EVALUATION OF NCEP/NCAR REANALYSIS PROJECT MARINE SURFACE WIND PRODUCTS FOR A LONG TERM NORTH ATLANTIC WAVE HINDCAST

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1. INTRODUCTION

This study is a part of a larger research program, described elsewhere in this volume by Swail *et al.* (1998), to utilize the NCEP reanalysis (NRA) products (Kalnay *et al*., 1996) to produce a high-quality homogeneous long-term wind and wave database for assessment of trend and variability in the wave climate of the North Atlantic (NA). This paper describes the evaluation phase of the program. In the evaluation phase we compared three alternative NCEP sources of marine boundary layer winds: (1) the 1000 mb wind fields on the 2.5° latitude-longitude grid; (2) the lowest sigma level (0.995) wind fields on the 2.5° latitude-longitude grid; (3) the 10 m surface wind fields on the Gaussian grid. Since the reanalysis process itself involved, at least to some extent, the assimilation of measured surface marine data into each of these products, it is not possible to derive an independent assessment of the accuracy of the alternative wind fields only from comparisons with wind measurements.

An alternative evaluation approach is suggested by recent studies with advanced third generation (3-G) ocean wave prediction models (Cardone *et al.,* 1995). Those studies show that, when such models are driven by accurate surface wind fields, nearly perfect simulations of the principal scale and shape (significant wave height and spectral peak period) properties of the surface gravity wave field result. On the other hand, if erroneous winds are used, the ocean response is modelled with obvious bias and/or scatter when compared to wave measurements. Copious high quality wave measurements have been provided within the past two decades from buoys moored near the continental margins and satellite altimeters which provide full-basin coverage. Our approach, therefore, is to hindcast the surface wave field in the North Atlantic Ocean from alternative NRA surface marine wind fields for selected months using a proven 3-G wave model, and then to assess the errors in the wind fields through a comprehensive evaluation of the resulting wave hindcasts against all available wave measurements.

The best of the NRA alternatives identified in this evaluation provides a background wind field for use in the production phase of the hindcast. In the production phase of the long term hindcast, which is also outlined briefly herein, the NRA wind fields are improved by adding details of the evolution of tropical and extratropical cyclone wind field features missed in the NRA objective analyses. The efficacy of this approach is also illustrated briefly in this paper. A preliminary evaluation of the first decade or so of production hindcasts is given at this conference by Swail *et al*. (1998).

2. EVALUATION METHODOLOGY

Eight months were chosen from the available period, 1979 through 1995, for the wind field evaluation. Months 8103 and 8301 were chosen for having the highest and lowest values, respectively, of the mean North Atlantic atmospheric zonal circulation index described by Kushnir (1994). The months 9110, 9303 and 9504 each contained extreme western North Atlantic storms hindcast in recent studies (Cardone *et al.,* 1996 and Swail *et al.,* 1995), while 9509 was chosen as a hurricane dominated month. The remaining months (7906, 8808) were added to provide more even representation over time of the part of the NRA available at the time this evaluation was carried out.

Wind fields for each month were interpolated from the NRA source grids onto a 0.625° by 0.833° latitude-longitude wave model grid covering the North Atlantic Ocean (see Swail *et al.*, 1998) using the IOKA (Interactive Objective Kinematic Analysis) algorithm (Cox *et al.,* 1995), and then time interpolated to a one-hour time step. Oceanweather's third generation (3-G) wave model (Khandekar *et al*., 1994) was used in deep water mode for all hindcasts. Wave and interpolated wind results were then compared (time series, scatter plots and statistics) to all available deep-water buoys (U.S., Canadian, European), offshore North Sea platforms, U.S. C-MAN (Coastal Marine Automated Network) and ERS-1/2 altimeter and scatterometer measurements. All measured winds were adjusted for height and stratification to 10 meter reference height and neutral stability, while hourly wind and wave measurements were smoothed over ±1 hours using equal weights (1,1,1). ERS-1/2 altimeter and scatterometer measurements were extracted from Ifremer's CD-ROM set using the recommended quality controls, temporally binned within a 6-hour window, and then spatially binned onto the wave model grid every 6 hours.

3. EVALUATION RESULTS

The results of the statistical comparisons of the three sets of NCEP winds and the waves they produced with all buoys, platforms and C-MAN stations on the western and eastern Atlantic continental margins, and with ERS-1/2 satellite altimeter winds and waves are summarized in Tables 1 and 2. Table 1 shows statistical comparisons for March 1993 - the other evaluation months showed generally comparable results. While the statistics for correlation coefficient and scatter index for winds were largely similar among all wind fields, there were clear advantages in bias, scatter index, and ratio for the waves produced by the surface wind fields. From these results it was clear that there was no advantage in selecting the 1000 mb winds; therefore the 1000 mb winds were dropped from further consideration. Table 2 shows the bias and scatter index comparisons for all 8 evaluation months versus the *in situ* measurements, and for the 3 months for which ERS-1/2 altimeter data were available. It is clear from Table 2 that the best wind field was the surface wind. The bias for the surface wind field was generally lower for both winds and resulting waves; the scatter indices for winds were similar for both data sets, although the independent satellite comparisons always favored the surface winds. The scatter index for waves hindcast from the surface winds was always superior.

