# SPECIFICATION OF GLOBAL WAVE CLIMATE: IS THIS THE FINAL ANSWER?

**V. J. Cardone[1], A.T. Cox[1] and V.R. Swail[2]**

[1]Oceanweather Inc.
Cos Cob, CT

[2]Environment Canada
Downsview, Ontario

## 1. INTRODUCTION

By the beginning of the decade of the 1980s, the so-called hindcast approach for specification of environmental data for the design of offshore structures was well established. For example, a U.S. National Research Council Marine Board review (National Academy of Sciences, 1980) concluded that: "Hindcasting techniques using verified environmental models coupled with statistical treatment of occurrences of natural events gives an appropriate and adequate technical basis for determining environmental exposure". This 6th in a series of international workshops since 1986 on the subject of wave hindcasting further attests to the acceptance of this approach. This paper reviews briefly the development of wave hindcasting and explores whether it is capable of and ready to provide a complete and accurate description of the global wave climate for all practical engineering and scientific purposes.

The hindcast approach was first applied in the decades of the 70s and 80s to develop sea state extremes for engineering design in specific areas of offshore development such as, for example, the US Gulf of Mexico as part of the ODGP program (Cardone *et al.*, 1976, Ward *et al.*, 1979) and to the Hibernia, Grand Banks design (Cardone *et al.*, 1989). These early programs almost always included a dedicated measurement program and hindcast model calibration and validation activities. Over the next decade (i.e. 1990s) the approach was applied to develop definitive wind and wave criteria for entire basins of mature or planned offshore development, usually within Joint Industry Projects (JIP) supported by consortia of oil companies. Major JIPs (acronyms noted) have addressed the Gulf of Mexico (GUMSHOE and WINX), the Bering and Chukchi Seas (BSCOMP, CSCOMP), Russian Arctic Seas (RASMOS), Sakhalin Island (SIMOS), the South China Sea (SEAMOS, Cardone and Grant, 1994), the west coast of Africa (WAX, Cardone *et al.*, 1995), the North Sea (NESS; Peters *et al.*, 1993), the east Coast of Canada (CCC-91; Swail *et al.*, 1995), Brazil (Cardone and Lima, 2000). JIPs are currently underway for the Mediterranean Sea Nile Delta and the Caspian Sea. Many of these JIPs have undergone recent updates as the passage of time has allowed the simulation of an additional decade or so of history and use of newer 3G wave models. For example, CCC-91 was updated to include the many severe storms observed through 1995, with all previous and new storms (a total of 82 events between 1957-1995) rehindcast with Oceanweather's third generation model (OWI3G) model (Swail *et al.*, 1995). The updates to the NESS, CCC-91, SEAMOS and the more recent JIPs (all carried out by OWI) have utilized a new interactive PC-based wind workstation (WWS) to hindcast the surface winds fields following an Interactive Objective Kinematic Analysis (IOKA) (Cox *et al.*, 1995). WWS greatly reduces the degree of manual labor over classical kinematic analysis required to develop the most accurate wind fields possible for a given historical meteorological data set.

The JIPs noted above have typically included the application of the hindcast method to simulate several continuous years in addition to the core study hindcast of many (20-100) individual high-ranked historical storms. The continuous hindcasts provided time series and statistical summaries useful for the development of wind and wave normals for use in fatigue analysis and planning of routine operations in areas where a sufficiently long-term measured database does not exist. Recently, we have explored the convergence of the storm and continuous hindcast approaches through simulation of multi-decade continuous periods on an oceanic or global scale using high–resolution wave models and reanalyzed wind fields. This approach has been stimulated in part by a 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; Wang and Swail (2000)). A sufficiently accurate global 40-50 year hindcast has the potential to describe the global deep water wave climate and its trend and variability and to provide extremal and operational wave deep water wave statistics at a considerable saving compared to the cost of many separate site-specific or basin studies.

In Section 2, we review several recently completed continuous hindcasts, including the new 40-year AES40 and GROW and 20-year GROW2000 simulations. The skill thresholds which must be attained before any simulation may be dubbed the “final answer”, are discussed in Section 3. Section 4 gives a critical assessment of these new continuous hindcasts and Section 5 gives our conclusions and outlook.

