Deep-Water Waves

- How waves are generated
- Definition of wave height
- Factors & processes that determine wave height
- Factors & processes that determine wave speed
- Interactions of waves with each other
  - "Interference"
- Rogue waves

Wave Forecasting

- Suppose you are a:
  - Surfer
  - Small (or even large) boater
- You want to know:
  - How big the waves are going to be
  - When they will arrive
- Wave forecasters:
  - Observe open-ocean storms & waves
  - Forecast how big they will be
  - And when they will reach shore

Wave Forecasting

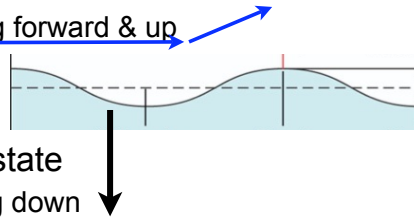
- Recent Marine Forecast

```
-OFFSHORE WATERS FORECAST
-NATIONAL WEATHER SERVICE WASHINGTON DC
-OCEAN PREDICTION CENTER/OCEAN FORECAST BRANCH
-930 PM PDT THU OCT 19 2006
-WATERS FROM CAPE SHOALWATER WA TO CASCADE HEAD OR OUT 20 TO 60 NM-

-TONIGHT
-N WIND 10 TO 15 KT WITH GUSTS TO 20 KT. WIND WAVES 2 FT. W SWELL 8 FT AT
 12 SECONDS. CHANCE OF DRIZZLE.

-COLUMBIA RIVER BAR-
-856 PM PDT THU OCT 19 2006

-...SMALL CRAFT ADVISORY FOR ROUGH COLUMBIA RIVER BAR IN EFFECT FROM
 FRIDAY AFTERNOON THROUGH FRIDAY EVENING...

-IN THE MAIN CHANNEL
-COMBINED SEAS 7 TO 8 FT TONIGHT AND 8 TO 9 FT FRI BUILDING TO 9 FT DURING
 THE EBB CURRENT AROUND 415 AM FRI
-AND BUILDING TO 11 FT WITH BREAKERS POSSIBLE DURING THE EBB CURRENT
 AROUND 445 PM FRI.
```

www.ndbc.noaa.gov/data/Forecasts/FZUS56.KPQR.html

Wave Terminology

- Disturbing force
  - Provides the energy to create water motion
    - Such as wind pushing forward & up
- Restoring force
  - Draws water surface back to undisturbed state
    - Usually gravity pulling down
- Wave results from combination
  - Disturbing + restoring
  - Oscillation like a spring



Wave Terminology

- Forced wave
  - Still being acted on by disturbing force
    - For example, while/where the wind is still blowing
- Free wave
  - Keeps traveling after force is removed
    - Wave keeps moving for a while after wind stops
    - Stored energy
    - Until energy is dissipated

Garrison Fig. 10.11 p. 236

Wave Generation

- Wind acting on water
  - Friction of moving air transfers energy to surface water
    - Inefficient on a smooth surface
  - "Capillary waves" form first
    - Restoring force is surface tension
    - Small ripples = "Cat's paws"

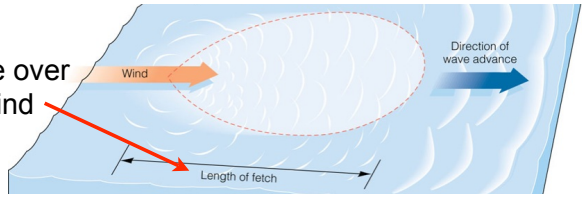
Wave Generation

- Wind "gets a grip"
  - Rippling on surface increases wind friction
  - Waves grow larger than 1.73 cm (0.68 in.)
  - Gravity becomes restoring force
    - "Gravity waves" mostly what we see on the ocean
- Travel 1000's of miles with very little energy loss

Wave Height

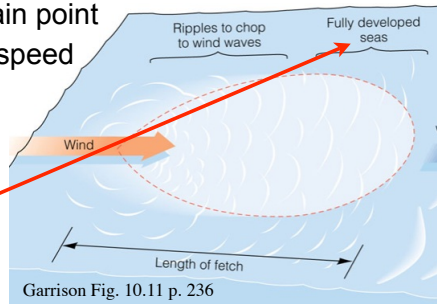
- 3 factors control growth of wave height
  - Wind speed
    - Wind carries more energy at higher speeds
    - More energy transferred to water surface
  - Wind duration
    - The longer the wind blows, the more energy is transferred to water surface
  - "Fetch"
    - Distance over which wind acts on water

Garrison Fig. 10.11 p. 236



Development of "Sea State"

- Wave height reaches a maximum
  - Limit on wave height may be set by any of the three factors
    - E.g., longer duration of wind will not increase wave height after a certain point
    - Depends on wind speed & fetch
  - When this limit is reached, waves are "fully developed."



