# Global Distribution and Associated Synoptic Climatology of Very Extreme Sea States (VESS)

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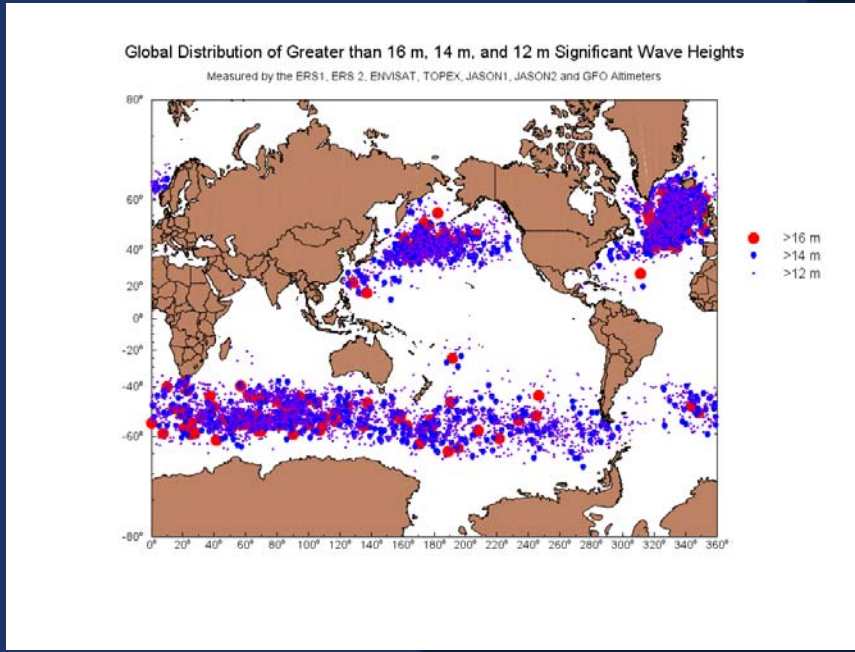
## *Motivation*

- ***Contribution to JCOMM community database of VESS occurrences***
- ***Development of a conceptual model of "winter hurricane" model forcing***
- ***Differential performance of a third-generation wave model in VESS storms when forced by Climate Forecast System Reanalysis (CFSR) wind fields and kinematically reanalyzed wind fields***



## *Methodology*

- **Scan GlobWave altimeter database for basin-specific orbit segment peaks of HS > 12 m and distill to a population of associated extra-tropical cyclones in a man-machine mix procedure**

- **For the unique set of 120 storms with peak VESS > 16 m extract from CFSR and selected further kinematic reanalyses characteristic meteorological properties of storm center and surface wind jet streak evolution**

- **Hindcast with the MSC50 3G North Atlantic wave model the two back to back storms associated with the two highest ranked VESS in that basin and evaluate skill relative to skill in a CFSR driven hindcast with the same 3G wave model physics**

## *Conclusions*

- *Over 5,000 basin-specific orbital segments with peak HS > 12 m were identified in the GlobWave database and distilled to 120 unique storms with at least one peak Hs > 16 m.*

- *The highest individual peaks were found in the Northern Hemisphere, with 10 peaks greater than 18 m in the North Atlantic (NAO) and 4 in the North Pacific (NPO). Only 3 such peaks were found in the Southern Oceans.*

- *The frequency of VESS is not proportional to basin size. The NAO had the greatest frequency, followed by the NPO, SPO, SIO, and SAO.*

- *The detection rate of intense extra-tropical cyclones with VESS > 16 m appears to be insensitive to number of altimeter missions active as long as there at least two. An average of 5 such storms/year on global basis was found in this study.*

- *Only four of the 120 scanned VESS were associated with tropical cyclones.*

- *Peak wind speeds in the top ranked VESS storms may exceed 40 m/s, which is equivalent to a Category 3 hurricane on the Saffir-Simpson Scale. The radius of maximum winds are much larger than typical of a typical tropical cyclone but much smaller than typically diagnosed in the atmospheric reanalysis products.*

- *A 3G model can be applied with confidence in a VESS, as long as the forcing is accurately prescribed at least with respect to specification of storm peak HS.*

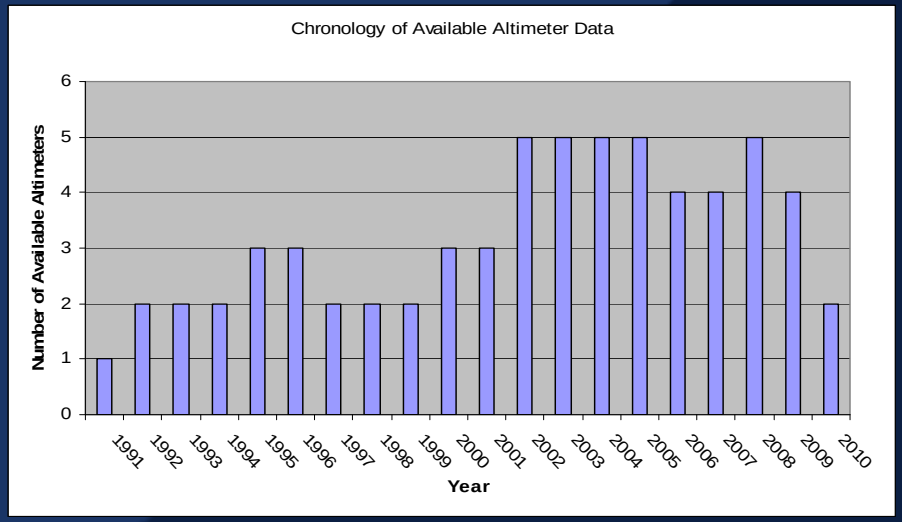
# *GlobWave Altimeter Database*

- **GlobWave provides a new, homogenized, quality controlled, single point of access database containing virtually the entire record of satellite altimeter HS and WS measurements acquired since 1991.**