## 2. CONTINUOUS HINDCAST PROJECTS

The first attempts to develop long-term wave climatologies from continuous integrations of spectral ocean wave models applied to Northern Hemisphere basins only. These include the U.S. Navy 20-year (1956-1975) Northern Hemisphere project using the SOWM model (Naval Oceanography Command, 1983), the U.S. Army 20-year (1956-1975) North Atlantic and North Pacific Wave Information Study (WIS) project using the WIS wave model (Corson *et al.*, 1981), a 35-year simulation of the North Atlantic Ocean carried out by the Norwegian Meteorological Institute using the WINCH model (Eide *et al.*, 1985) and a 40-year hindcast of the northeast North Atlantic Ocean using the WAM model (Gunther *et al.*, 1998). Since the mid-1980’s several major NWP centers (U.S. Navy FNMOC, ECMWF, U.S. NCEP) have operated global spectral ocean wave models in real time and have accumulated the analysis products to form preliminary estimates of the global wave climate. Recently the ECMWF global wave model was applied to hindcast a 15-year period 1979-1983 (Sterl *et al.*, 1998).

An unfortunate property of the earlier hindcast studies and of real time NWP operations is that changes over time in data sources, improvements in data analysis techniques and evolution and upgrades in numerical models have tended to impart a temporal or “creeping” inhomogeneity into the real time products of such centers which naturally feed into the wave simulations. Therefore, output data not only vary in quality but also vary over time and subtle changes in climate may be masked.

Known deficiencies in archived real time atmospheric analyses have led to several major attempts to produce a consistent analysis of the atmosphere spanning a 40-year period. The first of these projects to be completed is the NOAA/NCEP/NCAR Reanalysis project (henceforth NRA, Kalnay *et al.*, 1996). The NRA products to date have been used to drive three continuous wave hindcasts: AES40, GROW, GROW2000.

**AES40**. The OWI3G spectral wave model was used for this hindcast with the spectrum resolved at each grid point in 24 directional bins and 23 frequency bins covering the range .039 Hz to .32 Hz. Deep-water physics is assumed in both the propagation algorithm and the source terms. OWI3G is adapted on a latitude-longitude grid consisting of a 122 (in latitude) by 126 (in longitude) array of points with grid spacing of 0.625° in latitude by 0.833° in longitude. The eastern boundary is at 20° E longitude and the northern boundary is at 75.625° N latitude. After deductions for land there are 9023 grid points. The south edge of the grid is at the equator. This boundary was treated as open; wave spectra were interpolated from the output of a lower resolution (2.5 degrees at a 3-hour time step) global model (GROW, see below). The hindcast was carried out in monthly segments. Ice cover was specified for each month from mid-monthly ice tables specified on the wave grid from the best available historical ice data. The output of the model consists of 17 'fields' quantities (e.g. significant wave height, peak period, vector mean direction, partitioned fields, directional and angular spreading) at all grid points and the full two-dimensional spectrum at 233 grid points. The spectral save points were selected to allow even coverage of the basin (every 5° of latitude and longitude), as well as to allow the possibility to drive finer mesh models for the US East Coast, the Scotian Shelf and Grand Banks of Newfoundland and the European West Coast. Spectra were also saved at the locations of selected moored buoys and offshore platforms.

The most important, and unique, element of the AES40 hindcast was the enormous effort devoted to producing the wind fields for the wave model; this effort accounted for more than 10,000 meteorologist-hours of effort spent in manual and interactive kinematic analysis. Details of the wind field generation are given in Swail and Cox (2000). Briefly, the process included the transformation of the NRA Surface (10m) winds to effective neutral stability, the re-assimilation at proper equivalent 10 m height of high quality wind observations from buoys, ships, coastal stations and ERS1/2 scatterometers and the assimilation of winds in tropical cyclones generated in a separate mesoscale model simulation of each such cyclone within the 40 years modeled. The very labor intensive detailed kinematic analysis effort noted above was devoted to incorporation of all the wind information noted above into the final analysis with particular attention spent on strong extra-tropical systems, blending tropical model winds into the NCEP surface wind field, and in the quality control of surface data. As part of this process, kinematically analyzed winds from previous storm hindcasts of severe extratropical storms in the northwest Atlantic (Swail *et al.*, 1995) were incorporated into AES40 wind fields. Final wind fields for each month were interpolated onto the 0.625° by 0.833° latitude-longitude wave model grid using the IOKA (Interactive Objective Kinematic Analysis) algorithm (Cox *et al.*, 1995) and then time interpolated from the 6-hourly analysis interval to a one-hour time step. The validation of this database is described at this workshop by Swail *et al.*, (2000).