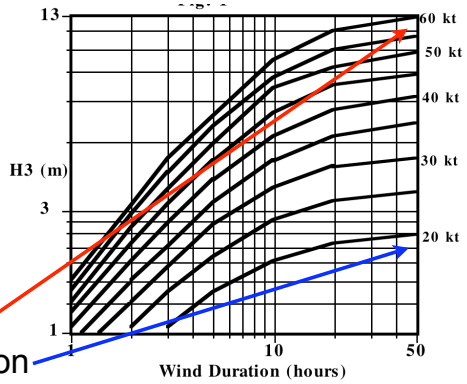
Garrison Fig. 10.11 p. 236

Definition of Wave Height

- In a storm, waves not all the same height
  - Mix of large & small waves
- How to describe the height in a useful way?
  - Average? Maximum?
- "Significant Height"
  - Abbreviated H_3
  - Average of largest 1/3 of all waves
    - Root mean square
    - Energy proportional to height squared

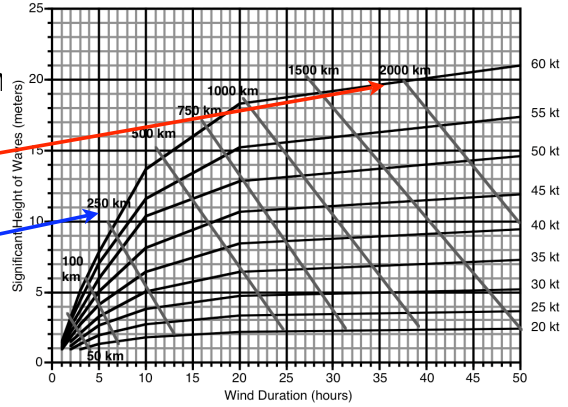
Development of "Sea State"

- Significant wave height H_3 becoming fully developed
  - Derived from US Navy method
  - Used to predict seas for D-Day
- Seas fully developing at:
  - High wind speed
  - Long wind duration
    - Logarithmic scale



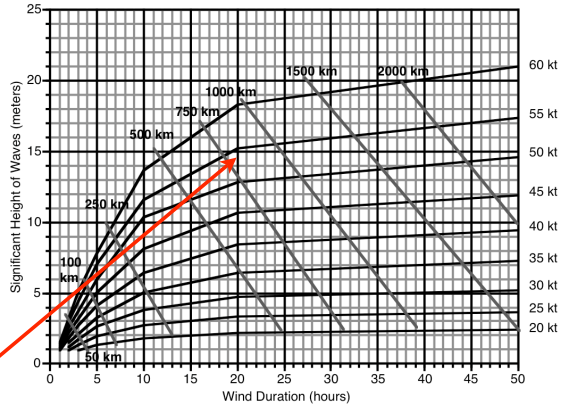
Role of Fetch

- If fetch is short, seas develop less
  - Limits H_3 as speed & duration increase
  - Long fetch
  - Short fetch
  - Diminishing effect



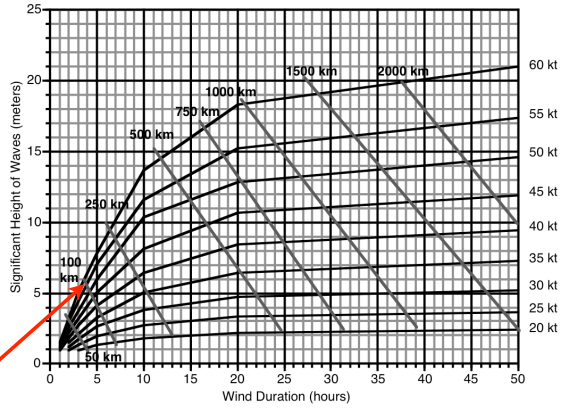
Reading the Wave Graph

- Suppose the wind blows at 55 knots for 20 hours
  - Open ocean
  - Infinite fetch
- What is H_3 wave height forecast?
  - ~15 m



