EVALUATION OF NCEP REANALYSIS SURFACE MARINE WIND FIELDS FOR OCEAN WAVE HINDCASTS

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ABSTRACT

The National Center for Environmental Prediction (NCEP) Reanalysis (NRA) surface marine wind fields are evaluated as the forcing of a third-generation ocean wave model adapted to the North Atlantic (NA) Ocean on a high resolution grid. This evaluation is part of a larger study to produce a high-quality, homogeneous, long-term wind and wave database for assessment of trend and variability in the wave climate of the NA.

It is found that while NRA wind fields appear to be a significant improvement over operational wind fields, if for no other reason than they are more homogeneous over time than real time products, they still suffer from poor resolution of areas of high winds in extratropical storms and lack of resolution of most tropical systems. It is shown that the NRA wind fields may be improved by reassimilation of measured wind data in a kinematic analysis approach, but only after the limitations of each data source are considered to reduce bias associated with variable measurement height and averaging interval and to recognize limitations of dynamic range, especially for remotely sensed wind speed.

1.
HISTORICAL PERSPECTIVE

One of the products of the NCEP/NCAR Reanalysis project (henceforth NRA, Kalnay *et al.*, 1996) is a description of the global marine surface wind field on synoptic time (6-hourly) and space (roughly 2-degrees) scales. The NRA is an appealing and convenient source of forcing for ocean response modelling but it is fair to ask whether it is sufficiently accurate and free of bias for such purposes. The principal purpose of this paper is to describe our evaluation of the NRA winds through analysis of the errors in a simulation of the wave climate (Swail and Cox, 1999) made when NRA winds are used to force a proven spectral ocean wave model adapted to the North Atlantic Ocean. Wave modelling has been shown to be particularly well suited to the evaluation of marine wind fields (Cardone *et al.*, 1995). Before presenting our evaluation, however, it is interesting to review the more traditional approaches to specification of marine surface wind fields, because we will find that some elements of those methods still have a role to play in the derivation of wind fields of maximum accuracy from NRA products.

At the time when the first author of this paper first became interested in specification of marine surface wind fields (circa 1965) and as recently as the late 1970s, basically only one data source and two approaches were available (the analyst's life was therefore quite simple though the results were not always rewarding!). The data source consisted of ships' synoptic weather reports, mainly from transient merchant vessels supplemented in the northern hemisphere (NH) by a few stationary ocean station vessels. The two approaches consisted of: (1) derivation of winds from fields of sea level pressure and other Marine Planetary Boundary Layer (MPBL) variables, themselves derived from ships' observations of sea level pressure, air temperature and sea temperature, using simple empirical rules or fairly complex MPBL models; (2) kinematic analysis of ship wind observations.

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The error characteristics of wind fields hindcast for a sample of NH extratropical storms by the alternative approaches were explored by Cardone *et al.* (1980). It was found that wind fields produced by application of an MPBL model to either hand analysed or objectively analysed pressure fields tended to be negatively biased (typical bias of –1.5 to –2.0 m/s) with the bias contributed to mainly by the higher wind speeds. It was suggested that the bias in wind speed was, therefore, better expressed as a percentage (10-15 per cent) reduction. Cardone (1991) summarized a number of similar evaluations of MPBL-derived winds conducted through the 1970s and 1980s (Overland and Gemmill, 1978; Gemmill *et al.*, 1988; Dobson and Chaykovsky, 1991) and concluded that random wind speed errors in MPBL-derived wind speeds derived from carefully reanalysed pressure fields are about 3 m/s (rms) about a mean negative bias of about –0.5 m/s when the MPBL winds were compared to NOAA buoy winds or GEOSAT altimeter winds and –1.6 m/s when evaluated against ship winds after the ship winds were adjusted for measurement height and type and stability (Cardone *et al.*, 1990).

With the widespread implementation of multi-level primitive-equation numerical weather prediction (NWP) models in the 1980s, new sources of marine surface wind data became available as a by-product of the NWP analysis-forecast cycle of the major centres such as the Canadian Meteorological Center (CMC), the US Navy’s Fleet Numerical Meteorology and Oceanography Center (FNMOC, formerly FNOC) NCEP, the United Kingdom Met Office (UKMO), the European Centre for Medium Range Weather Forecasting (ECMWF) and the Goddard Space Flight Centre of the National Aeronautics and Space Administration (NASA). At some centres, the 10 m level was explicitly resolved in the NWP model and the initial analysis benefited from the assimilation of winds measured from ships, moored buoys and, by the early 1990’s, from satellite sources of wind data. Unfortunately, the data assimilation eliminates from consideration marine data that could have otherwise served as independent data to evaluate the accuracy of the NWP wind fields.

The Surface Wave Dynamics Experiment (SWADE) conducted off the US East Coast in 1990 (Weller *et al.*, 1991) provided an opportunity to develop a surface wind fields database with much better coverage from measured data than had been previously possible. This is because the SWADE wind fields database itself incorporated a second database of storms which incorporated high quality surface wind measurements from buoys. These buoys were sufficiently well distributed to ensure, for the first time in such a database, the avoidance of gaps typically found in similar data sets for open ocean areas. Initially, it was thought that the availability of the SWADE enhanced database in real time to the NWP centres’ objective analysis and data assimilation schemes would then necessarily lead to high-quality wind fields. Unfortunately, when those NWP centre wind fields for SWADE IOP-1 (an 11-day period centered on the development of an intense US East Coast cyclone of 23-31 October 1990) were used to drive the WAM-4 wave model adapted to the SWADE area at high resolution, errors in modelled sea states were found to be intolerably large (Graber *et al.*, 1991). However, when the same database was subjected to an intensive manual analysis using classical kinematic analysis and the resulting wind fields were used to drive the WAM-4 wave model, wave hindcasts of unprecedented skill were found (Cardone *et al.*, 1995). Figure 1 compares hindcast and buoy measurements of significant wave height (HS) at NOAA buoy 41001 moored east of Cape Hatteras, from WAM-4 hindcasts driven by the various NWP analysis wind fields and by the kinematically-derived winds (labelled OWI in the figure). The maximum wind speed and HSL observed in the SWADE array during IOP-1 were about 25 m/s and 9 m respectively. Therefore, at least for this regime of moderate wind forcing, the SWADE study demonstrated that wind field errors could be reduced to very low levels through an available, though tedious, analysis method, namely kinematic analysis, provided that accurate surface wind measurements are available at a data density roughly comparable to that achieved in the buoy array off the US East Coast during SWADE.

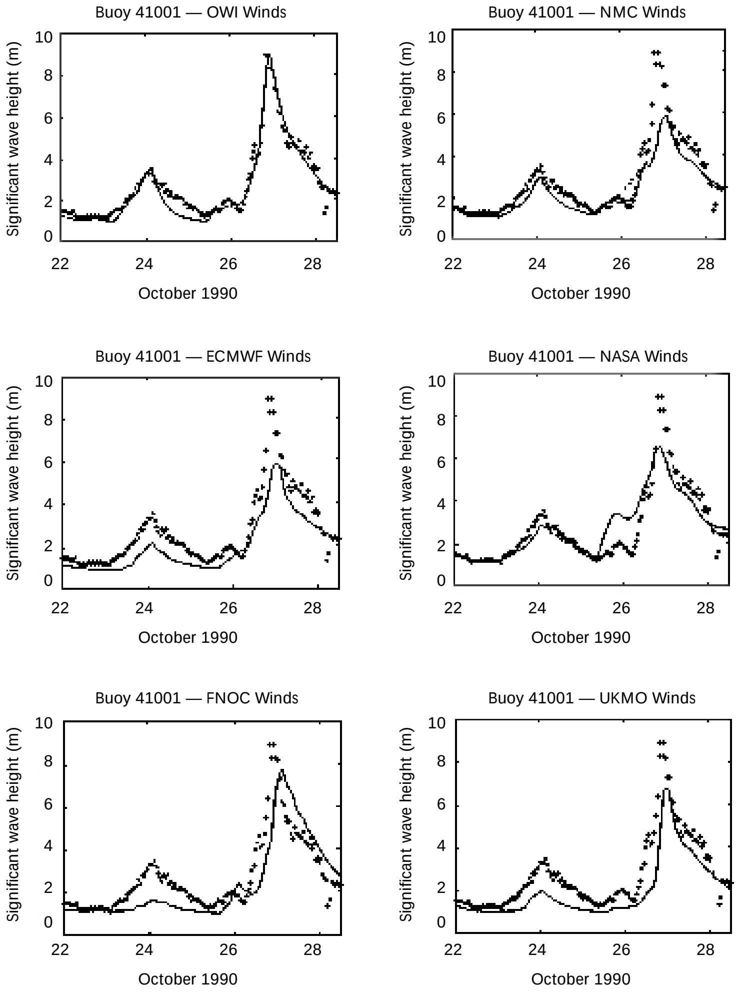


Figure 1—Comparison of WAM-4 hindcasts (solid line) of significant wave height and buoy measurement at buoy 41001 (East of Hatteras) in SWADE IOP-1 (Cardone et al., 1995).

