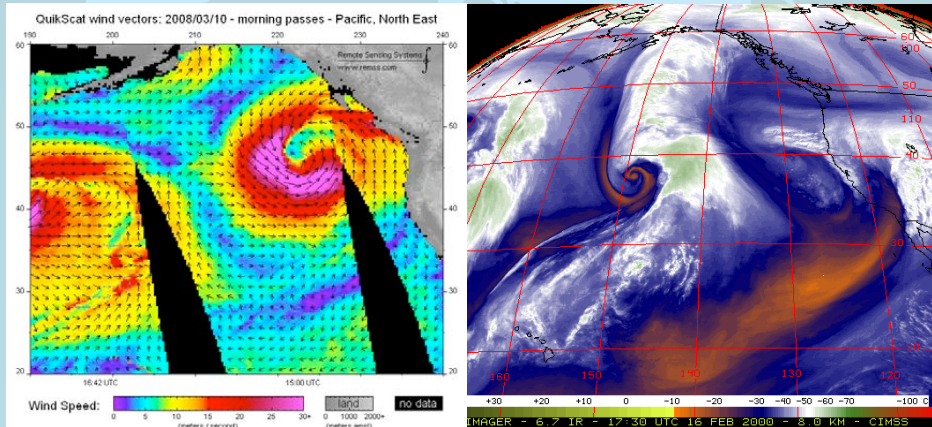


MET 200 Lost at Sea: Hurricane Force Wind Fields and the North Pacific Ocean Environment



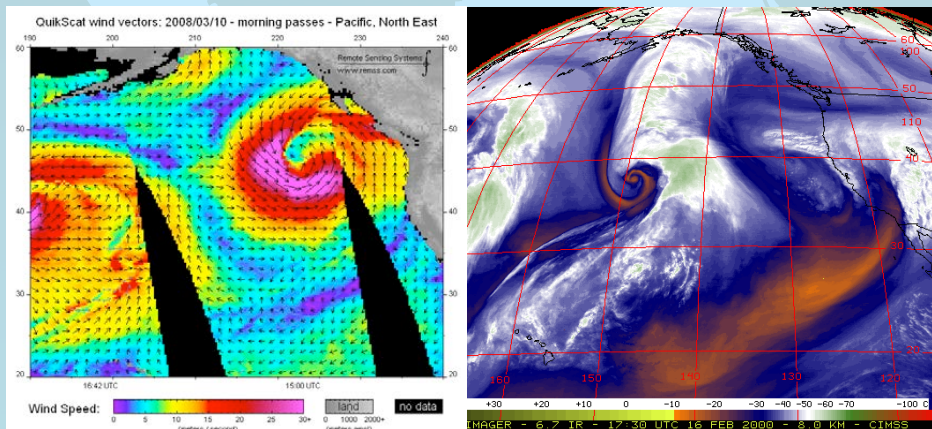
1

Lost at Sea: Hurricane Force Wind Fields and the North Pacific Ocean Environment



2

Lost at Sea: Hurricane Force Wind Fields and the North Pacific Ocean Environment



3

Motivation

In Hawaii, surf is the number one weather-related killer.
More lives are lost to surf-related accidents every year in Hawaii than any other weather-related event.



4

Going for an Unintended Swim?



- Lulls: Between sets, lulls in the waves can draw inexperienced people to their deaths.

5

Motivation

to help raise awareness of the hazards created by hurricane force winds in extratropical cyclones and their relationship with extreme open-ocean and coastal sea states in the North Pacific.



6

Lost at Sea

"One large ship sinks every week on average worldwide, but the cause is never studied to the same detail as an air crash. It simply gets put down to 'bad weather.'" Dr. Wolfgang Rosenthal, lead scientist for the MaWave Project convened in 2000 to investigate the disappearance of ships.

"Severe weather has sunk more than 200 supertankers and container ships exceeding 200 metres in length during the last two decades. Rogue waves are believed to be the major cause in many such cases". A press release by the European Space Agency in 2004



7

Lost at Sea



- Every hour, on average, one large shipping container is falling overboard never to be seen again.
- ~10,000 of these large containers are lost at sea each year.

8

Lost at Sea

Given the lack of survivors or evidence, exact statistics* of ships scuttled by giant waves are difficult to come by. The fact remains that every year large ships sink or otherwise go missing, taking their crews along with them. If you also consider smaller vessels, the numbers are sobering.

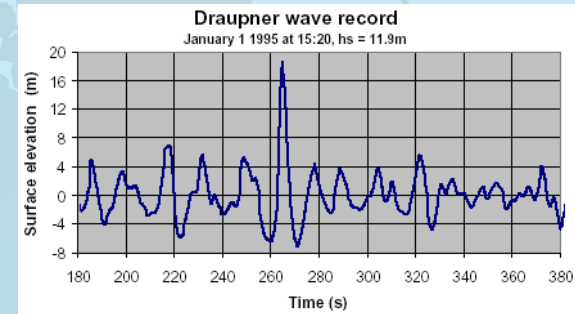
*Response from Navy to my FOI request (2012-NSC-19) for data on ships lost at sea was, "I regret to inform you the requested documents do not exist within the files at this command."



9

Possible Causes of the Losses

- Rogue Waves – (aka freak waves) – waves whose height is more than twice the significant wave height (SWH), which is defined as the mean of the largest third of waves in a wave record.
- Rogue waves occur where physical factors such as **extreme wind fields** and strong currents cause waves to merge to create a single exceptionally large wave, or soliton.

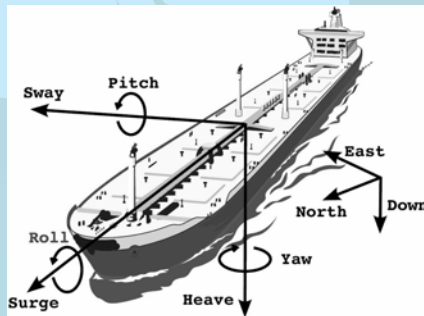


The Draupner wave or New Year's wave is often believed to be the first rogue wave to be detected by a measuring instrument, occurring at the Draupner platform in the North Sea off the coast of Norway on 1 January 1995.

10

Possible Causes of the Losses

- Synchronous rolling – takes place because of resonance between the natural period of roll of the ship & the natural period of the oscillation of the waves. The rolling will gradually increase to high capsizing values.
- Parametric roll – occurs when natural roll period of the ship is between 1.8 to 2.1 times the encounter period (normally associated with the pitching period)



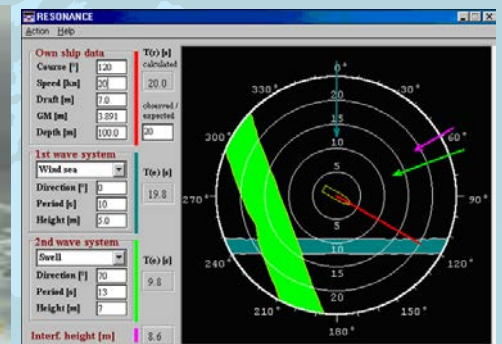
The larger the flare on container ships the more likely is the occurrence of parametric roll and wider the range of resonance.

11

Parametric Roll



The cruise ship Voyager in Cyclone Valentina (Mediterranean Sea), on February 14th 2005.



Computerized Presentation of potential dangerous Areas of speed and heading in polar diagram as Stripes for synchronous resonance and interference effects for two wave directions.

It requires a group of waves above a threshold or critical height for parametric roll to be initiated and sustained. The threshold depends on hull size and shape.

12

Parametric Roll

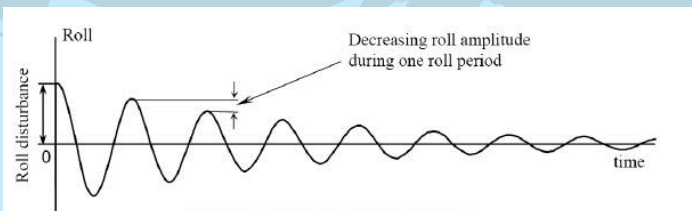


Figure 2.4: Roll in calm sea [2]

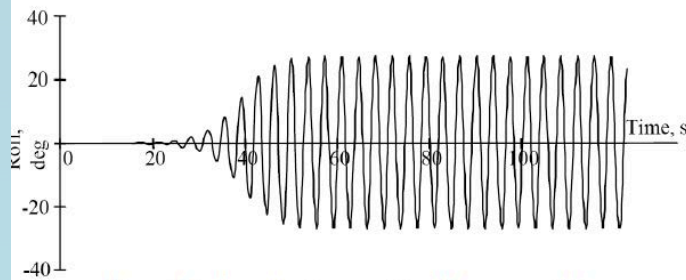


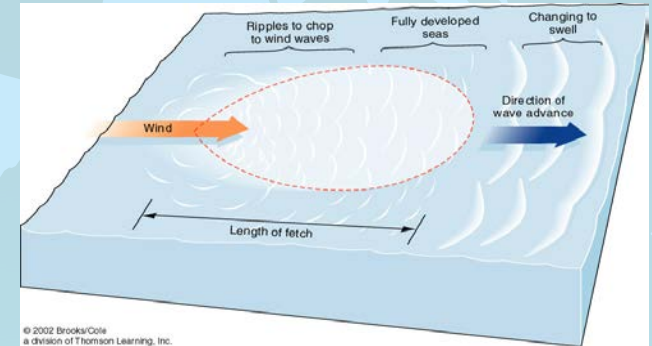
Figure 2.5: Example of parametric roll resonance [2]

13

Factors Affecting Wind Wave Development

The following factors control the size of wind waves:

1. Wind strength
2. Wind duration
3. Fetch - the uninterrupted distance over which the wind blows without changing direction.
4. Air-sea temperature difference
5. Ocean depth



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14

Ocean Waves

Terminology

Wavelength - L is the horizontal distance from crest to crest.

