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

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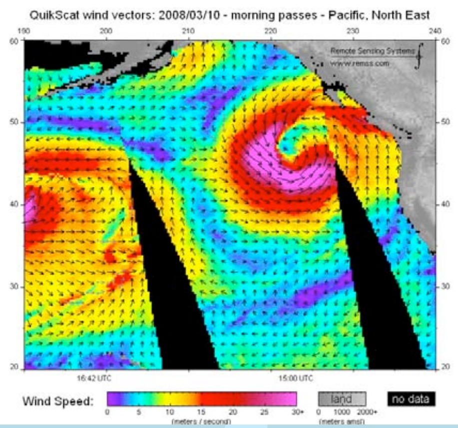


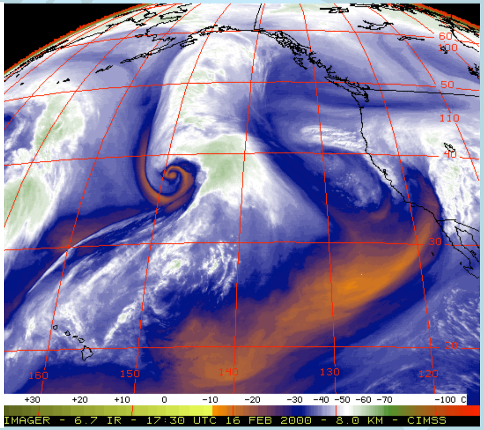


Steven Businger and Selen Yildiz
SOEST at University of Hawaii at Manoa
This research is supported by ONR

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# Hurricane Force (HF) Wind Fields

## Outline

- Motivation – Lost at Sea
- Background: Nature of Ocean Hazard and Explosive Cyclogenesis
- Impacts of HF Wind Fields on the West Coast and Hawaii
- Climatology of HF Wind Fields over North Pacific Ocean
- Evaluation of GFS and WWIII Performance
- Conclusions
- Future Work

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# Motivation

My goal in this talk is to help raise awareness of the hazards created by hurricane force winds in extratropical cyclones to marine and coastal interests, and to present results of a study of the distribution of HF winds in extratropical cyclones documented by QuikSCAT data from 2003 to 2008 and their relationship with extreme open-ocean and coastal sea states in the North Pacific.

Commander Richard Behn, NOAA Corps

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# Lost at Sea

Right now, as you read this, there are five to six million shipping containers on enormous cargo ships sailing across the world's oceans. And every hour, on average, one is falling overboard never to be seen again. It's estimated that 10,000 of these large containers are lost at sea each year, and our understanding of what happens to them afterwards is scant at best.



# Lost at Sea

Dr. Wolfgang Rosenthal, lead scientist for the MaWave Project convened in 2000 to investigate the disappearance of ships, stated "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.'"

A press release by the European Space Agency in 2004 claimed that "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".




# Lost at Sea

The preceding numbers are exaggerated, but 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."




# Possible Causes of the Losses

- Rouge Waves – (aka freak waves) are relatively large and spontaneous ocean surface waves that occur far out at sea, and are a threat even to large ships and ocean liners.
- Rouge waves are more precisely defined as 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 are not necessarily the biggest waves found at sea; they are, rather, surprisingly large waves for a given sea state.
- Rogue waves seem not to have a single distinct cause, but occur where physical factors such as **extreme wind fields** and strong currents cause waves to merge to create a single exceptionally large wave.

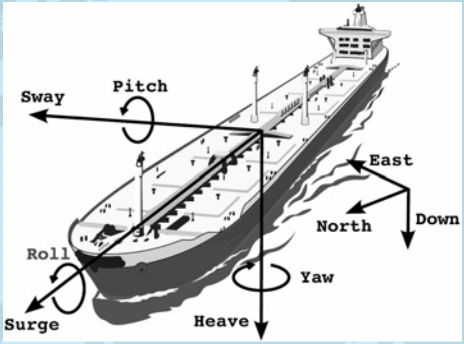
# Possible Causes of the Losses

- Synchronous rolling – inversely proportional to the square root of the metacentric height and directly proportional to the beam of the ship – 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 is between 1.8 to 2.1 times the encounter period (normally associated with the pitching period)

*Stability Analysis of Parametric Roll Resonance. B.J.H. van Laarhoven DCT 2009.062



# Parametric Roll




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

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



# Parametric Roll

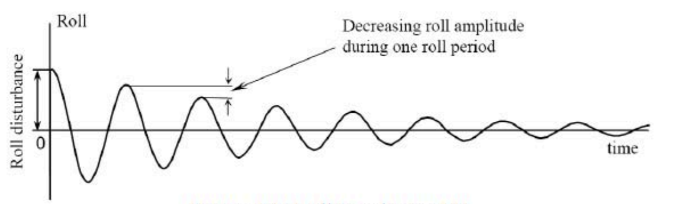



Figure 2.4: Roll in calm sea [2]

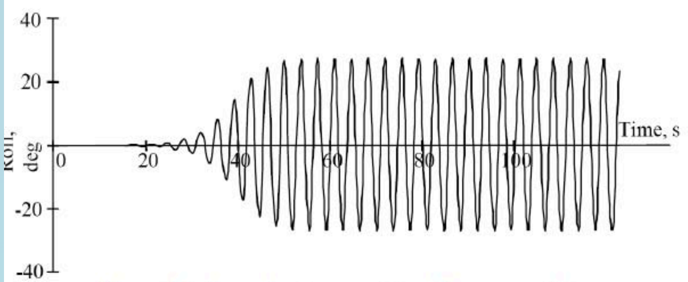


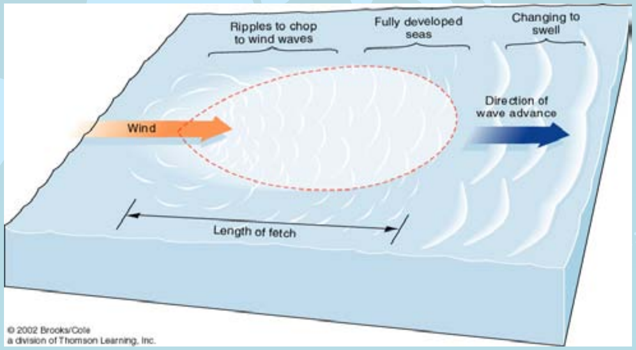

Figure 2.5: Example of parametric roll resonance [2]



# 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



# Wave Steepness and Ship Hazard

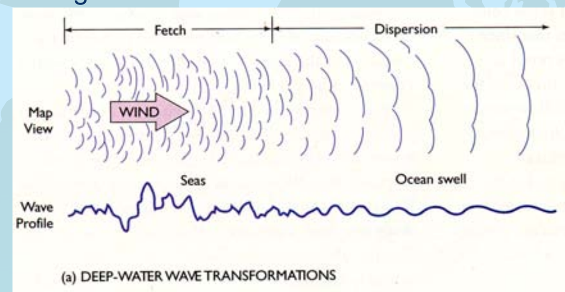
- Wave steepness= Wave Height/ Wave Length
- Young waves are steeper than older waves
- Steep waves pose significant risk to marine vessels en route
- The wave steepness in 60% of the global ship accidents ranged from .03 to .04.