- **The database is described in a general way in the Wave Data Handbook for GlobWave (Ash et al, 2011) with an in-depth description of the quality control and calibration of each of the missions by Queffeulou and Croize-Fillon (2010)**

| Satellite | Product | Cycles | Time Period | Comments |
|---|---|---|---|---|
| ERS1 | OPR | not defined | 01-08-1991 to 30-03-1992 | Phases A&B 3-days |
| | | 83 to 101 | 14-04-1992 to 20-12-1993 | Phase C 35-days |
| | | not defined | 24-12-1993 to 10-04-1994 | Phase D 3-days |
| | | not defined | 10-04-1994 to 21-03-1995 | Phases E&F 168-days |
| | | 144 to 156 | 24-03-1995 to 02-06-1996 | Phase G 35-days |
| ERS2 | OPR | 1 to 146 | 15-05-1995 to 11-05-2009 | Mission going on |
| ENVISAT | GDR | 9 to 84 | 27-09-2002 to 07-12-2009 | Mission going on |
| TOPEX Poseidon | M-GDR | 1 to 481 | 25-09-1992 to 08-10-2005 | |
| Jason-1 | GDR | 1 to 300 | 15-01-2002 to 03-03-2010 | Mission going on |
| Jason-2 | GDR | 0 to 60 | 04-07-2008 to 26-02-2010 | Mission going on |
| GEOSAT FO | GDR | 37 to 222 | 07-01-2000 to 07-09-2008 | |

***Altimeter missions contained in GlobWave (above) and number of missions by year (below)***

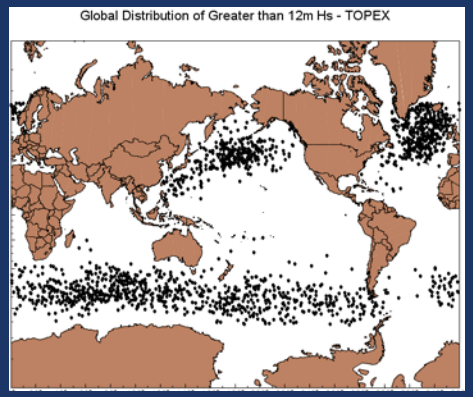


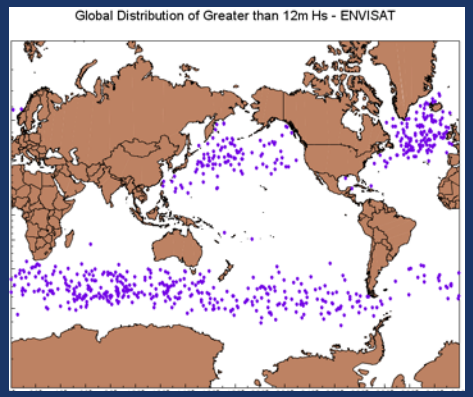
# *VESS Detection by Altimeter Mission*

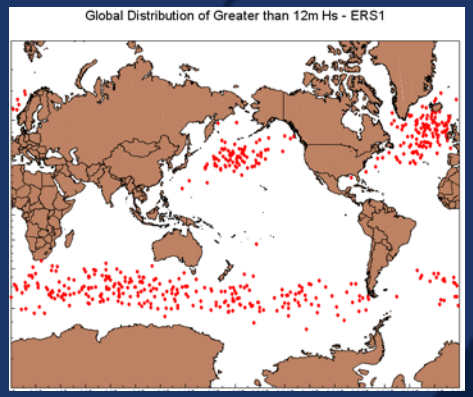
**GlobWave distribution of basin orbit-segment peaks of HS > 12 m along (counts and relative percentage occurrence) sorted by altimeter mission and basin**

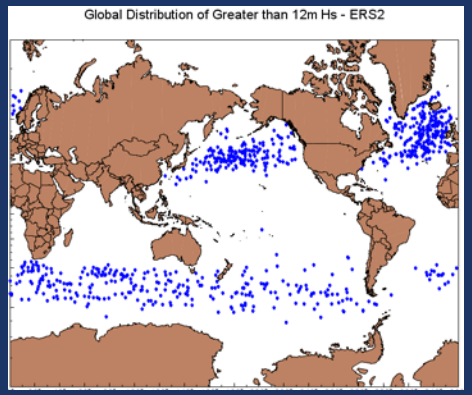
| Satellite | NATL | %NATL | NPAC | %NPAC | SATL | %SATL | SPAC | %SPAC | SIND | %SIND | TOTAL | %TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ERS1 | 130 | 9.67 | 83 | 8.37 | 41 | 11.71 | 85 | 9.54 | 167 | 9.95 | 506 | 9.63 |
| ERS2 | 246 | 18.29 | 180 | 18.15 | 39 | 11.14 | 81 | 9.09 | 162 | 9.65 | 708 | 13.47 |
| TOPEX | 404 | 30.04 | 301 | 30.34 | 97 | 27.71 | 290 | 32.55 | 495 | 29.50 | 1587 | 30.19 |
| ENVISAT | 146 | 10.86 | 106 | 10.69 | 53 | 15.14 | 117 | 13.13 | 239 | 14.24 | 661 | 12.58 |
| GFO | 160 | 11.90 | 165 | 16.63 | 59 | 16.86 | 138 | 15.49 | 299 | 17.82 | 821 | 15.62 |
| JASON1 | 223 | 16.58 | 144 | 14.52 | 54 | 15.43 | 154 | 17.28 | 273 | 16.27 | 848 | 16.13 |
| JASON2 | 36 | 2.68 | 13 | 1.31 | 7 | 2.00 | 26 | 2.92 | 43 | 2.56 | 125 | 2.38 |
| TOTAL | 1345 | 25.59 | 992 | 18.87 | 350 | 6.66 | 891 | 16.95 | 1678 | 31.93 | 5256 | 100.00 |

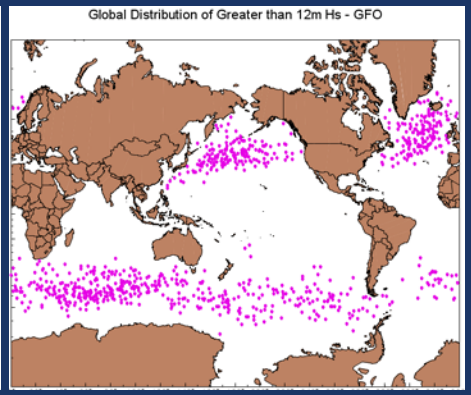
# *12 Meter Events By Altimeter Platform*