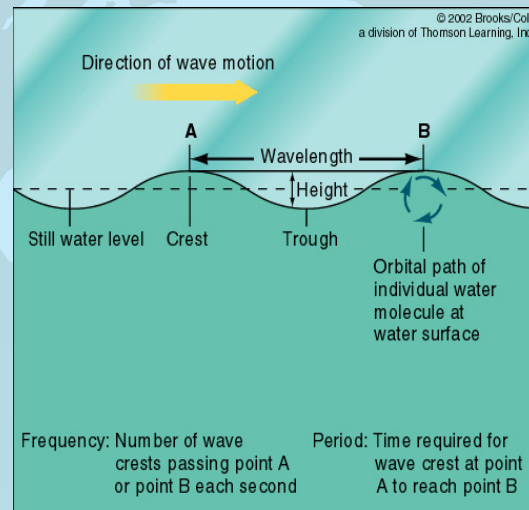
Wave height - the vertical distance from crest to trough.

Wave period - T is the time between one crest and the next crest.

Wave frequency - the number of crests passing by a certain point in a certain amount of time.

Wave speed - C is the rate of movement of the wave.

$$C = L/T$$



15

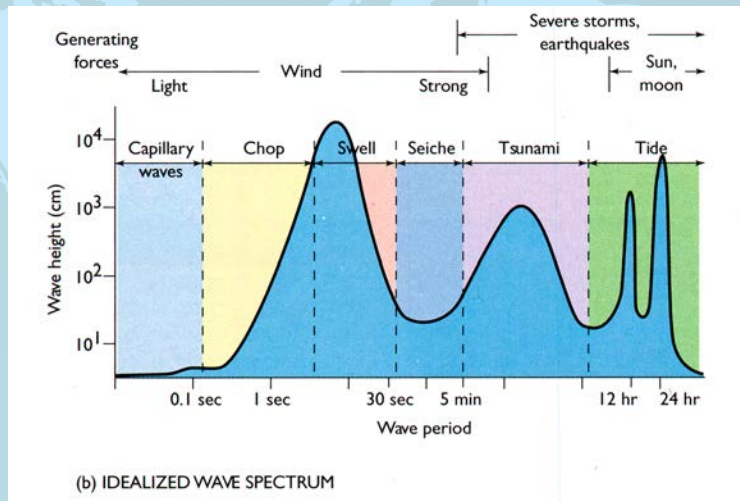
Wave Steepness and Ship Hazard

- ♦ Wave steepness = Wave Height / Wave Length
- ♦ Young waves are steeper than older waves
- ♦ Steep waves pose significant risk to marine vessels en route
- ♦ The wave steepness in 60% of the global ship accidents ranged from .03 to .04.



16

Wave Spectra

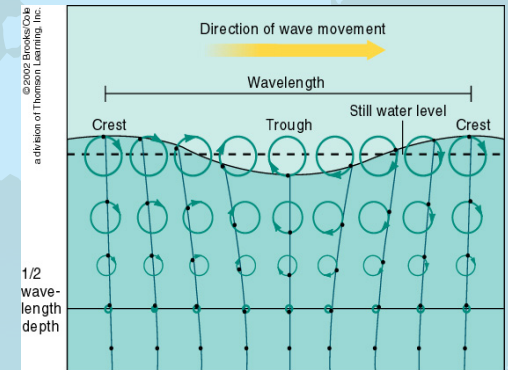


Wave spectra as a function of wave period

17

Open Ocean - Deep Water Waves

- Orbits largest at the sea surface
- Decrease with depth
- When depth > L/2
 - essentially no movement
 - bottom is not felt
- Depth of L/2 = Wave Base
- A Deep Water Wave is one for which the water depth is > L/2

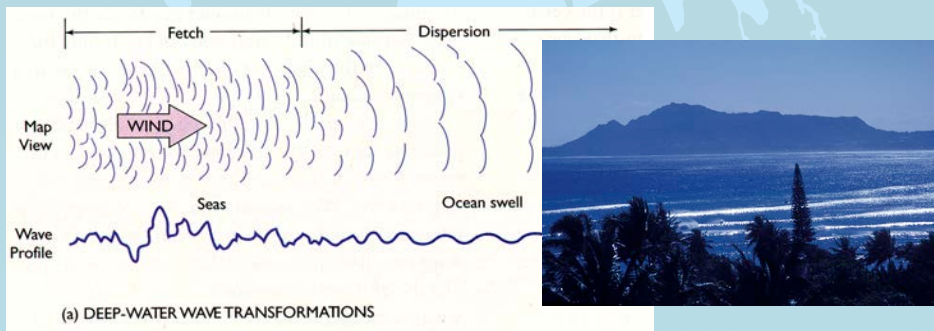


18

Swell and Wave Lifecycle

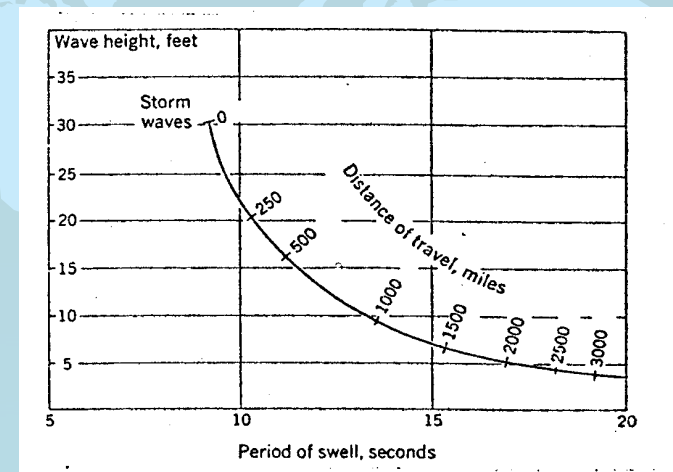
Three things happen to large waves when they leave the storm region.

1. Dissipation – internal friction
2. Dispersion – $C = (gL/2\pi)^{1/2}$
3. Angular spreading – broad fetches favored



19

Wave Decay



Dissipation

20

Deep Water Waves: Dispersion & Swell



In deep water, waves of different wavelengths travel at different speeds. Waves with the longest wavelengths move the fastest and leave an area of wave formation sooner. Because of their different speeds, waves separate out from one another into groups with similar wavelength. This process is called **dispersion**. Dispersion causes groups of waves with the same wavelength to travel together, causing a very regular, undulating ocean surface called **swell**.

21

Deep Water Waves and Dispersion

Depth $> L/2$, where L is wavelength - defines deep water waves.

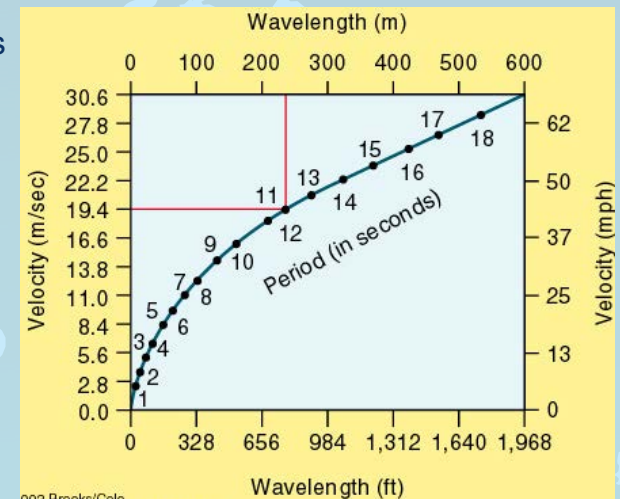
Longer waves move faster

$$C = (gL/2\pi)^{1/2}$$

C = wave speed

g = gravity (9.8 m/s^2)

Dispersion of waves of differing wavelength leads to swell that run ahead of storm.