# Swell and Wave Lifecycle

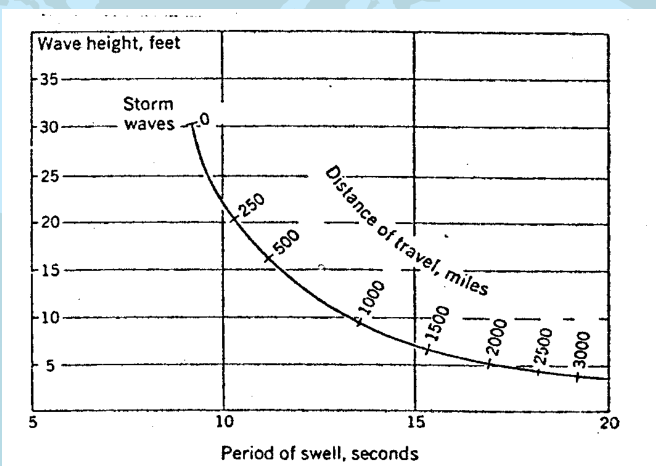
Three things happen to large waves when they leave the storm region.

1. Dissipation: Wave amplitude gradually dies out as the waves travel away from their source. Opposing wind enroute can accelerate the dissipation or decay of wave energy.
2. Dispersion: Swell disperse over the open ocean: longer wavelength swell move faster than shorter wavelength swell.
3. Angular spreading: Shorter wavelengths (steeper waves) have more angular spreading.






# Wave Decay




Dissipation



# Deep Water Waves and Dispersion

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

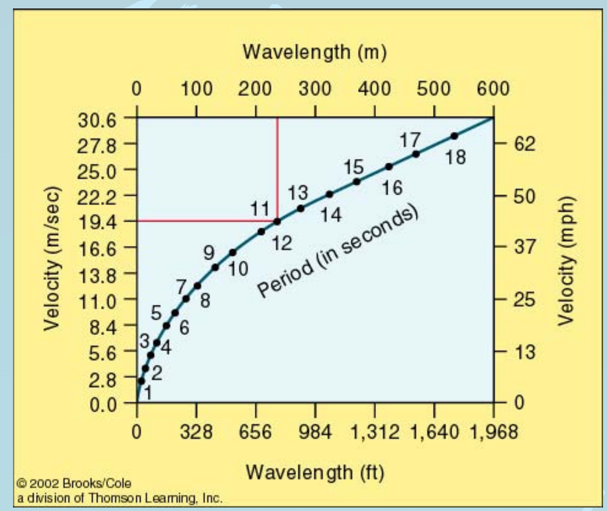
Longer waves move faster

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

C = wave speed

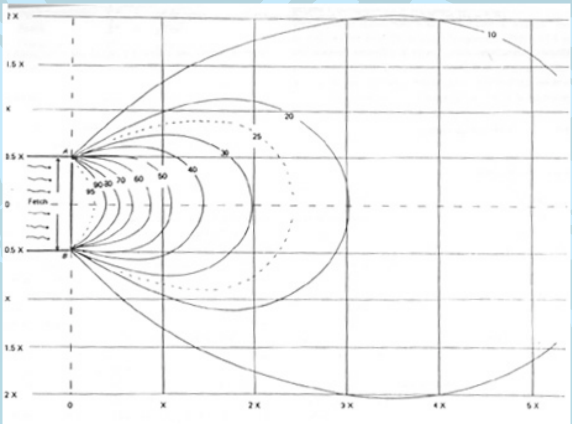
g = gravity (9.8 m/s $^2$)

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




Graph of the relationship between wave speed and wavelength.

## Angular Spreading



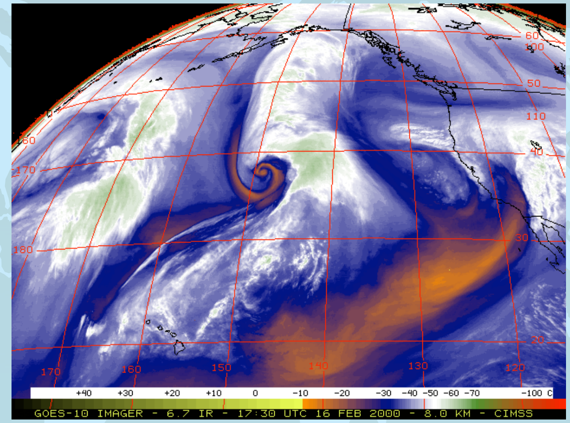
Angular spreading is proportional to swell energy.

Swell from broad fetches experience less angular spreading.

Steep waves dissipate more quickly through angular spreading.



## 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).

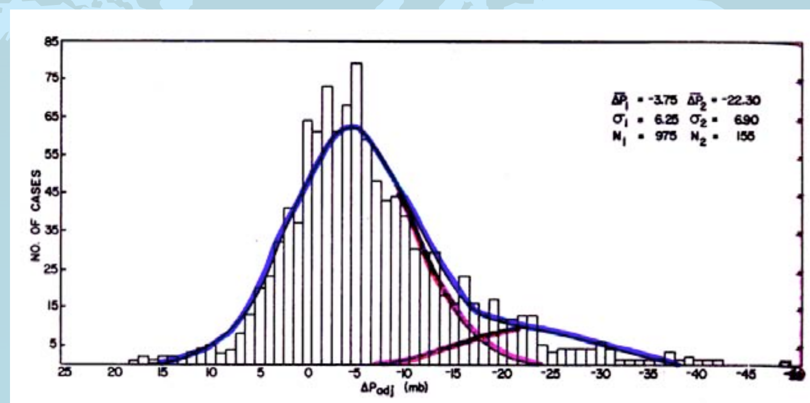


## Synoptic-Dynamic Climatology of "Bombs"

- 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.