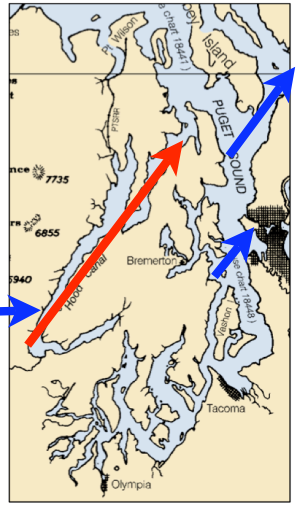
Reading the Wave Graph

- Suppose the wind blows at 55 knots for 20 hours
  - Puget Sound
  - Fetch = 100 km
- What is H_3 wave height forecast?
  - ~6 m



Case Study of Fetch

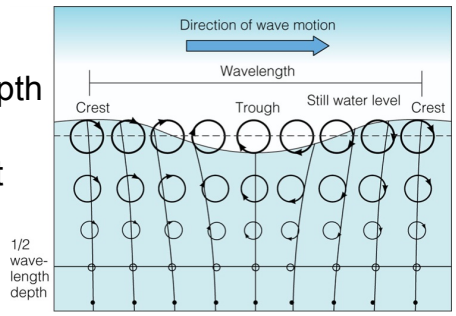
- Hood Canal Bridge
  - Storm February 13, 1979
  - Winds from SSW 80 mph
    - = 70 kt (gusts to 120 mph)
  - Duration = "several hours"
  - Fetch 55 miles = 92 km
- Less fetch = less damage



www.historylink.org/essays/output.cfm?file_id=5501

Depth of Wave Motion

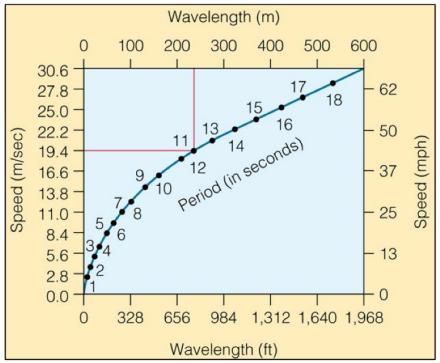
- Source of energy for wave is at the surface
  - Energy is transmitted downward
  - Internal resistance (viscosity) of water absorbs some energy
  - Amount of energy decreases with depth
    - Size of "orbits" too
  - No wave motion at & below L/2
  - If depth >L/2 = "deep water"



Garrison Fig. 10.3 p. 230

Deep-Water Wave Speed

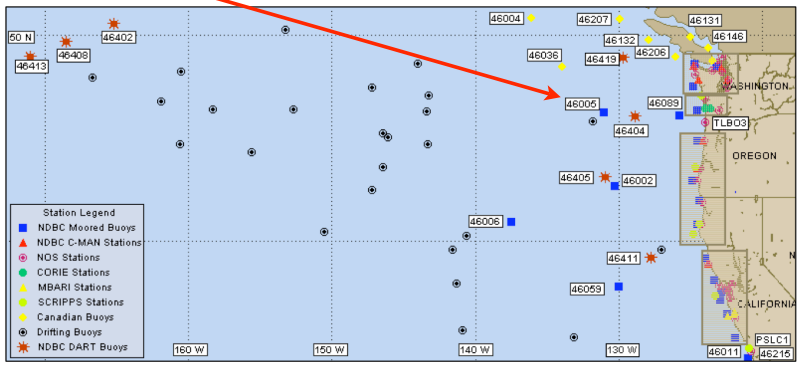
- Long waves are faster
  - Speed C proportional to T (period)
  - Speed proportional to √L (wavelength)
  - L proportional to T^2
- Measure C, L, or T
  - Other 2 can be calculated
  - T is easiest to measure



Garrison Fig. 10.7 p. 233

Observing Deep Waves

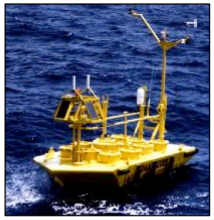
- Federal government system of wave buoys
  - www.ndbc.noaa.gov/station_page.php?station=46005