While the NCEP surface wind fields produce the least biased and most skillful wave hindcasts overall, the scatter index values are much higher than found in hindcast studies of continuous periods (Cardone *et al.,* 1995) or storms (Cardone *et al.,* 1996) where kinematically reanalyzed wind fields are used to drive the wave model. The hindcasts were also found to systematically underestimate storm peaks. The overall skill in the hindcasts is improved and the underestimation of storm peaks is greatly reduced when the NCEP surface winds are kinematically reanalyzed with the aid of an interactive Wind Workstation. Figure 1 (left) shows the impact of this kinematic reanalysis at a buoy off the US east coast during SWADE IOP-1 relative to the hindcast made with unmodified NRA surface winds. It was also found that tropical storms are poorly resolved in the NCEP wind fields. Figure 2 compares the NCEP winds and final IOKA winds during Hurricane Emily (September 1993). The improvement is achieved through a combination of interactive kinematic analysis of the wind fields in conjunction with winds generated by a proven tropical cyclone model. The resulting wave comparison at buoy 44014 is shown in Figure 1 (right).

4. PRODUCTION PHASE

The production phase, whereby wave hindcasts will be carried out for the entire 40 years of the NCEP reanalysis period, is described in detail by Swail *et al.* (1998); that paper also includes a preliminary evaluation of the climatological aspects of the production wave hindcasts completed to date. Presented here is a description of the quality control products generated by the hindcast which show the impact of the IOKA methodology.

Quality control of the production hindcast consists mainly of comparisons of the wave hindcast against measurements evaluated against 12 deep-water buoys (Figure 3) and ERS 1/2 altimeter wave measurements. Table 3 shows the standard difference statistics computed for a typical month (9211) based on differences between 6-hourly hindcast and measurement time series. Note that the mean difference in wave height over all buoys is only 10 cm and scatter indices are in the range 0.15-0.21 at most buoys, which are comparable to those exhibited for peak-peak comparisons in the very best hindcast studies. The small negative bias in hindcast wave period is due at least in part to the wave model. Several other hindcast studies carried out with 3-G wave models (e.g. Cardone *et al*., 1996) also show that most variants of the 3-G wave model tend to underpredict wave period.

Figure 4 shows a typical example of the time series comparison of wind speed, wind direction, wave height, wave period and wave direction for buoy 44137 during December 1992. The excellent agreement in the winds is a consequence of the IOKA, which has naturally assimilated the buoy observation into each 6-hourly analysis. The buoy wave height and period (there is no wave direction measurement at this buoy) time series, however, provides an independent assessment of the wave hindcast. Mean and maximum monthly wind speed and wave height fields are also extracted as part of the quality control process (Figure 5). Finally, the wave model grid-averaged altimeter wave measurements are binned every 0.5 meters and compared with the matching hindcast (within 3-hours) waves as shown in Figure 6, which shows all wave height residuals for bins with greater than 15 comparisons. While the buoy comparisons indicate the skill in the hindcasts near the continental margins, the altimeter samples the entire North Atlantic basin more or less evenly in space and time. It is encouraging, therefore, that wave hindcasts shows very good agreement with the altimeter throughout the range of wave heights. The mean difference in wave height over all 10,910 observations in this month is only -0.04 m and within ± 20 cm in most individual bins. Hindcast wave heights under 1.5 meters show a slight systematic overestimation which may be attributed to a natural tendency for the gridded wind and wave fields to fail to resolve small areas of calm winds and seas.

Given the emphasis in the IOKA on specification of storm wind fields, it is interesting to compare the production wave hindcasts with wave hindcasts made with the unmodified NRA surface winds during storm peaks. Figure 7 shows the comparison of storm peaks greater than 3 meters (as measured by the buoy) at buoy 44138 for the 4 overlapping evaluation and production months.

5. CONCLUSIONS

Three alternative NCEP reanalysis marine boundary layer wind fields were evaluated by hindcasting the surface wave field in the North Atlantic from each, and then assessing the errors in the wind fields through evaluation of the resulting wave hindcasts against wave measurements. The NCEP surface 10 m wind fields produced the least biased and most skillful wave hindcasts overall, and also produced the best wind field comparisons when compared to independent wind data from ERS 1/2. However, the skill in the hindcasts is greatly enhanced, particularly in storm peaks, when the NCEP surface winds are kinematically reanalyzed with the aid of interactive techniques in general, and, for tropical storms specifically, of a proven tropical cyclone wind model. In the production phase of this study, currently underway and scheduled for completion in late 1998, all wind fields for the 40 years are kinematically reanalyzed as described above.

6. REFERENCES

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Wind Field	Bias (H-M) m (m/s)	rms error m (m/s)	Scatter Index	Ratio	Corr. Coeff.
Surface	0.0 (0.0)	0.98 (2.74)	0.44 (0.35)	0.52 (0.51)	0.83 (0.82)
Sigma	1.0 (2.0)	1.65(3.36)	0.60 (0.34)	0.85 (0.79)	0.81 (0.83)
1000 mb	0.6 (1.2)	1.36 (3.13)	0.54 (0.36)	0.76 (0.68)	0.78 (0.80)

Table 1. Comparison wave summary statistics (wind statistics in brackets) for March 1993 for NCEP surface, sigma and 1000 mb wind fields. (Scatter index is standard deviation/ mean measurement; ratio is percentage of points above/below the 1:1 line)