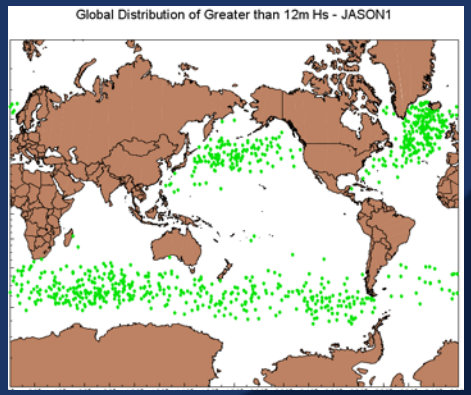


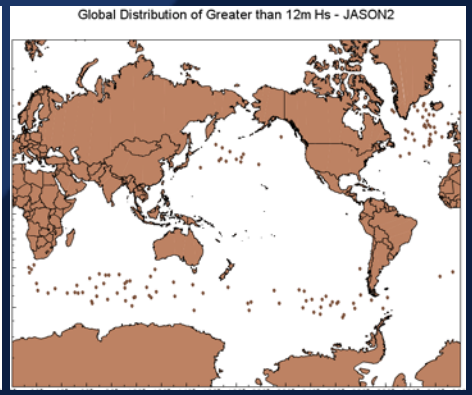



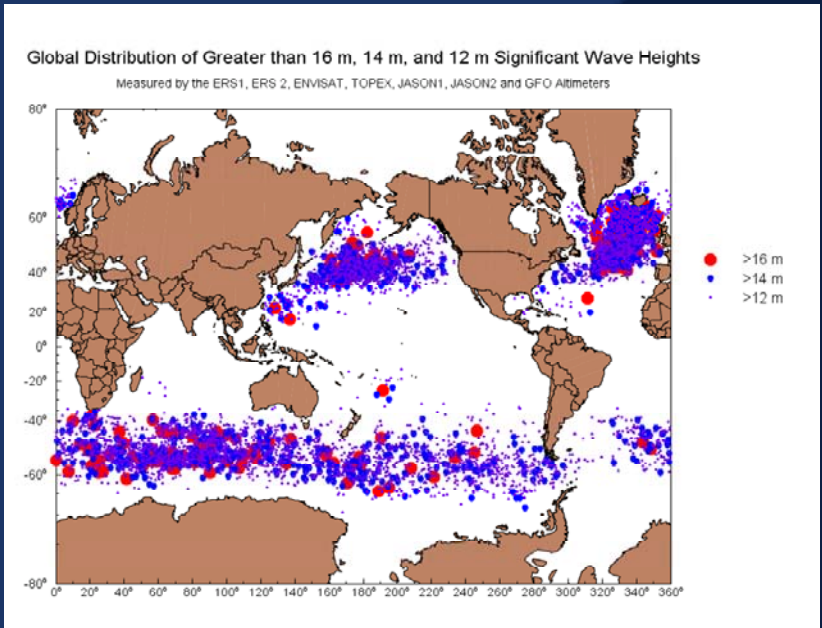



# *VESS Detection by Significant Wave Height*

**Distribution of orbit segment peaks (counts and relative percentage occurrence) sorted by basin for indicated HS thresholds**

