Wave Climate Study of the Caribbean Sea

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1. INTRODUCTION

The need for reliable normal and extreme wave climate data in the Caribbean Sea (CS) has increased significantly within the past decade in response to increased offshore and coastal development in many areas. The basin is subject to generally benign yet persistent mean conditions forced by trade winds, but as confirmed by recent scatterometer data, even the trade wind regime can become quite severe in certain regions and seasons (Brown and Burr, 2001). In all areas, extremes are dominated by tropical cyclones but the frequency of such cyclones increases sharply across the basin from south to north.

This paper describes a comprehensive hindcast study of the basin (CARIMOS, for CARIbbean Sea Metocean Statistics), which utilized a third generation (3G) wave model adapted on a nested grid system and a two-dimensional (2-D) hydrodynamic model to describe storm generated currents and water level anomalies. The domain of CARIMOS is illustrated in Figure 1. The wave hindcast extended to all significant tropical cyclones over the 79-year period 1921-1999 and to the 15-year continuous period 1981-1995. There is a conspicuous lack of public domain measured data in the Caribbean Sea against which to validate the hindcast methodology. We show below a validation of the continuous wave hindcast against NOAA data buoy sea state measurements at one location and TOPEX and ERS satellite altimeter wave height data basin-wide. Verification was carried out on paired data and probability distributions. The hindcast results are used to show the implications on extreme wave design criteria estimation of a recently published hypothesis that the frequency of intense tropical cyclones in the basin is modulated significantly by large scale North Atlantic sea surface temperature anomalies which vary on a multi-decadal time scale. This analysis demonstrates the importance of very long term (at least 50 years) wave time series in the Caribbean for reliable estimation of extreme design data. Finally, some normal and extreme metocean design data provided by CARIMOS are given for a sample location.

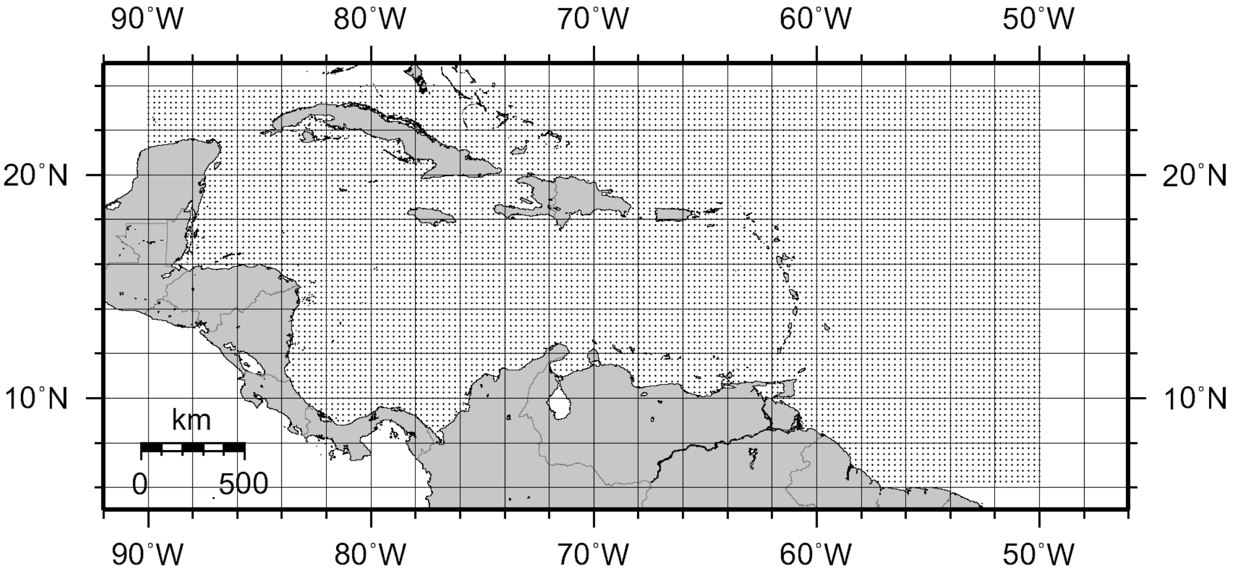


Figure 1 - CARIMOS Model Domain illustrating Coarse Grid Points

2. WIND FIELD SPECIFICATION

2.1 Tropical Cyclones

Oceanweather applied a numerical model of the boundary layer flow in a moving vortex to specify the time and space varying wind field associated with a propagating cyclone. The methodology was first documented by Cardone *et al.* (1976) and the most recent version of the model is described by Thompson and Cardone (1996).

To ensure the validity of the wind field, great care was taken to assemble and utilize all available observations of the tropical cyclones studied. The data utilized ranged from standard archived historical surface analyses and routine observations reports by merchant ships to measurements made by US Air Force, US Navy and NOAA Reconnaissance aircraft. The latter have routinely flown into hurricanes in the region since 1944 and provide very valuable information on a hurricane's properties. The parameters required by the model were synthesized by an experienced meteorologist using a graphical user interface on a PC. Cox and Cardone (2000) describe the method in more detail.

2.2 Continuous Wind Fields

Continuous wind fields, for the period 1981 to 1995, were developed to a high accuracy utilizing Oceanweather's WindWorkStation (WWS) running an Interactive Objective Kinematic Analysis (IOKA) program. The input to the system comprises 6 hourly "background" wind fields and all (adjusted) measured surface wind data. A meteorologist applies quality control to the input data in addition to addition of kinematic control points (KCPs) for each analysis. The general analysis process is described by Cox *et al.* (1996).

An assessment of available background wind fields (1980s and 1990s) indicated that the NOAA Reanalysis Project "10-m Gaussian surface wind fields" provided the best fields. The available wind fields were assessed on the basis of the bias exhibited in monthly mean sea state variables of significant wave height and mean period compared to buoy data at higher latitudes and climatologies based on ship report and altimeter estimates at low latitudes

Measured winds from ships and coastal and inland stations, adjusted to over water exposure and standard anemometer height, ERS scatterometer winds (post 1991) and analyst input winds were objectively assimilated into the background wind fields.

