Data buoys are 2-200mi off shore, with waves traveling 15-20mph, gives 10+ hours forecast time for buoy generators located 2 mi out

(wave data From National Data Buoy Center, Power estimated from 5 buoys off the Oregon coast over past 10 years)

Power from a wave is $P = \frac{\rho g^2 T H^2}{32\pi}$ W/m of crest length (distance along an individual crest)

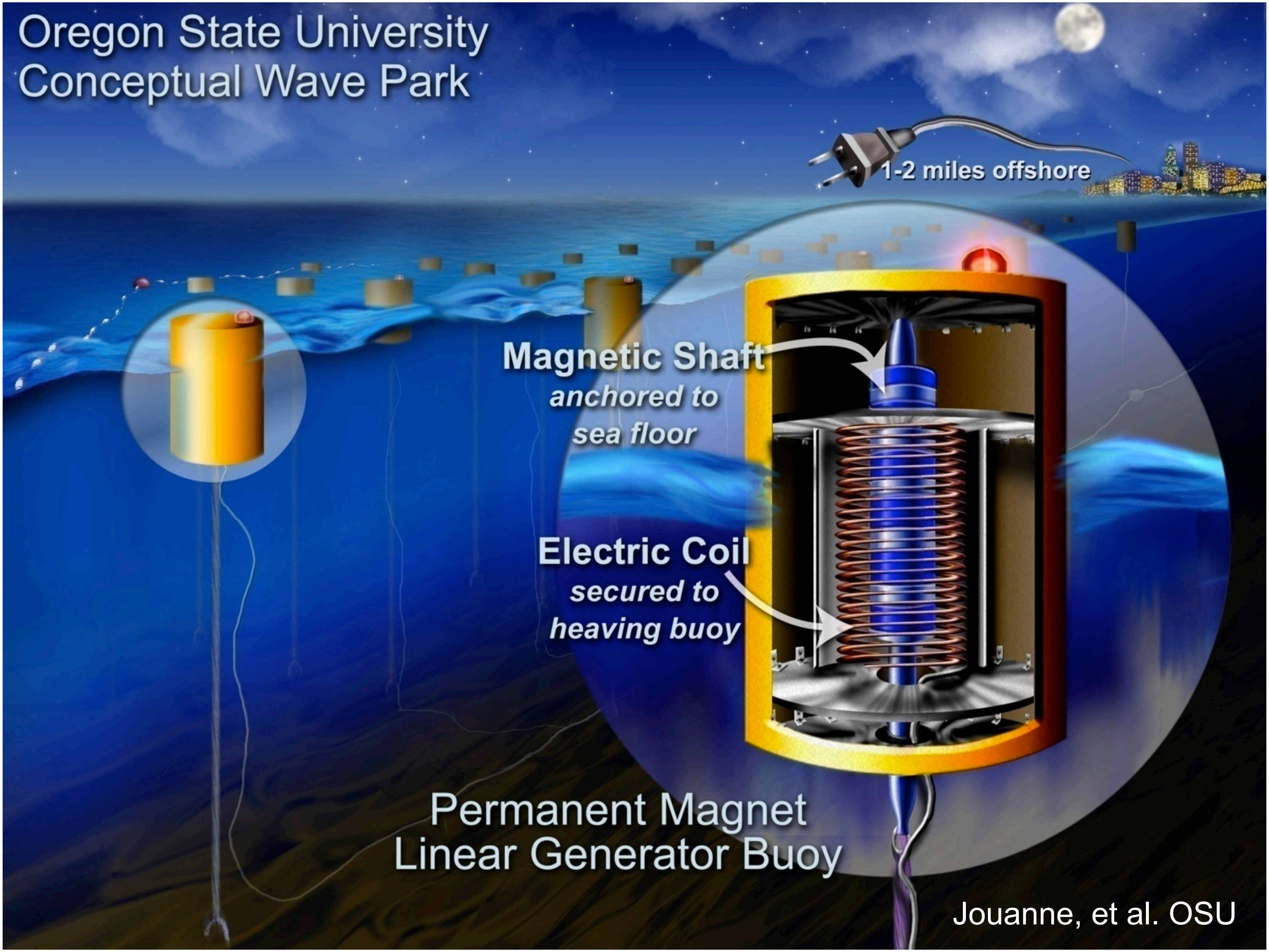
ρ = the density of sea water = 1025 kg/m^3

g = acceleration due to gravity = 9.8 m/s^2

T = period of wave (s) (averages 8s in the winter to 6s in the summer)

H = wave height (m) (averages 3.5m in the winter to 1.5m in the summer)

Jouanne, et al. OSU


Oregon State University
Conceptual Wave Park
1-2 miles offshore
Magnetic Shaft
anchored to
sea floor
Electric Coil
secured to
heaving buoy
Permanent Magnet
Linear Generator Buoy
Jouanne, et al. OSU