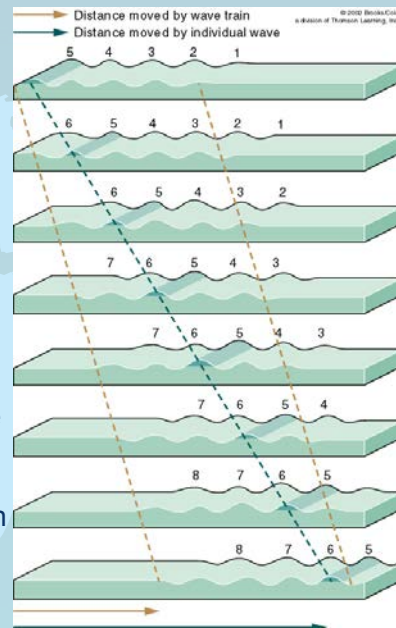


Graph of the relationship between wave speed and wavelength.

22

Group Velocity

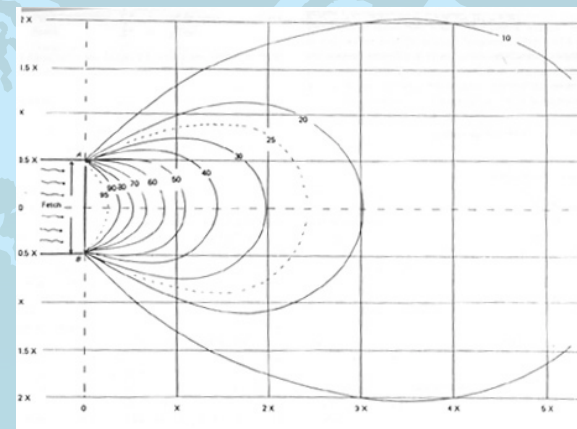
- Individual waves within a set of waves move faster than the group of waves moves.
- The group velocity is 1/2 the individual wave velocity.
 - Waves in the front lose energy in lifting an “undisturbed” ocean surface.
 - Waves in the back benefit from the energy of waves ahead.
 - The leading wave dissipates and the trailing wave grows, resulting in the slower group velocity.



The group velocity is 1/2 the individual wave velocity.

23

Angular Spreading



Angular spreading is proportional to swell energy. Swell from broad fetches experience less angular spreading. Steep waves dissipate more quickly through angular spreading.

24

Swell and Wave Lifecycle

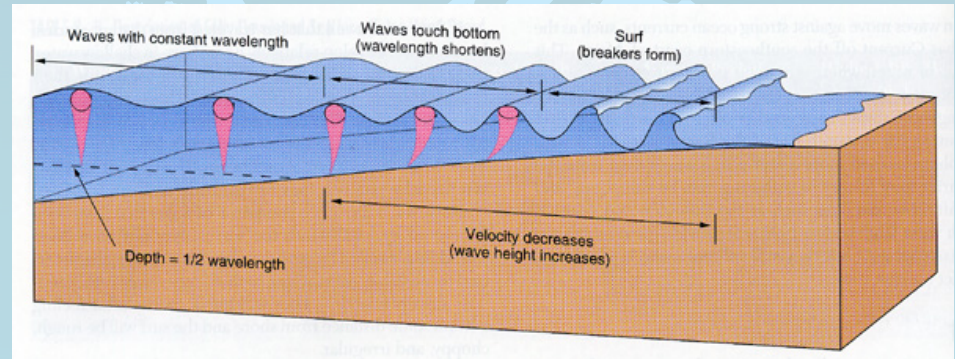
Two things happen to large swell waves when they near shore.

1. Shoaling: As waves move into shallow water they slow and become steeper as they increasingly feel the bottom, until finally the top of the wave pitches forward and the wave breaks.
2. Refraction: As waves move into shallower water, they slow down and thus turn toward the shore.



25

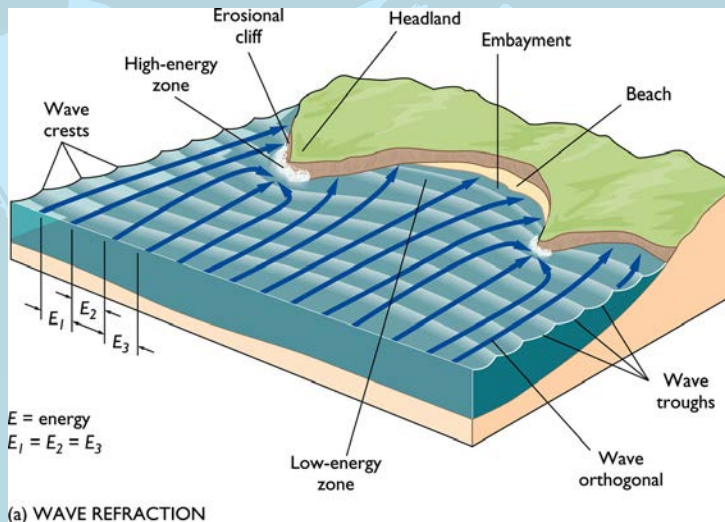
Wave Refraction and Shoaling



- Waves “Feel the Bottom” at depth $< 1/2$ wavelength – causes refraction
- Wave speed and length decrease with depth, $C = (gD)^{1/2}$
- But period and energy remain same
- Thus, wave height increases
- Waves break when the ratio of height/wavelength $\geq 1/7$

26

Shoaling results in Refraction



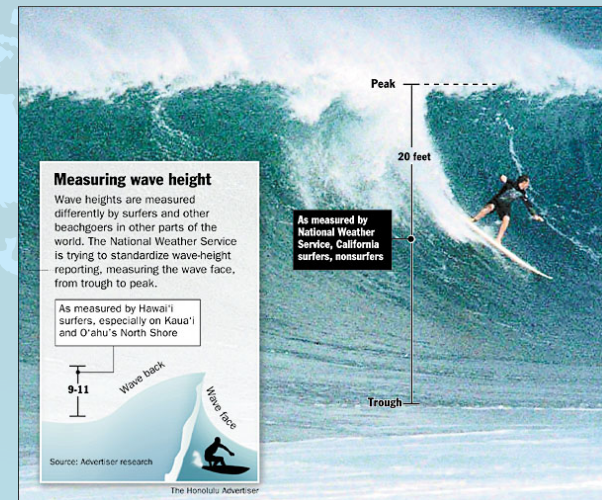
$E = \text{energy}$
 $E_1 = E_2 = E_3$

(a) WAVE REFRACTION

Waves Diverge in Bays (lower energy) and Converge on Headlands (higher energy)

27

Lifeguard Observations: Wave Height



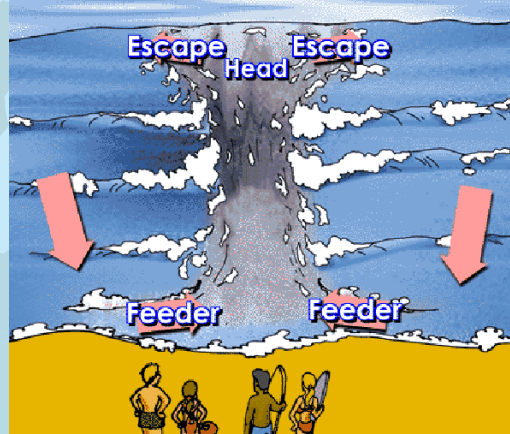
Hawaii surf scale is roughly equal to 50% of the wave face. Photo shows 10 ft (3 m) wave Hawaii scale.

28

Rip Currents

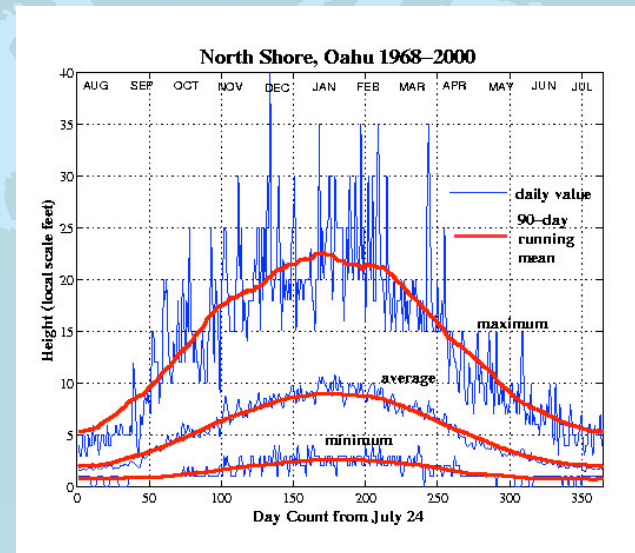
Water streams seaward in narrow jets called rip currents.

Water moves toward shore where the waves are breaking.