3. WAVE HINDCAST MODEL

The wave hindcast model adapted for CARIMOS is Oceanweather's standard UNIWAVE code that incorporates second generation (2G) or third generation (3G) physics. The most recent 2G physics module is known as ODGP2 and the 3G physics module is known as OWI3G. Khandekar *et al.* (1994) and Cardone *et al.* (1996) give descriptions of these physics modules as well as performance statistics. The wave propagation scheme of UNIWAVE incorporates great circle propagation effects in general, and depth induced refraction and shoaling in shallow water. The propagation scheme is described by Greenwood *et al.* (1985).

Uniwave is a discrete spectral wave model. In such a model, the wave spectrum is resolved in discrete frequency-direction bins. A grid of points is formulated in the basin of interest and a solution is obtained by integration of the spectral energy balance equation. This process successively simulates, at each model grid point and for each time step, the physical processes of wave growth and dissipation (through the source terms of the energy balance) and wave propagation.

Three grids were utilized for the CARIMOS wave hindcasts and summary details are provided in Table 1. The swell grid, which covered most of the North Atlantic Ocean, was used only for the continuous hindcast and was run to provide boundary spectra along the eastern and northern boundary of the nominal grid used to cover the entire Caribbean Sea. The swell grid was adopted to allow swell exported from migratory North Atlantic extratropical cyclones to propagate to the eastern side of the Lesser Antilles and through gaps in the Greater Antilles, and to allow resolution of the full fetch over which easterly trade wind seas are generated in the tropical and subtropical North Atlantic.

Table 1: Summary of Model Grid Systems

GRID	SWELL	COARSE	FINE
Spacing (lat. by long.)	1.25° by 2.5°	0.25° by 0.25°	0.0625° by 0.0625°
Minimum grid spacing	71.9 km	25.4 km	6.7531 km
Number of points	1268	8216	5419
Growth time step	0.75 hours	0.25 hours	0.25 hours
Propagation step	1.50 hours	0.5 hours	0.125 hours
Wind field input step	1.50 hours	0.5 hours	0.25 hours
Archive time step Fields / archive spectra Boundary spectra	 3 hours 1.5 hours	 3 hours continuous hindcast 1 hour tropical cyclone hindcast 0.5 hours boundary spectra	 1 hour 0.5 hour
Propagation physics	Deep water	Shallow water	Shallow water
Source term physics	ODGP2 deep water	ODGP2 deep water (continuous) OWI3G shallow water (tropical cyclones)	OWI3G shallow water (tropical cyclones)
Spectral resolution	23 frequency bands by 24 direction bands		

The depth fields for the coarse and fine grids were based on the National Geophysical Data Center (NGDC) ETOP05 database. In the area around Trinidad and to the north of Venezuela these data were supplemented by bathymetry data from a number of DMA charts.

4. HYDRODYNAMIC MODEL

A state of the art current/surge model that benefited from a basin wide simulation, rather than traditional approaches limited to stretches of continental shelf, was applied to the coarse grid of the CARIMOS model domain. The original model was described by Bunpapong *et al.* (1985).

The theoretical formulation of the model is based on the vertically integrated momentum and conservation equations for quasi-hydrostatic large scale disturbances in a basin of variable depth. The model is formulated to handle up to two layers, but used in the single layer mode for CARIMOS.

The normal mode equations are solved by finite-difference on a time marching model, employing an alternating direction implicit differencing scheme. The model is quasi-linear, and tides are not included. However, variable bathymetry, variable Coriolis parameter and variable atmospheric pressure are modelled. The inverted barometric effect is therefore implicit in the model and is automatically included in the modelled water level anomalies.

5. MODEL VALIDATION

5.1 Tropical Storms Hindcast

No wave measurements are available in the Caribbean Sea during the passage of tropical cyclones, so it was not possible to validate the tropical storm wave hindcast directly. However the hindcast methodology has been validated against high quality wave measurements in intense tropical and extra-tropical storms (Cardone and Resio, 1998) outside the Caribbean Sea and there is no reason to believe that the high level of skill achieved in general with this wave model does not apply here.

As a quality control measure, the hindcast programs adapted to CARIMOS were tested and verified by hindcasting a 48 hour (42 hours before landfall, 6 hours after landfall) period of Hurricane Camille (a 1969 severe Gulf of Mexico hurricane) on a simulated track across the southern part of the Caribbean Sea.

The patterns and magnitudes of simulated winds and waves agree with Oceanweather's benchmark Gulf of Mexico run made with OWI3G. The skill of the storm hindcasts may be inferred from prior studies carried out with the hindcast methodology in other basins affected by tropical cyclones. For most cyclones which have occurred since 1944 and which have been probed by aircraft, the hindcasts of peak significant wave height are unbiased (bias less than 0.25 m) with scatter index in the range 10% to 15%. For earlier storms, the scatter will be larger except for those storms in which measurement of eye pressure and surface wind time histories were acquired as the storm passed over island weather stations. For all storms hindcast, the parameters of the cyclone wind model were developed from source data insofar as possible in order to avert the “creeping inhomogeneities” in standard source, such as the NOAA HURDAT file. A complete reanalysis of HURDAT is underway by NOAA, and when completed that source may provide an additional source of data for any future Caribbean Sea hindcast studies.

5.2 Continuous Hindcast

The validation of the continuous hindcast was based on limited *in-situ* over-water measurements and satellite data. Figure 2 shows our comparison of hindcast wind speed (WS) and direction (WD), significant wave height (HS) and dominant wave period (TP) and the measurements of same at the NOAA National Data Buoy Center (NDBC) data buoy 41018 for the period of data overlap (August 1994 – December 1995 with a gap in summer 1995). This buoy, a 3-meter discuss buoy with a standard NOAA NBDC payload, was moored near 15N, 75W in the west-central Caribbean Sea about 350 nm southwest of the area of interest here. Winds were measured at about 5 m above sea level and are corrected to 10 m for this comparison. Since neither the wind nor the wave measurements were assimilated into the hindcast process, these buoy data serve as a completely independent check of the hindcast skill. Figure 2 shows that agreement between model and measured data is quite good both for winds and sea state. The difference statistics over the 2758 wind and 2602 wave comparison pairs are given in Table 2. The mean difference (always hindcast – measurement in this report) in wind speed and direction are only -0.36 m/s and -7.77 degrees respectively, the scatter index (ratio of standard deviation of difference to mean of measurements) is only 0.17. For waves, the mean difference in HS and TP are only 0.08 m and 0.03 sec respectively and the scatter index on HS is only 0.20, which is at the lower (i.e. most skilful) end of the range usually reported for high-quality continuous hindcasts.