	WIND SPEED				SIGNIFICANT WAVE HEIGHT			
	BIAS (H-M)		SCATTER INDEX		BIAS (H-M)		SCATTER INDEX	
	Surface	Sigma	Surface	Sigma	Surface	Sigma	Surface	Sigma
Vs in-situ								
7906	***-0.4***	1.1	***0.44***	0.45	***0.0***	0.4	***0.56***	0.60
8103	***-0.4***	1.2	0.27	0.27	-0.4	0.4	***0.27***	0.33
8301	***0.1***	0.8	0.27	***0.23***	-0.3	***0.1***	***0.27***	0.29
8808	***0.2***	2.2	***0.48***	0.50	***-0.2***	0.4	***0.51***	0.61
9110	***-0.5***	1.4	0.39	***0.37***	-0.4	0.4	***0.61***	0.72
9303	***0.0***	2.0	0.35	***0.34***	***0.0***	1.0	***0.44***	0.60
9504	-1.2	***0.3***	0.38	***0.35***	***-0.2***	0.4	***0.44***	0.46
9509	-1.2	***0.5***	0.36	***0.32***	-0.4	***0.2***	***0.36***	0.43
vs altimeter								
9110	***0.1***	1.4	***0.30***	0.34	***0.0***	0.8	***0.34***	0.54
9303	***0.6***	2.2	***0.33***	0.37	***0.1***	1.2	***0.45***	0.63
9504	***0.2***	1.6	***0.3***	0.33	***0.1***	0.9	***0.41***	0.56

Table 2. Comparison of wind and wave bias and scatter index values by month for NCEP re-analysis sigma and surface winds (bold italics show closer agreement with measurements)

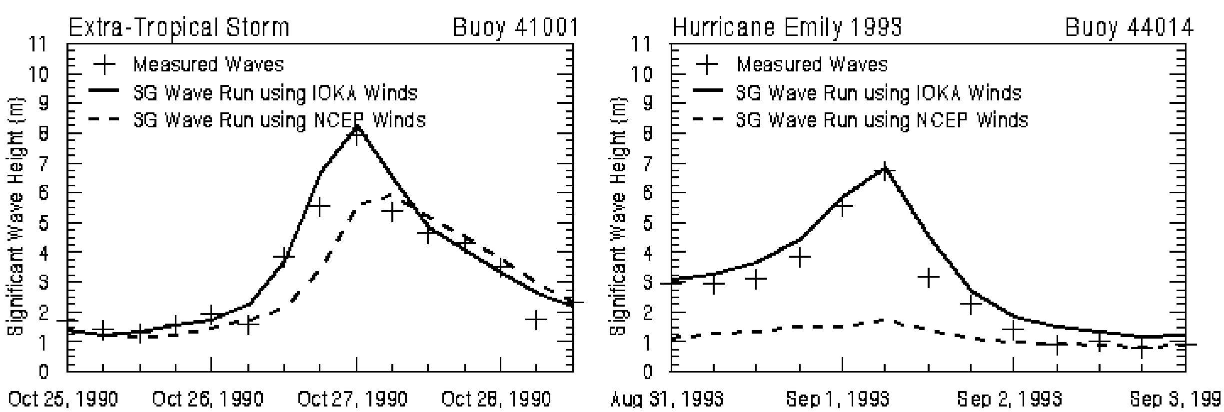


Figure 1. Effect of kinematic analysis on wave hindcast

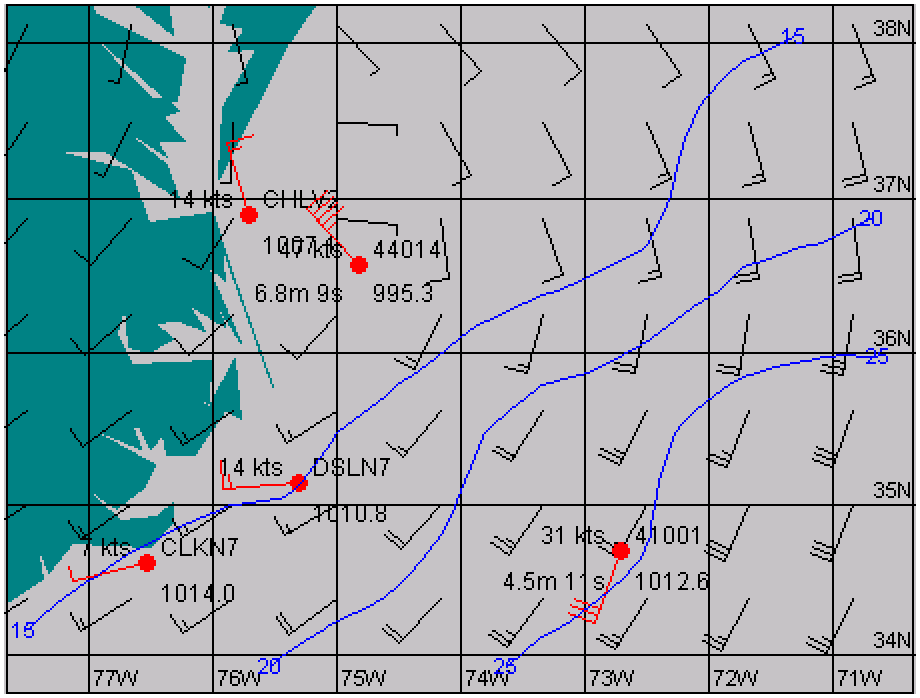


Figure 2a. NCEP surface wind field (unmodified).

