On the use of In-Situ and Satellite Wave Measurements for Evaluation of Wave Hindcasts

Andrew T. Cox and Vincent J. Cardone
Oceanweather Inc. - Cos Cob, CT

Val R. Swail
Environment Canada - Toronto, Ontario

ABSTRACT

Two long-term wave hindcasts based on the NCEP/NCAR Reanalysis (NRA) products have recently been completed. The Global Reanalysis of Ocean Waves (GROW) project ran 40 years of unmodified NRA winds on a global 1.25 x 2.5 degree wave grid. The AES40 project ran 40 years of re-hindcast wind fields based on the NRA products on a high resolution North Atlantic grid.

This paper discusses the use of in-situ and satellite wave measurements in evaluating and understanding the bias and skill in these wave hindcasts. Direct time-series, quantile-quantile, and other statistical properties of the wave hindcasts are presented. Comparisons of the change in wave height bias at buoy locations over the 1975-1997 period are evaluated to assess the homogeneity of the wave hindcasts over this period. Finally, regional statistical comparisons and spatial plots of wave height bias and scatter derived from satellite measurements are also included.

1. Introduction

The ocean wave climate has long been of interest to the ocean engineering community because of the need for accurate extreme and operational wave data for applications such as vessel design, specification of peak loads of coastal and offshore structures, and planning of naval and marine operations. In recent years, there has been a major resurgence of interest in wave climate within the scientific community as a result of indications of a worsening storm wave regimes in some areas (Bacon and Carter, 1991) and evidence that trends and variability in wave climate on a regional basis may be linked to more familiar modes of atmospheric climate trend and variability such as the North Atlantic Oscillation (NAO) (Kushnir *et al*., 1997). Even the response of the global wave climate to a possible global warming scenario has been studied using a GCM model (WASA, 1998).

Recently, two long-term wave hindcasts based on the NCEP/NCAR Reanalysis project (henceforth NRA, Kalnay *et al*, 1996) have been completed. In order to access their use for operational use and climate trend analysis, the skill and bias of the hindcasts over time must be validated. This study describes the use of *in situ* and satellite measurements in validating each of the wave hindcasts.

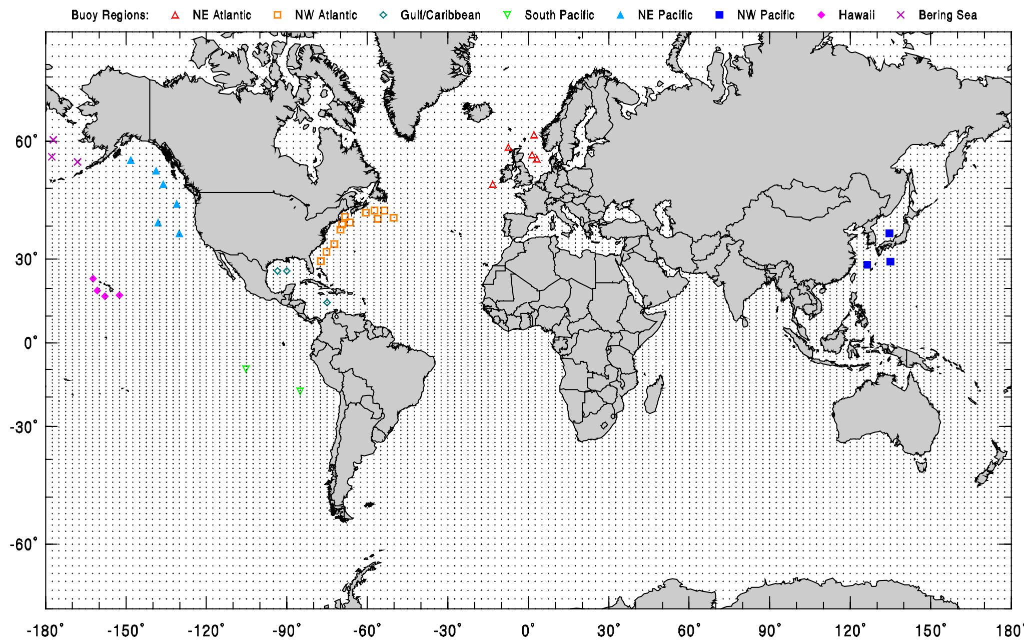
This paper is organized as follows. Section 2 briefly describes the two wave hindcasts being evaluated, while section 3 discusses the *in situ* and satellite datasets. Sections 4 and 5 present the validation results, while section 6 gives our conclusions.