The most significant wind field features found in the storms modelled in SWADE and in other recent storm studies (Cardone *et al.*, 1996), in terms of generation of storm peak sea states, were relatively small scale, rapidly propagating surface wind maxima or 'jet streaks' (typical jet core widths of 200 km or less) which by virtue of their spatial and temporal coherency provide a dynamic fetch to couple very effectively to the surface wave field. The propagation speeds of these jet streaks, typically 15-20 m/s, do not necessarily match the speed of the parent cyclone centre. The most extreme sea states in storms containing jet streaks are normally observed at buoys directly in the path of the core of jet streaks. Validation of wave hindcasts, therefore, provides a sensitive measure of skill in wind fields.

Unfortunately, the SWADE hindcast study also shows that the objective analysis systems used at major NWP centres did not realize the full potential of the enhanced buoy array for surface wind analysis, and did not resolve accurately the small scale rapidly evolving features. The wind fields provided by objective analysis at such centres have been used to drive wave models to provide hindcast time series for climate assessment, such as the US Navy's 20-year Spectral Ocean Wave Model (SOWM) and Norwegian 35-year Waves in Norwegian Coast-Hindcasting (WINCH) data sets. It is not surprising, therefore, that such data sets, though useful, are subject to both bias and scatter.

It was found that the deficiencies of the operational NWP wind fields observed during SWADE could not be attributed to model grid spacing or the size of the time step. This was shown by Graber *et al.* (1995), who used the SWADE kinematic winds in IOP-1 to systematically investigate the effect of degrading the spatial and temporal resolution of the reference SWADE wind fields on the accuracy of the hindcasts. The effect of degrading the temporal and spatial resolution was investigated through the validation of alternative SWADE hindcasts with the

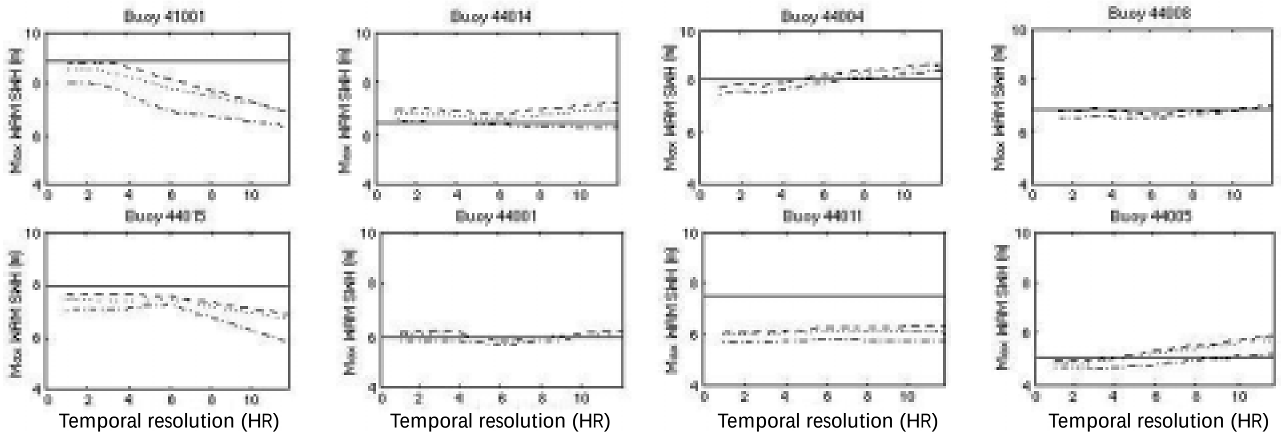


Figure 2—Hindcast of peak event HS relative to that measured (solid horizontal line) as a function of indicated temporal resolution for three indicated spatial resolutions: 0.5° (OWI) (dashed line); 1° (dotted line); 1.5° (dashed-dot line) (from Graber et al., 1995). Buoy locations: 41001 – 34°55.5'N, 72°57.1'W; 44014 – 36°35.0'N, 74°50.0'W; 44004 – 38°32.2'N, 70°42.3'W.

same wave model used for the reference SWADE hindcasts (Figure 2). The reference winds were specified on a 0.5 degree grid at hourly intervals. It was found that at the buoy directly in the path of the jet streak (41001), wind fields with a 0.5 degree spatial resolution and 3-hour time step were required for accurate specification of the peak HS. At buoys moored north of the storm track (e.g. 44014, 44004) in a nearly linear slowly evolving wind field, even 12-hour sampling and 1.5 degree spacing did not degrade specification of the local HS storm peaks. Well outside the SWADE array (e.g. 44011), where even the reference winds were not very accurate, the storm peak HS was uniformly underestimated for all resolutions simulated. Within the SWADE array, however, it was found that the errors in the hindcasts of storm peaks resulting from the actual operational wind fields (Figure 1) were always significantly greater than the errors for the particular cases simulated which matched the spatial and temporal resolution of the operational centre winds, thereby confirming the presence of additional error sources in the NWP centre wind fields.

The deficiencies exhibited in the NWP winds during SWADE (conducted in 1990) may not be indicative of the accuracy of NWP winds later in the 1990s and at the present time because analysis and data assimilation methods have undergone almost continuous refinement. Also, in some areas the volume of high-quality in situ measured data has increased, particularly off the east and west coasts of North America and offshore Western Europe. In addition, remotely-sensed marine wind data became available on a global basis in the early 1990s from passive and active microwave sensors. However, there remain questions of accuracy and bias, especially at wind speeds above about 15 m/s with all types of in situ and remotely-sensed marine wind observations, which have not been fully resolved and will be discussed further below.

Nevertheless, the NRA provides a new and convenient database and indications are that the NRA marine wind fields will be widely used for ocean response modelling. Section 2 of this paper gives our evaluation of the alternative files of marine winds available within the NRA database. In section 3, we describe the remaining deficiencies of even the best of the NRA wind fields evaluated, and we describe how they were resolved at least in part by applying kinematic analysis and manual intervention to the NRA database with a graphical user interface. Section 4 elaborates on the above-noted observational error issues and implications of same on the development of an optimum marine wind analysis system. Conclusions are given in section 5.

2.

EVALUATION OF THREE ALTERNATIVE NRA WIND FIELDS

A. EVALUATION METHODOLOGY

In the evaluation phase of our study we compared three alternative NRA 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; and (3) the 10 m surface wind fields on the so-called Gaussian grid. A fourth method is available, namely the application of a diagnostic MPBL model applied to NRA pressure fields and other MPBL variables, but this was not utilized because it was expected a priori that the boundary layer formulation within the NRA NWP model provided a physically more correct representation of the boundary layer than that provided by any steady state diagnostic MPBL. However, we have recently had cause to reconsider the validity of this assumption.

Eight months were selected from the available period (1979-1995) 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; Swail *et al.*, 1995), while 9509 was chosen as a hurricane-dominated month. The remaining months (7906, 8808) were added to provide a more even representation over time of the part of the NRA available (1979–1995).