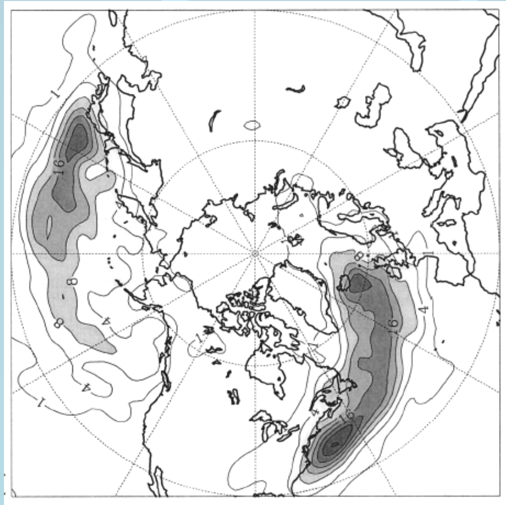


## Distribution of Pressure Falls in Bombs




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

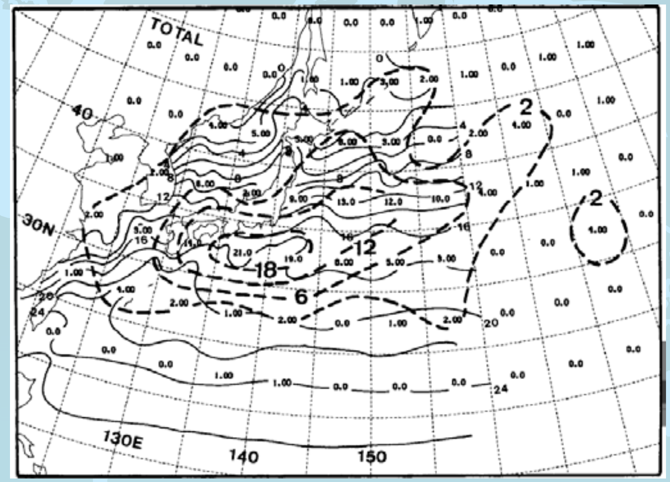
# Distribution of Bombs



Explosive cyclone density [contour interval $4\times10^{-5}$ explosive cyclones (°$lat^{-2}$), 1979-1999 (From Lim and Simmonds (2002).



# SST and Distribution of Bombs




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



# Surface Sensible Heat Fluxes

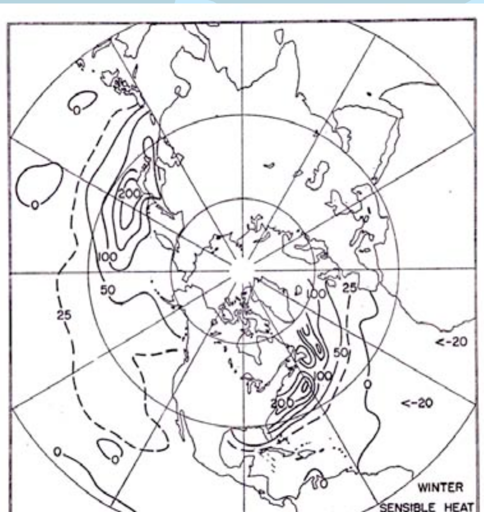
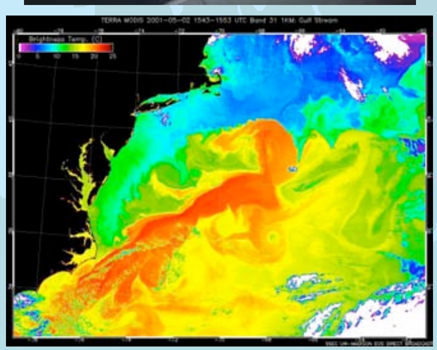


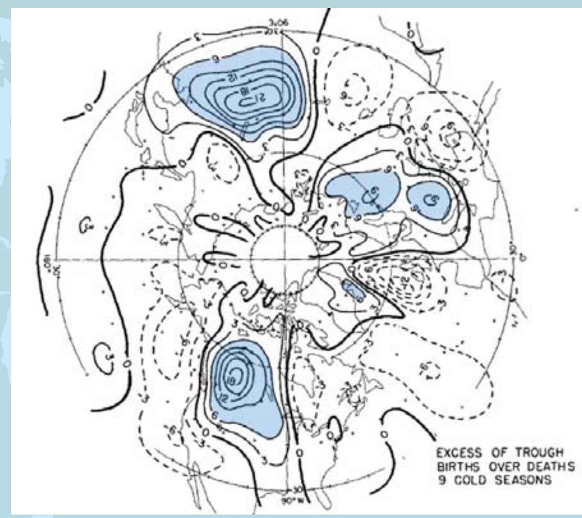

FIG. 20.3.5. Mean amount (in gram calories per square centimeter per day) of sensible heat exchanged between the sea and the atmosphere in winter. (*After Jacobs* [7].)

Distribution of sensible-heat fluxes



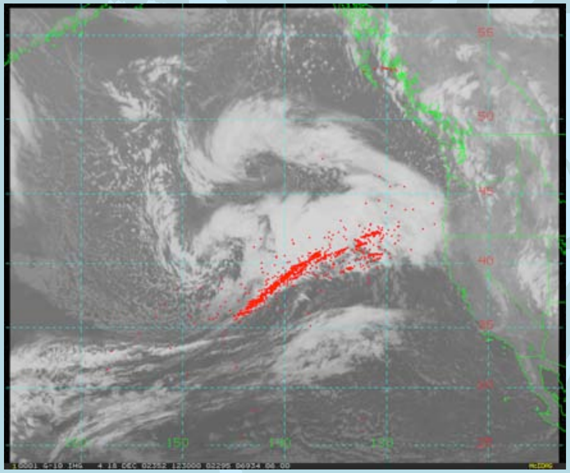


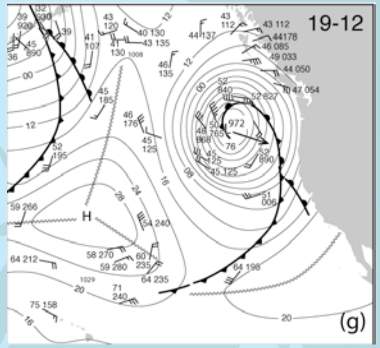
# Vorticity Advection – Shortwaves




Short waves aloft provide strong mid-tropospheric cyclonic vorticity advection where needed.