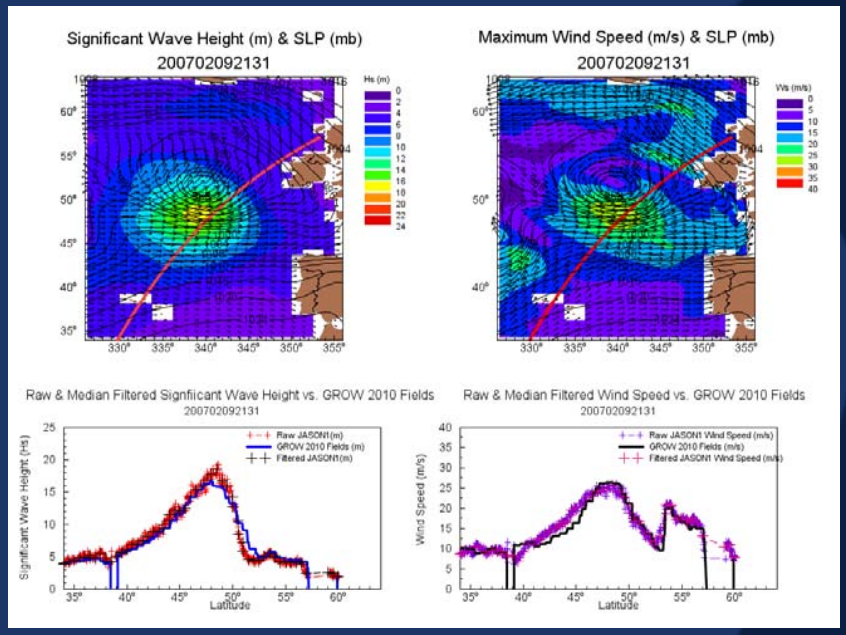


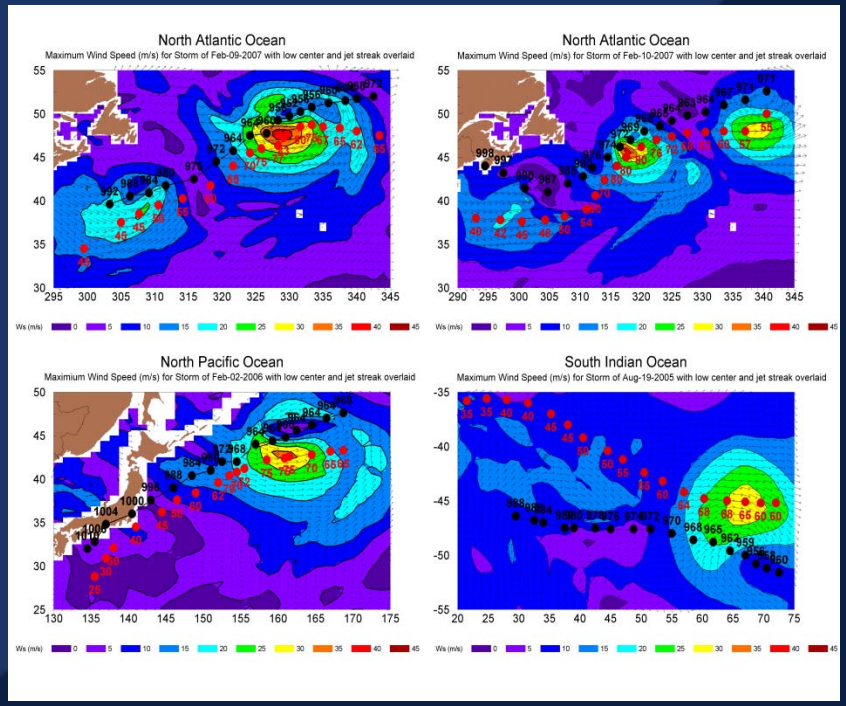

| Hs | NATL | %NATL | NPAC | %NPAC | SATL | %SATL | SPAC | %SPAC | SIND | %SIND | TOTAL | %TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| >16 m | 65 | 4.83 | 34 | 3.43 | 6 | 1.71 | 15 | 1.68 | 65 | 3.87 | 185 | 3.52 |
| >14 m | 310 | 23.05 | 222 | 22.38 | 58 | 16.57 | 138 | 15.49 | 318 | 18.95 | 1046 | 19.90 |
| >12 m | 1345 | 25.59 | 992 | 18.87 | 350 | 6.66 | 891 | 16.95 | 1678 | 31.93 | 5256 | 100.00 |
| Maximum Hs (m) | 20.24 | | 20.63 | | 16.57 | | 17.51 | | 18.84 | | | |

# *VESS Storms*

- From the global distribution of VESS, 185 peaks were discovered with Hs greater than or equal to 16 m. Using time series plots of altimeter data plotted against the output of a 70-km global wave model forced by CFSR wind inputs, as well as weather map sequences, these 185 peaks were found to be associated with 120 unique storms.

- Representative storms were chosen for the North Atlantic, North Pacific, and South Indian Oceans for extraction of basic meteorological properties. Basic continuity charts tracking the low center and jet streak for each storm aided in this process.



# *Sample Table of 16m+ Altimeter and CFSR Parameters*

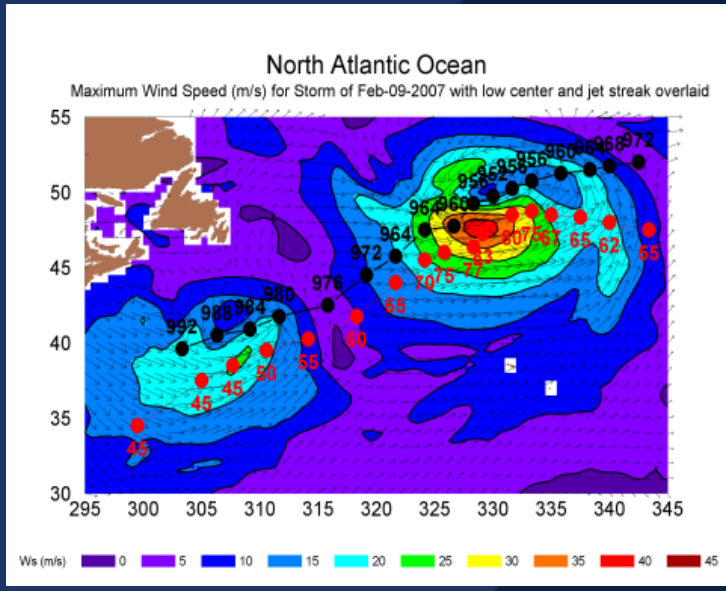
| Full Stormname | Latitude | Longitude | Satellite | Altimeter Peak Hs (m) | Bearing | Range (degrees) | Lowest CFSR SLP (mb) | CFSR Po / Delta T (mb/day) | CFSR Max Ws (kts) |
|---|---|---|---|---|---|---|---|---|---|
| 199903180526 | 45.61 | 183.4 | TOPEX | 20.63 | SSW | 6.5 | 949 | 28 | 73 |
| 200702101108 | 48.14 | 327.35 | GFO | 20.24 | SW | 3 | 963 | 24 | 75 |
| 199903212109 | 51.14 | 176.81 | TOPEX | 19.5 | SSE | 2.5 | 937 | 52 | 73 |
| 200602031141 | 40.79 | 178.3 | JASON1 | 19.39 | SSW | 6 | 959 | 44 | 75 |
| 200702092131 | 48.63 | 341.15 | JASON1 | 19.15 | SSE | 3 | 951 | 36 | 77 |
| 199502020709 | 50.75 | 326.56 | TOPEX | 19.1 | SSE | 5 | 935 | 50 | 71 |
| 200610090425 | -53.59 | 110.36 | GFO | 18.84 | NNE | 3 | 939 | 42 | 71 |
| 200501171517 | 57.13 | 328.43 | TOPEX | 18.78 | SW | 6.5 | 945 | 32 | 69 |
| 200705130900 | -39.71 | 57.04 | JASON1 | 18.71 | NW | 8 | 943 | 28 | 63 |
| 200002081151 | 57.73 | 336.52 | GFO | 18.64 | SW | 2.5 | 953 | 42 | 75 |

# VESS Storms – Typical Meteorological Properties

***Preliminary* estimates of average associated meteorological properties of minimum central pressure and maximum wind speed and its distance to the storm center for the highest ranked VESS storms in the NAO, NPO and SIO basins.**

| Basin | Min SLP (Mb) | Max Deepening Rate (mb/24 hrs) | Max Deepening Rate (Bergerons) @ 45N | Max Surface Wind Speed (m/s) | Min Radius of Max Winds (Km) | Location of Max Wind (Degrees) |
|---|---|---|---|---|---|---|
| North Atlantic | 955 | 34 | 1.7 | 41 | 225 | 2 |
| North Pacific | 953 | 33 | 1.7 | 36 | 263 | 2.4 |
| South Indian | 945 | 29 | 1.5 | 34 | 426 | 3.9 |