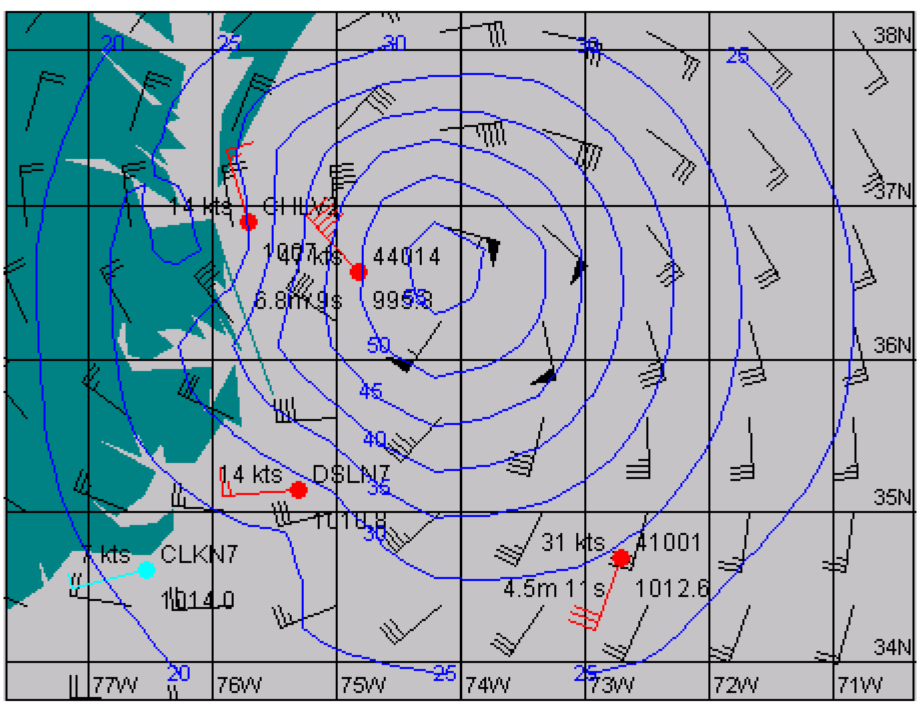


Figure 2b. IOKA final wind field with tropical vortex model winds incorporated.