# Deep Convection in HF Storms






Surface analysis
Valid 1200 UTC
19 December 2002

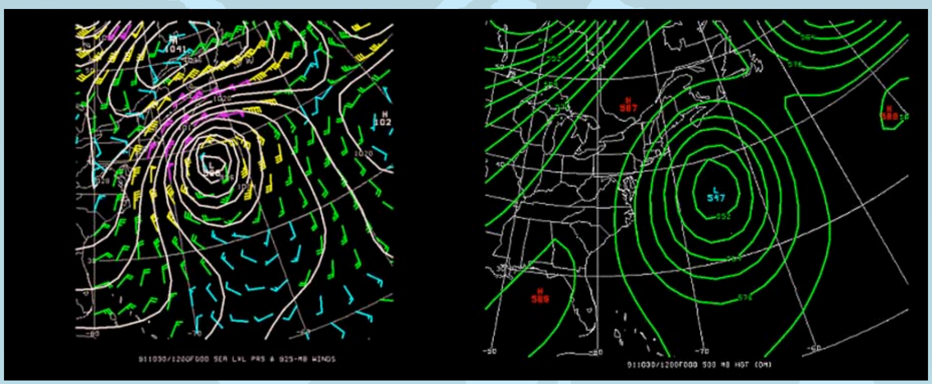
Northeast Pacific Storm 18-20 December 2002
was under forecast by more than 10 mb by NCEP.

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






# Animation of the "Perfect Storm"



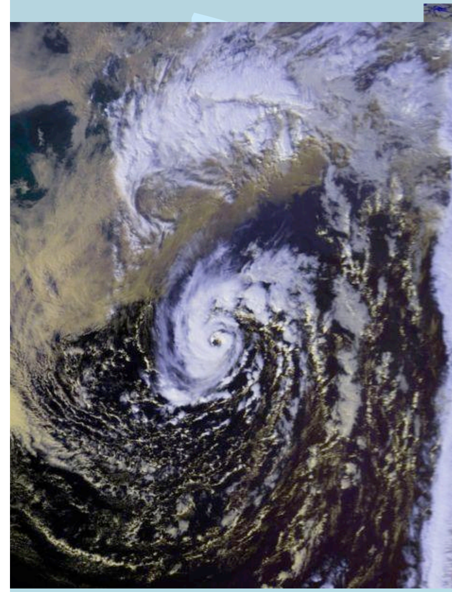
Sea-level Pressure/Winds

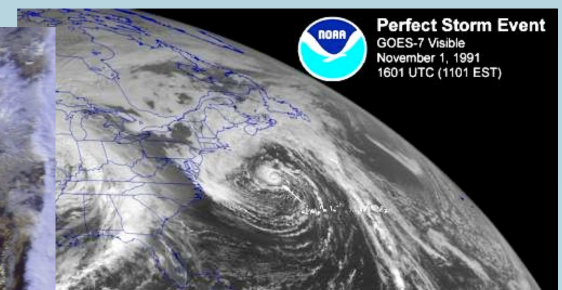
500-mb Heights

The perfect storm absorbed Hurricane Grace in October 1991. The Andea Gail swordfish boat sank in this storm on 10/28/91.



# Hurricane-like Core in Perfect Storm

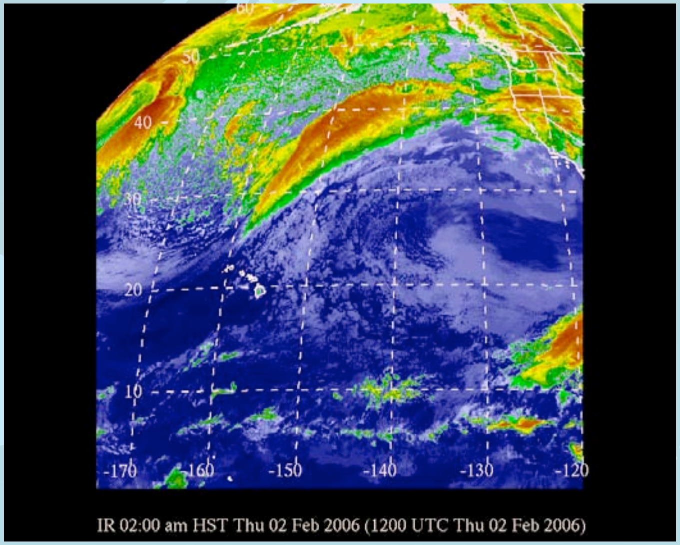





# West Coast Windstorms

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.