2. Wave Hindcasts

a. Global Reanalysis of Ocean Waves (GROW)

GROW was carried out by Oceanweather Inc. using a deep-water version of its proven spectral ocean wave model ODGP2 as described in Khandekar *et al.* (1994). The model was adapted

Figure 1. GROW wave model grid with buoy locations.



to a grid spacing of 1.25° in latitude by 2.5° in longitude on a global projection as shown in Figure 1. The model was run in deep mode with first generation (1G) formulation. Ice tables were provided from long-term mean monthly historical ice concentration data.

Wind fields driving the GROW model were the NRA 10 meter wind fields. The NRA winds were adjusted to neutral stability using the technique described by Cardone *et al.* (1990) and interpolated on to the wave model grid. No other adjustments were made to the input wind fields. Additional information on GROW can be found in Cox and Swail (1999).

b. North Atlantic 40-Year Reference Wind and Wave Climatology (AES40)

AES40 used the same ODGP2 wave model as GROW; however, it was run with third generation (3G) physics (see Khandekar *et al.* (1994) for description) on a higher resolution grid. The wave model grid (Figure 2) is 0.625° in latitude and 0.833° in longitude on a projection covering the North Atlantic. The southern boundary along the equator was updated with interpolated wave spectra from GROW to preserve any South Atlantic swells. Ice tables were updated monthly, rather than long-term monthly averages used in GROW.

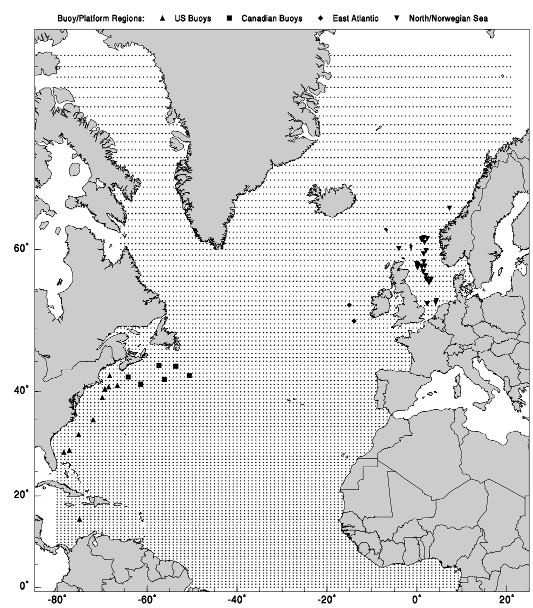


Figure 2. AES40 wave model grid with buoy/platform locations.

The most striking difference between GROW and AES40 is in the generation of the input wind fields. NRA adjusted winds were used as primary wind inputs; however, modifications of intense extra-tropical storms were performed using interactive kinematic techniques. Furthermore, all tropical systems in the 40-year period were hindcast using a proven tropical boundary layer model and included in the final wind fields. Finally, ships, buoys and satellite wind measurements were assimilated after adjusting each to a reference level of 10 meters. Further information on AES40 can be found in Swail and Cox (1999).

3. Validation Datasets

a. Buoys and Platforms

The *in situ* validation data set included buoys and measurement platforms mainly located in the Northern Hemisphere along the continental margins (Figures 1 and 2). The *in situ* measured wind and wave data came from a variety of sources. U.S. buoy data came from the NOAA Marine Environmental Buoy Database on CD-ROM; the Canadian buoy data came from the Marine Environmental Data Service marine CD-ROM; the remaining buoy and platform data (notably the northeast Atlantic and northwest Pacific) came from the Comprehensive Ocean Atmosphere Data Set (COADS) data set described by Slutz *et al*. (1985). Comparisons were restricted to well-exposed deep-water sites with the longest records. The wave measurements are comprised of 20-minute samples (except for Canadian buoys which were 40 minutes) once per hour. The wind measurements were taken as 10-minute samples, scalar averaged, except vector averaged at the Canadian buoys, also once per hour. The wind and wave values selected for comparison with the hindcast were 3-hour mean values centered on each six-hour synoptic time with equal (1,1,1) weighting. All wind speeds were adjusted to 10-m neutral winds following the approach described in Cardone *et al.* (1990).

b. Data from Ocean Weather Station Bravo

Data from OWS Bravo were obtained from the U.S. National Climatic Data Center. A large number of vessels occupied OWS Bravo; however, they tended to be one of two classes, with anemometer heights of 24 m. All ship wind speeds were also adjusted to 10-m neutral winds using the technique described by Cardone *et al*. (1990).