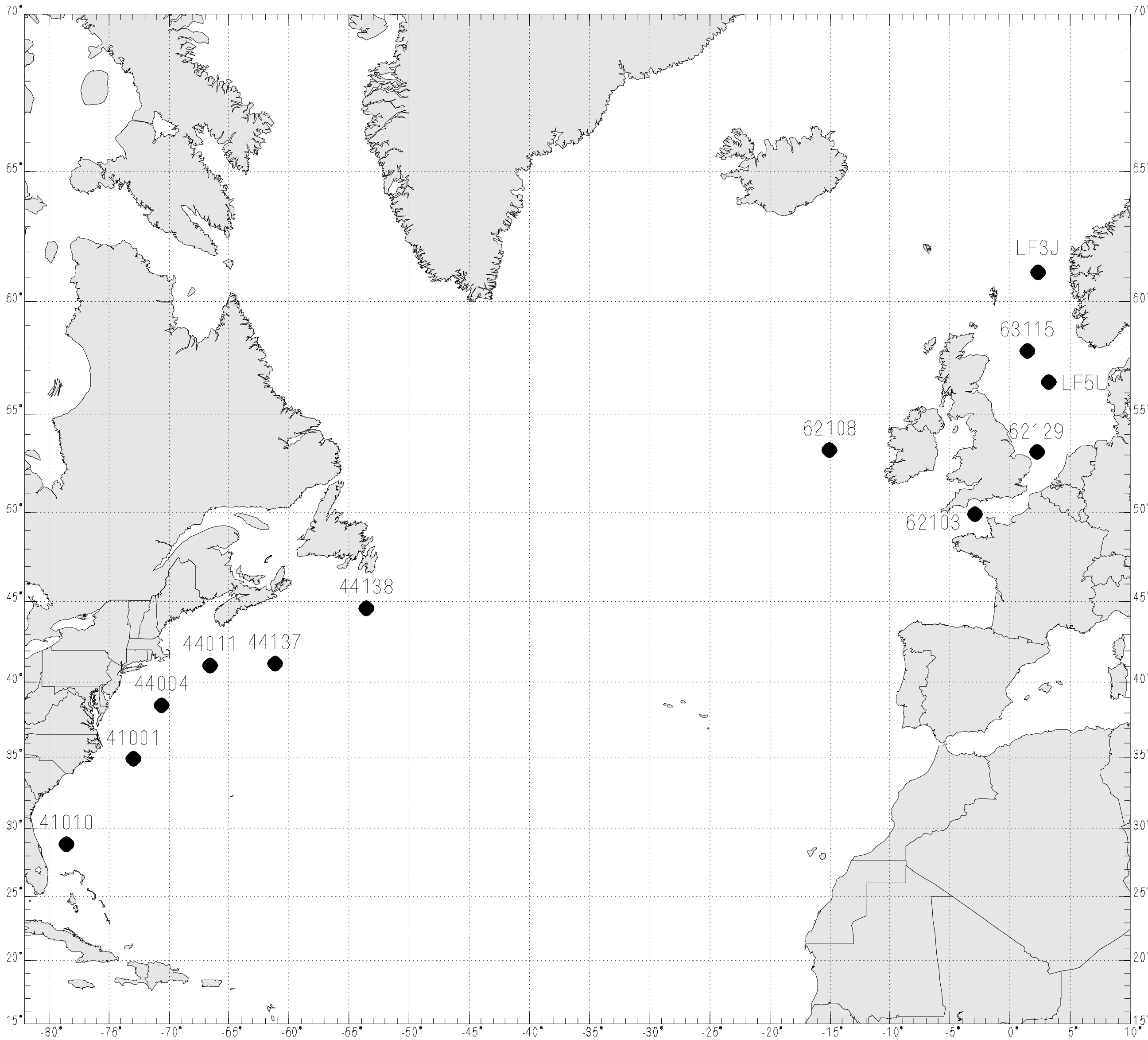


Figure 3. Buoy locations used in production verification.

AES North Atlantic Reference Wind and Wave Climatology
Hindcast Period: 1992100100 through 1992110100

	Station	Number of Pts	Mean Meas	Mean Hind	Diff (H-M)	RMS Error	Stnd Dev	Scat Index	Ratio	Corr Coeff
Wind Spd. (m/s)	41001	125	7.79	7.78	-0.01	0.52	0.52	0.07	0.54	0.99
Wind Dir. (deg)	41001	125	294.08	293.67	0.35	N/A	5.95	0.02	N/A	N/A
Sig Wave Ht (m)	41001	125	2.00	2.07	0.07	0.33	0.32	0.16	0.66	0.95
Ave. Period (s)	41001	125	5.81	5.39	-0.41	0.65	0.51	0.09	0.20	0.83
Wind Spd. (m/s)	41010	125	7.08	7.01	-0.07	0.24	0.23	0.03	0.33	1.00
Wind Dir. (deg)	41010	125	40.30	47.79	-0.25	N/A	3.99	0.01	N/A	N/A
Sig Wave Ht (m)	41010	125	1.94	1.98	0.04	0.32	0.32	0.16	0.64	0.96
Ave. Period (s)	41010	125	6.09	5.56	-0.52	0.76	0.55	0.09	0.18	0.90
Wind Spd. (m/s)	44004	125	7.63	7.66	0.03	0.32	0.31	0.04	0.54	1.00
Wind Dir. (deg)	44004	125	332.41	310.77	0.42	N/A	4.52	0.01	N/A	N/A
Sig Wave Ht (m)	44004	125	1.90	1.97	0.07	0.38	0.38	0.20	0.63	0.90
Ave. Period (s)	44004	125	5.72	5.27	-0.45	0.93	0.81	0.14	0.22	0.58
Wind Spd. (m/s)	44011	125	7.34	7.39	0.05	0.17	0.16	0.02	0.58	1.00
Wind Dir. (deg)	44011	125	339.35	297.73	0.78	N/A	3.20	0.01	N/A	N/A
Sig Wave Ht (m)	44011	125	1.87	2.01	0.15	0.32	0.29	0.15	0.68	0.93
Ave. Period (s)	44011	125	5.77	5.41	-0.36	0.69	0.59	0.10	0.25	0.65
Wind Spd. (m/s)	44137	125	9.79	9.74	-0.05	0.32	0.32	0.03	0.34	1.00
Wind Dir. (deg)	44137	125	340.56	299.26	0.83	N/A	8.22	0.02	N/A	N/A
Sig Wave Ht (m)	44137	125	2.73	2.80	0.07	0.56	0.56	0.21	0.58	0.90
Peak Period (s)	44137	125	9.92	8.73	-1.18	3.53	3.33	0.34	0.38	0.11
Wind Spd. (m/s)	44138	124	8.66	8.65	-0.01	0.22	0.22	0.03	0.50	1.00
Wind Dir. (deg)	44138	124	354.68	290.63	-0.52	N/A	1.96	0.01	N/A	N/A
Sig Wave Ht (m)	44138	118	2.64	2.87	0.23	0.79	0.75	0.29	0.64	0.86
Peak Period (s)	44138	118	10.18	9.05	-1.13	3.99	3.82	0.38	0.40	-0.12
Wind Spd. (m/s)	62108	123	9.86	9.83	-0.03	0.16	0.15	0.02	0.33	1.00
Wind Dir. (deg)	62108	123	350.76	333.74	-0.08	N/A	1.94	0.01	N/A	N/A
Sig Wave Ht (m)	62108	123	3.15	3.22	0.07	0.58	0.57	0.18	0.61	0.95
Ave. Period (s)	62108	123	7.74	6.30	-1.45	1.82	1.10	0.14	0.07	0.74
Wind Spd. (m/s)	63115	7	11.45	9.33	-2.11	4.27	3.71	0.32	0.43	0.36
Wind Dir. (deg)	63115	7	359.07	306.43	-21.42	N/A	50.51	0.14	N/A	N/A
Sig Wave Ht (m)	63115	7	2.29	2.25	-0.03	0.86	0.86	0.38	0.71	0.66
Ave. Period (s)	63115	7	5.86	5.28	-0.58	1.21	1.06	0.18	0.43	0.12
Wind Spd. (m/s)	LF3J	104	7.35	8.06	0.71	1.03	0.75	0.10	0.81	0.99
Wind Dir. (deg)	LF3J	104	2.34	36.98	3.09	N/A	12.44	0.03	N/A	N/A
Sig Wave Ht (m)	LF3J	95	2.31	2.52	0.21	0.53	0.48	0.21	0.65	0.93
Ave. Period (s)	LF3J	95	6.90	5.97	-0.93	1.19	0.74	0.11	0.11	0.74
Wind Spd. (m/s)	LF5U	111	7.42	8.08	0.66	1.17	0.96	0.13	0.77	0.95
Wind Dir. (deg)	LF5U	111	355.96	333.63	-2.02	N/A	12.04	0.03	N/A	N/A
Sig Wave Ht (m)	LF5U	110	2.10	2.12	0.02	0.38	0.38	0.18	0.54	0.91
Ave. Period (s)	LF5U	110	5.73	5.33	-0.40	0.73	0.62	0.11	0.31	0.74
Wind Spd. (m/s)	ALL BUOYS	1094	8.14	8.25	0.11	0.65	0.65	0.08	0.52	0.99
Wind Dir. (deg)	ALL BUOYS	1094	341.72	325.42	0.17	N/A	8.02	0.02	N/A	N/A
Sig Wave Ht (m)	ALL BUOYS	1078	2.29	2.39	0.10	0.49	0.48	0.21	0.63	0.93
Period (s)	ALL BUOYS	1078	7.09	6.33	-0.76	2.01	1.86	0.26	0.24	0.66