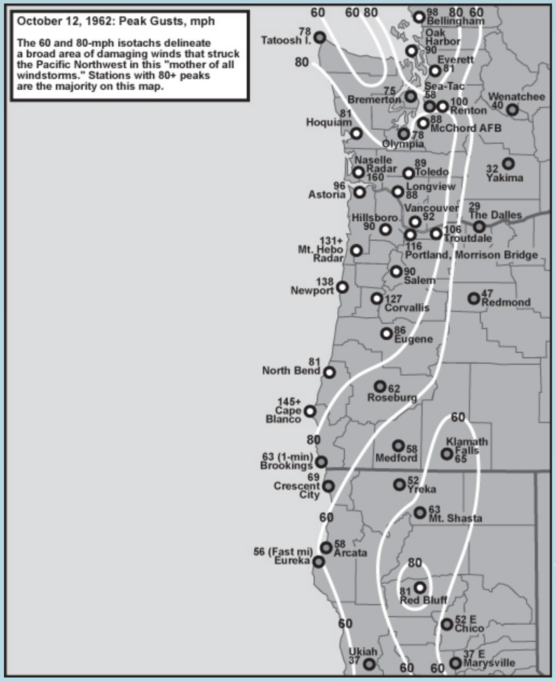
# Mother of all NW Windstorms

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



# NW Windstorms and Bridges

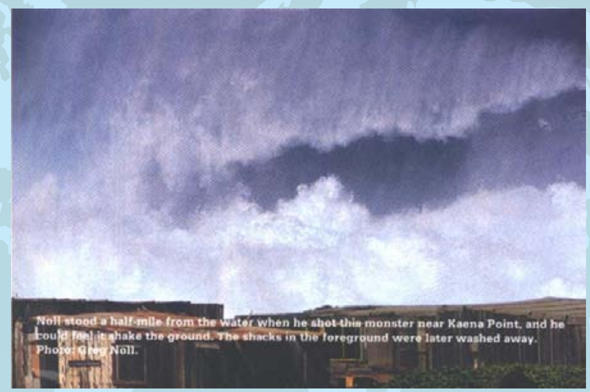

Tacoma Narrows Bridge 7 November 1940



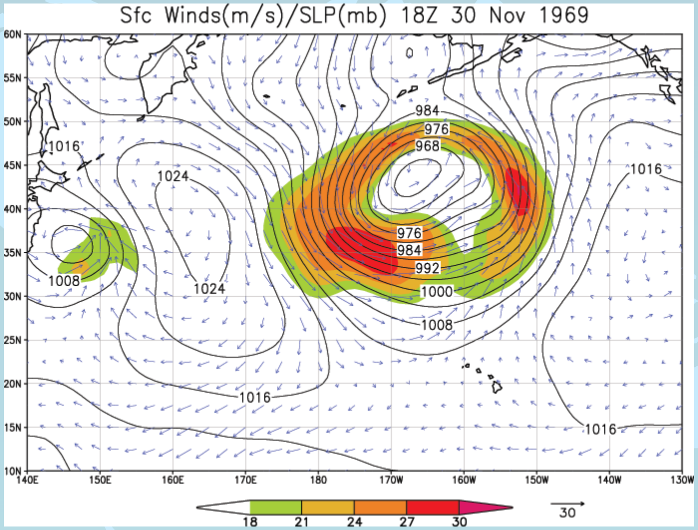
# Hawaii: Two Epic Wave Events



# 1969 Wave Damage on Oahu



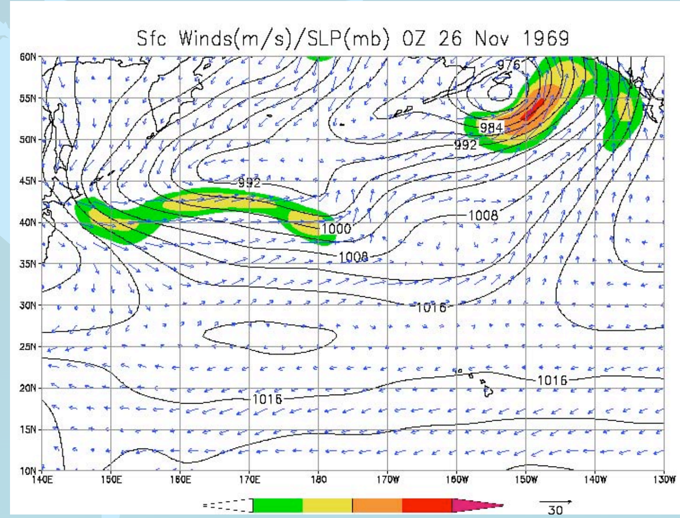

# HF Storm of December 1969




NCAR/NCEP Reanalysis Data for 8 AM 30 November 1969



# 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.

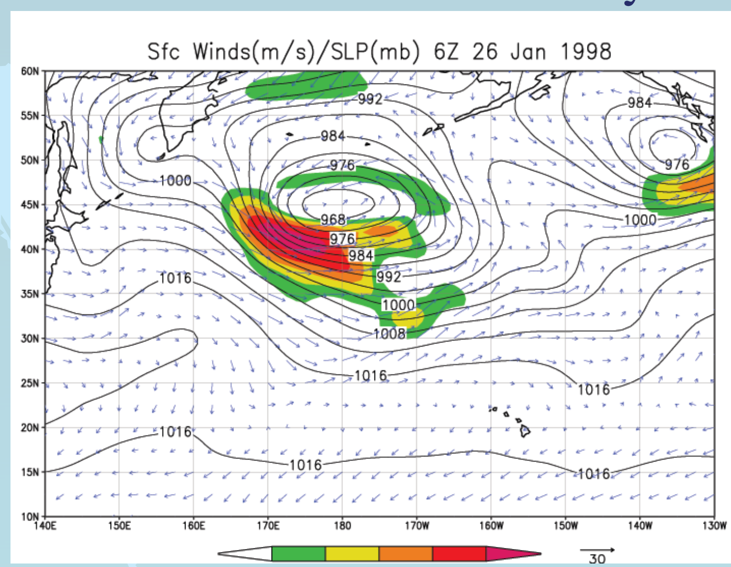


# HF Storm Jan. 1998

Photos by S. Businger

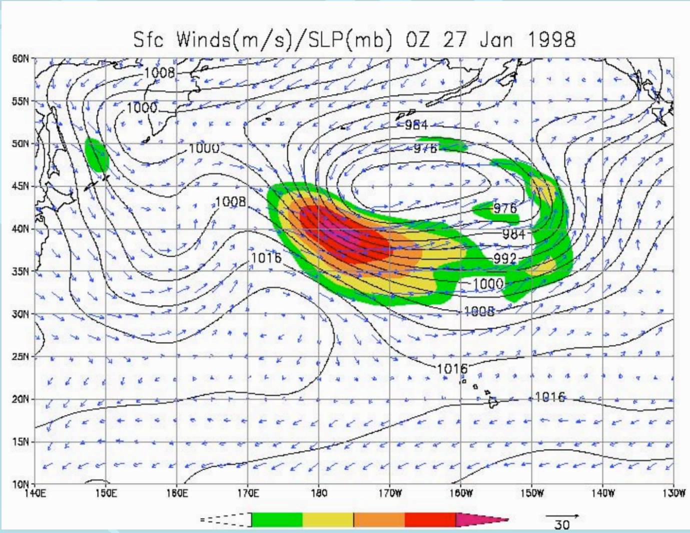


# HF Surface Winds on 26 January 1998




NCAR/NCEP Reanalysis Data for 8 PM 25 January 1998

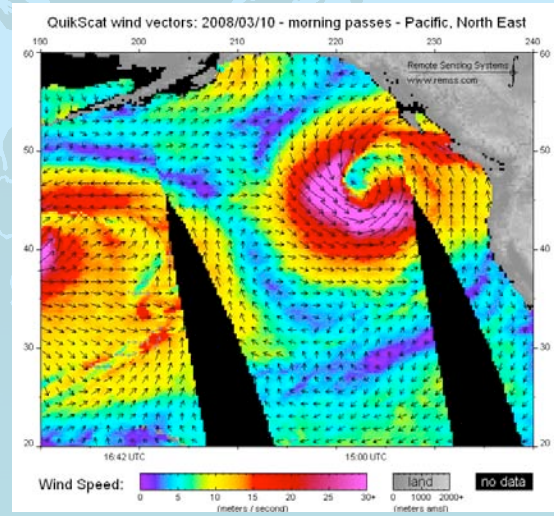
# Animation of SLP Analyses Jan. 1998




Note the captured fetch that again occurred in this case.