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 using the IOKA (Interactive Objective Kinematic Analysis) algorithm (Cox *et al.*, 1995) and then time interpolated linearly from a six-hour time step to a one-hour time step. Oceanweather's third generation (OWI3G) 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 (US, Canadian and European), offshore North Sea platforms, US C-MAN (Coastal Marine Automated Network) and ERS-1/2 altimeter and scatterometer measurements. All measured winds were adjusted for height and stratification to a 10 m reference height and neutral stability (Cardone *et al.*, 1990), while hourly wind and wave measurements were smoothed over ±1 hour 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.

B. RESULTS

The results of the statistical comparisons of the three sets of NCEP winds and the modelled waves 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 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 and other properties of the hindcast results studied it was concluded 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 eight evaluation months versus the in situ measurements and for the three months for which ERS-1/2 altimeter data were available. Table 2 shows that the best wind field was the Gaussian grid 10 m surface wind field. The bias for these winds 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 favoured the surface winds. The scatter index for waves hindcast from the surface winds was always superior.

Table 1—Comparison wave summary statistics (wind statistics in brackets) for March 1993 for NRA 10 m surface, sigma and 1000 mb input wind fields (Scatter index is the ratio of the standard deviation (SD) of the difference between hindcast (H) and measurement (M) and the mean of the measurements; ratio is percentage of points above/below the 1:1 line on a scatter plot (0.5 is ideal) of the paired hindcast-measured data).

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 2—Comparison of wind and wave bias and scatter index values by month for NRA sigma and 10 m surface winds (bold italics show closer agreement with measurements).

	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	***0.30***	0.33	***0.1***	0.9	***0.41***	0.56

3. DEFICIENCIES AND CORRECTIONS OF NRA WINDS

A. DEFICIENCIES

While the NCEP surface wind fields produce the least biased and most skillful wave hindcasts overall, the scatter index values were much higher (hence less skill) than found in hindcast studies of continuous periods (Cardone *et al.*, 1995) or storms (Cardone *et al.*, 1996) where kinematically reanalysed wind fields were used to drive the wave model. The hindcasts were also found to systematically underestimate storm peaks. For example, Figure 3 (left-hand side) shows the effect on the hindcast of the poor NRA representation of the winds at a buoy off the US East Coast during SWADE IOP-1. It was also found that tropical storms were poorly resolved in the NRA wind fields as shown in Figure 4 for Hurricane Emily (September 1993).

Table 3 shows the results of hindcasts using the NRA 10 m surface wind fields for four of the eight months selected (those months for which ERS 1/2 altimeter data were available); results for the other four months indicated similar results (not shown). The hindcasts were compared to measurements from buoys moored in deep water off the US and Canadian East Coasts and off Northwest Europe and to the satellite data over the whole of the model domain. With respect to the buoy comparisons overall, the HS SI of 26 per cent indicates less skill in these hindcasts than provided by kinematically reanalysed wind fields. On the other hand, this skill is equal to, or better than, the best of the SWADE hindcasts driven by the wind fields from the operational centres (Cardone *et al.*, 1995). The HS bias of 3 cm is satisfyingly small.

The altimeter comparisons in Table 3 provide evaluation of the hindcast over the whole of the NA. These comparisons exhibit a mean difference of 18 cm and HS SI of 23 per cent. Interestingly, these comparisons suggest that the skill

Table 3—Validation of North Atlantic Ocean continuous hindcasts of indicated months with OWI-3G driven by NRA 10 m surface winds, against buoy and ERS-1 altimeter wave measurements.

Year/ Month	Variable	Num	All Buoys Bias	rms	S.I.	ERS-1 Altimeter Num	Bias	rms	S.I.
9110	WS (m/s)	882	0.12	2.96	0.34	16,808	0.34	2.13	0.29
	HS (m)	758	0.01	0.77	0.24	16,703	-0.20	0.65	0.24
9303	WS (m/s)	868	-0.28	2.31	0.24	17,517	0.43	2.19	0.26
	HS (m)	871	-0.07	0.73	0.24	16,972	-0.05	0.61	0.20
9504	WS (m/s)	600	-0.15	2.30	0.33	17,693	0.37	1.97	0.27
	HS (m)	720	0.04	0.60	0.26	17,551	-0.01	0.54	0.23
9509	WS (m/s)	761	0.36	2.68	0.41	18,081	0.05	2.30	0.35
	HS (m)	834	-0.11	0.62	0.30	18,059	-0.46	0.74	0.25
All	WS (m/s)	3,111	0.01	2.59	0.33	70,099	0.30	2.15	0.29
Months	HS (m)	3,183	-0.03	0.68	0.26	69,285	-0.18	0.64	0.23

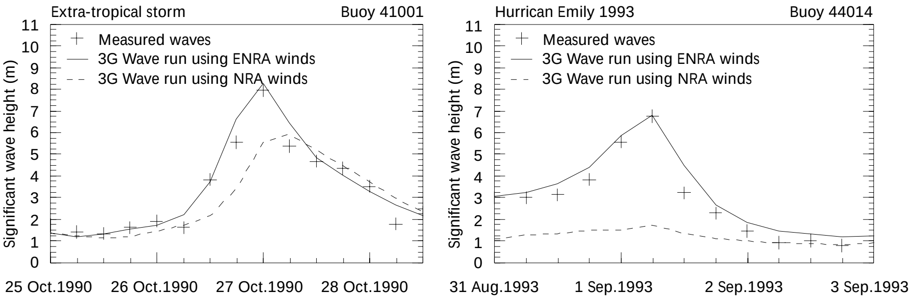


Figure 3— Effect of kinematic analysis on wave hindcast.

indicated by the buoy comparisons is indicative of skill over the whole of the model domain.

Another deficiency in the NRA reanalysis concerns the assimilation of surface marine wind data from the Comprehensive Ocean-Atmosphere Data Set (COADS). The assimilation scheme treated all observations at a 10 m reference level, whereas ship and drilling platform observations may actually range from about 15 m to more than 100 m, and buoy observations are typically taken at about 5 m. Over the 40-year duration of the NCEP reanalysis this may introduce biases similar to those found by Cardone *et al.* (1990) due to the increasing heights of shipboard anemometers and the higher fraction of wind measurements compared to wind estimates. To overcome any potential bias in this project, all surface wind data were reassimilated after first being adjusted to the 10 m reference level (Cardone *et al.*, 1990).

B. ENHANCEMENT OF NRA WINDS

While it has been shown that NRA surface wind fields produce wave hindcasts of good quality, they are evidently susceptible to further improvement to achieve skill comparable to hindcasts driven by kinematically reanalysed wind fields. Of particular concern was the finding that the hindcasts tended to systematically underestimate storm peaks.

Basically, three steps were taken to enhance the NRA winds. First, the NRA wind fields and the wind observations were processed to make them representative of the average effective neutral wind at 10 m height. This was done for the NRA surface winds by computing an equivalent neutral wind using the NRA 2 m surface temperature and sea-surface temperature fields and the algorithm described by Cardone *et al.* (1990). To remove potential biases in the data to be reassimilated into NRA, all wind observations including buoy observations, ship reports (from COADS) and C-MAN stations were also transformed to effective neutral 10 m wind speed taking into account the method of observation, anemometer height and stability. ERS 1/2 scatterometer winds were made available to the analysis only after a meteorologist had the opportunity to filter areas of suspected saturation of wind speed and incorrect wind directions due to obvious failure of the ambiguity removal algorithm.

Second, wind fields for all significant storms were kinematically reanalysed using the IOKA system with the aid of an interactive wind workstation (Cox *et al.*, 1995). The NRA surface wind fields were brought into the wind workstation every six hours in monthly segments for evaluation by a trained marine meteorologist. The interactive hindcast methodology used by the analysts follows similar previous hindcast studies (Cardone *et al.*, 1995, 1996). Particular attention was given to strong extratropical systems and the quality control of surface data. Kinematically analysed winds from previous hindcasts of severe extratropical storms in the north-west Atlantic (Swail *et al.*, 1995) were incorporated into the present analysis on the North Atlantic wave model grid.