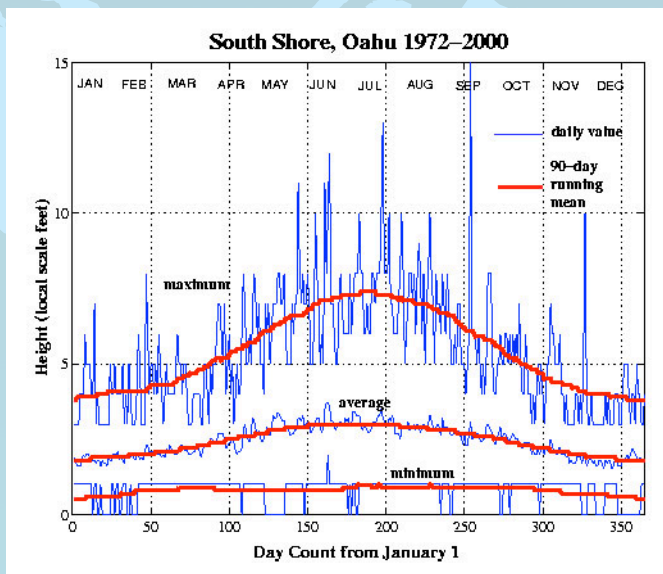
29

Climatology of North Shore Surf



30

Climatology of South Shore Surf



31

NWS Watches and Warnings for Hawaii

NWS HIGH SURF ADVISORY AND WARNING CRITERIA

Location	Advisory*	Warning*
North-Facing Shores	15 Feet	25 Feet
West-Facing Shores/Big Island	8 Feet	12 Feet
West-Facing Shores/Remaining Islands	12 Feet	20 Feet
South-Facing Shores	8 Feet	15 Feet
East-Facing Shores	8 Feet	15 Feet

*Heights of wave face at time of peak cresting.

32

Lost at Sea

In the high-tech marine world of radar, distress radio beacons, GPS, and satellite surveillance, how can hundreds of enormous vessels just get swallowed up by the sea? And furthermore, how can this be happening with scarce media notice?



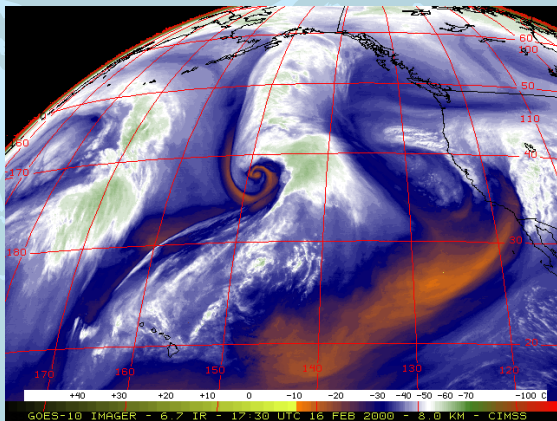
33

The Perfect Storm



34

Background: Explosive Cyclogenesis



>80% of storms that produce hurricane force winds undergo a period of explosive cyclogenesis (aka **"bombs"**).

A bomb is defined as a midlatitude cyclone that deepens 1 mb/hr for 24 hours (at 60°N equivalent).

35

Synoptic-Dynamic Climatology of "Bombs"

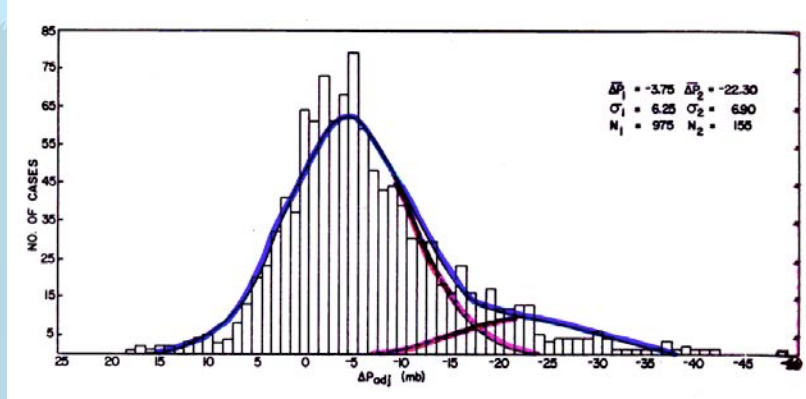
Bombs are a winter-time phenomenon that primarily occur over the western parts of ocean basins at mid and high latitudes.

Development occurs on a spatial and temporal scale of the order of 100's of km and a few hours (6-12).

- Important ingredients include: strong baroclinic zone, low static stability, and large moisture.
- Strong mid-tropospheric cyclonic vorticity advection.
- Boundary layer fluxes that generate low static stability and vorticity rich environments in the lower troposphere.
- Intense thunderstorm activity near low center.

36

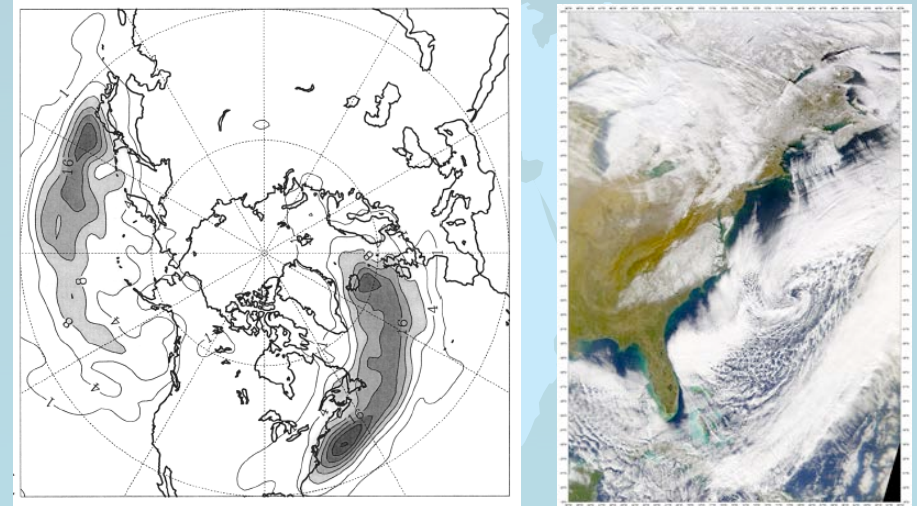
Distribution of Pressure Falls in Bombs



Distribution of pressure falls in 24 hours
(Sanders and Gyakum 1980)

37

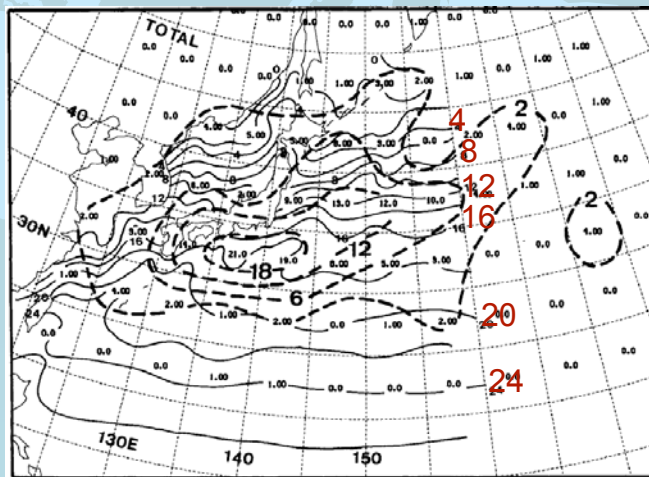
Distribution of Bombs



Explosive cyclone density [contour interval 4×10^{-5} explosive cyclones ($^\circ\text{lat}^2$), 1979-1999 (From Lim and Simmonds 2002).

38

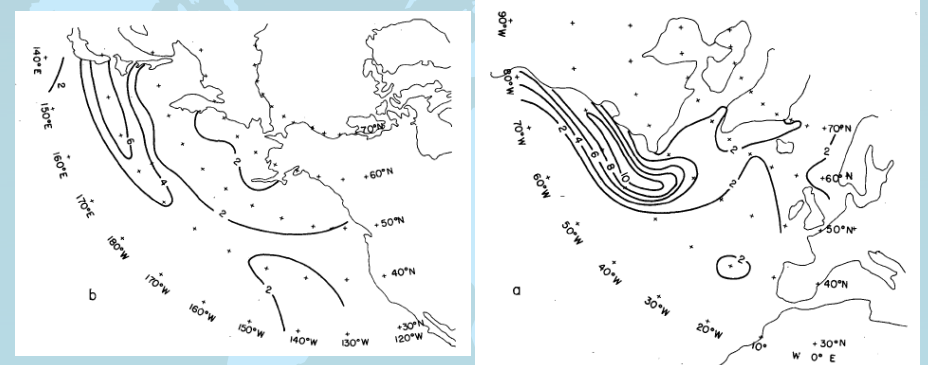
SST and Distribution of Bombs



Distribution of bomb events in the North Pacific Ocean 1974-1984 with SST (Chen and Fu 1997).