# HF Wind Fields: Data and Methods



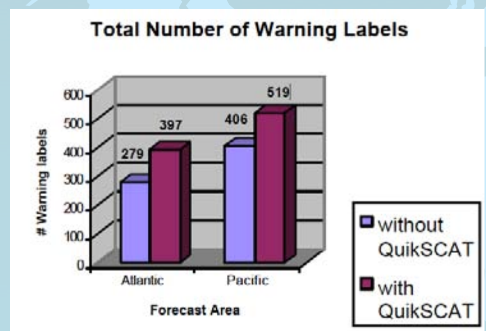


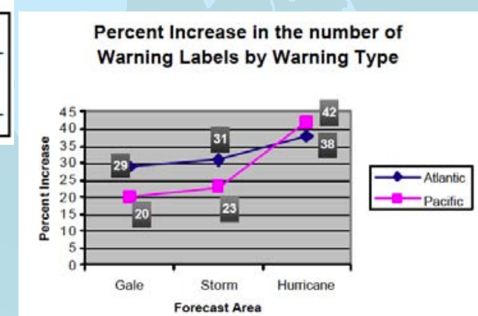

# HF Wind Fields: Data and Methods

1. 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.
2. QuikSCAT can measure wind speeds up to 30 m $s^{-1}$ (near hurricance force) with an accuracy of ±2 m $s^{-1}$ (Shirtliffe, 1999). OPC forecasters routinely observe QuikSCAT winds in excess of 32.9 m $s^{-1}$.
3. Used QuikSCAT data to isolate cases of hurricane force winds in winter storms for 2003-2008, and compared maxima in QuikSCAT winds to maxima in GFS analyses.
4. Selected cases where threshold conditions (7.5 m estimated breaker height) were measured at a buoy.
5. Compared observations of the significant wave height and dominant period at buoys against Wavewatch III (WW3) output.



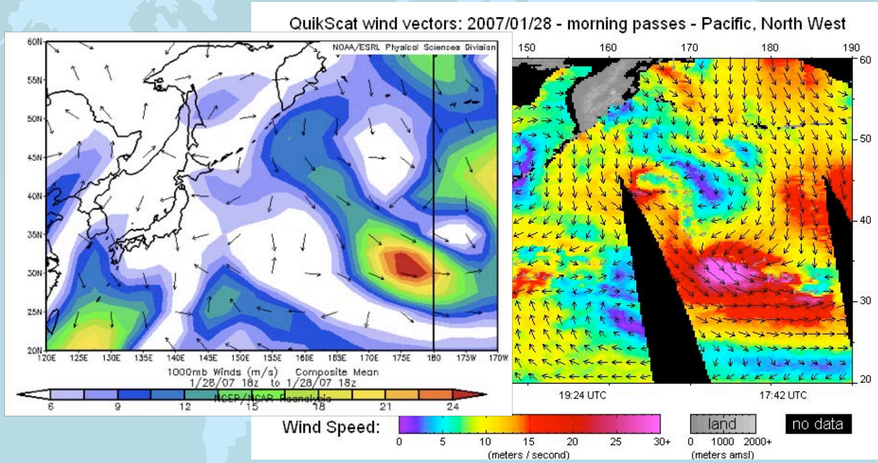
# QuikSCAT Increases # of Warnings




Ahn et al. 2009

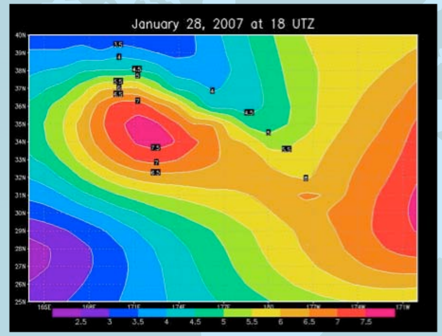
# HF Storm Example: 28-29 Jan. 2007



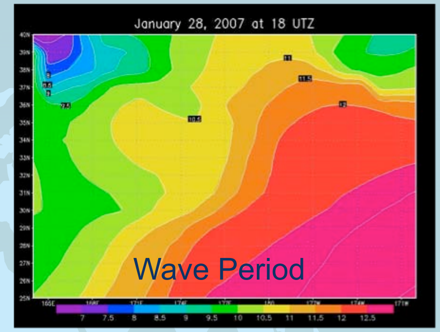

QuikSCAT wind image and GFS wind analysis for same time.



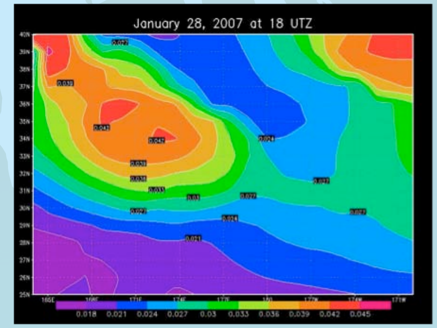
# WWIII Wave Fields




Wave Height



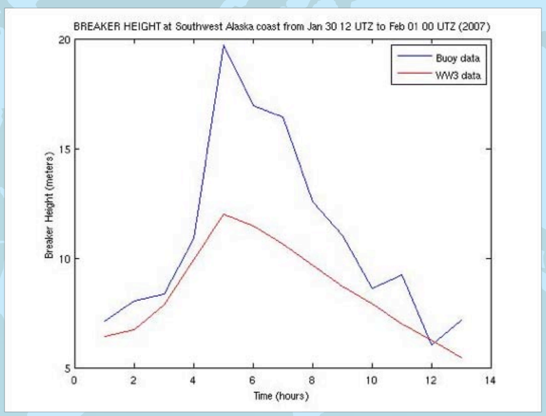

Wave Period




Wave Steepness



# Comparison of Breaker Heights

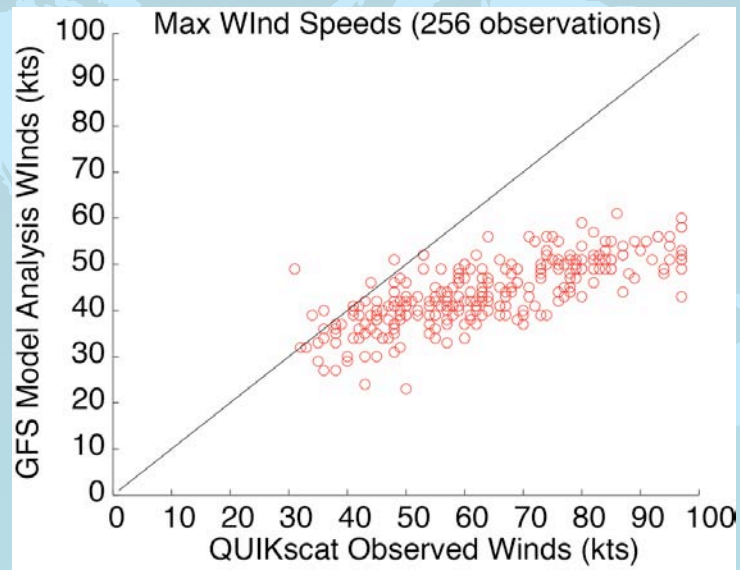



Breaker height = wave height x periods x shoaling factor

Wave steepness reached .07 along the AK coast.