Table 3. Verification statistics for 12 buoys.

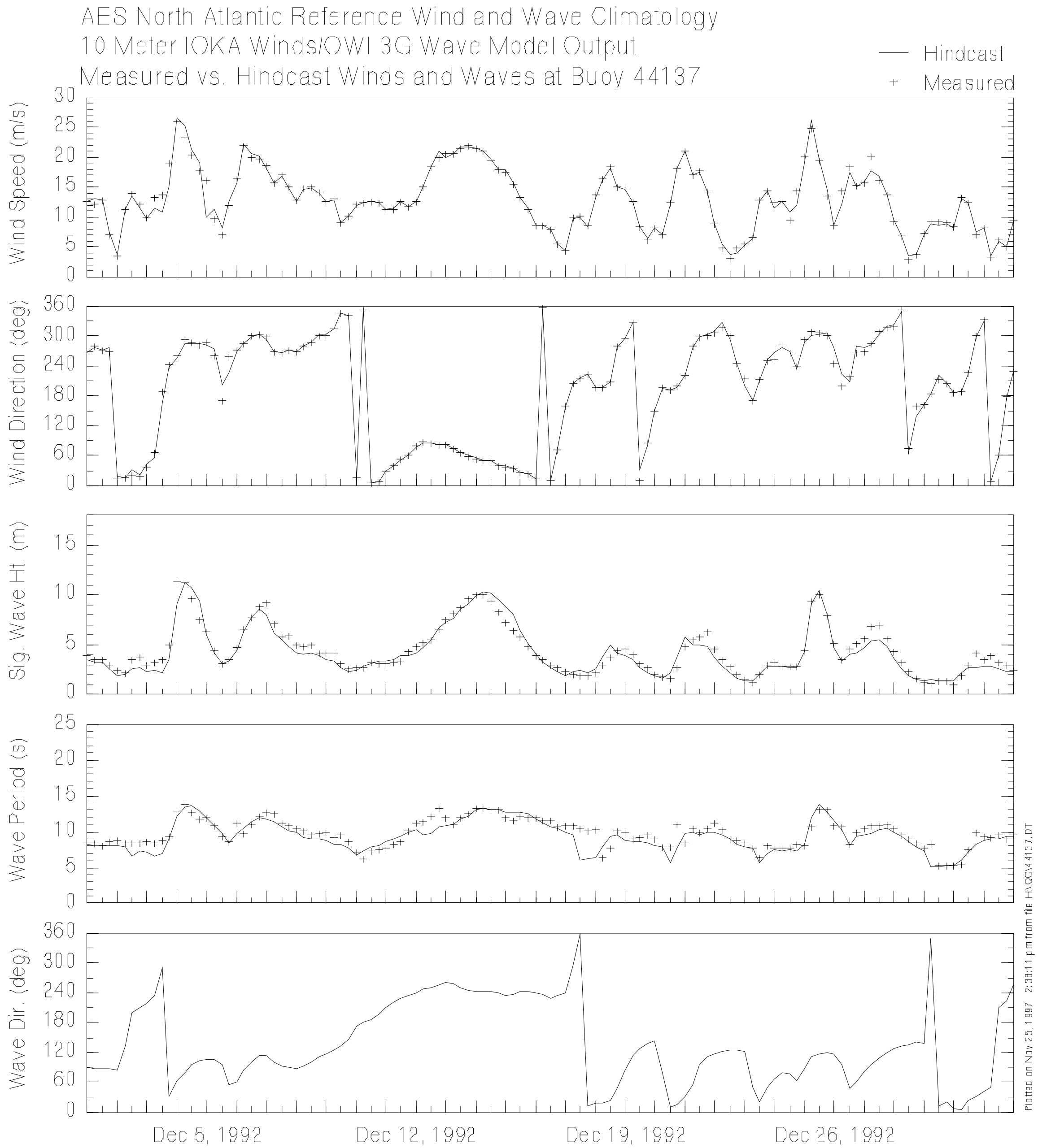


Figure 4. Time series comparison at Buoy 44137 during December 1992.