# *Conceptual Model of a "Winter Hurricane"*




**Stage I – Duration 12-24 hours**:

Surface Wind Field is poorly organized, 10-20 m/s, 3-5 degrees equator-ward of pressure center

Initial Peak Sea state is at background level

**Stage II – Duration – 24 hours:**

Explosive deepening of parent extratropical cyclone (1 Bergeron or at least 24 mb/day)

More typically the VESS "bombs" at a rate of 1.5 Bergerons

Radius of maximum winds in the right or right rear quadrant migrates to ~ 2 degrees of pressure center in NH and 2-4 degrees in SIO storms

Peak winds of super-Beaufort speeds ( > 33 m/s)

Rapid growth of VESS from background to Hs > 12 m

Storm forward speed of 15-20 m/s

**Stage III - Duration ~ 12 hours:**

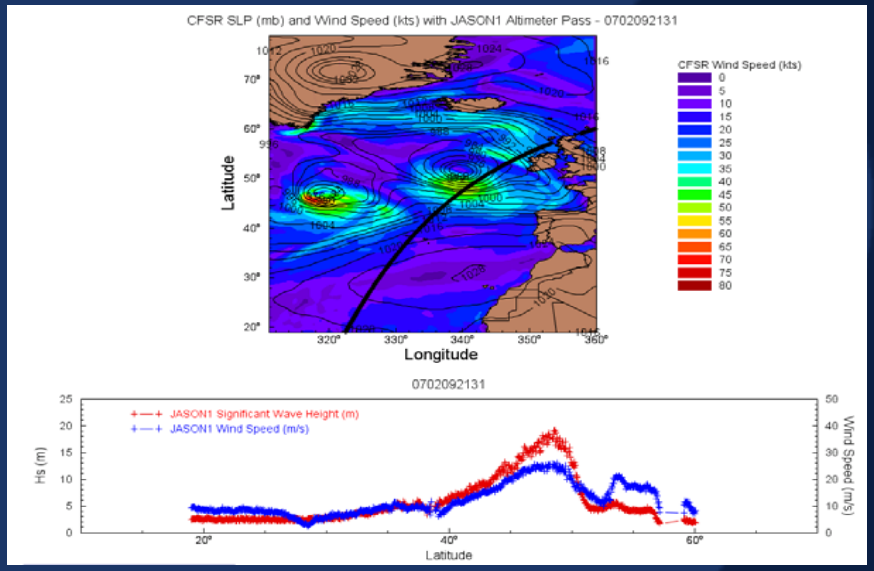
Quasi-equilibrium stage of maximum intensity with respect to minimum central pressure and magnitude and location of maximum wind speed, but with slow continued growth in peak VESS to its storm peak value

**Stage IV - Duration 24-48 hours**:

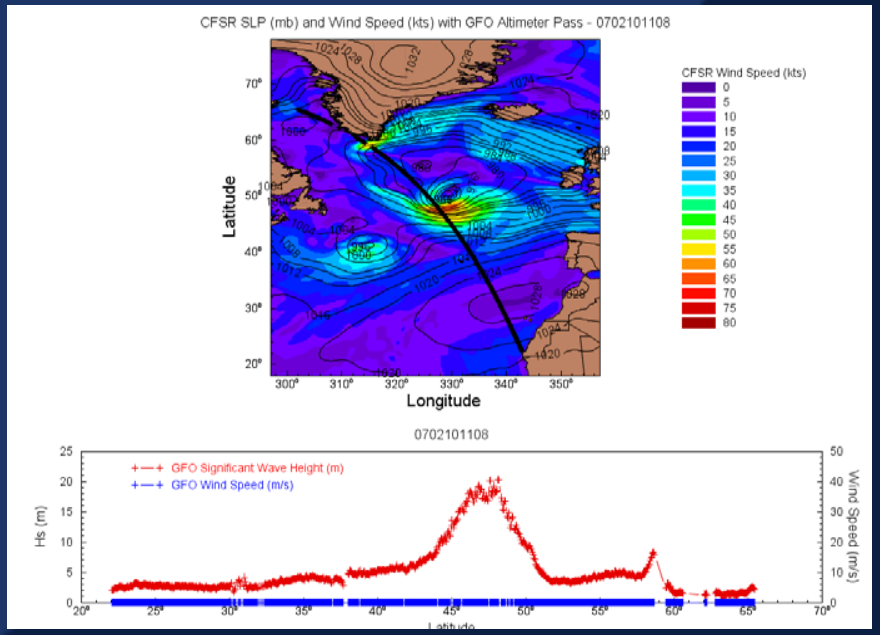
Decay Stage: central pressure rises rapidly, peak wind speed, and peak sea states decrease rapidly, and the radius of maximum wind speed increases gradually as the overall storm circulation expands

# *Hindcast of February 2007 North Atlantic Dual Winter Hurricanes*

- *February 9, 2007: Peak Hs from JASON-1 Ku Band Altimeter returned was 19.15 m*