Altimeter wave measurements were used in an inverse wave-modelling approach as follows. First of all, a global coarse wave run was made and hindcast wave heights over the North Atlantic Ocean were compared to altimeter wave measurements. The global wave fields were generated using Oceanweather's 1-G wave model (Khandekar *et al.*, 1994) adapted to a 1.25° by 2.5° latitude-longitude grid for the entire globe. NRA surface winds (adjusted to neutral stability) were

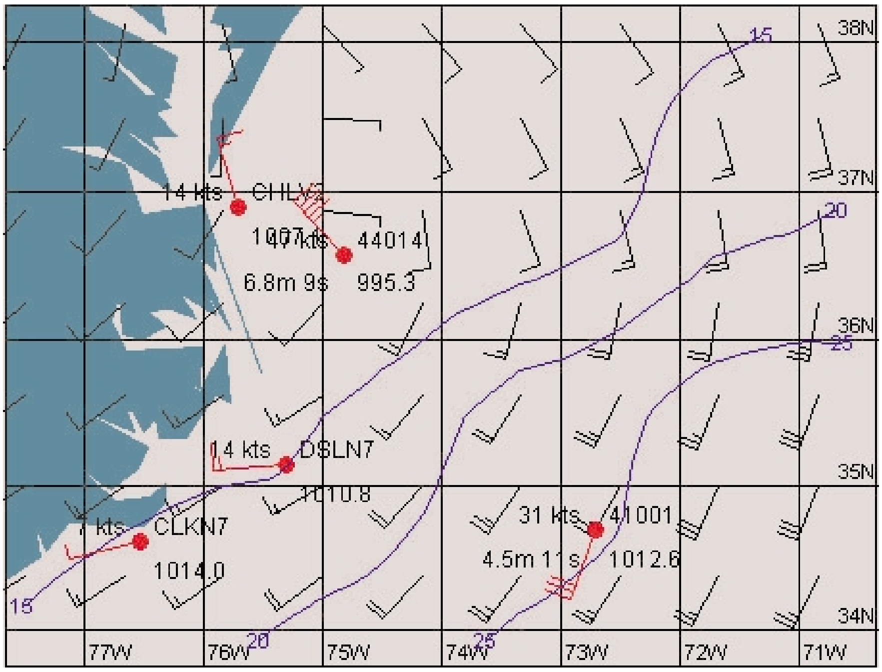


Figure 4(a)—NRA surface wind field (unmodified).

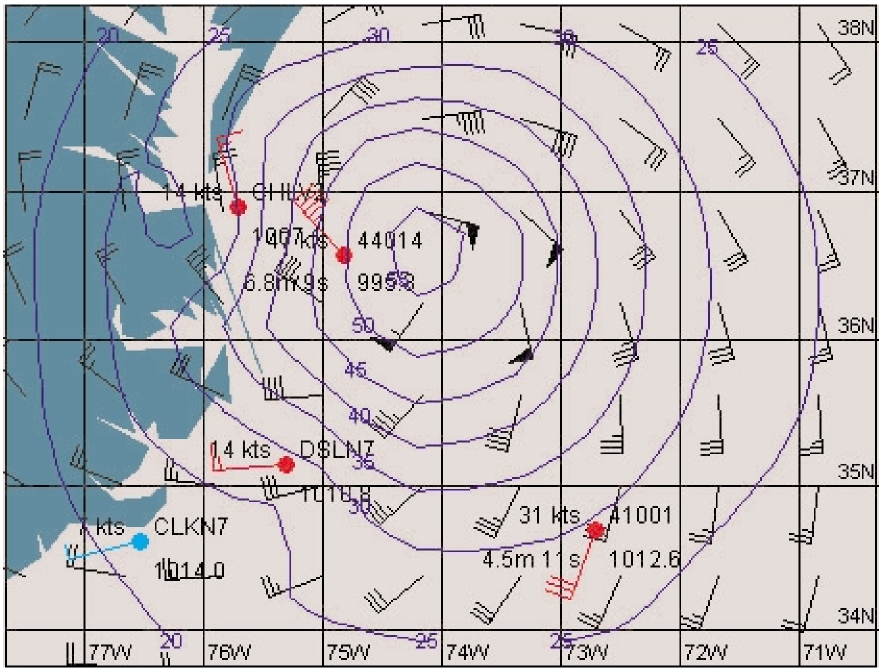


Figure 4(b)—ENRA final wind field with tropical vortex model winds incorporated.

used to drive the global wave model. Areas where the resulting wave fields were deficient, as indicated by the altimeter, were brought to the analyst's attention and the analyst subjectively altered the wind fields in the relevant space-time domains until the output from the 1G wave model agreed better with the altimeter measurements.

Third, high resolution surface wind fields for all tropical cyclones, as specified by a proven tropical cyclone boundary layer model (Cardone *et al.*, 1994; Thompson and Cardone, 1996), were assimilated into the wind fields to provide greater skill and resolution in the resulting wave hindcasts. Track and initial estimates of intensity were taken, with some modification, from the NOAA Tropical Prediction Center's (TPC) HURDAT database. The radius of maximum wind was determined using a pressure profile fit to available surface observations and aircraft reconnaissance data. Surface winds generated from the model were then evaluated against available surface data and aircraft reconnaissance wind observations adjusted to the surface as described by Powell and Black (1989). Model winds within 240 nautical miles from the centre were then exported on a 0.5° latitude-longitude grid for inclusion and blending using the wind workstation. Approximately 400 tropical cyclones were added to the NRA in this way.

C COMPARISON OF HIGH-FREQUENCY WIND AND WAVE RESULTS

Figure 3 (left-hand side) shows the hindcast made with NRA surface winds at a buoy off the US East Coast during SWADE IOP-1 and the hindcast made after the NRA winds were kinematically enhanced (hereafter ENRA). This case is typical of the improvement in skill of the hindcast overall and the reduction in the under-estimation of storm peaks when the NRA surface wind fields were reanalysed.

Figure 4 compares the NRA winds and ENRA 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 as described above. The resulting wave comparison at buoy 44014 is shown in Figure 3 (right-hand side).

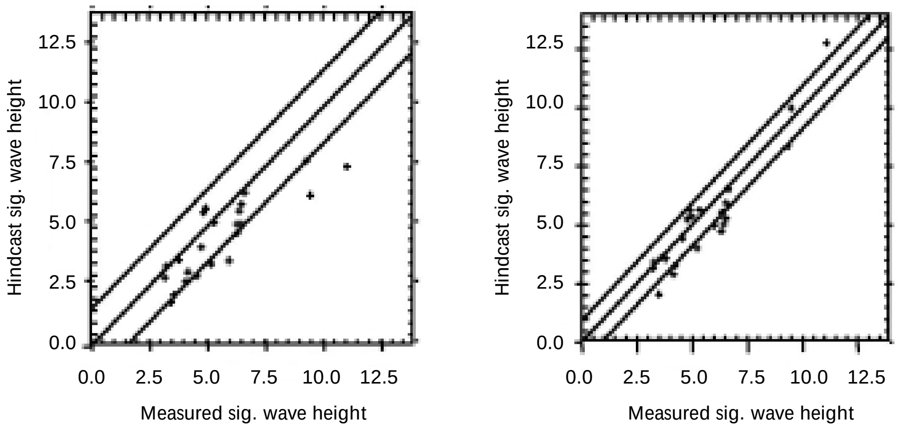
Table 4 shows the validation of the hindcasts against buoy and altimeter data for hindcasts made using the ENRA wind fields for the same four months shown in Table 3. At the buoys there is a significant reduction in the scatter index for wind speed, nearly a factor of two reduction over all buoys, which is to be expected because the buoy winds have been reassimilated at the correct height. The wave height SI is reduced as well but by only about 10 per cent overall. Altimeter wind speeds and wave heights were not assimilated so the altimeter statistics give an independent measure of skill in the hindcasts. By comparing Table 3 and Table 4 it is seen that there is no significant difference in the scatter statistics (i.e. rms and SI) between runs made with NRA and ENRA winds. This result is not surprising since the scatter statistics were dominated by lower sea states, which would not be changed substantially by the IOKA process. However, there is a reduction in the wave height bias overall from 18 to 4 cm. This reduction in bias is contributed to mainly by increased skill in specification of storm generated sea state. Figure 5 shows the comparison of storm peaks greater than 3 m (as measured by the buoy) at buoy 44138 for the four overlapping evaluation and production months. This figure shows a clear reduction in both the bias and scatter when using the ENRA wind fields.