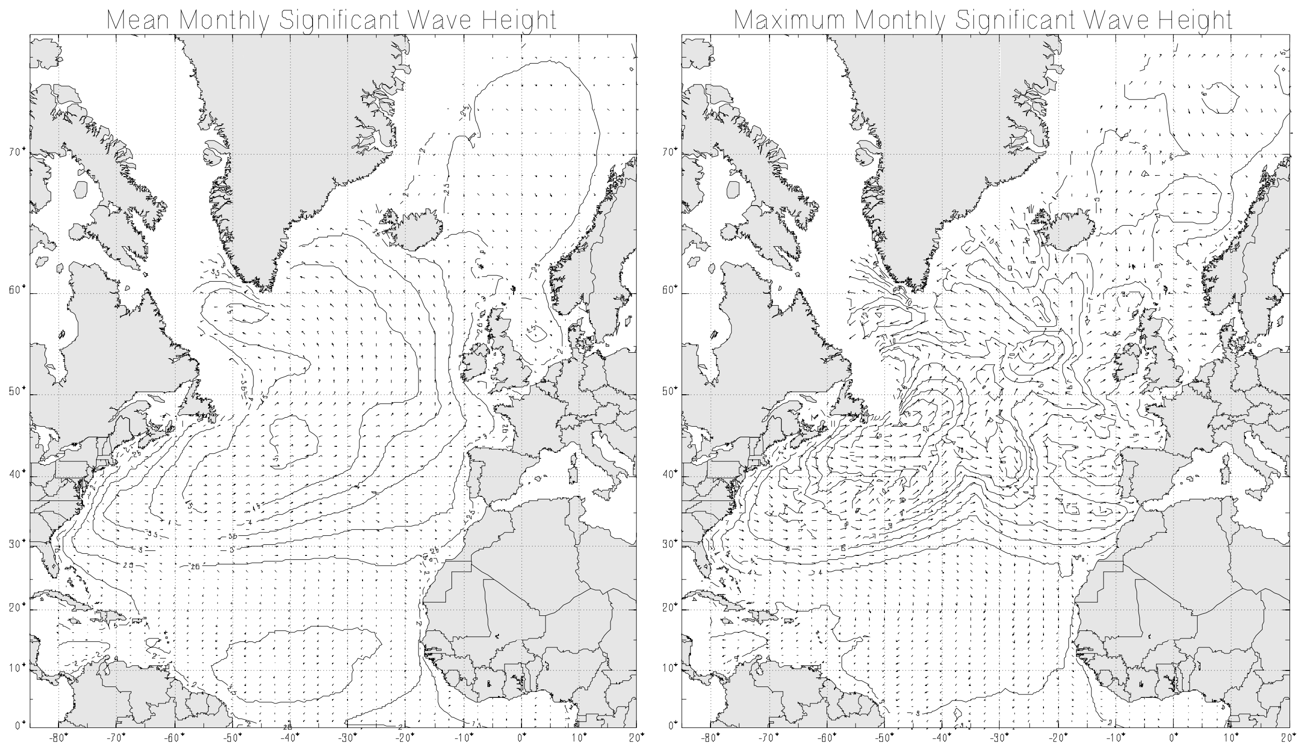


Figure 5. Mean and maximum wave heights for January 1985.