During the period the buoy was deployed, the ERS-2 and TOPEX satellites also provided estimates of the HS and WS. Table 3 gives difference statistics for all hindcast-altimeter estimates found in a 5-degree latitude-longitude box centered on the buoy during the period of August 1, 1994 - January 1, 1996. Over the 2038 comparisons available the mean difference in WS is -0.56 m/s and the mean difference in HS is 0.02 m. Both of these differences are considered within the measurement uncertainty. The altimeter comparisons confirm the high quality of the continuous hindcasts at least in this part of the CARIMOS domain.

Since the continuous data are used to develop wind speed and wave height distributions it is also important to compare the hindcast and measurement distributions. Figure 3 gives a comparison of the buoy and hindcast measurements of WS, HS and TP in terms of exceedance distributions and quantile-quantile scatter plots over the range of 1-99% non-exceedance probability. Agreement is obviously excellent. Figure 4 shows the same comparisons based on the altimeter matches in the 5-degree box centered on the buoy. Figure 5 makes the same comparisons but this time based on altimeter-model comparisons over the whole of the hindcast model domain. This comparison strongly suggests that the good agreement exhibited by the continuous hindcast in the vicinity of the buoy and during the buoy period measurement is indicative of hindcast skill in all deepwater areas and that the hindcasts are unbiased.

Table 2: Wind and Wave Statistics for CARIMOS Operational Hindcast vs. Buoy 41018

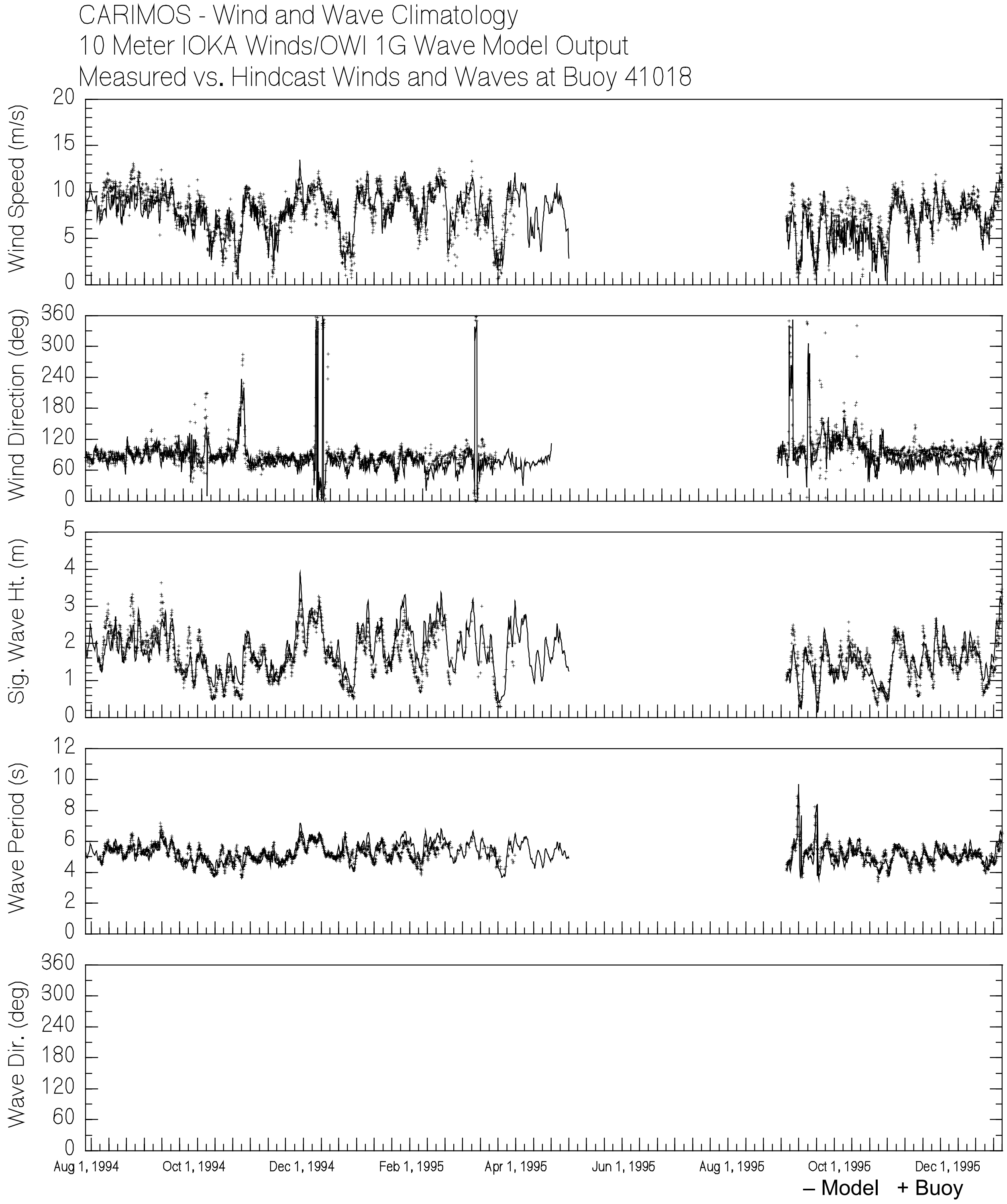
Hindcast Period : 1994080100 to 1996010100

Parameter	Number of Points	Mean Meas.	Mean Hind.	Diff (H-M)	RMS Error	Stnd Dev	Scatter Index	Ratio	Corr Coeff
Wind Speed (m/s)	2758	7.79	7.43	-0.36	1.40	1.35	0.17	0.39	0.83
Wind Dir. (deg)	2758	90.93	83.23	-7.77	N/A	18.44	0.05	N/A	N/A
Sig Wave Ht (m)	2602	1.63	1.71	0.08	0.34	0.33	0.20	0.62	0.85
Wave Period (s)	2602	5.19	5.22	0.03	0.46	0.46	0.09	0.53	0.74

Table 3: Wind and Wave Statistics for CARIMOS Operational Hindcast vs. Altimeter Data