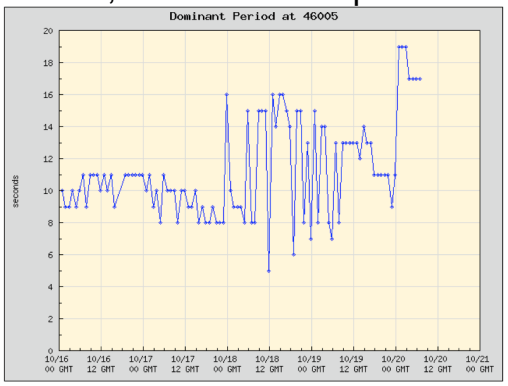


www.ndbc.noaa.gov/maps/Northwest.shtml

Observing Deep Waves

- Buoy 46005 off Aberdeen, WA measures:
  - Atmospheric pressure, air & water temperature
  - Wind direction & speed
  - Wave height & period

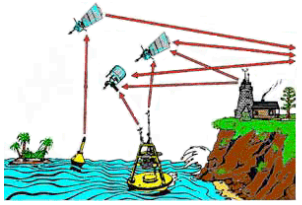


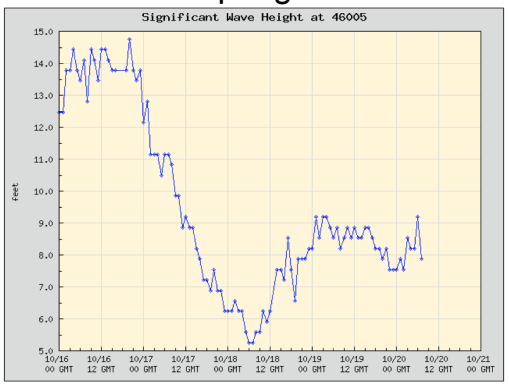


www.ndbc.noaa.gov/station_page.php?station=46005

Observing Deep Waves

- Buoy data transmitted to satellite
  - Downlinked to NOAA Silver Spring MD
  - Processed & posted online
  - All automated

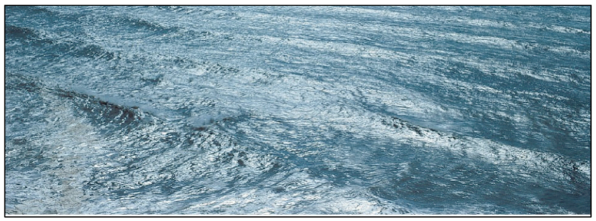




www.ndbc.noaa.gov/tour

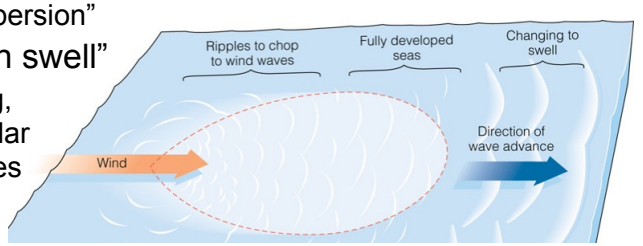
Wave Forecasting

- Use buoy data to determine height
  - And calculate crest speed from period
  - Calculate arrival time at any distance
- But 2 complications
  - Waves change as they propagate
  - Waves do not travel at C



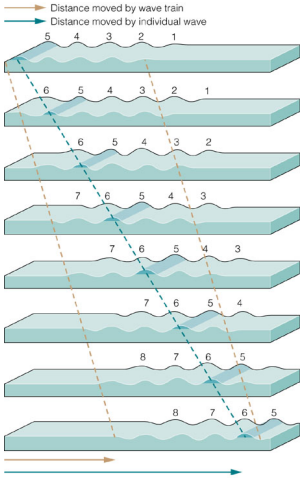
Wave Dispersion

- Waves of different L & T (& H) begin mixed together in storm
  - Waves travel away from the storm or origin
  - Longer, faster waves leave shorter, slower waves behind
    - "Dispersion"
  - "Ocean swell"
    - Long, regular waves



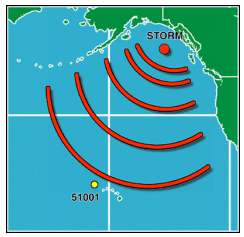
Wave Group Velocity

- Ocean swell arrives at distant location
  - Leading wave in train dissipates
  - New waves appear at rear of train
- Wave train/group travels more slowly than crests
  - V= "Group velocity"
  - V = C/2



Wave Forecasting Revisited

- Period T from buoy data
  - Long-period waves will arrive as swell
  - Calculate crest speed C (celerity)
  - Divide by 2 to get group velocity V
  - Calculate arrival time at any distance
- Height H_3 from buoy data
  - Obtain height distant from storm (swell)
  - Decreases gradually with distance
    - As waves radiate from storm