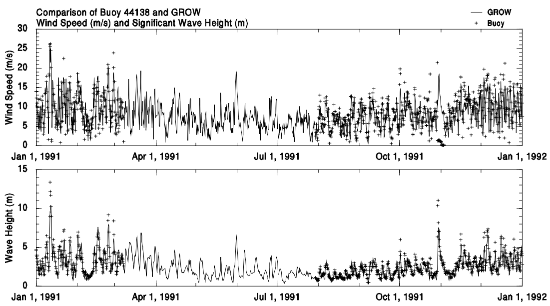
c. Satellite Data

Altimeters from the ERS-1, ERS-2 and TOPEX/Poseidon instruments were used for global wind and wave comparisons. The ERS-1/2 altimeter data sets were obtained from the Ifremer CD-ROM data set, while TOPEX data (GDR Generation-B CD-ROM set) was obtained from the NASA Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory/California Institute of Technology. Both data sets were decoded using the recommended quality controls described in each respective documentation. Further adjustments and quality control measures were used as recommended by Cotton and Carter (1994). Individual data points were then spatially binned onto the wave model grid, and output on to 6-hour synoptic times using a ±3-hour window. Additional quality control was performed for measurements along land and ice edges where some contamination of the altimeter wave measurements was encountered despite rigorous checking of ice/quality control flags available with each data set.

4. *In situ* Comparisons

a. Validation against buoy and platform measurements

Figure 3 shows a typical time series of wind speed and significant wave height for buoy 44138 for both GROW and AES40. The buoy time record is not continuous and has periods where wind and/or wave observations were not available. In general, both the GROW winds and waves track the buoy observations. The largest discrepancies occurred when strong extra-tropical systems passed close to a measurement site. The highest winds and waves in each type of event tended to be underpredicted; typically the lowest winds and waves tended to be somewhat overpredicted. The AES40 winds track very closely, as a result of the wind assimilation. The waves also track very well, and tend to better resolve the highest wave heights. This is partially as result of the local wind assimilation, but mainly due to the kinematic reanalysis of the storms that concentrate on following the major "jet streaks" of wind maxima associated with storms.



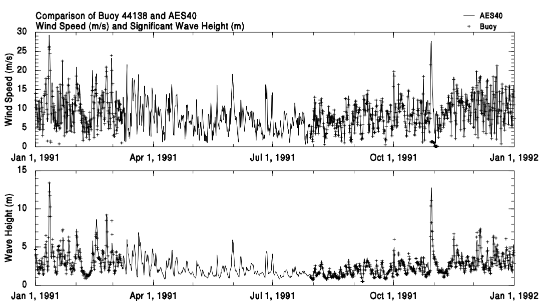


Figure 3. Comparison of buoy 44138 wind speed (m/s) and wave height (m) vs. GROW (top) and AES40 (bottom).

Individual buoys and platforms were then grouped by region (Figure 1) for comparison against GROW. Table 1 shows regional grouped statistics and represents more than 500,000 wind and wave observations. Highest scatter indices (SI, RMS/Mean Measurement) are from the northwest Pacific and northeast Atlantic regions, which were made up exclusively of COADS data. The COADS data lacks both the time resolution (3/6 hours versus 1 hour) and coding accuracy (winds nearest 1 knot, waves 0.5 m) than the other regions obtained from the CD-ROM marine data sets, which may explain some of the differences in SI. The Canadian and U.S. buoys were grouped into one data set since they represented the best science quality validation data set. These statistics show very good agreement with a mean bias of 0.12 m/s for winds and 0.10 m for waves and SI of 0.31 and 0.27, respectively.

Table 1. Regional statistical comparison of GROW vs. *in situ* buoy and platform observations.