Hindcast Period :	1994080100 to 1996010100
Latitude Range :	12.50 to 17.50
Longitude Range :	-77.50 to -72.50

Parameter	Number of Points	Mean Meas.	Mean Hind.	Diff (H-M)	RMS Error	Stnd Dev	Scatter Index	Ratio	Corr Coeff
Wind Speed (m/s)	2038	7.87	7.31	-0.56	1.61	1.51	0.19	0.34	0.78
Sig Wave Ht (m)	2022	1.66	1.69	0.02	0.38	0.38	0.23	0.55	0.82



CARIMOS - Wind and Wave Climatology
10 Meter IOKA Winds/OWI 1G Wave Model Output
Measured vs. Hindcast Winds and Waves at Buoy 41018

Figure 2

CARIMOS 28KM Grid Reference Wind and Wave Climatology
Percent Exceedance and Quantile-Quantile Plots (Wind Speed, Wave Height & Wave Period)
Buoy 41018 vs. G.P. 3106 During the Period 9408 - 9512

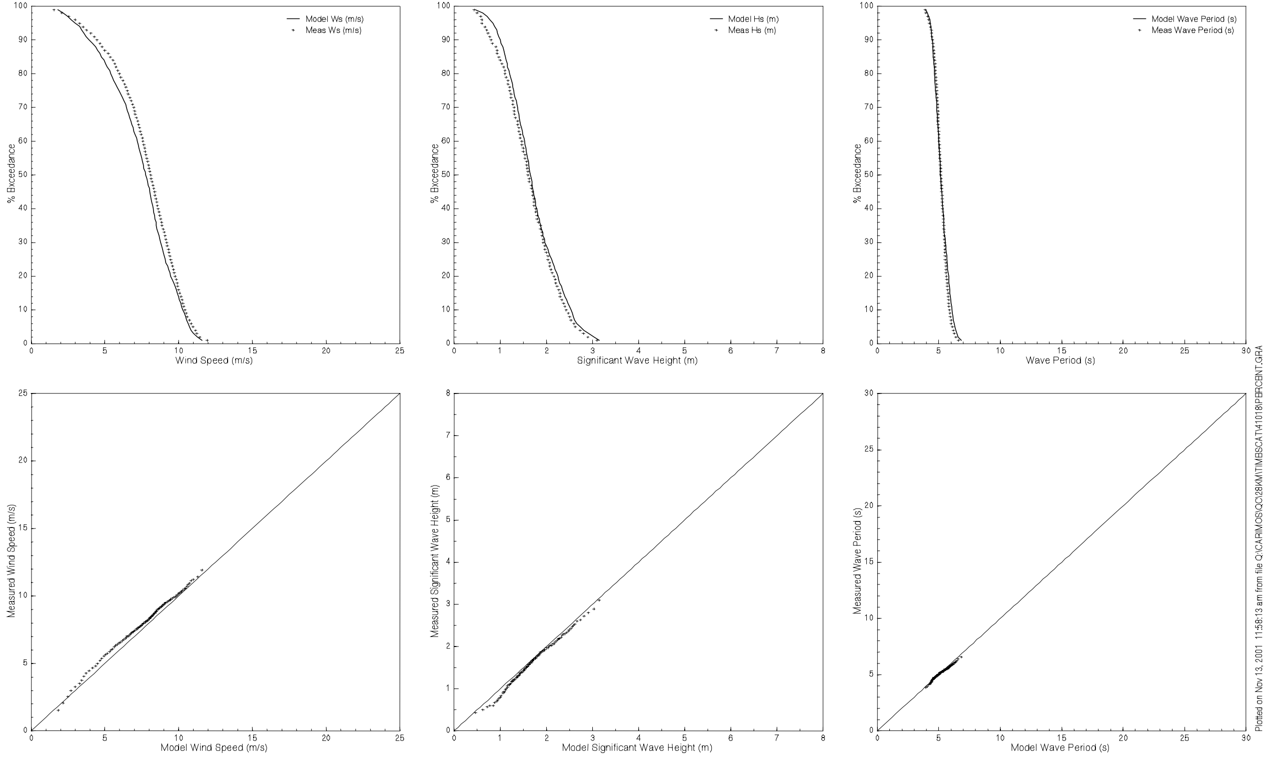


Figure 3

CARIMOS 28KM Grid Reference Wind and Wave Climatology
Percent Exceedance and Quantile-Quantile Plots (Wind Speed, Wave Height & Wave Period)
For All Altimeter Hits During Buoy 41018 Running Time