Wave Forecasting Revisited

- Wave climate at destination
  - Is there win?
  - If so, it will generate waves locally
  - "Wind waves"
- Combined seas
  - Wind waves are superimposed on incoming ocean swell
  - Sometimes forecast separately
    - As height of wind waves & height of swell
  - Sometimes "combined seas" forecast
    - H_3 of wave assemblage

Wave Forecasting

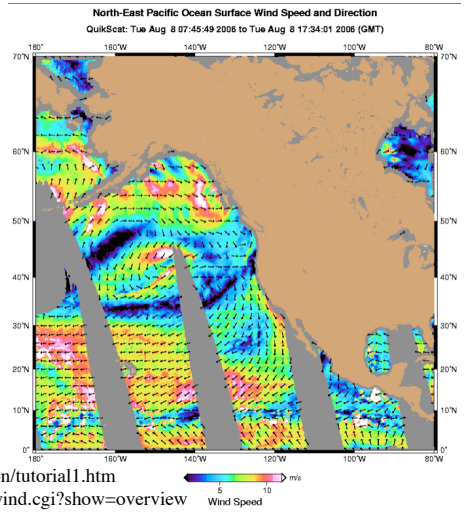
- Recent Marine Forecast

```
-OFFSHORE WATERS FORECAST
-NATIONAL WEATHER SERVICE WASHINGTON DC
-OCEAN PREDICTION CENTER/OCEAN FORECAST BRANCH
-930 PM PDT THU OCT 19 2006
-WATERS FROM CAPE SHOALWATER WA TO CASCADE HEAD OR OUT 20 TO 60 NM-

-TONIGHT
-N WIND 10 TO 15 KT WITH GUSTS TO 20 KT. WIND WAVES 2 FT. W SWELL 8 FT AT
 12 SECONDS. CHANCE OF DRIZZLE.

-COLUMBIA RIVER BAR-
-856 PM PDT THU OCT 19 2006

-...SMALL CRAFT ADVISORY FOR ROUGH COLUMBIA RIVER BAR IN EFFECT FROM
 FRIDAY AFTERNOON THROUGH FRIDAY EVENING...

-IN THE MAIN CHANNEL
-COMBINED SEAS 7 TO 8 FT TONIGHT AND 8 TO 9 FT FRI BUILDING TO 9 FT DURING
 THE EBB CURRENT AROUND 415 AM FRI
-AND BUILDING TO 11 FT WITH BREAKERS POSSIBLE DURING THE EBB CURRENT
 AROUND 445 PM FRI.
```


www.ndbc.noaa.gov/data/Forecasts/FZUS56.KPQR.html

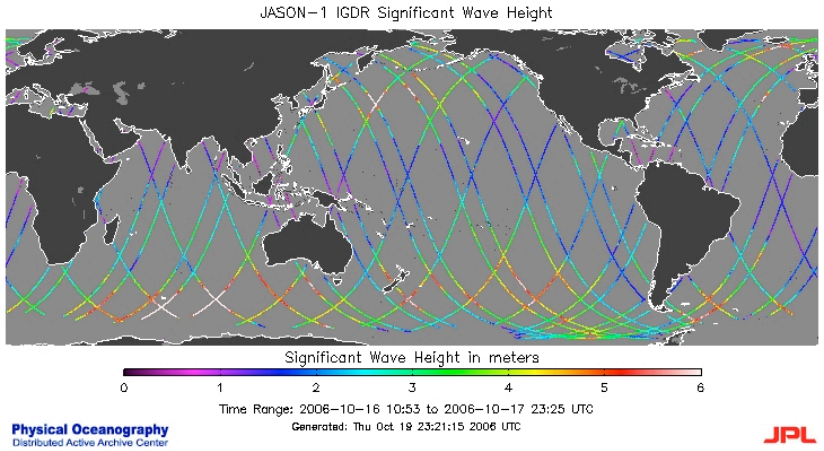
21st Century Forecasting

- Satellites measure wind & waves rapidly over wide areas
  - Very sensitive radar
  - Measures roughness of sea surface
  - Wind inferred



http://sealevel.jpl.nasa.gov/education/tutorial1.htm
http://nereids.jpl.nasa.gov/cgi-bin/wind.cgi?show=overview