	Number of Points	Mean Meas	Mean Hind	Diff (H-M)	RMS Error	Std. Dev.	Scatter Index	Corr. Coeff.
North East Atlantic								
Ws (m/s)	30026	8.40	8.73	0.33	2.73	2.71	0.32	0.80
Wd (°)	30032	243.06	238.06	-4.81	N/A	29.78	0.08	N/A
Hs (m)	24530	2.58	2.84	0.26	1.29	1.27	0.49	0.76
North West Atlantic								
Ws (m/s)	179938	7.14	7.54	0.40	2.57	2.54	0.36	0.78
Wd (°)	179940	248.55	270.12	4.40	N/A	36.00	0.10	N/A
Hs (m)	175256	1.98	2.04	0.06	0.57	0.56	0.28	0.89
Gulf of Mexico/Caribbean								
Ws (m/s)	59104	6.20	6.47	0.27	2.02	2.01	0.32	0.76
Wd (°)	59104	101.09	90.47	-5.78	N/A	31.87	0.09	N/A
Hs (m)	55642	1.17	1.49	0.33	0.49	0.36	0.31	0.88
South Pacific								
Ws (m/s)	12727	6.48	6.77	0.29	1.42	1.39	0.21	0.77
Wd (°)	12727	122.71	125.27	2.60	N/A	19.21	0.05	N/A
Hs (m)	12607	2.14	1.82	-0.32	0.48	0.36	0.17	0.77
North East Pacific								
Ws (m/s)	121323	7.99	8.04	0.05	2.26	2.26	0.28	0.82
Wd (°)	121323	252.01	250.03	1.40	N/A	32.32	0.09	N/A
Hs (m)	121793	2.75	3.01	0.26	0.67	0.62	0.23	0.92
North West Pacific								
Ws (m/s)	37893	7.44	6.72	-0.71	2.79	2.70	0.36	0.73
Wd (°)	37896	357.96	4.58	-3.40	N/A	43.07	0.12	N/A
Hs (m)	29555	1.40	1.88	0.48	0.97	0.85	0.60	0.67
Hawaii								
Ws (m/s)	70304	7.17	6.53	-0.64	1.85	1.74	0.24	0.74
Wd (°)	70304	73.68	75.62	1.12	N/A	23.01	0.06	N/A
Hs (m)	69289	2.38	2.10	-0.29	0.50	0.42	0.17	0.82
Bering Sea								
Ws (m/s)	19600	8.60	8.79	0.19	2.49	2.49	0.29	0.81
Wd (°)	19601	34.99	42.84	-1.44	N/A	33.61	0.09	N/A
Hs (m)	16271	2.68	3.08	0.40	0.75	0.64	0.24	0.93
US and Canadian Data Combined								
Ws (m/s)	466252	7.30	7.42	0.12	2.30	2.30	0.31	0.79
Wd (°)	466258	107.88	94.02	1.41	N/A	32.40	0.09	N/A
Hs (m)	453750	2.18	2.28	0.10	0.59	0.58	0.27	0.90

Table 2 shows the same statistics for AES40, although a different number of buoys/platforms were selected for this comparison (Figure 2). The North/Norwegian Sea observations show higher SI in waves in comparison to AES40, the same finding as GROW. Wind speed scatter at the Canadian buoys is high, 0.31, mainly due questionable data from one buoy which was left out in the wind assimilation but left in the comparisons shown here. Overall, AES40 has similar bias with lower SI and higher correlation coefficients when compared to GROW at the buoys/platforms.

Table 2. Regional statistical comparison of AES40 vs. *in situ* buoy and platform observations.

	Number of Points	Mean Meas	Mean Hind	Diff (H-M)	RMS Error	Std. Dev.	Scatter Index	Corr. Coeff.
U.S. Buoys								
Ws (m/s)	169927	6.92	7.18	0.26	1.31	1.28	0.19	0.94
Wd (°)	169925	240.47	251.65	0.99	N/A	16.65	0.05	N/A
Hs (m)	164834	1.83	1.94	0.12	0.43	0.42	0.23	0.93
Canadian Buoys								
Ws (m/s)	49272	7.94	8.41	0.46	2.54	2.50	0.31	0.84
Wd (°)	49272	263.46	268.87	1.58	N/A	29.48	0.08	N/A
Hs (m)	48890	2.51	2.53	0.03	0.53	0.53	0.21	0.93
East Atlantic Buoys								
Ws (m/s)	11019	9.75	9.71	-0.04	1.64	1.64	0.17	0.93
Wd (°)	11027	245.40	244.27	-0.44	N/A	17.98	0.05	N/A
Hs (m)	8071	3.73	3.47	-0.27	1.68	1.65	0.44	0.74
North/Norwegian Sea Platforms and Buoys								
Ws (m/s)	117198	8.58	9.14	0.56	2.24	2.17	0.25	0.88
Wd (°)	117204	240.17	239.27	-1.09	N/A	22.64	0.06	N/A
Hs (m)	107301	2.47	2.67	0.20	0.96	0.94	0.38	0.83
U.S. and Canadian Data Combined								
Ws (m/s)	219199	7.15	7.45	0.31	1.67	1.64	0.23	0.91
Wd (°)	219197	247.72	257.67	1.11	N/A	20.14	0.06	N/A
Hs (m)	213724	1.98	2.08	0.10	0.46	0.45	0.23	0.93

While overall statistics are useful for evaluating the skill of a hindcast, they don't indicate how the hindcast has changed over time relative to the *in situ* data. A comparison of seasonal wave height bias and scatter over the 1975-1997 period (Figures 4-7) show any trends that may exist in the hindcasts. Of course, trends may also occur in the measurements themselves (number of observations available, differing instrumentation, etc.) and the measured data must be evaluated carefully. These plots were produced by computing bias and SI for each region for every 3 months and plotting the resulting time series. All 4 figures show good agreement between the buoy observations and GROW/AES40 over time. The plots show nearly linear bias and SI over time indicating that both GROW and AES40 have remained consistent over the 22 years that the buoy measurements are available. Highest SI occur in the data from COADS, while the US and Canadian comparisons are more consistent. Early US buoy comparisons show more bias and slightly higher SI, which may be due the relatively few experimental buoys available in late 70's/early 80's.