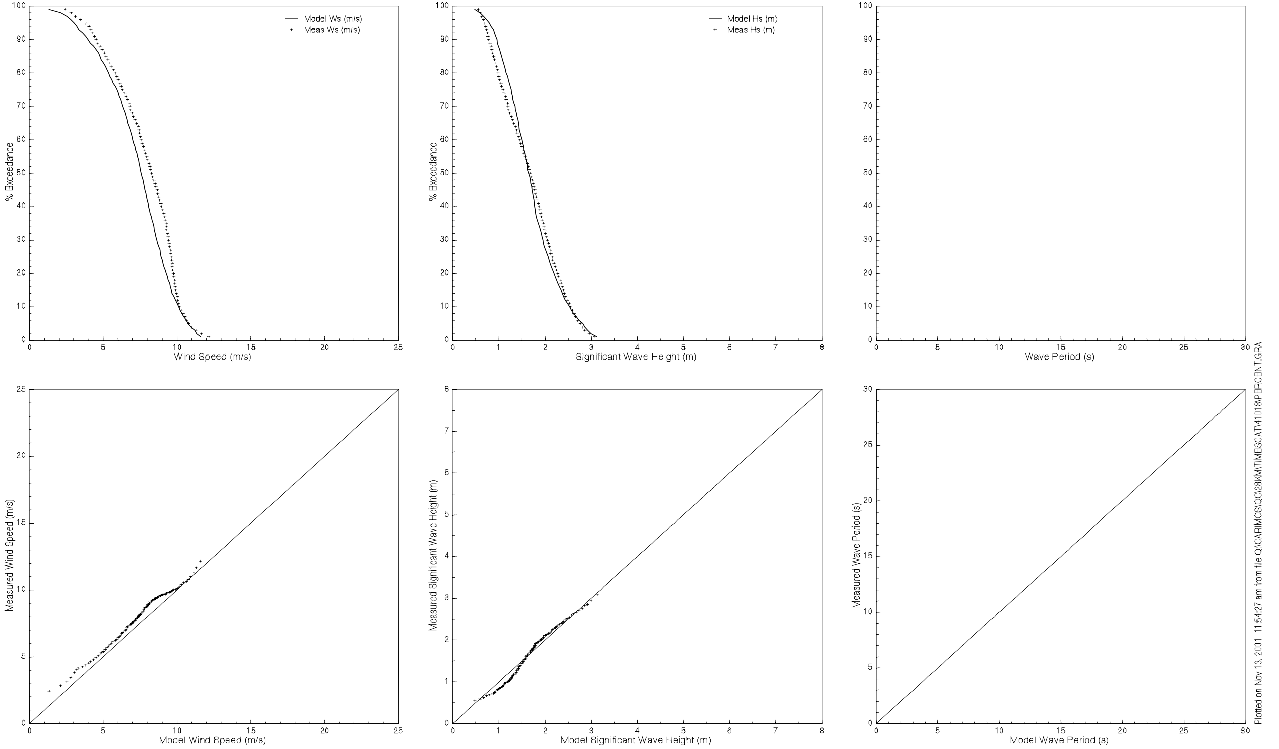


Figure 4

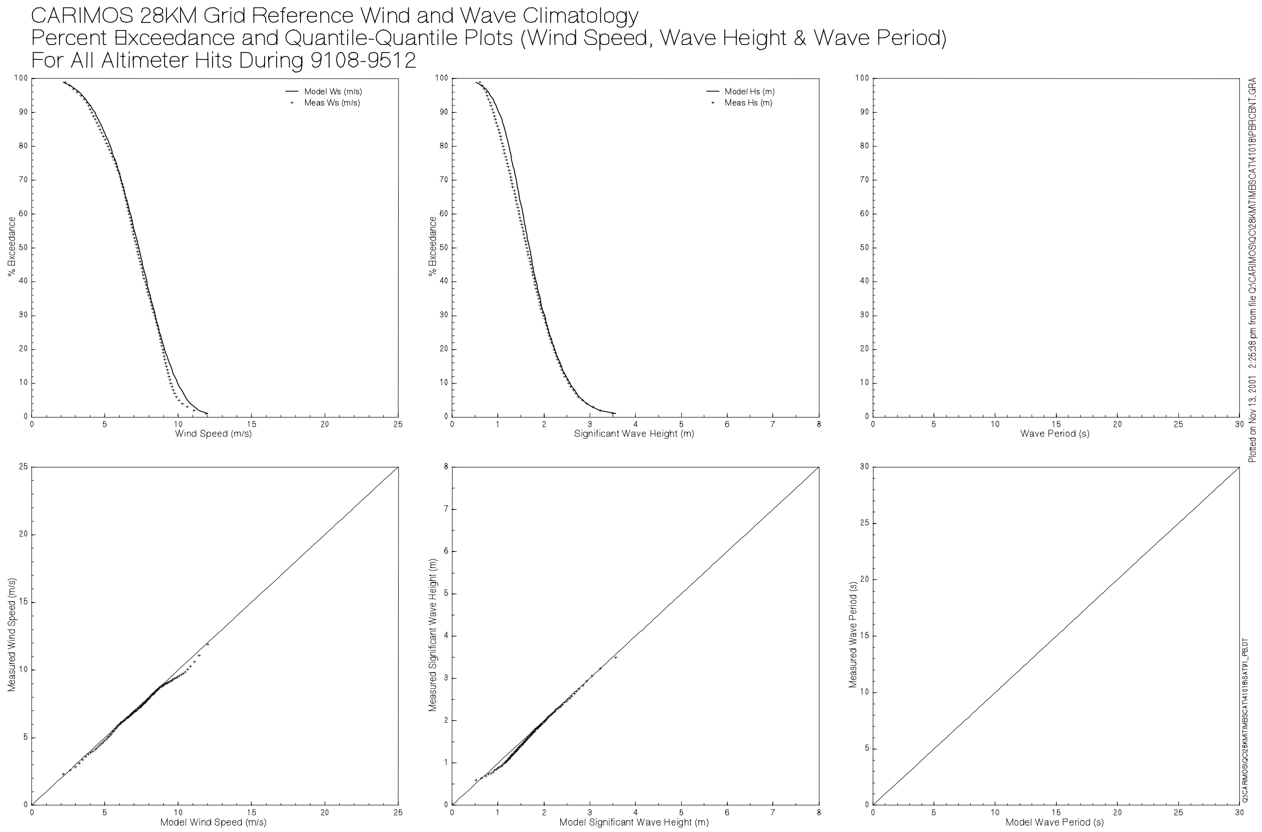
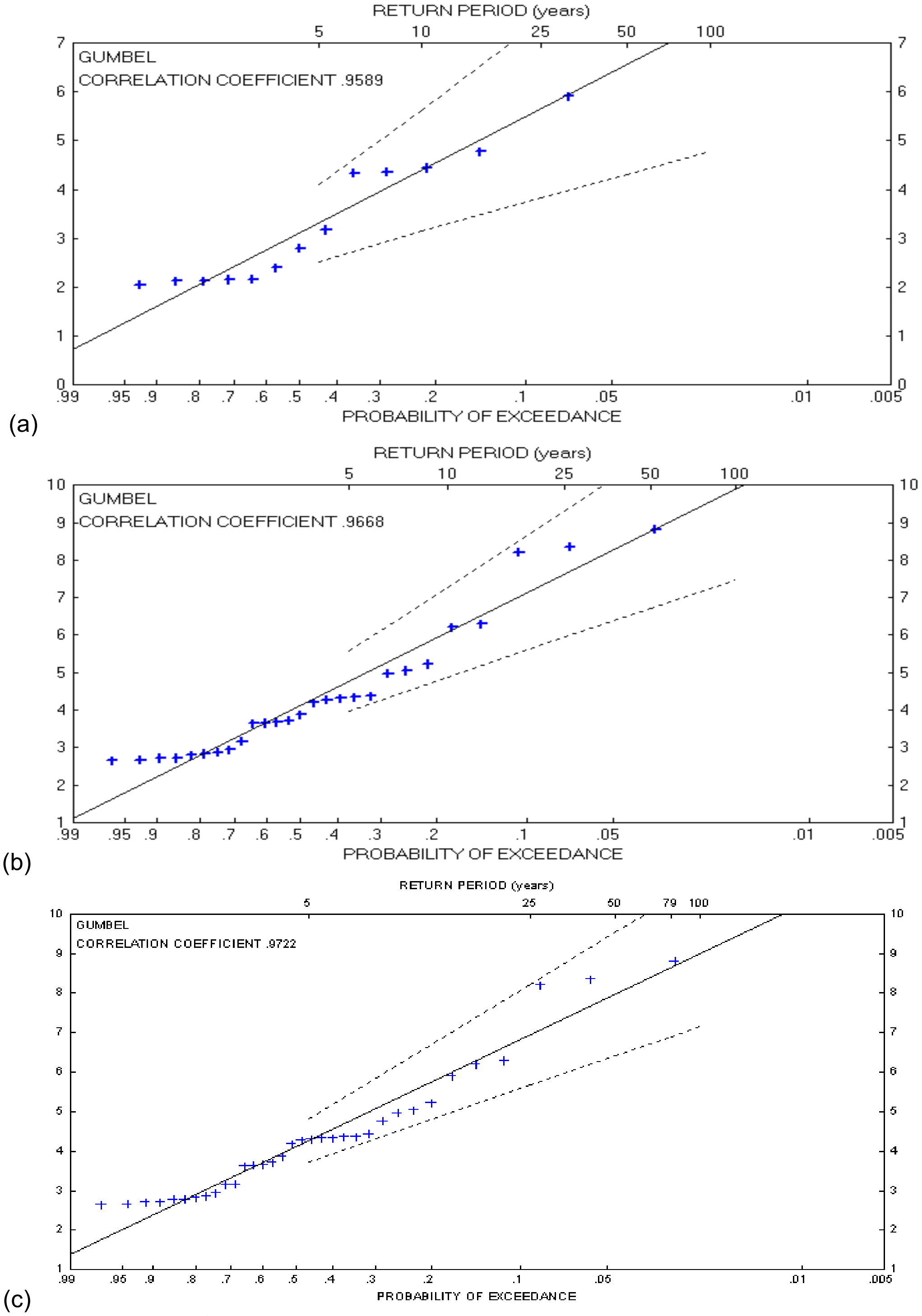