Figure 6 shows the wave model grid-averaged altimeter wave measurements binned every 2 m compared with the matching hindcast waves (within ±3 hours), showing the mean bias for each bin over the four evaluation months. 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 even in space and time. It is encouraging, therefore, that wave hindcasts show very good agreement with the altimeter throughout the range of wave heights. The mean in bias in wave height derived from the ENRA winds over the four months is within ± 30 cm, while the NRA analysis had biases of nearly twice that value. Hindcast wave heights of less than 1.5 m show a slight systematic overestimation, which may be attributed to an inherent tendency for the gridded wind and wave fields to fail to resolve small areas of calm winds and seas.

Table 4—Validation of North Atlantic Ocean continuous hindcasts with OWI-3G driven by ENRA winds against buoy and ERS-1 altimeter wind speed and wave height measurements.

Year/	*Variable*	*All Buoys*				*ERS-1 Altimeter*			
Month		*Num*	*Bias*	*rms*	*S.I.*	*Num*	*Bias*	*rms*	*S.I.*
9110	WS (m/s)	882	0.69	2.41	0.26	16,808	0.39	2.19	0.30
	HS (m)	758	0.26	0.76	0.25	16,703	-0.06	0.64	0.25
9303	WS (m/s)	868	0.19	1.04	0.11	17,517	0.46	2.26	0.27
	HS (m)	871	0.09	0.68	0.22	16,972	0.05	0.63	0.21
9504	WS (m/s)	600	-0.05	1.85	0.09	17,693	0.38	1.94	0.27
	HS (m)	720	0.11	0.55	0.22	17,551	0.07	0.53	0.22
9509	WS (m/s)	761	0.42	1.28	0.19	18,081	0.13	2.20	0.34
	HS (m)	834	0.09	0.53	0.26	18,059	-0.23	0.60	0.24
All	WS (m/s)	3,111	0.40	1.73	0.17	70,099	0.39	2.15	0.29
Months	HS (m)	3,183	0.13	0.64	0.24	69,285	-0.04	0.60	0.23

Figure 5—Comparison of peak-to-peak wave height using NRA (left) and ENRA (right) wind fields to drive 3-G wave model for four months.



Total points:	23	Total points:	23
Mean X:	5.666	Mean X:	5.666
Mean Y:	4.569	Mean Y:	5.280
Mean diff:	-1.097	Mean diff:	-0.386
Root mean square:	1.524	Root mean square:	0.919
Standard dev.:	1.058	Standard dev.:	0.834
Scatter index:	0.187	Scatter index:	0.147
Ratio:	0.130	Ratio:	0.304
Correlation coeff:	0.852	Correlation coeff:	0.938

Given the emphasis in the ENRA on specification of storm wind fields, it is interesting to compare the production wave hindcasts with wave hindcasts made with the NRA surface winds during storm peaks. In Figure 7, TOPEX altimeter wave measurements along a swath are compared in an extratropical storm off the east coast of Canada. The improvements resulting from the ENRA winds are clearly evident along the TOPEX track; the figure shows that not only does the ENRA capture more accurately the peak of the storm but also the spatial characteristics of the wave field.

D. REPRESENTATION OF WIND AND WAVE CLIMATOLOGY

Comparisons of the ENRA wind and wave climatology at six buoys and platforms selected to give a comprehensive geographical coverage over the North Atlantic Ocean, well away from the coast, in deep water, were carried out for the period 1990–1995.

The hindcast and measured wind speed climatologies are not independent since all the wind data used contributed heavily to the data assimilation scheme in the NCEP reanalysis, and again in the kinematic reanalysis. Nevertheless, it is

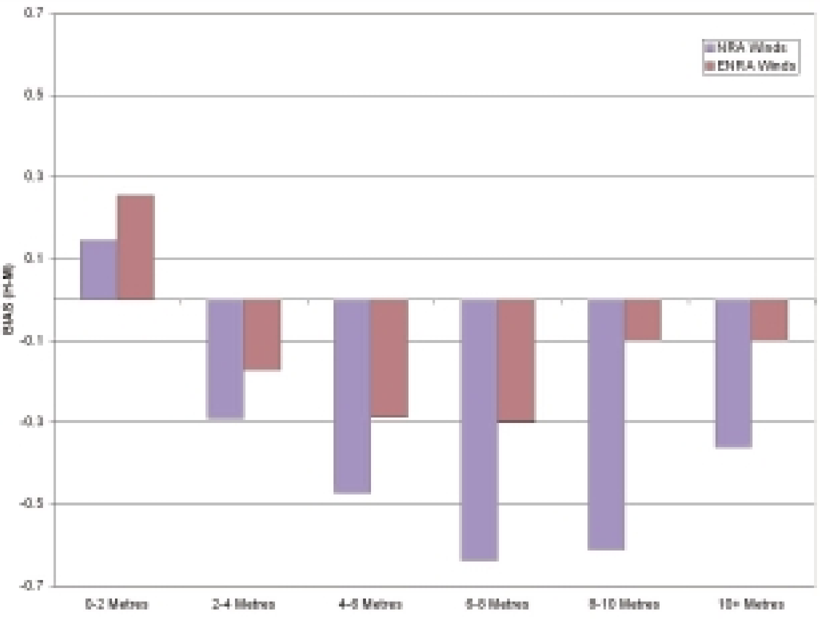


Figure 6—Comparison of bias statistics (H-M) vs. binned ERS altimeter measurements.