Validation against Ocean Weather Station Bravo

Ocean Weather Ship Bravo, located in the North Atlantic, gives an opportunity to evaluate the hindcasts well away from the coast and for the time period 1958-1974 where the buoy observations are not available.

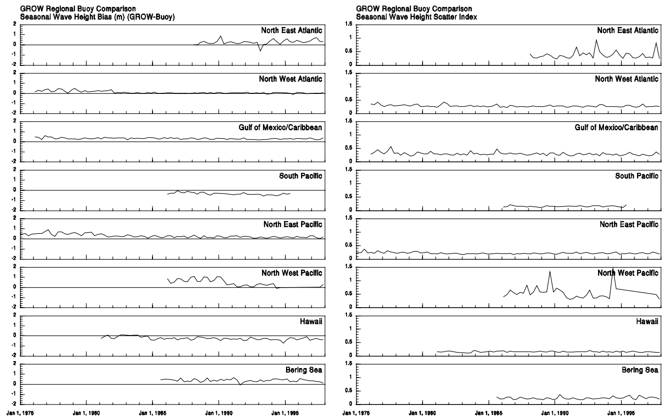


Figure 4/5. Seasonal wave height bias (m) (left) an SI (right) comparison of GROW vs. buoys by region

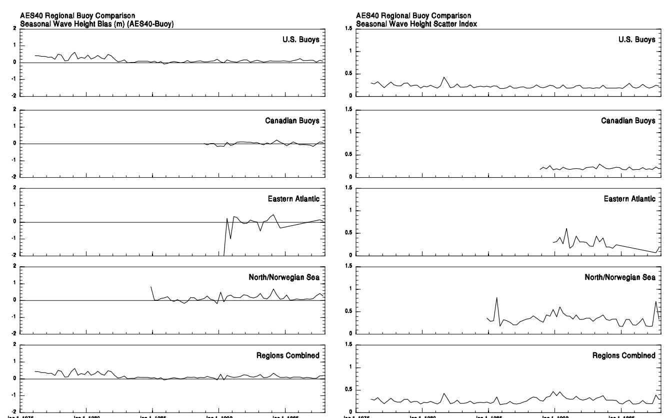


Figure 6/7. Seasonal wave height bias (m) (left) an SI (right) comparison of AES40 vs. buoys by region

Time-series comparisons (not shown) show similar characteristics as the buoy time-series figures. Storms tend to be underpredicted in GROW and better resolved in AES40. Figure 8 shows the seasonal bias and SI for Bravo wave heights. Both bias and SI comparisons show less bias/SI in the 1960's than the 1970's which results in an apparent trend. Whether this is due to changing measurement instrumentation/platform or a trend in the hindcasts is not known, although the "step-up" nature of the comparison around 1968/69 suggests changes in the Bravo measurements.

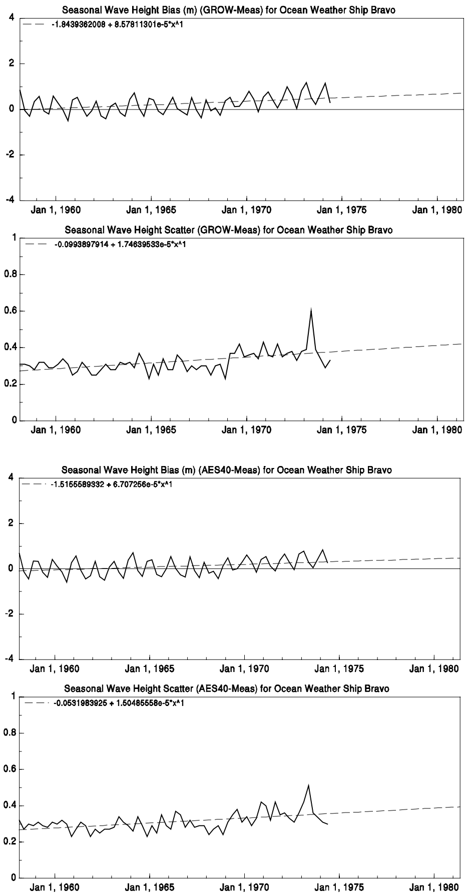


Figure 8. Seasonal wave height bias (m) and SI for ocean weather ship Bravo vs. GROW (top) and AES40 (bottom)

5. Satellite Comparisons

Altimeter wind and wave measurements provide the best spatial coverage to evaluate wave hindcasts. Statistics and plots from the individual instruments (ERS-1, ERS-2, and TOPEX) showed very good agreement between each other, so the data sets were combined for these comparisons. The GROW model comparison was broken into four regions: Southern Hemisphere (SH) (65S to 20S), Tropical (TROP) (20S to 20N), Northern Hemisphere (NH) (20N to 70N), and all regions combined (65S to 70N). The AES40 comparisons were done for the full basin only. Statistics are summarized in Table 3.