Figure 5

6. IMPLICATIONS OF CLIMATE VARIABILITY ON CARIBBEAN HURRICANE WAVE DESIGN CRITERIA

The Caribbean Sea hurricane population is a part of the larger North Atlantic basin population. The recent marked increase (since 1995) in hurricane activity in this basin has been linked to a multi-decadal cycle in the sea surface temperature pattern of the North Atlantic. Goldenberg *et al.* (2001) describe the relevant mode of variability which links SST anomalies in the northern North Atlantic and in the main development region of tropical cyclones between 10N and 20N. They further grouped the anomaly pattern observed in the last century into "cold" years (1903-1925, 1971-1994) and "warm" years (1926-1970, 1995-2000) and showed a marked increase in Caribbean hurricanes in the "warm" years relative to the "cold" years. The very long time period addressed in the CARIMOS tropical cyclone hindcasts (79 years) allows us to test the hypothesis that the extreme wave climate may respond to this climate variability signal as well. This was done simply by applying a peaks-over-threshold extremal analysis to the hindcast sea state peaks on separate populations of peaks from hurricanes of the "cold" and "warm" years. We show the results here for grid point 3106 (the same grid location used to validate the hindcast against the NOAA buoy data in the previous section) but similar results were obtained in other areas as well. Figure 6 shows the extremal analysis on storm peak HS, using the Gumbel distribution and method of moments fitting, for the 29 cold years, the 50 warm years and all years combined. The differences are quite striking. For the cold years, the 100-year return period HS is 7.4 m, for the warm years it is 9.9 m. Over all years (the nominal CARIMOS result) it is 9.0 m. Similar differences were noted for the Weibull distribution (7.9 m, 10.3 m and 9.2 m respectively). Goldenberg *et al.* predict that the increased level of activity in Atlantic basin cyclone activity may persist for the next few decades, which raises the question of whether somewhat conservative hurricane design data should be considered for new engineering projects in this basin.



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CS Gpt 3106: HSig (m).  (a) "Cold" Years, (b) "Warm" Years, (c) All Years
Period   (a) Gumbel    lcl     ucl   (b) Gumbel    lcl     ucl   (c) Gumbel    lcl     ucl
    5.         3.32   2.52    4.11         4.77   3.97    5.57         4.26   3.72    4.81
   25.         5.64   3.83    7.45         7.63   5.94    9.32         6.94   5.68    8.21
   50.         6.55   4.32    8.78         8.77   6.71   10.82         7.98   6.42    9.54
  100.         7.44   4.79   10.09         9.89   7.47   12.31         9.00   7.14   10.85
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Figure 6: Extremal analysis of CARIMOS hurricane storm peak HS at grid point 3106 in (a) "cold", (b) "warm" (see text), and (c) all years combined.

7. CARIMOS EXTREME AND NORMAL WAVE CRITERIA

The hindcast database allows the specification of the full range of normal and extreme wind and wave design data required for engineering applications on the scale of the grid systems adopted. For very near-shore and very shallow water requirements, the CARIMOS data may serve as boundary conditions for even finer mesh localized models. The nominal extremes computed from the hindcast results are for return periods of 5, 25, 50, 100, 200, 1000 years for:

- Wind speed: 1-hour, 1 minute, peak gust at 10 m height
- Significant wave height
- Maximum wave height
- Maximum crest height
- Associated wave period
- Storm driven surge height
- Maximum vertically average current speed

Table 4 gives sample return period extremes of HS and WS for Grid Point 3106.

Fatigue and operability data are typically presented as follows.