39

Synoptic-Dynamic Climatology of the "Bomb"



Distribution of sea surface temperature gradient ($^\circ\text{C}$ per 180 n mi)

40

Surface Sensible Heat Fluxes

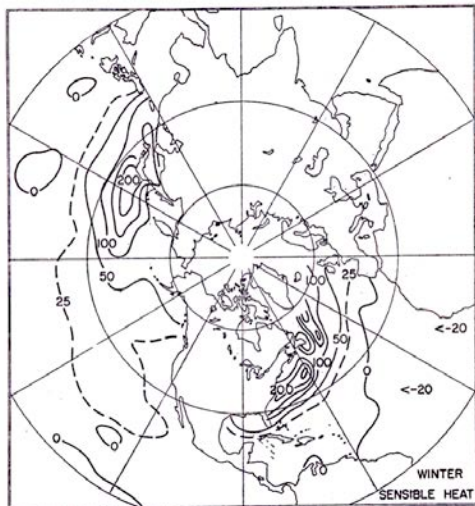
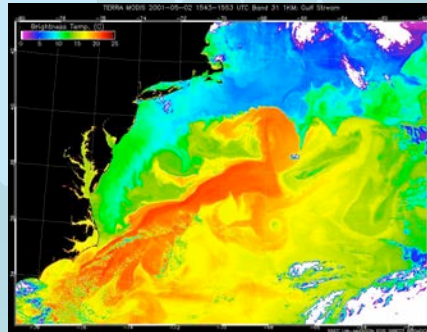


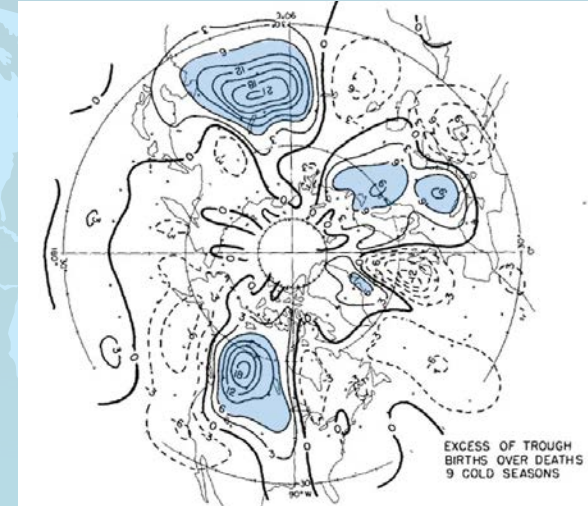
FIG. 20.3.5. Mean amount (in gram calories per square centimeter per day) of sensible heat exchanged between the sea and the atmosphere in winter. (After Jacobs [7].)

Distribution of sensible-heat fluxes



41

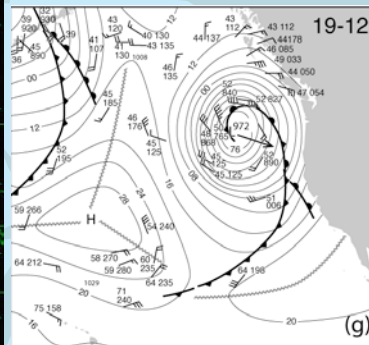
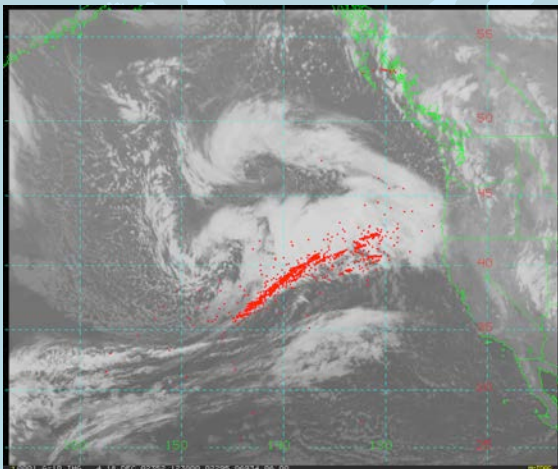
Genesis of Shortwaves – PVA



Short waves aloft provide strong mid-tropospheric quasi-geostrophic forcing where needed.

42

Deep Convection in HF Storms



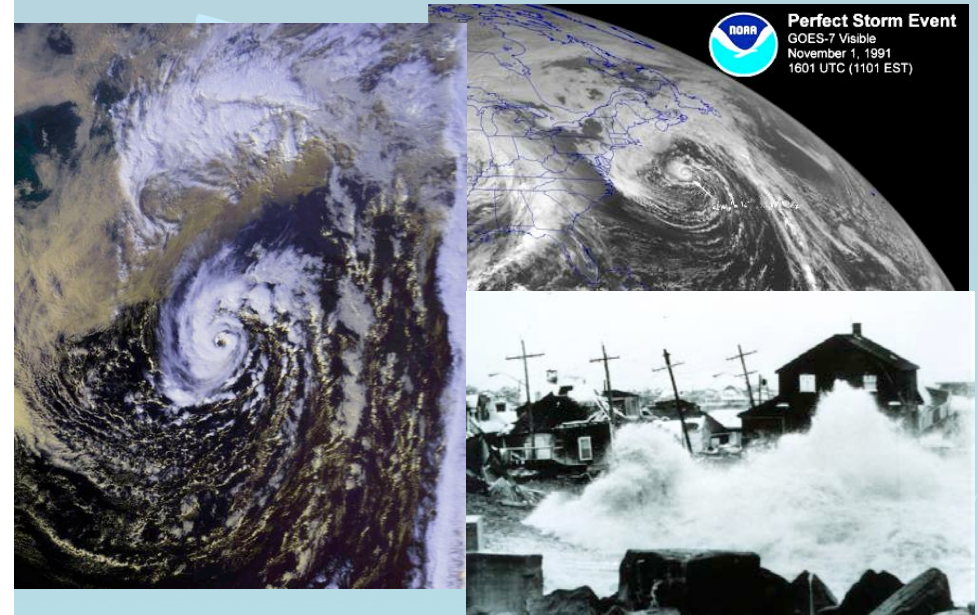
Surface analysis
Valid 1200 UTC
19 December 2002

Northeast Pacific Storm 18-20 December 2002
was under forecast by more than 10 mb by NCEP.

Pessi, A. T., and S. Businger, 2009: Mon. Wea. Rev., 137, 3177-3195.

43

Hurricane-like Core in Perfect Storm



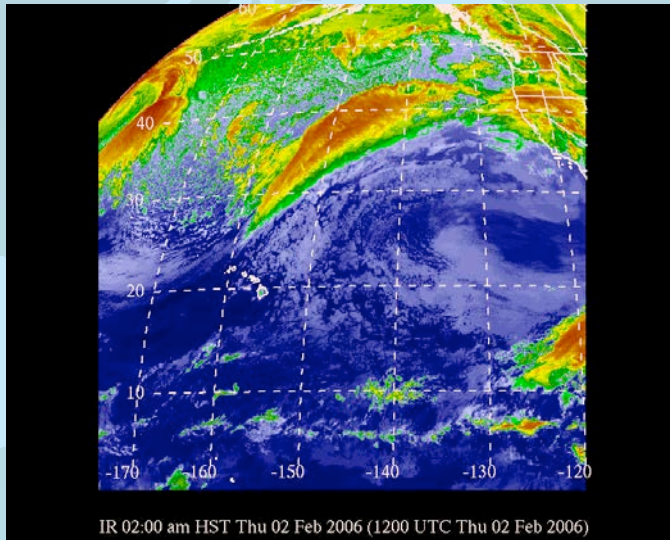
NOAA
Perfect Storm Event
GOES-7 Visible
November 1, 1991
1601 UTC (1101 EST)

44

West Coast Windstorms

SEATTLE - 2/4/06

Hurricane force winds cut power to nearly 200,000 homes and businesses in Western Washington on Saturday, forced the closure of the floating bridge on Lake Washington for the first time in nearly seven years, and resulted in at least one fatality when a tree fell on a car.



West Coast Windstorms



SEATTLE - 12/15/06

Fierce winds cut power to nearly 800,000 homes and businesses in Western Washington on Friday. This home in Redmond had ten fallen trees on it when the winds died down.