Table 3. Regional statistical comparison of GROW and AES40 vs. altimeter measurements.

	Number of Points	Mean Meas	Mean Hind	Diff (H-M)	RMS Error	Std. Dev.	Scatter Index	Corr. Coeff.
GROW: Southern Hemisphere (65S to 20S)								
Ws (m/s)	4004211	8.68	8.62	-0.06	2.40	2.40	0.28	0.79
Hs (m)	4001377	3.39	3.34	-0.05	0.79	0.79	0.23	0.85
GROW: Tropics (20S to 20N)								
Ws (m/s)	2608601	6.02	5.99	-0.03	1.86	1.86	0.31	0.71
Hs (m)	2593660	1.96	1.87	-0.08	0.46	0.45	0.23	0.77
GROW: North Hemisphere (20N to 70N)								
Ws (m/s)	2086601	7.43	7.60	0.18	2.09	2.08	0.28	0.84
Hs (m)	2067467	2.54	2.56	0.02	0.65	0.65	0.26	0.91
GROW: Global Comparison								
Ws (m/s)	8699413	7.60	7.60	0.00	2.18	2.18	0.29	0.81
Hs (m)	8662504	2.73	2.73	-0.04	0.68	0.67	0.24	0.89
AES40: North Atlantic Comparison								
Ws (m/s)	3471109	7.66	7.81	0.15	1.94	1.94	0.25	0.86
Hs (m)	3523575	2.52	2.51	-0.01	0.56	0.56	0.22	0.93

Quantile-quantile (Q-Q) plots of the combined altimeter versus GROW (Figure 9) show excellent agreement for both wind speed and wave height. At the highest percentiles, winds appear to be over-predicted while waves are under-predicted. This is suspected to be wind speed saturation problem with the altimeter in wind speeds above 15 m/s. The wave under-estimation appears to be a property of the GROW wave hindcast. A Q-Q comparison of AES40 (Figure 10) shows the same over-estimation of wind speed, but tracks the waves up to the 99th percentile. This is a result of AES40's intensive reanalysis of the strongest storms.

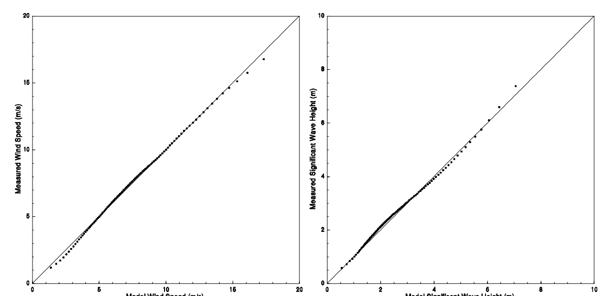


Figure 9. Q-Q wind speed (m/s) and wave height (m) comparisons of GROW and altimeter measurements.

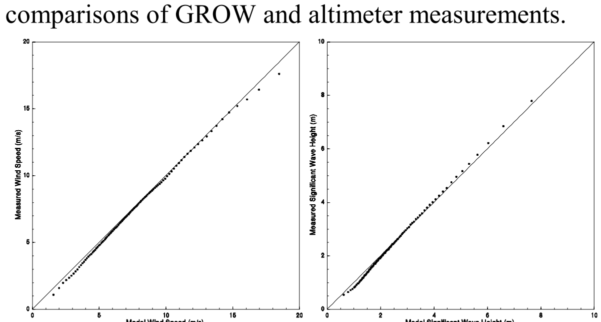


Figure 10. Q-Q wind speed (m/s) and wave height (m) comparisons of AES40 and altimeter measurements.