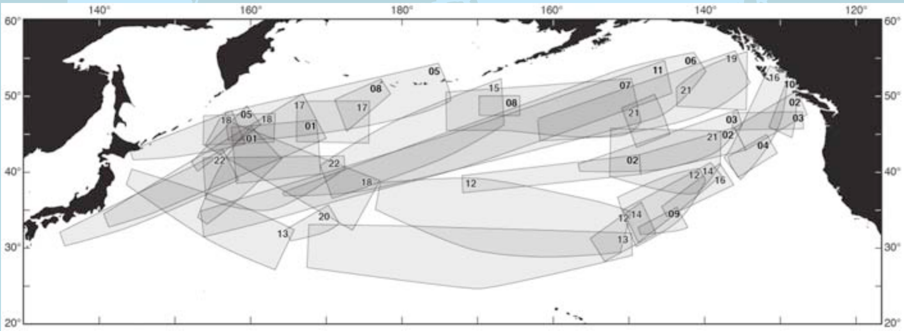


# QuikSCAT vs GFS Analyses



# Hurricane Force Fetch Climatology

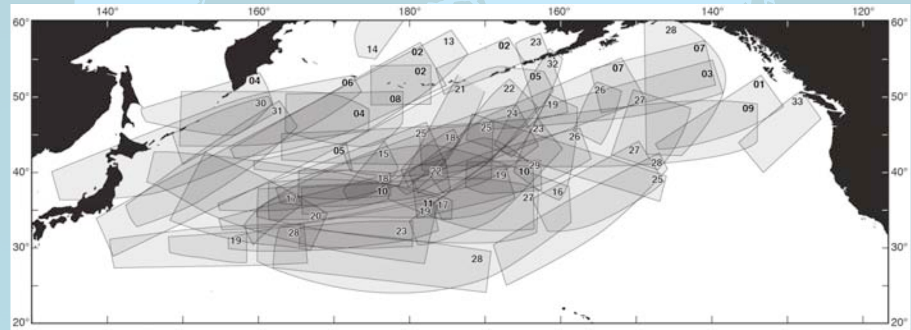
## 2003-2004 Winter





# Hurricane Force Fetch Climatology

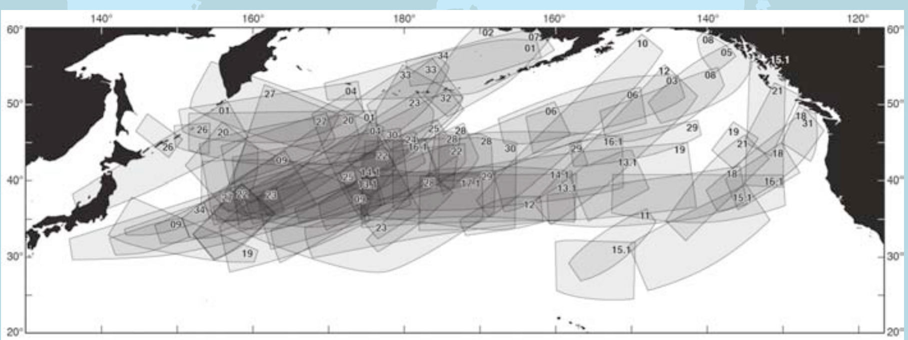
## 2004-2005 Winter





# Hurricane Force Fetch Climatology

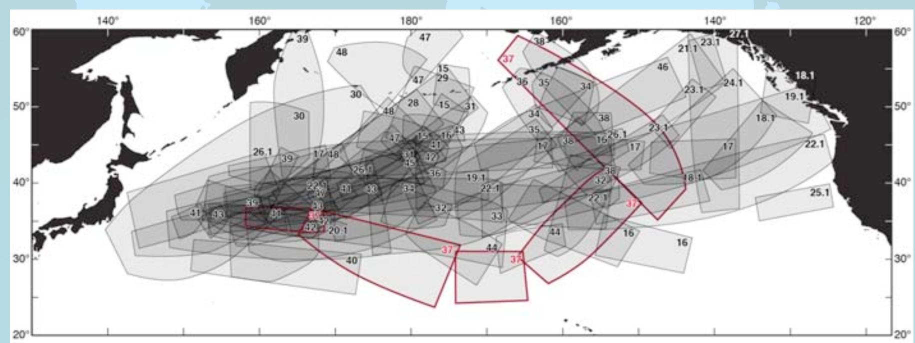
## 2005-2006 Winter





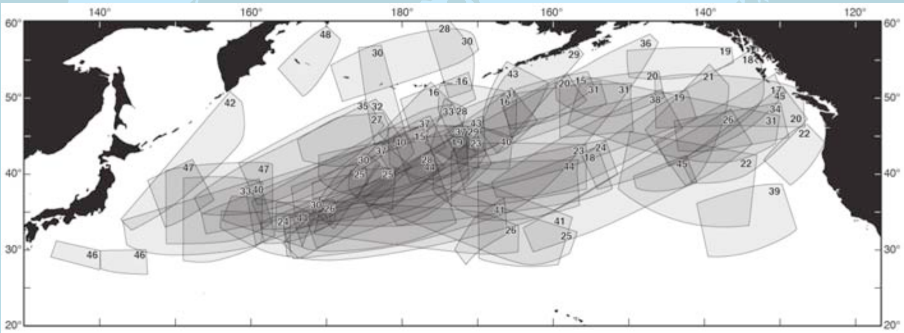
# Hurricane Force Fetch Climatology

## 2006-2007 El Niño



# Hurricane Force Fetch Climatology

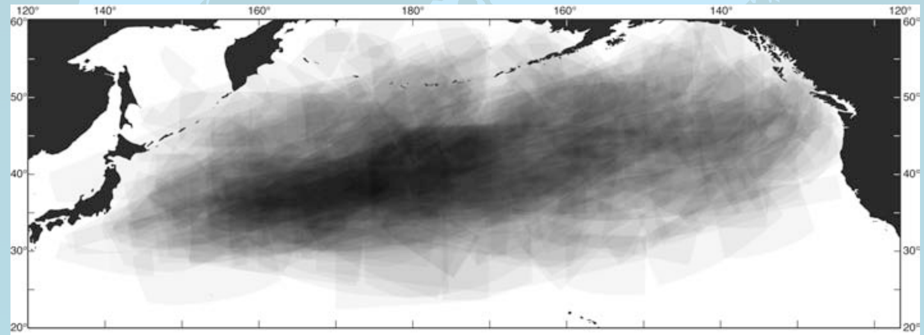
## 2007-2008 La Niña





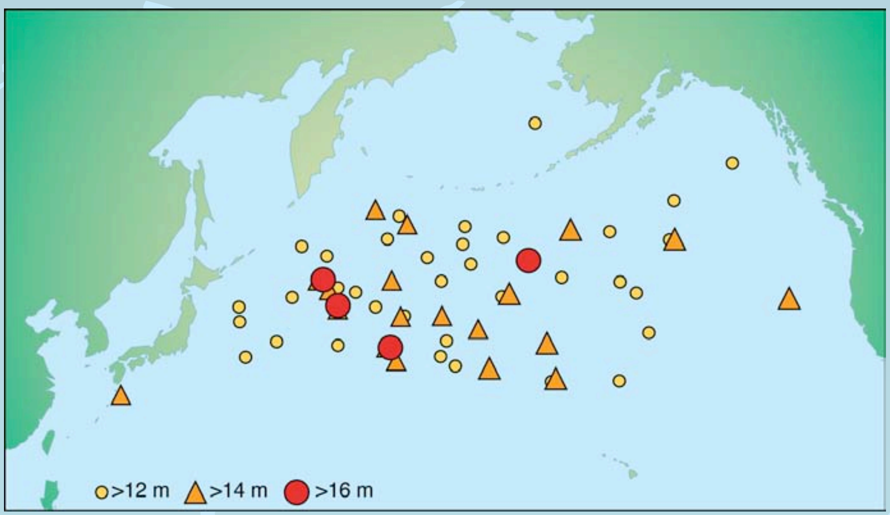
# Hurricane Force Fetch Climatology

## Jan 2003 through May 2008





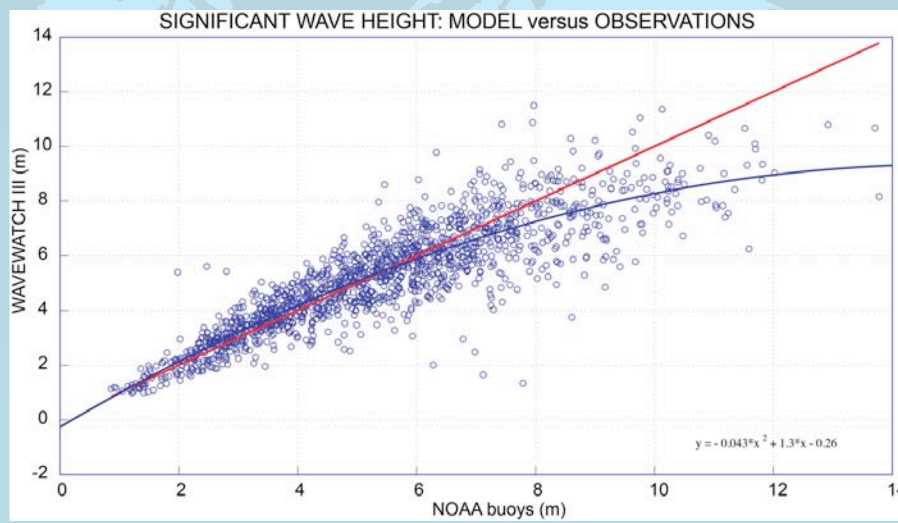
# Very Extreme Sea-State Events



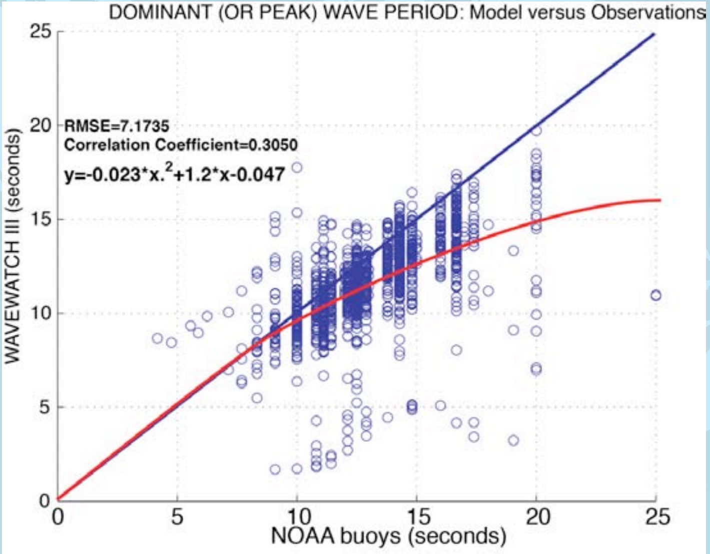

Distribution of 12+m significant wave height events as measured by the TOPEX, ENVISAT and JASON Altimeters (Cardone et al. 2005).



# WW3 vs Buoys: Significant Wave Height



# WW3 vs Buoys: Dominant Wave Period






# Conclusions

- Storm fetches show the location of greatest hazard and the extent of interannual variability.
- During El Niño the area of greatest hazard shifts westward, whereas during La Niña the area of greatest hazard shifts eastward within the overall zone of greatest hazard.
- The GFS weather model analyses underestimate the strength of the winds in these strong storms when compared to QuikSCAT Satellite wind observations.
- The buoy observations show that the WWIII under forecasts large wave events over the North Pacific Ocean, consistent with the under forecast of the winds.
- WWIII wave steepness is greatest in the core of the fetches and is greater than damage threshold for ships.



# Recommendations

The results of this study suggest that a replacement for QuikSCAT winds should be priority. Better data assimilation methods need to be developed to ingest satellite wind data.

Ship accidents occur when the wavelength is systematically above half the ship length. Each ship (captain) should therefore interpret the marine forecasts with respect to their ship type and loading state.

It would be of great benefit to have a ship's black box, i.e., a data-recording device onboard storing the information needed to improve safety of ship operations. In combination with a detailed hindcast of the sea state conditions great progress could be made.

Add fold-out stabilizing fins to ships.

Track the weight/inventory of containers to help organize their loading.



# Future Work

The results of this study suggest that there is an opportunity to improve GFS and WWIII model performance.

Future work is needed to analyze the performance of the GFS and WWIII models without QuikSCAT.

Despite considerable efforts, currently there are no plans in the U.S. to launch future scatterometers.

# Acknowledgements

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