- Standard monthly and annual bivariate frequency of occurrence and duration tables. The bivariate tables are for the pairs:
  - Wind speed by wind direction
  - Significant wave height by peak spectral period
  - Significant wave height by wave direction

- Duration tables (monthly sort only) are provided for:
  - Exceedance and non-exceedance of wind speed thresholds
  - Exceedance and non-exceedance of significant wave height thresholds

Figure 7 and the associated table give the annual distribution of interesting HS statistics at grid point 3106 for each individual year in the continuous hindcast time period and over all 15 years combined for the month of December. The interannual variability of the “normal” wave climate is quite large. For example, the HS for the annual 90 percentile non-exceedance probability varies from a low as 2.97 m in 1989 to as high as 5.53 m in 1984. This variability has not been explained but is likely to be associated, at least in part, to climate shifts associated with the ENSO cycle and the North Atlantic Oscillation. However, no secular trends have been identified in either the tropical cyclone or long-term hindcast databases.

Table 4: Sample Significant Wave Height and Wind Speed Extremes for Grid Point 3106

```
Significant Wave Height (m) (Peak values)
Gumbel and Borgman Parameters: Location 3.584004, Scale 1.443238
Weibull Parameters: Location 2.59798, Scale 1.771439, Shape 1.009429
 Period     Prob. Gumbel    lcl    ucl Borgman    lcl    ucl Weibull    lcl    ucl  Galton
    5.0 0.4647059   4.26   3.72   4.81   4.54   3.82   5.15   3.96   3.66   4.34   4.25
   25.0 0.0929412   6.94   5.68   8.21   7.07   6.01   7.99   6.77   5.20   9.30   6.69
   50.0 0.0464706   7.98   6.42   9.54   7.83   6.65   8.86   7.98   5.73  11.83   7.63
  100.0 0.0232353   9.00   7.14  10.85   8.52   7.22   9.64   9.18   6.23  14.53   8.56
  200.0 0.0116177  10.01   7.86  12.15   9.14   7.75  10.35  10.38   6.70  17.37   9.48
 1000.0 0.0023235  12.34   9.50  15.17  10.45   8.84  11.84  13.16   7.71  24.44  11.66

Wind Speed (m/s) (Peak values)
Gumbel and Borgman Parameters: Location 10.04901, Scale 3.811296
Weibull Parameters: Location 8.3692, Scale 3.596693, Shape 0.9133066
 Period     Prob. Gumbel    lcl    ucl Borgman    lcl    ucl Weibull    lcl    ucl  Galton
    5.0 0.2981132  14.01  12.43  15.59  15.11  13.28  16.73  12.80  11.81  14.08  13.68
   25.0 0.0596226  20.68  17.61  23.75  21.13  18.60  23.39  19.56  15.76  25.31  19.08
   50.0 0.0298113  23.38  19.68  27.08  23.13  20.34  25.61  22.60  17.34  30.95  21.20
  100.0 0.0149057  26.05  21.73  30.37  24.95  21.93  27.63  25.71  18.88  36.97  23.27
  200.0 0.0074528  28.71  23.76  33.65  26.63  23.40  29.51  28.86  20.38  43.33  25.33
 1000.0 0.0014906  34.85  28.46  41.24  30.17  26.48  33.46  36.33  23.75  59.20  30.11
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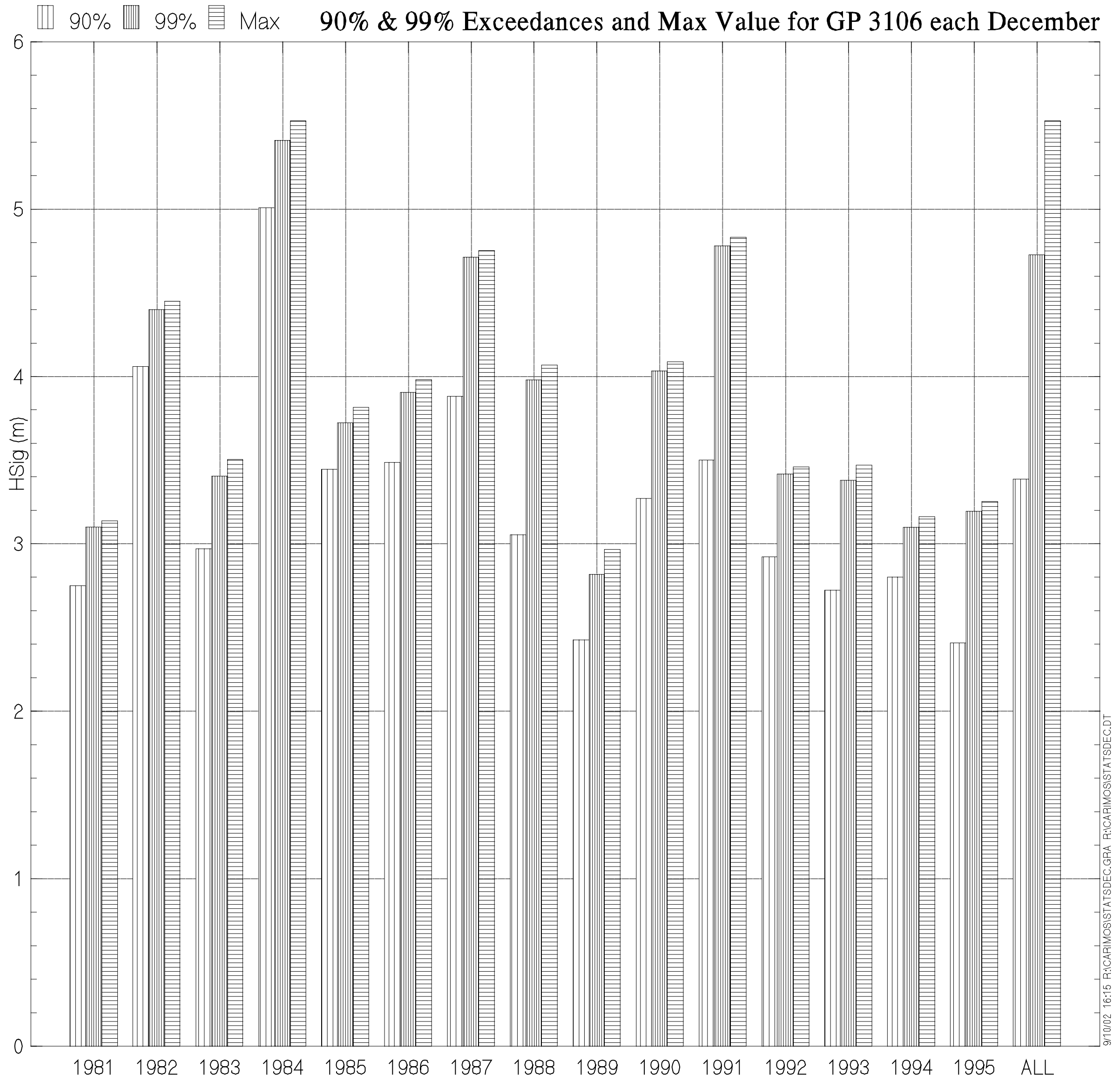

CO Gpt 3106, Lat 15.0n, Long 75.0w, Depth 4024.333m
Defined Period: December

Year	**Min**	**Max**	**Mean**	**Std. Dev.**	**Median**	**90%**	**99%**
1981	1.4230	3.1380	2.1273	0.4448	2.0825	2.7511	3.1014
1982	1.1700	4.4490	2.8366	0.9592	2.8420	4.0609	4.4000
1983	1.0630	3.5030	2.2229	0.5144	2.2150	2.9698	3.4044
1984	1.2480	5.5270	3.0176	1.0502	2.7165	5.0068	5.4094
1985	1.7550	3.8150	2.6992	0.4802	2.6430	3.4461	3.7226
1986	1.1690	3.9820	2.5999	0.6301	2.5170	3.4880	3.9056
1987	0.6860	4.7510	2.4571	1.0808	2.3065	3.8812	4.7122
1988	1.3010	4.0680	2.2926	0.5791	2.1430	3.0528	3.9778
1989	1.0410	2.9680	1.9006	0.4457	1.9345	2.4266	2.8173
1990	1.3200	4.0870	2.4645	0.6332	2.4660	3.2708	4.0311
1991	1.6210	4.8330	2.6577	0.6930	2.5715	3.5023	4.7791
1992	1.2560	3.4590	2.0357	0.5547	1.8520	2.9231	3.4181
1993	1.1110	3.4690	1.9681	0.5648	1.8560	2.7223	3.3803