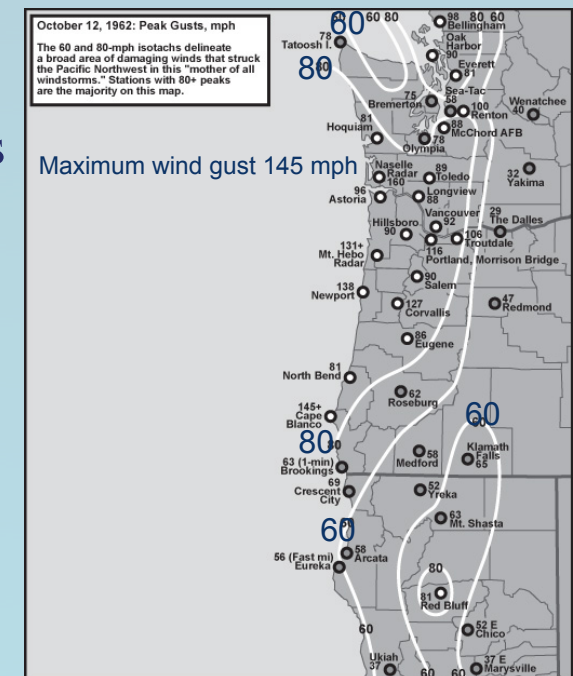
Mother of all NW Windstorms

Columbus Day Storm of 1962



Mother of all
NW Windstorms

Columbus Day Storm of 1962



NW Windstorms and Bridges



Hood Canal Bridge sinks on 13 Feb. 1979

49

NW Windstorms and Bridges



Tacoma Narrows Bridge 7 November 1940

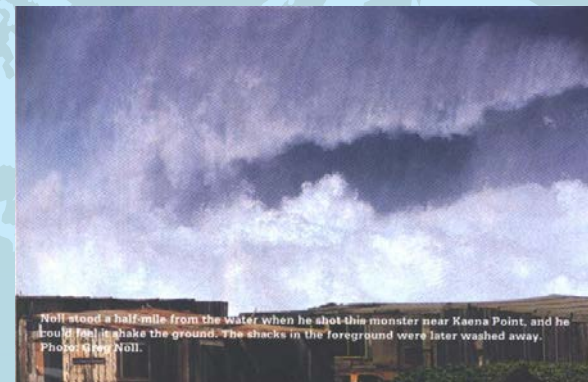
50

Hawaii: Two Epic Wave Events



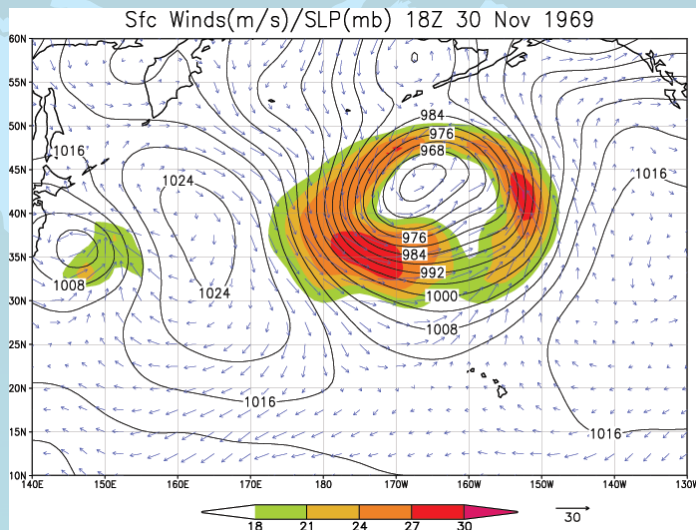
51

1969 Wave Damage on Oahu



52

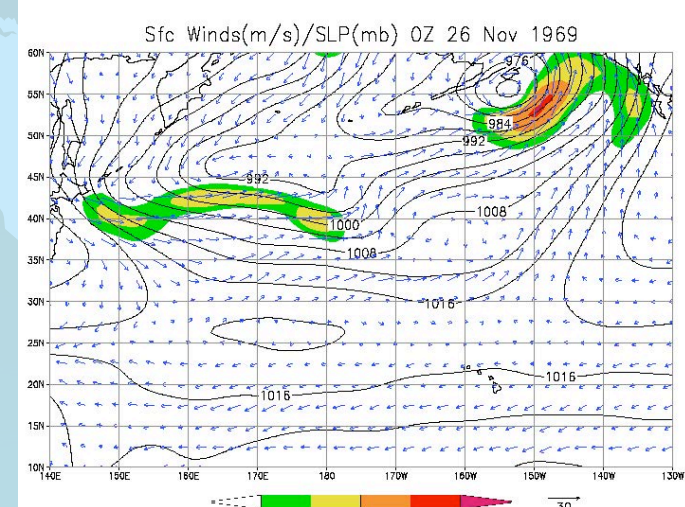
HF Storm of December 1969



NCAR/NCEP Reanalysis Data for 8 AM 30 November 1969

53

Animation of SLP Analyses Dec. 1969



A captured fetch occurs when the swell travel at the same speed as the storm, so that high winds remain over the swell region.

54

HF Storm Jan. 1998

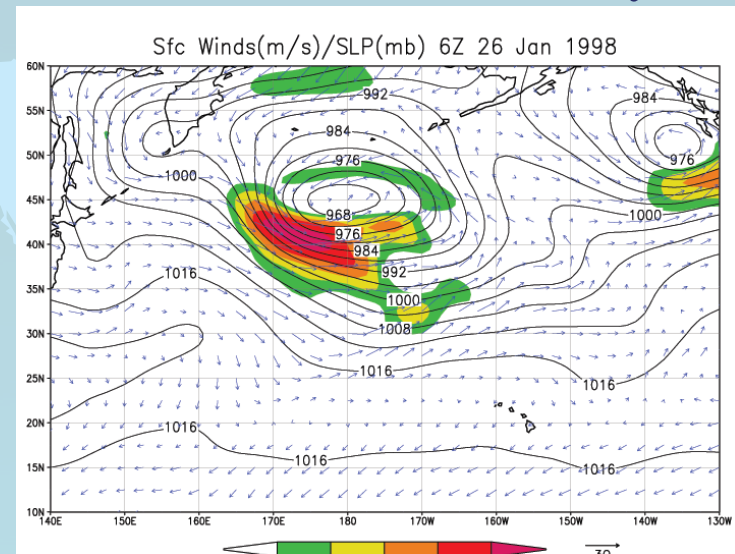


Photos by S. Businger



55

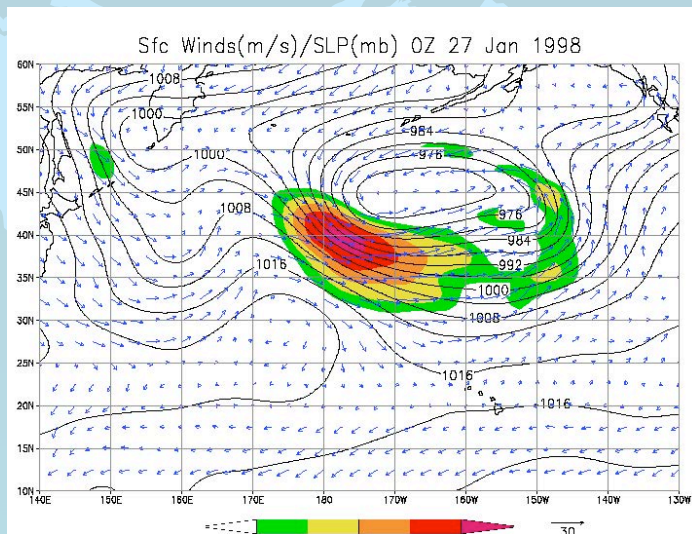
HF Surface Winds on 26 January 1998



NCAR/NCEP Reanalysis Data for 8 PM 25 January 1998

56

Animation of SLP Analyses Jan. 1998



Note the captured fetch that again occurred in this case.

57

Waves are Scale Invariant



Breaking waves are scale invariant; its difficult to tell how large they are without a surfer for scale.

58

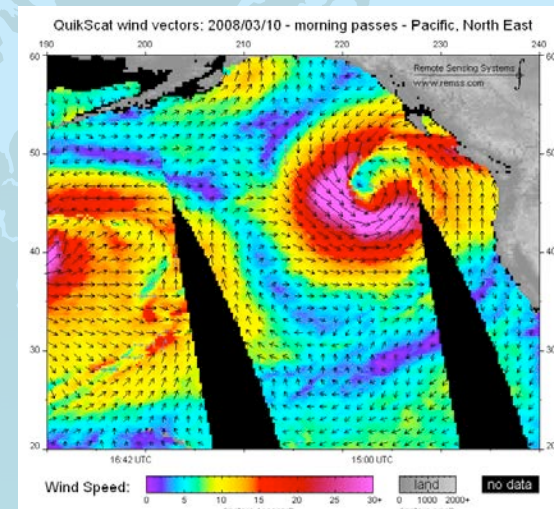
HF Wind Fields Data and Methods

Sites providing in-situ ocean measurements cover a very small portion of the global oceans with a distinct bias toward the margins of the major basins (Cardone et al. 2005). Ships tend to avoid storms.



59

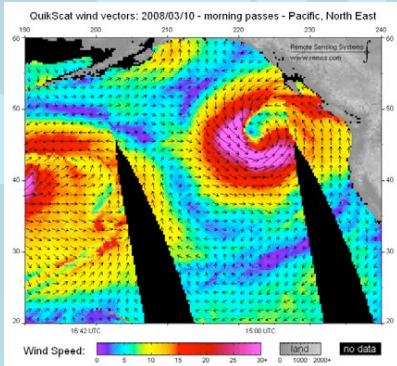
HF Wind Fields: Data and Methods



60

QuikSCAT

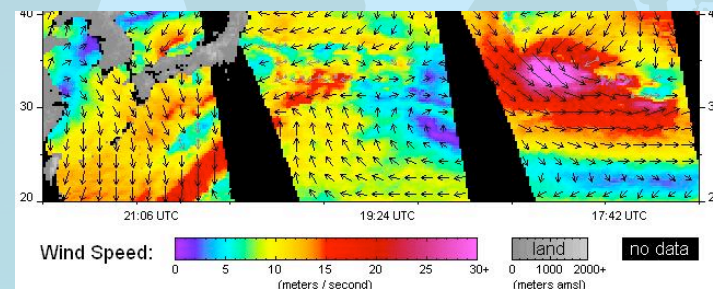
- QuikSCAT was launched in 1999 and failed in November 2009. Instrument sends microwave pulse, backscatter observation estimates wind speed through surface roughness. Data has ~25 km resolution.
- QuikSCAT can measure wind speeds up to 30 m s^{-1} (near hurricane force) with an accuracy of $\pm 2 \text{ m s}^{-1}$ (Shirtliffe, 1999). OPC forecasters routinely observe QuikSCAT winds in excess of 32.9 m s^{-1} .