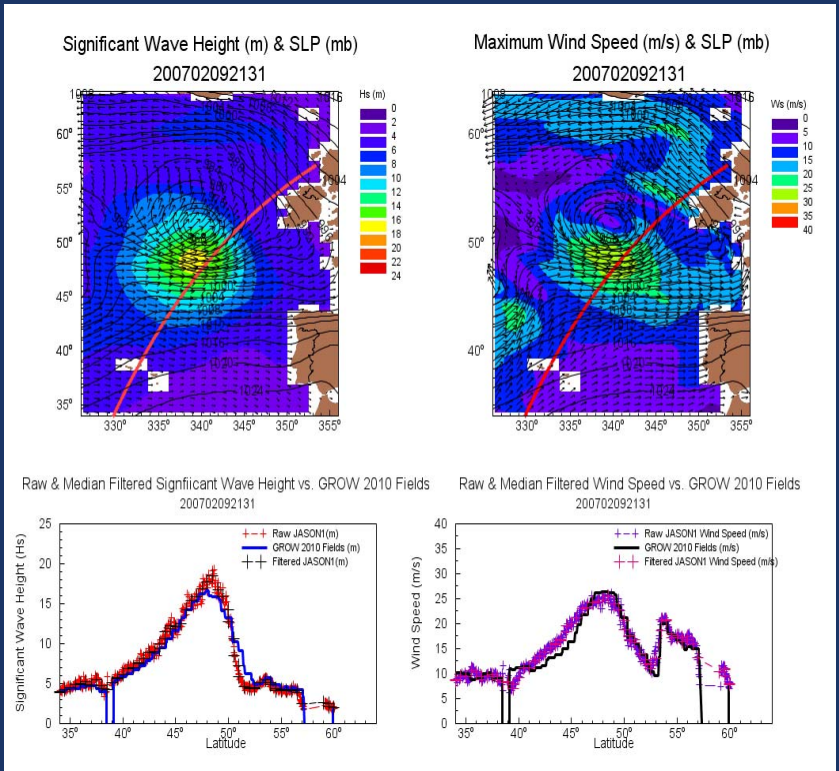



- *February 10, 2007: Peak Hs from GFO Ku Band Altimeter returned was 20.24 m*

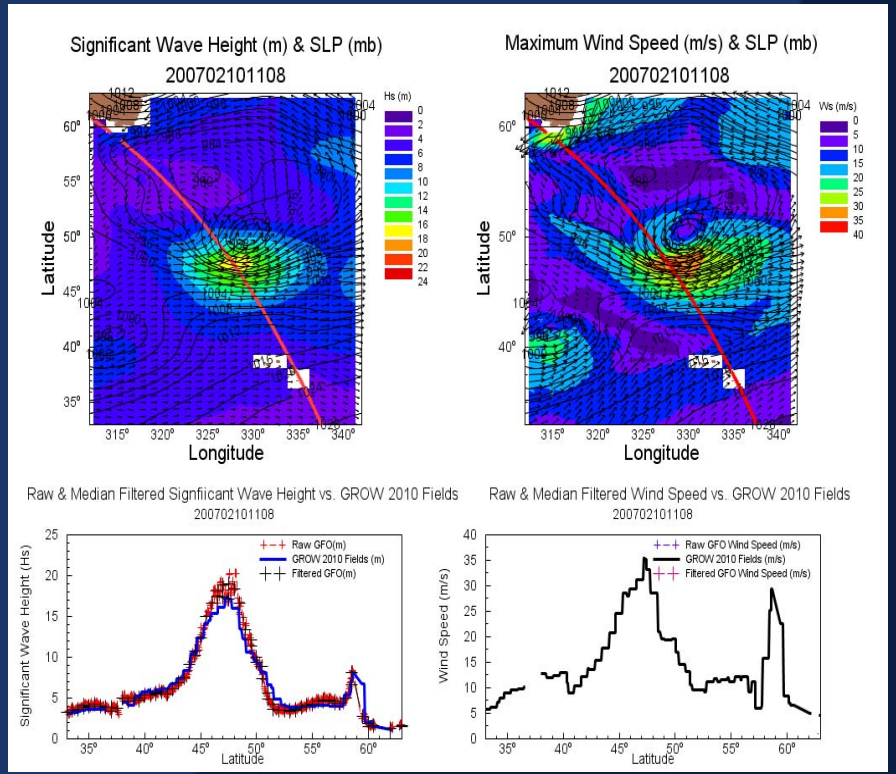


# *Global 70-km 3G Wave model (forced by CFSR wind input) comparisons to top peaks found in February 2007 winter hurricanes*