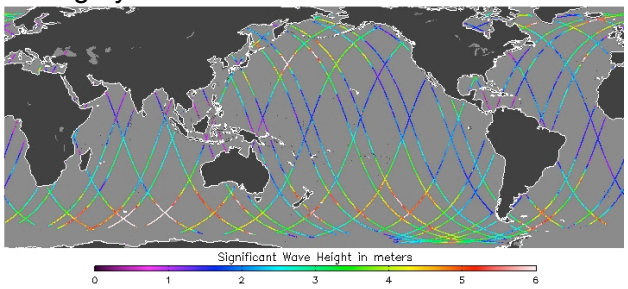
21st Century Forecasting



http://nereids.jpl.nasa.gov/cgi-bin/ssh.cgi?show=overview

Where are Biggest Waves?

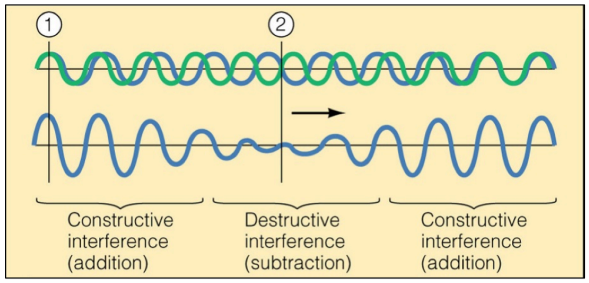
- Where winds are strongest
  - Storms most frequent at subpolar latitudes
  - Antarctic has unlimited fetch
    - No blocking by continents



 http://nereids.jpl.nasa.gov/cgi-bin/ssh.cgi?show=overview

Where are Biggest Waves?

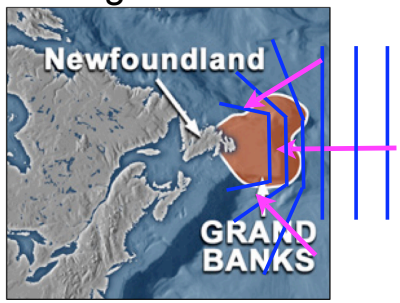
- Where large normal waves coincide
  - "Interference"
  - Several wave trains traveling together
    - Two crests & troughs may coincide



 Garrison Fig. 10.15 p. 239

Where are Biggest Waves?

- Where large normal waves shoal
  - Length & speed decrease
  - Height & steepness increase
- Refraction causes convergence
  - Increased wave energy & height
  - Large swell can break unexpectedly
  - The Perfect Storm



 Garrison Fig. 10.15 p. 239

Rogue Waves

- A solitary wave much bigger than surrounding waves
  - Reported occasionally but difficult to document

http://news.nationalgeographic.com/news/2004/08/0810_040810_rogue_waves.html
www.esa.int/esaCP/SEMOKQL26WD_index_0.html

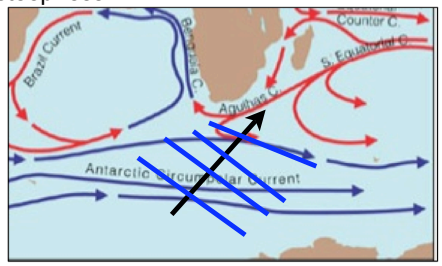
Rogue Waves

- Now documented extensively by satellites
  - Measured up to 30 meters
  - Ten waves >25 meters observed in 3 weeks

http://news.nationalgeographic.com/news/2004/08/0810_040810_rogue_waves.html
www.esa.int/esaCP/SEMOKQL26WD_index_0.html

Rogue Waves

- Always thought to occur in specific areas
  - Where large normal waves encounter fast opposing currents
    - Acts like shallow water
      - Decreased length & speed
      - Increased height & steepness
  - Agulhas Current, S. Africa
    - Encounters waves from Antarctic storms
    - Shallow area too



Wave Forecasting Summary

- What factors determine wave height in deep water?
  - Wind speed
  - Wind duration
  - Fetch
- How are wave properties related to crest speed (celerity = C)?
  - Long wavelength L = faster speed C
  - Long period T = faster speed C
  - L proportional to T^2

Wave Forecasting Summary

- How is wave height expressed?
  - H_3 = significant height
  - (RMS) average of 1/3 of highest waves
- How to predict when big waves will arrive?
  - Measure period T
    - Of ocean swell
  - Calculate crest speed celerity C = f(T)
  - Calculate what?
    - Wave group velocity V = C/2
    - Time to travel known distance
  - Include wind waves (combined seas)