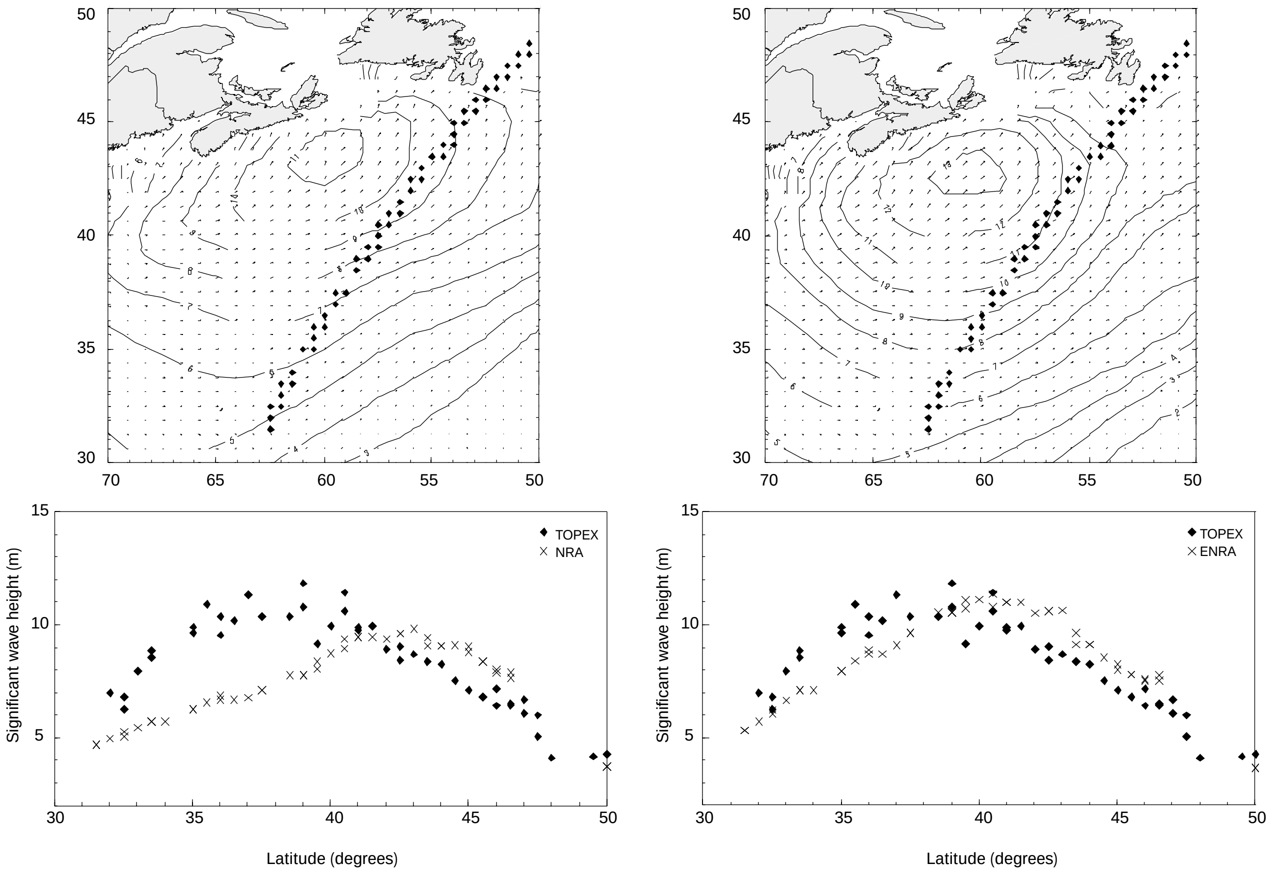


Figure 7—Hindcast and measured HS along indicated TOPEX track for NRA (lower left) and ENRA (lower right) winds. Upper panels show contours of hindcast HS (m) from NRA (left) and ENRA (right) winds.

useful to compare the two data sets to verify that the various adjustments for elevation and interpolation onto the wave model grid have not compromised the hindcast data set.

Figure 8 shows quantile-quantile (Q-Q) plots for ENRA hindcast wind speed versus measured wind speed for each of the six selected sites. Q-Q plots illustrate the comparison of the full frequency distributions, particularly in the extreme tails. These plots show very good agreement across the entire frequency distribution. There is a tendency for the ENRA winds to be slightly higher at Canadian buoys (44137), particularly for the highest wind speeds, possibly related to the vector averaging of the buoy wind samples as opposed to scalar averages elsewhere (see section 4 below). At the platform (LF3J) the model is noticeably higher than the measurements for the low end of the wind speed distribution.

Figure 9 shows Q-Q plots for model versus measured wave height for each of the six selected sites. These plots show very good agreement across the entire frequency distribution. There is a slight tendency for the model to overestimate the wave height compared to the measurements for low values of sea state. The model also is consistently higher at the platform, although the differences are negligible for the few highest observations. The effect of the Halloween storm (October 1991) is clearly seen at 44137 and 44138, where the peak measured waves clearly exceed the hindcast values. The Gullfaks platform in the North Sea (LF3J) does not strictly satisfy the conditions of deep-water open ocean; a model of much higher grid resolution would be required to properly describe the propagation of wave energy from the North Atlantic Ocean into the North Sea through the British Isles.

4.

DISCUSSION OF VARIOUS MARINE WIND DATA SOURCES

As noted in section 1, there has been a tremendous increase in the volume of instrumentally measured winds within the last two decades as acquired from moored buoys, automatic coastal weather stations, fixed platforms and satellites. The USA alone maintains over 160 instrumented sites. The Canadian Government supports more than 40 buoys. In the North Sea, Norwegian Sea and western approaches to Europe there are over 50 sites. In this section, we discuss

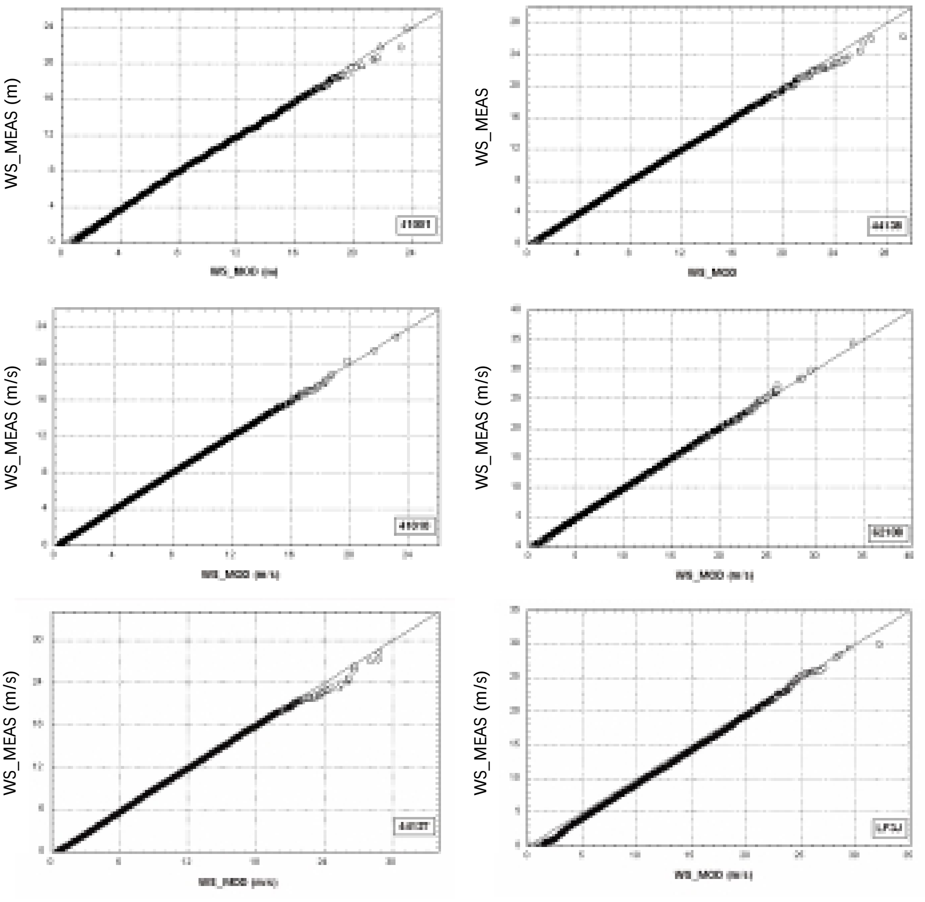


*Figure 8—Quantile-quantile plots of wind speed for selected measurement locations, based on ENRA-driven hindcasts.**

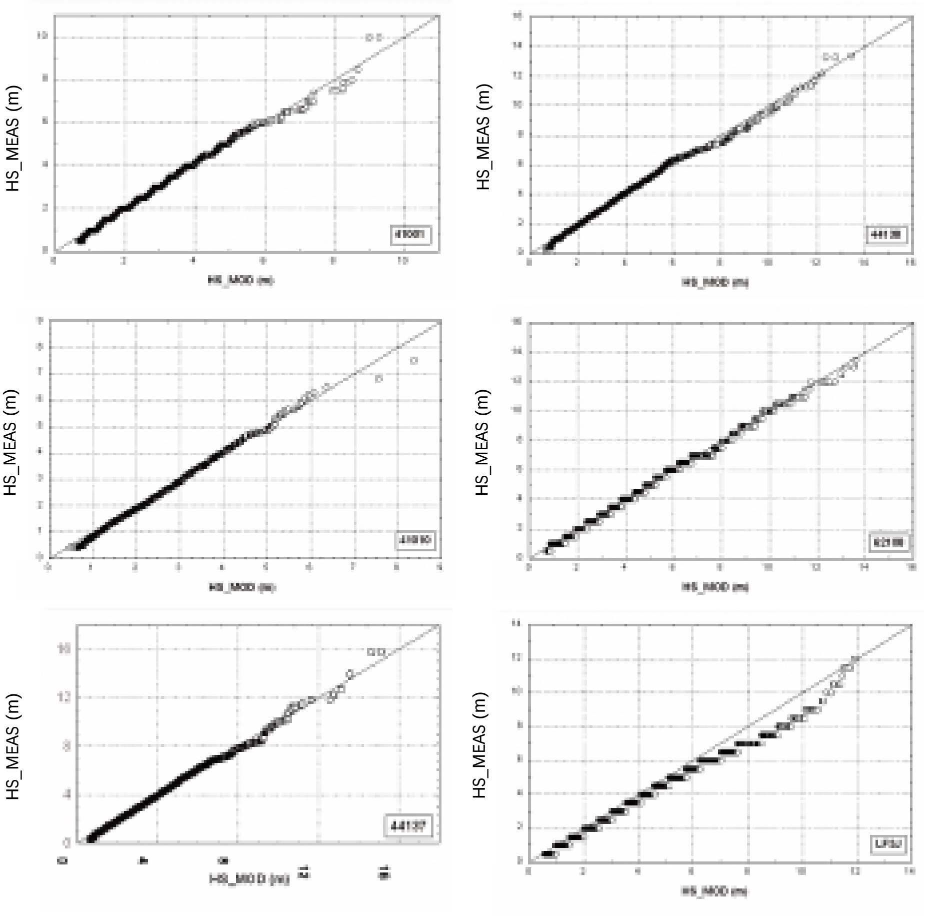


*Figure 9—Quantile-quantile plots of significant wave height for selected measurement locations, based on ENRA-driven hindcasts.**