1994	0.6870	3.1630	1.8926	0.6697	1.8050	2.8018	3.0982
1995	0.9320	3.2540	1.7469	0.4946	1.6785	2.4090	3.1968
ALL	0.6860	5.5270	2.3280	0.7771	2.2460	3.3867	4.7282

Figure 7

8. SUMMARY AND CONCLUSIONS

By virtue of the application of modern hindcasting techniques to a long-term meteorological database, CARIMOS has generated new descriptions of the long-term climate of wind and wave normals and extremes throughout the Caribbean Sea. The wind fields for all hindcast models were developed in a consistent way from source meteorological data utilizing an interactive expert system. The hindcast database is, therefore, believed to be free of temporal ("creeping") inhomogeneities which characterize archived products of real time forecast systems. Both the extreme and normal wave climate show interesting responses to larger scale atmospheric climate variability. It is expected that the database will be updated at regular intervals in order that it represent, insofar as possible, both the long term climate and its recent interdecadal and intradecadal fluctuations.

9. REFERENCES

Brown and Burr (2001): Marine Weather Review: Tropical Atlantic and Tropical East Pacific Areas -January through April, 2001. *Mariners Weather Log*, **45**, (August), 2001, pp. 13-28.

Bunpapong, M.R., R. Reid and R. Whitaker, 1985: An investigation of hurricane-induced forerunner surge in the Gulf of Mexico. Prepared for the U.S. Army Engineer Waterways Experiment Station and the Coastal Engineering Reseach Center, Contract DACW39-82-K-001, by Dept. of Oceanography, Texas A&M University, College Station, TX, Ref. 85-2-T. Research conducted through the Texas A&M Research Foundation, Project 4667.

Cardone, V.J., W.J. Pierson and E.G. Ward, 1976: Hindcasting the directional spectra of hurricane generated waves. *J. of Petrol. Technol.*, **28**, 385-394

Cardone, V.J., R.E. Jensen, D.T. Resio, V.R. Swail and A.T. Cox, 1996: Evaluation of contemporary ocean wave models in rare extreme events: Halloween storm of October 1991; Storm of the Century of March, 1993. *J of Atmos. And Ocean Tech*, **13**, 198-230.

Cardone, V.J. and D.T. Resio, 1998: An assessment of wave modelling technology. *Preprints of 5th International Workshop on Wave Hindcasting and Forecasting*, Jan 26-30, Melbourne, Fl.

Cox, A.T., V. J. Cardone, and V. R. Swail, 1998: Evaluation of NCEP/NCAR Reanalysis Project Marine Surface Wind Products for a Long Term North Atlantic Wave Hindcast. Proceedings 5th International Workshop on Wave Hindcasting and Forecasting, January 26-30, 1998, Melbourne, FL. p.30-33.

Cox, A.T., V.J. Cardone, and V.R. Swail, 1996:An interactive objective kinematic analysis system. *Proc. 4th International Workshop on Wave Hindcasting and Forecasting,* October 16-20, 1995, Banff, Alberta, 109-118.

Cox, A. T. and V. J. Cardone (2000): Operational System for the Prediction of Tropical Cyclone Generated Winds and Waves. *6th International Workshop of Wave Hindcasting and Forecasting*, November 6-10, 2000, Monterey, CA.

Goldenberg, S.B., C.W. Landsea, A.M. Mestas-Nuñez, and W.M. Gray, 2001: The recent increase in Atlantic hurricane activity: causes and implications, *Science*, **293**, 474-479.

Greenwood, J.A., V.J. Cardone and L.M. Lawson, 1985: Intercomparison test version of the SAIL model. **Ocean Wave Modelling,** The SWAMP Group, Plenum Press, 221-234.

Khandekar, M.L., Lalbeharry and V.J. Cardone, 1994: The performance of the Canadian spectral ocean wave model (CSOWM) during the Grand Banks ERS-1 SAR wave spectra validation experiment. *Atmosphere-Oceans*, **32**, 31-60.

Thompson, E.F. and V.J. Cardone, 1996: Practical Modelling of hurricane surface wind fields. *ASCE J. of Waterway, Port, Coastal and Ocean Engineering*. **122,4**,195-205.