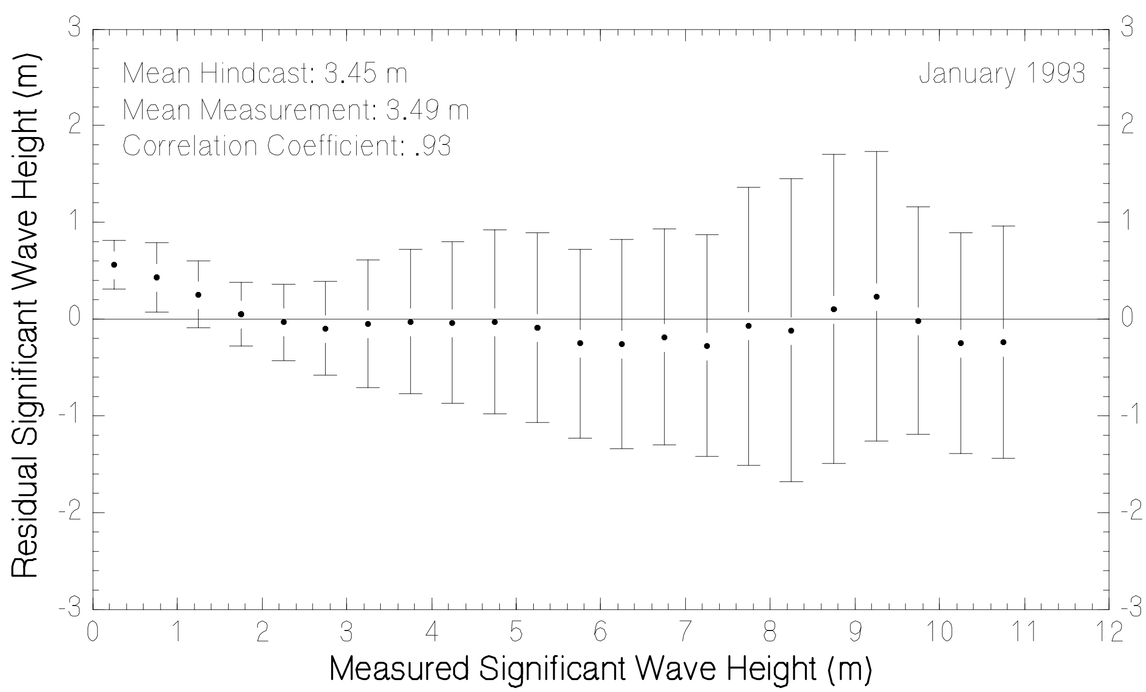
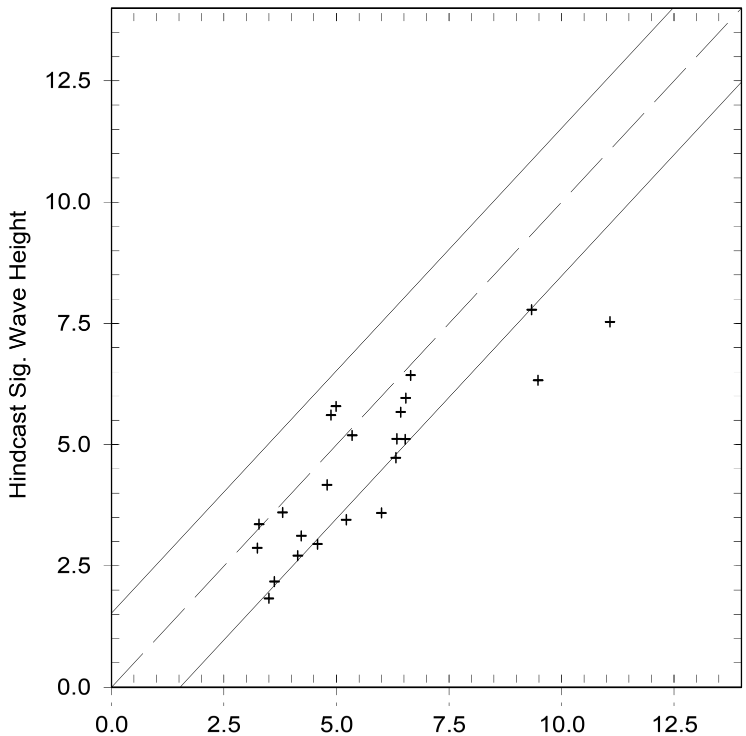


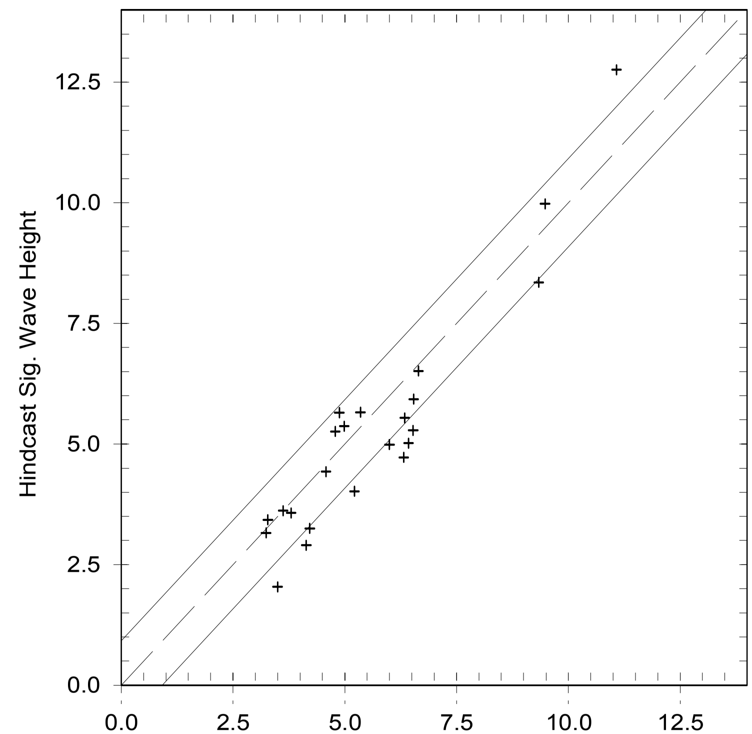
Figure 6. Comparison of hindcast vs. ERS altimeter significant wave height residuals in .5 meter bins.

NCEP Surface Winds



Total Points:	23
Mean X:	5.666
Mean Y:	4.569
Mean Diff:	-1.097
Root Mean Square:	1.524
Standard Dev.:	1.058
Scatter Index:	0.187
Ratio:	0.130
Correlation Coeff:	0.852

IOKA Surface Winds



Total Points:	23
Mean X:	5.666
Mean Y:	5.280
Mean Diff:	-0.386
Root Mean Square:	0.919
Standard Dev.:	0.834
Scatter Index:	0.147
Ratio:	0.304
Correlation Coeff:	0.938

Figure 7. Comparison of peak-to-peak wave height using NCEP and IOKA wind fields to drive 3-G wave model for 4 months.