*Buoy locations for Figures 8 and 9:

41001	34°55.5'N	72°57.1'W
41010	28°52.8'N	78°32.0'W
44137	41°11.6'N	61°07.8'W
62108	53°12.0'N	15°00.0'W
LF3J	61°12.0'N	02°18.0'E

the uncertainty in ship, buoy and satellite measurements of surface wind and sea state, emphasizing extreme conditions from the perspective of some new insights gained from recent and ongoing research programmes.

A. SHIP REPORTS

Ship reports of wind are either Beaufort estimates or anemometer measurements, and it is not always known which type a given report falls into. A great deal of new research has been reported to improve the conversion of Beaufort force or number into equivalent wind speed (e.g. Cardone *et al.*, 1990; see also Taylor *et al.*, 1995). While there are some differences between these proposed alternatives, the new scales imply that present and historical Beaufort wind speeds below about 15 m/s should be raised, and higher wind speeds lowered. Figure 10 (derived using the Cardone *et al.*, 1990 scale) shows the systematic differences between means of a population of ship wind speed reports and the 'true' mean, assuming that individual reports of Beaufort force and anemometer wind speed are themselves unbiased. The difference is a function of the proportion of anemometer measurements to Beaufort estimates and of the mean air-sea temperature difference. Until there is (if ever) a release of COADS in which ship winds have been adjusted to 10 m neutral winds in a systematic way, the adjustments must be made on a study-by-study basis.

For estimation of extremes in harsh climates, there is an additional limitation of ship reports. The upper limit of the Beaufort scale, namely Beaufort 12, is equivalent to wind speeds which vary according to which scale is adopted. This limit varies from 56 knots (29 m/s) according to the Cardone *et al.* (1990) scale to '>63 knots' (32 m/s) for the official WMO scale. Thus, even if the estimation of Beaufort force by an observer was unequivocal and the perfect equivalency scale was known, this system simply lacks adequate dynamic range to extend to wind speeds associated with the generation of extreme sea states. Even in extratropical storms, the maximum average 10 m wind speed may range up to 40 m/s.

There are numerous sources of error or uncertainty associated with wind measurement from ships, including the height of the anemometer above sea level, corrections (or lack thereof) for ship motion, averaging interval of the measurement and distortion of the true marine wind field by the superstructure of the ship itself. A detailed review of the accuracy of ship measurements is given by Taylor *et al.* (1995). The flow distortion errors are almost always non-negligible and may be the dominant factor at high wind speeds, depending on the location of the anemometer and relative direction of the wind to the ship. The errors may also be of either sign. For this reason, Dobson (1983) recommended that corrections to measured winds from ships for anemometer height not be done unless corrections were also done for flow distortion. The latter is very difficult since

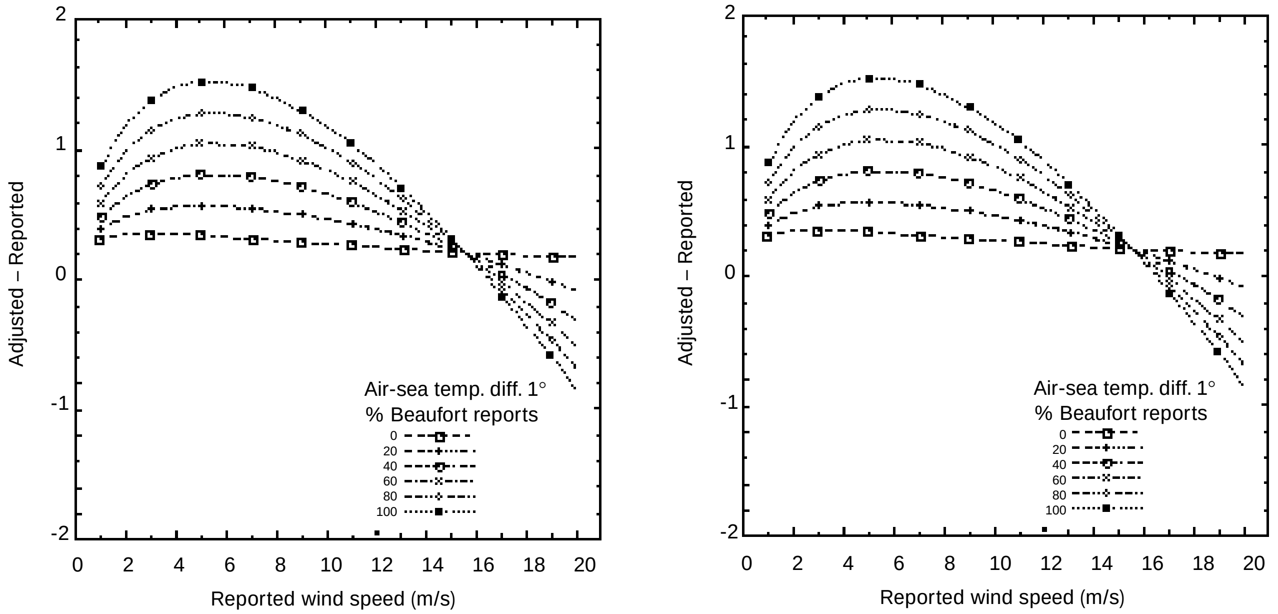


Figure 10—Difference between adjusted and reported mean wind speed for indicated percentages of estimated winds, and air minus sea virtual potential temperature (from Cardone et al., 1990).

there are many different, usually unknown, effects which contribute to the flow distortion problem. However, Cardone *et al.* (1990) and Taylor *et al.* (1995) both find improvements in overall wind estimation by adjusting for anemometer height. Recently, Kent *et al.* (1999) show that after all adjustments (except flow distortion) are made, the mean random observational error of ship reports of wind speed appears to be about 2 m/s, which is about half the value previously derived from comparisons of ship and US buoy winds (Wilkerson and Earle, 1990).

B. BUOY WINDS

Meteorological buoys are widely considered to be the best source of data for marine winds. In addition to their direct use in climate analysis, buoy winds are widely used for a number of different applications: operational NWP analysis schemes; validation of hindcast and forecast wind fields; and as 'truth' for the validation and calibration of satellite and radar remote sensing systems. Buoy winds by no means form a homogeneous data type. For example, considering only the US NOAA and Environment Canada arrays we find the following differences: (1) winds from NOAA buoys are 8.5 minute scalar average speeds and directions are unit vector averages; winds from Canadian buoys are historically 10 minute vector (now scalar) average speeds and directions; (2) winds from NOAA buoys may be at either 5, 10 or 13.8 m level; wind observations from Canadian NOMAD buoys are at 4.6 to 5.4 m; (3) NOAA buoys report the highest 5 second window average obtained in the 8.5 minute sample; Canadian buoys report the highest 8 second (now being changed to 5 second) running scalar mean peak wind speed in the 10 minute sample.