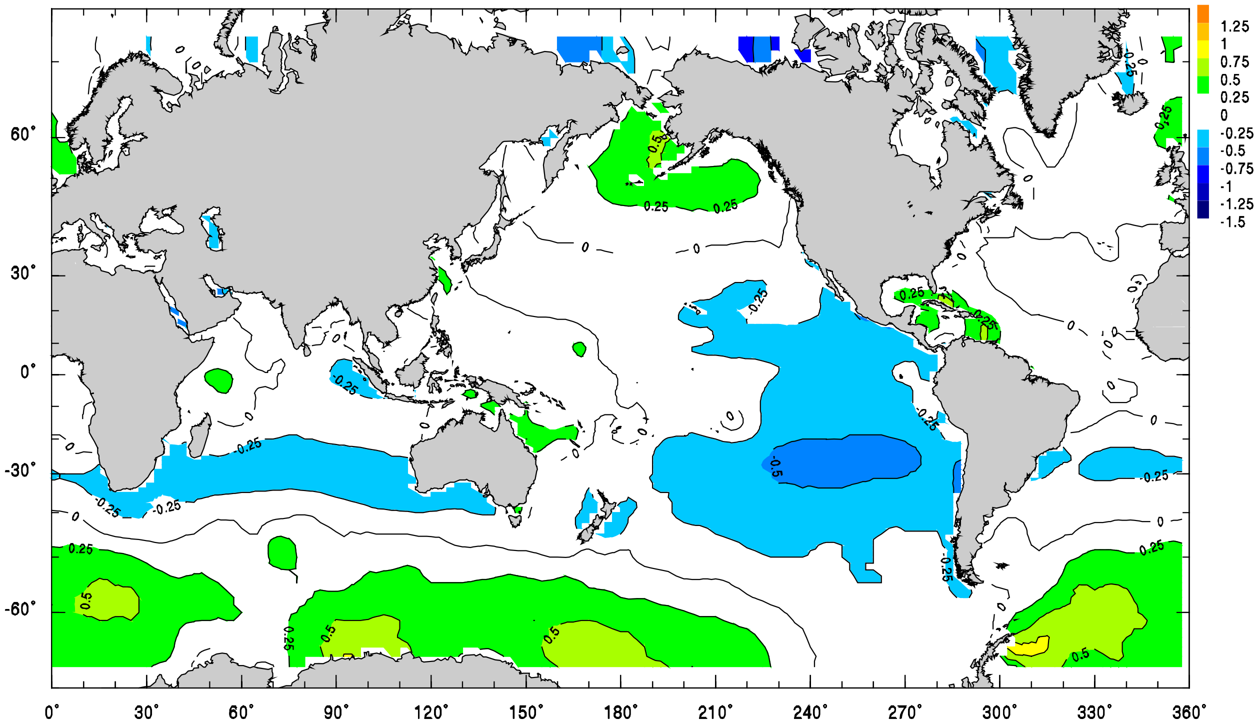


Figure 11. Mean difference of wave height (m) between GROW and altimeter measurements (GROW-Altimeter).

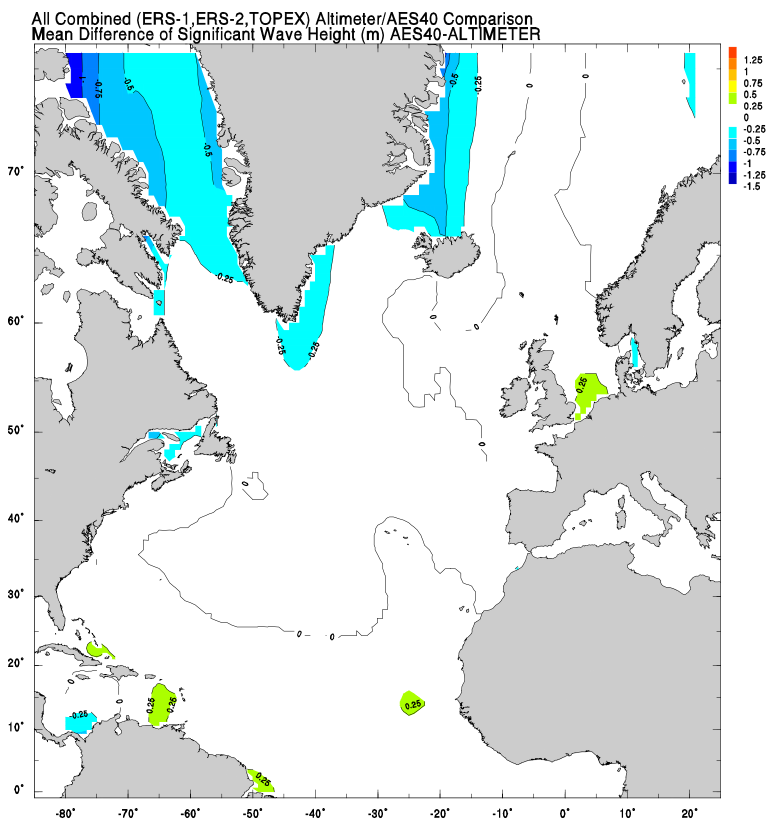


Figure 12. Mean difference of wave height (m) between AES40 and altimeter measurements (AES40-Altimeter)