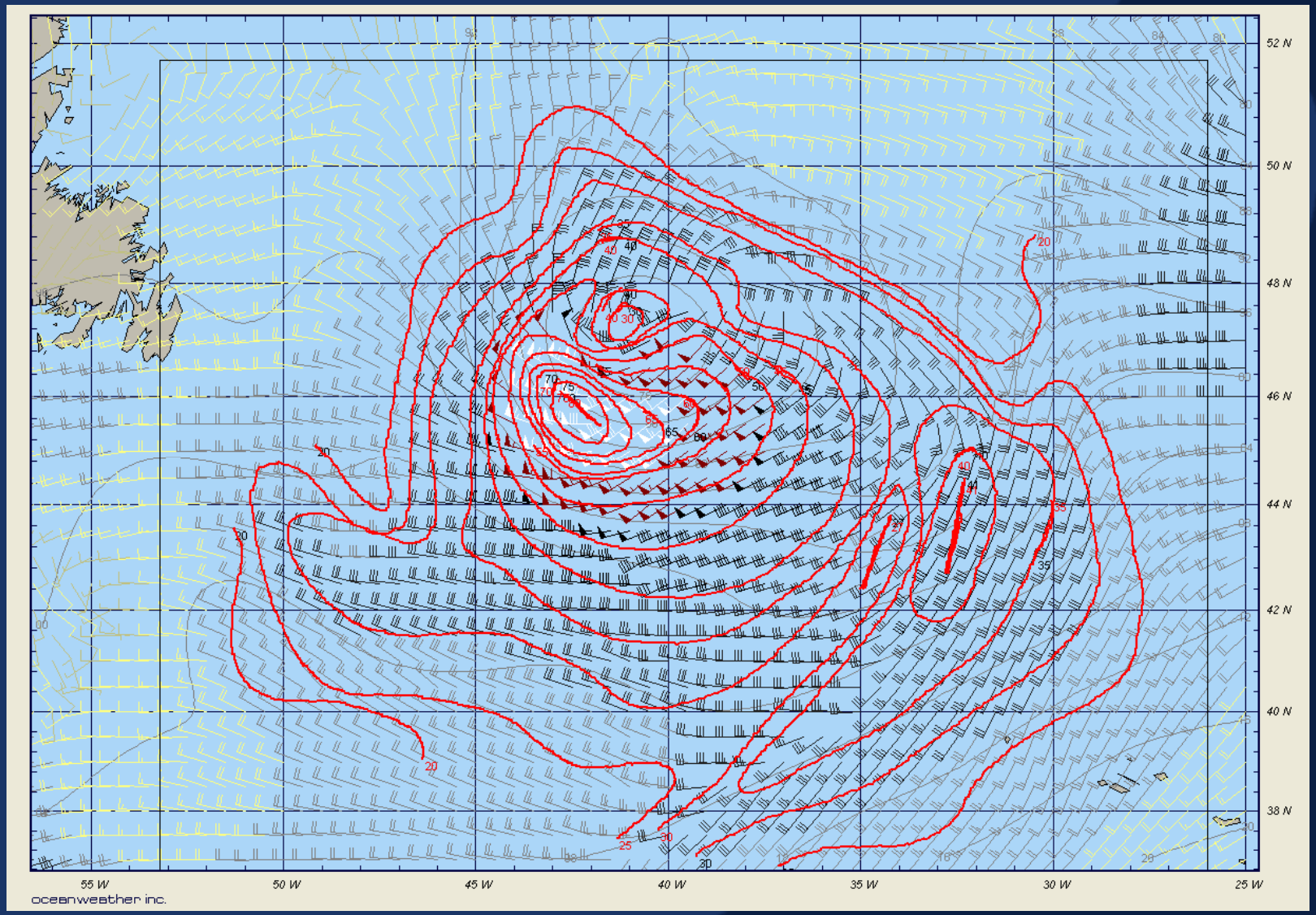
**February 9, 2007**



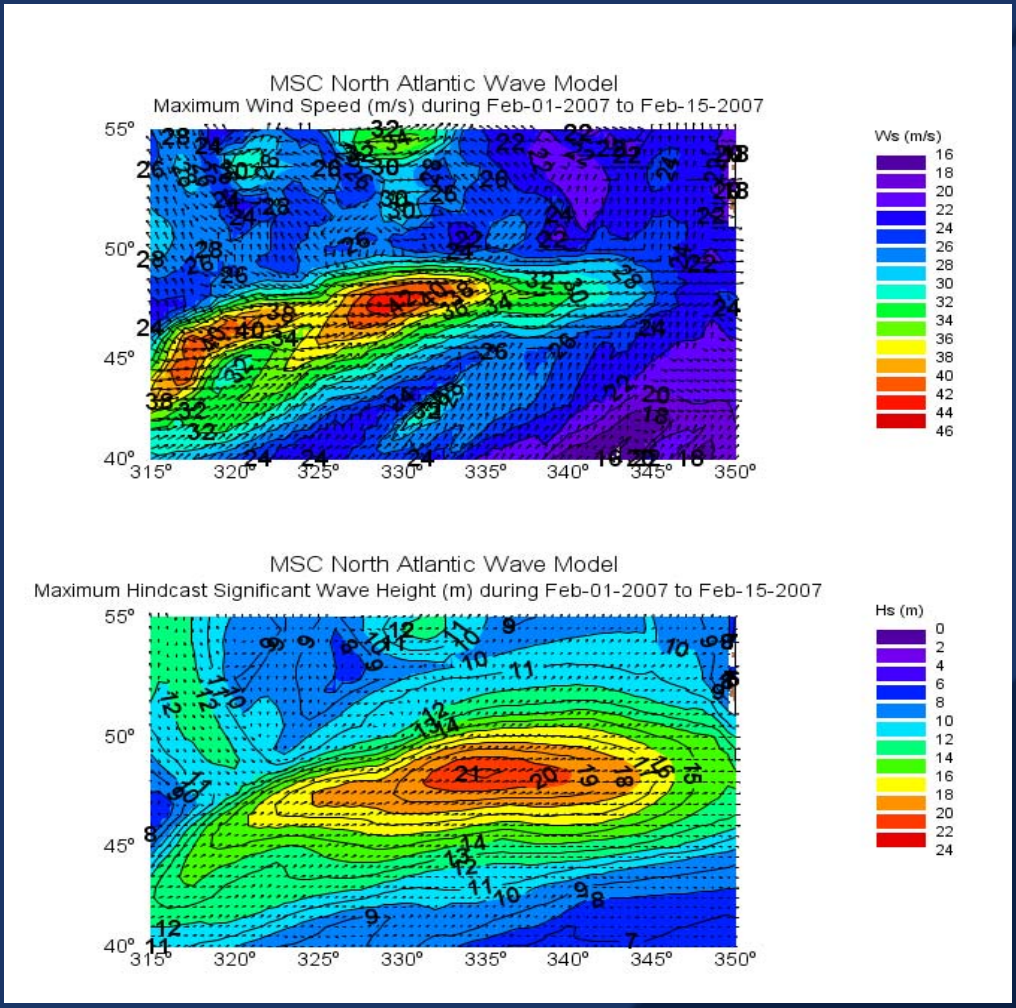

**February 10, 2007**



# Kinematic Analysis – February 10, 2007 event

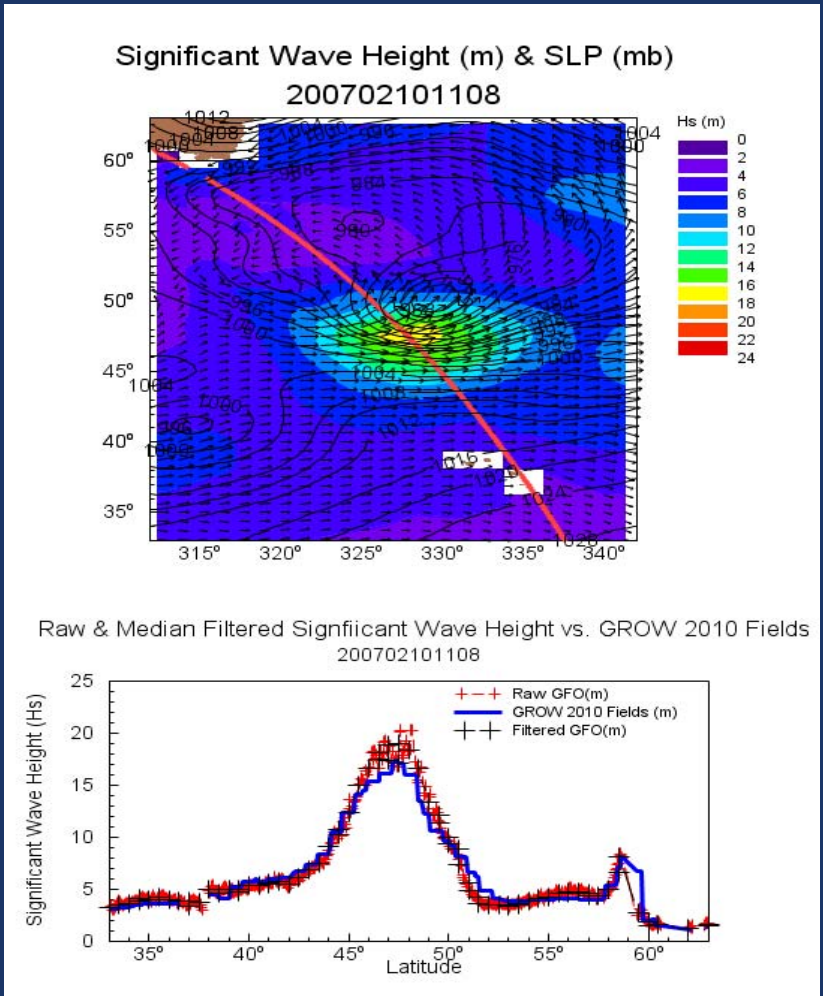


# *Envelopes of Maximum Wind Speed and Significant Wave Height resulting from the MSC North Atlantic Hindcast for February 2007 Dual winter hurricanes after kinematic analysis*

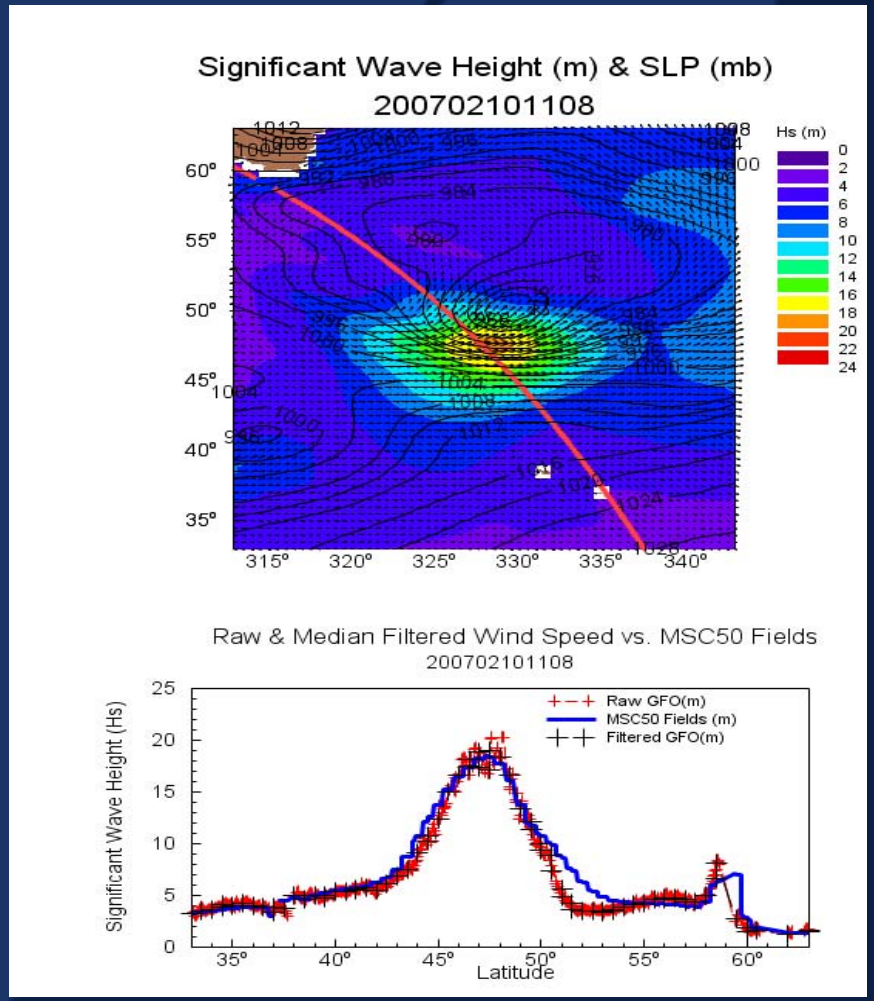


# *February 10, 2007 GFO peak event of Hs=20.24 m*

**GROW2010 Hindcast forced by CFSR wind field**




**MSC50 Hindcast forced by kinematically reanalyzed Wind field**



## *Pure CFSR driven Hindcast vs. Kinematic Analysis*

- Wave hindcasts forced by a pure CFSR wind field tend to be skillful overall, but often miss the peak HS by several meters in a VESS

- A careful continuity analysis of the dominant jet streak associated with a storm in combination with a kinematic analysis allows a resolution of the peak VESS with negligible bias, especially in cases where QuikSCAT scatterometer data is available

## *Conclusions*

- *Over 5,000 basin-specific orbital segments with peak HS > 12 m were identified in the GlobWave database and distilled to 120 unique storms with at least one peak Hs > 16 m.*

- *The highest individual peaks were found in the Northern Hemisphere, with 10 peaks greater than 18 m in the North Atlantic (NAO) and 4 in the North Pacific (NPO). Only 3 such peaks were found in the Southern Oceans.*

- *The frequency of VESS is not proportional to basin size. The NAO had the greatest frequency, followed by the NPO, SPO, SIO, and SAO.*

- *The detection rate of intense extra-tropical cyclones with VESS > 16 m appears to be insensitive to number of altimeter missions active as long as there at least two. An average of 5 such storms/year on global basis was found in this study.*

- *Only four of the 120 scanned VESS were associated with tropical cyclones.*

- *Peak wind speeds in the top ranked VESS storms may exceed 40 m/s, which is equivalent to a Category 3 hurricane on the Saffir-Simpson Scale. The radius of maximum winds are much larger than typical of a typical tropical cyclone but much smaller than typically diagnosed in the atmospheric reanalysis products.*

- *A 3G model can be applied with confidence in a VESS, as long as the forcing is accurately prescribed at least with respect to specification of storm peak HS.*

# Future Work

- Refine synoptic climatology for all cases of extreme VESS (Hs >16 m)
- Complete kinematic reanalysis and hindcast using basin specific fine wave models of all 120 extreme VESS storms
- Seek deficiencies in 3G wave model physics in VESS class storms

***Visible satellite image of the ERICA IOP 4 January 4, 1989 cyclone***
***Image from www.wunderground.com***