61

HF Wind Fields: Data and Methods

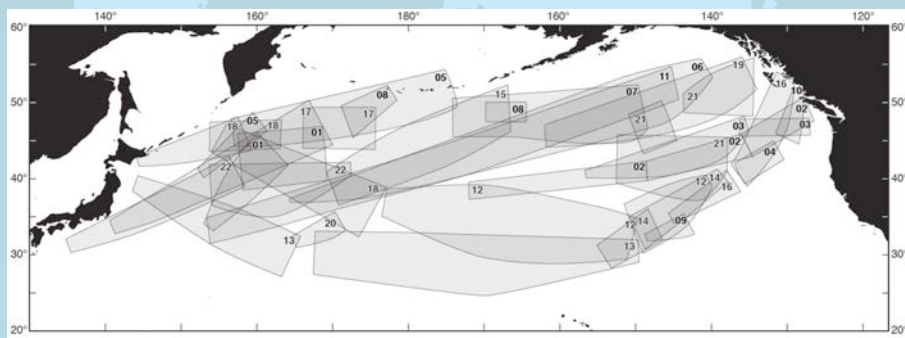
- Used QuikSCAT data to isolate cases of hurricane force winds in winter storms for 2003-2008, and constructed a climatology of ocean fetches ($v > 35 \text{ kt}$) associated with these storms.
- Compared maxima in QuikSCAT winds to maxima in GFS analyses.
- Selected cases where threshold conditions (7.5 m estimated breaker height) were measured at a buoy, and compared observations of the significant wave height and dominant period at buoys against Wavewatch III (WW3) output.