The global coverage of the altimeter measurements makes it possible to plot contours of wave bias on a global projection. Figure 11 shows the global wave height bias which indicates spatially coherent regions of GROW over-estimating and under-estimating the measured waves. Many of the regions, such as the Caribbean Sea, Aleutian Island Chain, and North Sea are suspected to be resolution effects of the GROW wave model as the grid spacing is too coarse to resolve the coastline. The large region of bias off Antarctica is suspected to be the effects of using mean-monthly ice tables for the entire hindcast. There appears to be a large area of under-estimation of wave height in the Southern Hemisphere along 30S with the strongest bias in the South East Pacific.

A spatial wave bias plot of AES40 (Figure 12) shows that over most of the North Atlantic AES40 has very little bias. The largest feature is the underestimation in the Baffin Sea and in the Denmark Strait. This is suspected to be a result of ice edge effects, and to some degree an underestimation of the wind speed in the NRA winds. While the AES40 winds were kinematically enhanced, the lack of data in these areas made it difficult to track all significant systems. When sufficient data were available, large discrepancies of the wind speed were found and corrected in the NRA winds. Grid scale effects explain most other areas of bias near island chains or in the shallow Southern North Sea.

6. Conclusions

This paper has presented the use of *in situ* and satellite observations to evaluate long-term wave hindcasts. Both the GROW and AES40 validation show that each hindcast compares well against the available buoy, platform, ocean weather ship and satellite measurements. Comparisons of *in situ* data over the full 1958-1997 period show that both hindcasts have remained consistent with the observations.

In the top percentiles, GROW shows a tendency to underpredict the highest sea states, while AES40 better resolves the peak storms. Spatial comparison of AES40 shows very little bias across most of the North Atlantic, while GROW appears to show some coherent areas of under and over-estimation that cannot be explained by grid/ice edge effects.

In summary, it has been shown that *in situ* and satellite data serve powerful and complementary roles in the evaluation of global and basin scale long-term hindcasts. However, we caution that due consideration must be given to the limitations of each measurement dataset before biases and trends that appear in the comparison statistics are attributed to either nature or model error.

REFERENCES

Bacon, S. and D.J.T. Carter, 1991. *Wave climate changes in the North Atlantic and North Sea.* Int. Journal of Climate, Vol. 11, 545-558.

Cardone, V.J., J.G. Greenwood and M.A. Cane, 1990. *On trends in historical marine wind data*. J. of Climate, 3, 113-127.

Cotton, P.D., and D.J.T. Carter, 1994. *Cross calibration of TOPEX, ERS-1, and Geosat wave heights.* J. of Geophysical Research, Vol 99, No. C12, pp. 25,025-25,033.

Cox, A.T., V.J. Cardone and V.R. Swail, 1997. *Evaluation of NCEP/NCAR reanalysis project marine surface wind products for a long term North Atlantic wave hindcast*. Proc. 1st WCRP International Conference on Reanalyses, Silver Spring, MD, October 27-31, 1997. WCRP-104, WMO/TD-NO. 876, p. 73-76.

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*. Proc. 5th International Workshop on Wave Hindcasting and Forecasting, Melbourne, FL

Cox, A.T., and V.R. Swail, 1999. *A global wave* *hindcast over the period 1958-1997: validation and climate assessment.* Submitted to JGR (Oceans).

Kalnay, E., *et al*, 1996. *The NCEP/NCAR 40-Year reanalysis project*. Bull. AMS, 77(3), 437-471.

Khandekar, M.L., R. 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-Ocean 31 (1), pp. 31-60.

Kushnir, Y., 1994. *Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions.* J. Climate, 7, 141-157.

Stutz, R.J., S.J. Lubker, J.D. Hiscox, S.D. Woodruff, R.L. Jenne, D.H.Joseph, P.M. Steurer, and J.D. Elms, 1985. *Comprehensive Ocean-Atmosphere Data Set Release 1*. NOAA Environmental Research Laboratories, Boulder, Colo., 268 pp. (NTIS PB86-105723).

Swail, V.R. and A.T. Cox, 1999. *On the use Of NCEP/NCAR reanalysis surface marine wind fields for a long term North Atlantic wave hindcast*. Accepted in J. Atmos. Ocean. Technology.

WASA Group, 1998. *Changing waves and storms in the Northeast Atlantic?* AMS Bul., Vol. 79, No. 5, May 1998 pp. 741-760.