The error characteristics of winds from buoys need to be better understood over a wide range of environmental conditions. Considerable work has been devoted to the demonstration of buoy capability in low to moderate sea states (e.g. Gilhousen, 1987). However, there has been little or no investigation of buoy winds in severe conditions. It is commonly believed by operational meteorologists in Canada and the USA that the buoy average wind speeds are significantly underestimated in these conditions and that the reported gust speed is a more reasonable measure of the true sustained wind speed.

A field programme supported by Environment Canada was undertaken during the winter of 1994/95 off the west coast of Canada (SWS-1) and near the Hibernia platform in the winter of 1997/98 (SWS-2) in which measured winds and waves from a NOMAD buoy were recorded twice per second when significant wave heights exceeded 8 m. Air temperature, heave, magnetometer, buoy heading and vertical wind speed were also recorded at 2 Hz; sea surface temperature was recorded every 10 minutes. Preliminary results (Skey *et al.*, 1998) show that wind speeds vary considerably over a very short time frame, e.g. a factor of 2 over less than 10 seconds even at moderate wind speeds. The wind direction may vary by more than 100 degrees over 10 minutes, with a standard deviation of 16 degrees. This variability will have a significant impact on the vector mean wind speed computed for the hourly wind report. Detailed analysis is presently being carried out to assess the magnitude of errors introduced by this vector averaging, as well as potential effects due to sheltering of the anemometers by the high waves and errors due to buoy motions. Preliminary estimates indicate that buoy average winds may be biased low by 20 per cent or more in extreme sea states (say HS > 10 m).

C. PLATFORM WINDS

Winds measured from offshore platforms are potentially the most accurate source of marine winds in extreme storms. Instrument error can be very low provided that the sensor is calibrated and checked periodically, that there is no appreciable sensor motion and that flow distortion is minimal for sensors mounted well above the platform superstructure. These conditions are increasingly being satisfied for the newer platforms in the Gulf of Mexico, North Sea, Norwegian Sea and in other frontier areas of offshore exploration and production. Typically, the anemometer is of a modern design, calibrated, and mounted at the top of the drilling derrick at heights of 40 m to as much as 140 m above the sea surface and electronically records average wind speed and direction. The only adjustments normally needed for such measurements are for sensor height and adjustment to neutral stratification. Interesting data sets have been acquired in recent North Sea extreme storms which indicate that sustained winds, defined as maximum one-minute scalar averaged wind speeds, in the marine boundary layer reduced to equivalent 10 m neutral stratification, can range as high as 50 m/s with gusts to as high as 60 m/s. Curiously, even in the recent storms in which buoys moored in the western North Atlantic have measured HS greater than 17 m, recorded maximum sustained wind speeds from buoys have not exceeded about 30 m/s. A remaining issue of concern, however, for the higher platform-mounted anemometers (above say 50 m) is that the sensor may be above the constant stress or surface boundary layer. It may be in the part of the boundary layer where more complex wind profiles (than simple power law or logarithmic) are needed to derive the 10 m neutral wind.

D. SATELLITE WINDS

Remote sensing of the ocean is clearly an essential component of the future global observing system, due to the immense area to be covered and the difficulties and expense of using conventional in situ systems. Several types of satellite sensors capable of producing information on ocean waves and marine winds have been developed in recent years, including scatterometers, passive microwave radiometers, altimeters and synthetic aperture radars (SAR). However, these remote systems do not measure the desired geophysical parameters directly, but instead measure other parameters such as radar backscatter. Algorithms which convert radar backscatter to surface wind are developed and tuned using high-quality in situ measurements from ships and buoys - this reinforces the importance of understanding the characteristics of the in situ measurements.

The scatterometer produces estimates of both wind speed and direction from the measured radar backscatter from the ocean surface. Wind speed accuracy may reach ± 1.5 m/s in low to moderate wind speed conditions and the uncertainty in wind direction is at least ± 10° after a directional ambiguity is removed by using neighbouring data or a good first guess field. Spatial sampling is of the order of about 25-50 km. Systematic errors derive from uncertainty in the backscatter-vector wind model function and in the optimum reference level for backscatter-derived winds. There is even some evidence that the uncertainty in optimum reference level is dynamic and a function of wave height. Further algorithm development in conjunction with reliable ground truth is needed to improve accuracy.

The altimeter and microwave radiometers do not provide information on wind direction. The radiometer provides wind speed data over a wide swath; the altimeter provides an averaged wind speed within its 5-10 km wide footprint directly underneath the satellite path. Accuracy is about ± 1-2 m/s for the altimeter, and about ± 2 m/s for the radiometer for most cases. Little or no calibration has been done for high wind speed cases.

The SAR provides detailed information over a wide swath with errors in wind speed of about ± 1 m/s for low to moderate wind speeds in comparison with accurate in situ measurements (Vachon and Dobson, 1995). The wind direction may be deduced from SAR imagery under some circumstances or may be taken from a wind analysis chart. The SAR data may be used to study kilometre-scale wind speed variations and is therefore useful in conjunction with mesoscale wind models.

With regard to extreme storm conditions, one key question, which remains unanswered, is the upper limit of sensitivity to wind speed for all remote sensors. Empirical evidence to date does not support sensitivity above equivalent 10 m wind speeds of about 20 m/s which, if also true for newer systems (e.g. QUIKSCAT), would seriously limit the usefulness of satellite winds to specification of storm wind fields and extreme wind statistics. However, a recent study of NSCAT winds in a typhoon (Jones *et al.*, 1999) suggests that sensitivity ultimately may be extended beyond 30 m/s with improved scatterometer geophysical model functions and data processing.

Another limitation of remote sensing systems which needs to be considered is temporal resolution. As noted previously, several recent hindcast studies suggest that the wind field features responsible for the generation of very extreme sea states (say HS > 12 m) are relatively small scale and evolve and propagate rapidly (Cardone *et al.*, 1996). Ideally, three-hourly sampling is needed to resolve such features. For even a wide-swath remote sensor to satisfy this requirement, it must be mounted on at least three operational polar orbiting satellites. It is doubtful that resources will be made available to support such an operational system in the foreseeable future, though the overlap of limited duration missions such as QUIKSCAT, ADEOS-2 and ERS-2 constitute in effect a useful, if sub-optimal, operational capability. Despite the limitations of dynamic range, the NSCAT experiment showed that significant improvements in NWP model forecasts may be realized (Atlas *et al.*, 1999) from an operational satellite remote wind vector sensing capability, whether achieved from active or passive systems.

Finally, we should note a new type of 'remote sensor' deployed from an aircraft - the Global Positioning System (GPS) dropwindsonde (Hock and Franklin, 1999). This device can measure the vertical wind profile below the aircraft, including the measurement of the 10 m wind speed, with an accuracy of 0.5 m/s to 1.5 m/s. The averaging interval of the measurement is only a few seconds so several successive drops are needed to produce an average wind profile. This instrument, which is already widely used operationally in North Atlantic tropical cyclones, promises to provide a powerful new tool to evaluate buoy, platform and satellite winds by virtue of its ability to provide truly unbiased estimates of the marine surface wind at wind speeds above 20 m/s.

5. CONCLUSIONS

While NRA wind fields appear to be a significant improvement over operational wind fields, if for no other reason than they are more homogeneous over time than real time products, they still suffer from poor resolution of areas of high winds in extratropical storms and from a lack of resolution of most tropical systems.

NRA wind fields may be improved by re-assimilation of measured data through an interactive, analyst-driven, kinematic approach. However, the limitations of each data source should first be considered to ensure that any biases associated with variable measurement heights, or different averaging intervals, are minimized. Similarly, the assimilation of any satellite measurements of high wind speeds, which are thought to be biased low through saturation, should be avoided.

Research programmes are under way to gain improved estimates of biases and random errors of various types of measurements.

QUIKSCAT and other advanced scatterometers may lead to a significant improvement in real-time wind field analyses and forecasts, but their value in storm conditions may continue to be limited by saturation at higher wind speeds above 20 m/s. Supplemental use of MPBL winds derived from pressure fields and inverse modelling using satellite wave measurements may remain useful tools in such regimes until in situ or remote sensors with greater proven dynamic range are developed and implemented.

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