62

Hurricane Force Fetch Climatology

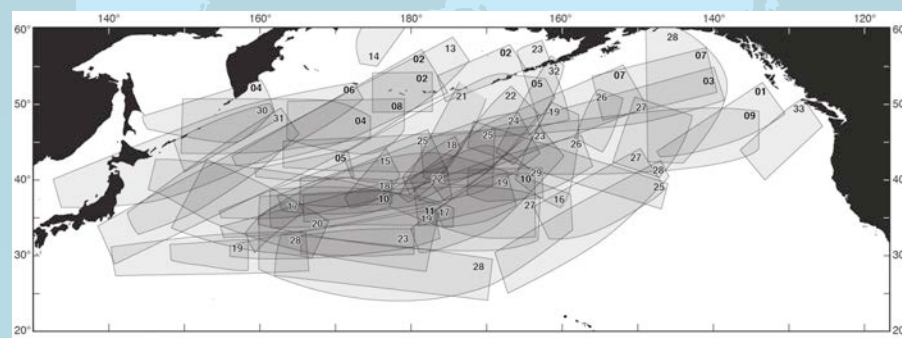
2003-2004 Winter



63

Hurricane Force Fetch Climatology

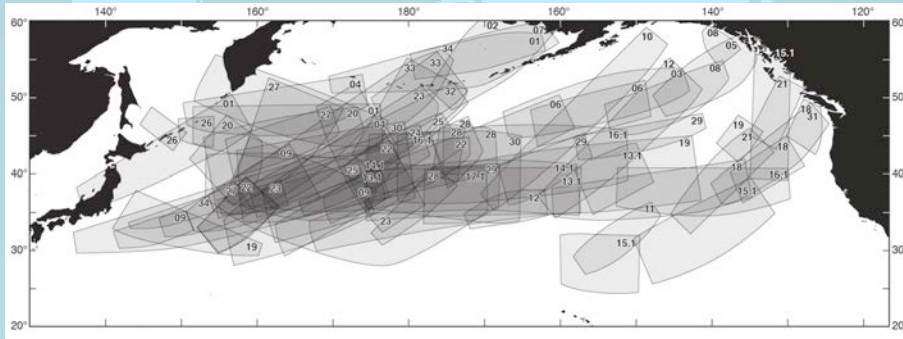
2004-2005 Winter



64

Hurricane Force Fetch Climatology

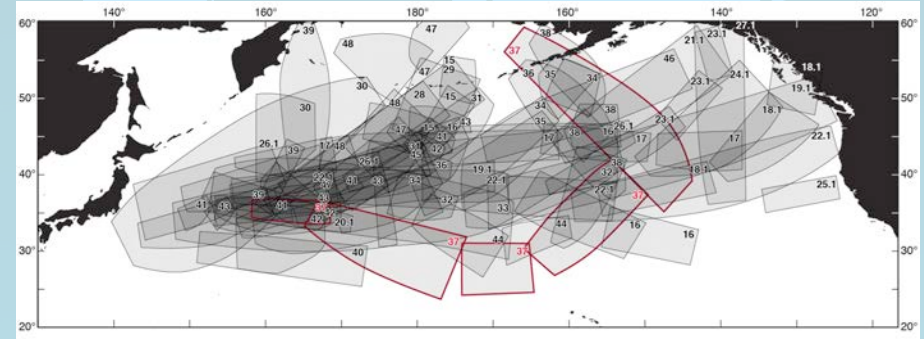
2005-2006 Winter



65

Hurricane Force Fetch Climatology

2006-2007 El Niño

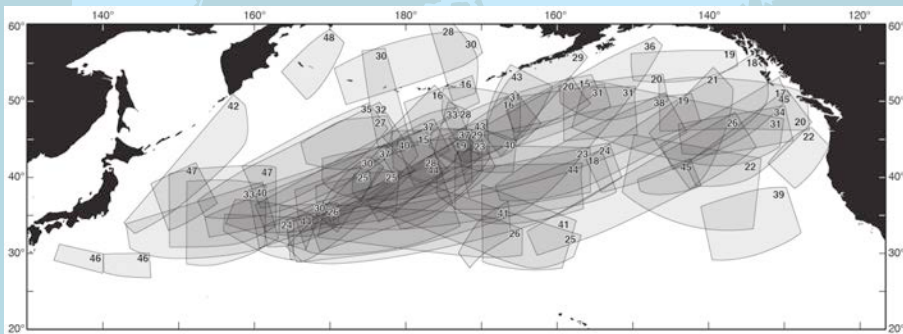


HF Storm Example: 28-29 Jan. 2007

66

Hurricane Force Fetch Climatology

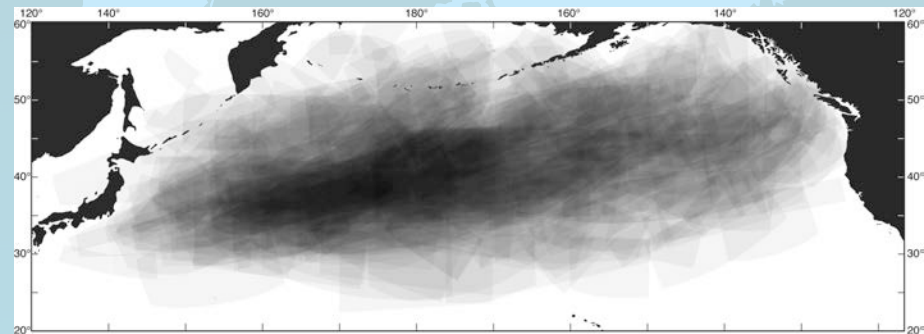
2007-2008 La Niña



67

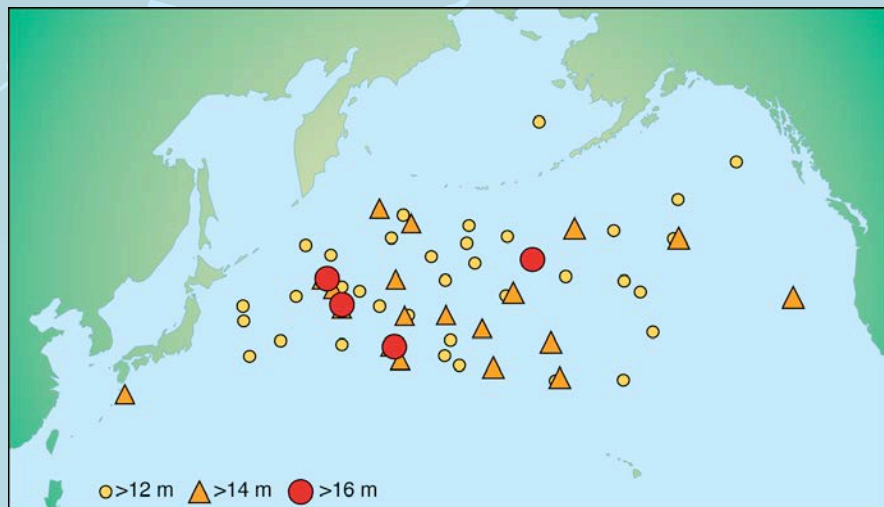
Hurricane Force Fetch Climatology

Jan 2003 through May 2008



68

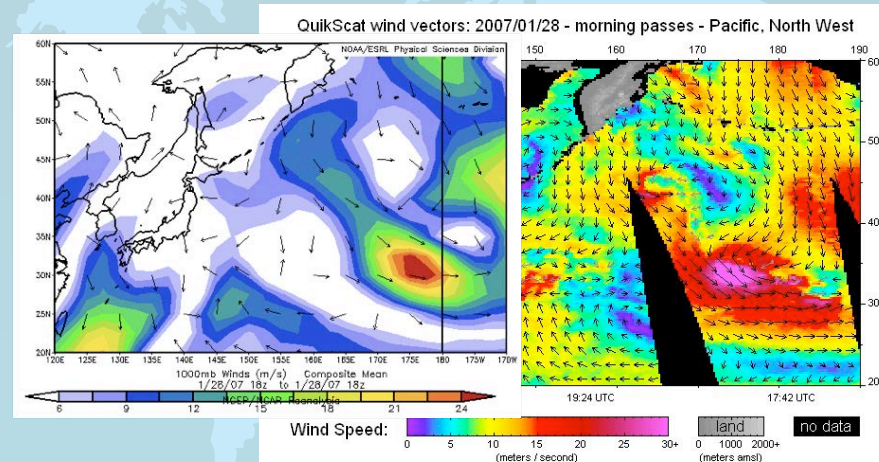
Very Extreme Sea-State Events



Distribution of 12+m significant wave height events as measured by the TOPEX, ENVISAT and JASON Altimeters (Cardone et al. 2005).

69

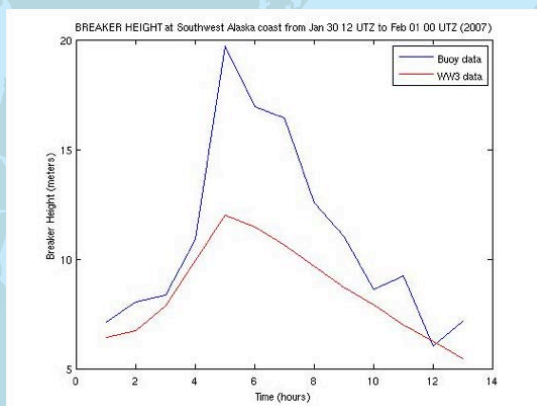
HF Storm Example: 28-29 Jan. 2007



QuikSCAT wind image and GFS wind analysis for same time.

70

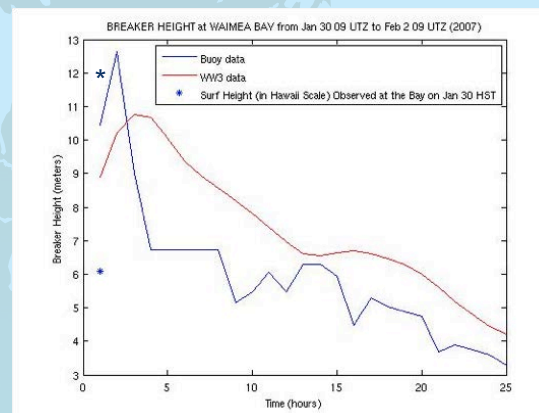
Comparison of WWIII Predicted vs Observed Breaker Heights: 1/30/2007



Breaker height = wave height x period x shoaling factor
Wave steepness reached .07 along the AK coast.

71

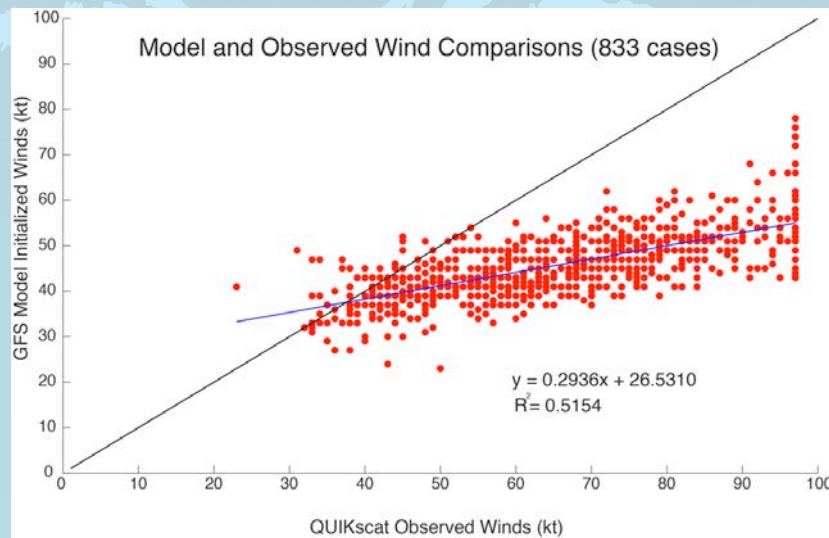
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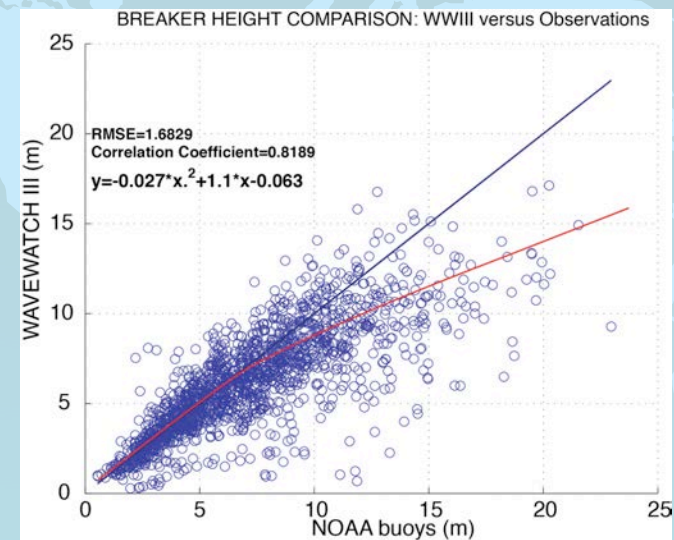
72

QuikSCAT vs GFS Analyses



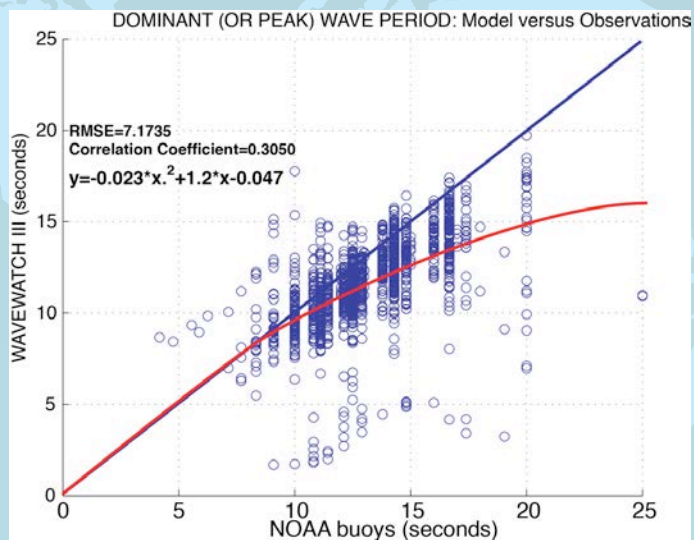
73

Breaker Height Comparison: WW3 vs Buoys



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Dominant Wave Period: WW3 vs Buoys



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Swell and Wave Forecasting

Additional tips for wave forecasting:

- Wave Sets: Swell travel with a group velocity that is ~1/2 the speed of individual waves. When a wave group arrives at the shore it is referred to as a set.
- Lulls: Between sets, lulls in the waves can draw inexperienced people to their deaths.
- Travel Time: Rule of thumb to estimate of travel time for large swells is 10° latitude per day (10° ~ 1110 km or 665 nautical miles). Thus, it will take ~3-4 days from the north Pacific and ~1 week from New Zealand for the swell to arrive.
- Coastal Surf Wave Height (h) can be estimated from open ocean buoy wave height (H) and period (P) observations through application of a shoaling factor (0.12 for N. Shore) as follows.

$$h = 0.12 \cdot H \cdot P$$

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Questions?



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Waves Caused by Strong Trade Winds



Large waves at Sandy Beach associated with prolonged strong NE trade winds.

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Parting Shots



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Pipeline

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Waimea Bay



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Bruce Irons - Eddy Aikau Contest



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Photo by S. Businger

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