**GROW (Global Reanalysis of Ocean Waves).** This database was generated in 1998 by OWI on a global grid using its ODGP2 deep-water wave model with spectral resolution as noted above for AES40. GROW is the first global 40-year hindcast based upon NRA products. The grid spacing is 1.25 degrees latitude by 2.5 degrees longitude. Winds were specified on the wave model grid directly from the 40-year (1958-1997) NRA surface 10-m 6-hourly wind file, except for transformation of wind speeds to effective neutral stratification using NRA 2-meter air temperature and sea surface temperature fields. That is, no attempt was made to re-assimilate wind observations or to modify wind fields kinematically in tropical or extratropical storms. The ice edge was specified on a monthly basis using a long-term monthly mean ice climatology. Winds were input at 6-hourly intervals for use with the model time step of 3 hours. Output wind and wave fields (again 17 "fields" variables) are archived at 6-hourly intervals at all model grid points, while spectra are archived at 6-hourly intervals only at 10 degree latitude-longitude intervals. GROW

SWH specifications were validated on a global basis against all available buoy, platform, ship and satellite altimeter (Cox and Swail, 2000). That validation showed that GROW provides reasonably accurate global (SWH) statistics and estimates of recent trends in global wave climate.

**GROW2000.** The experience of AES40 and GROW has been applied to an update of GROW called GROW2000. GROW2000 attempts to correct the main deficiencies of GROW but stops short of the enormous expenditure of labor which would be required to extend the AES40 wind hindcast methodology to the globe. To date GROW2000 has simulated the continuous 20-year period 1979-1998. First, the grid resolution was substantially increased by decreasing the grid spacing to 0.625 degrees latitude by 1.25 degrees longitude, yielding a global grid of 46,529 points. The higher resolution was needed to decrease obvious GROW model biases in SWH in the vicinity of major island groups and chains. Next, the systematic errors observed in NRA winds in GROW were addressed by applying to NRA wind speeds spatially varying regressions developed from global evaluation of NRA wind against adjusted in-situ data and corrected satellite scatterometer winds. Separate wind adjustment algorithms have been developed for three regions: Northern Hemisphere (NH) Extratropical, Southern Hemisphere (SH) Extratropical and Tropical Belt. In addition to the correction of the NRA winds, the time and space evolution of the wind field about each tropical cyclone was specified using OWI's mesoscale vortex model. For each cyclone, the parameters for the tropical cyclones (that is the inputs to the mesoscale model) were taken from the best source available. Therefore, for virtually all storms in the greater North Atlantic basin, the inputs are developed (as in AES40) by analysis of raw source data as analyzed by OWI analysts. The same is true for several hundred Western North Pacific tropical cyclones. In other areas (e.g Indian Ocean, Australia etc.) OWI used mainly its newly developed algorithm (Cox and Cardone, 2000) to extract the OWI model parameters from standard historical sources (Global Tropical and Extratropical Cyclone CD-ROM) and products of major warning centers (e.g. Navy's Joint Typhoon Warning Center, NOAA National Hurricane Center, Australian Bureau of Meteorology, Royal Observatory Hong Kong). However, no manual intervention was applied to blend cyclone winds into the adjusted NRA background or to modify winds in intense extratropical cyclones. Finally, the latest available historical ice data from the National Ice Center were manipulated to provide boundaries of monthly 50% ice cover grids for each individual month over the 20-year period simulated. A variant of OWI's ODGP wave model was used for the hindcast with the same spectral resolution as adopted for AES40 and GROW. This variant incorporates a new formulation of the Pierson-Moskowitz fully developed sea theory (Resio *et al.*, 1999). The new wind scaling used therein operates within a 1G or 2G model to correct the tendency of all previous wave models, including 3G models, to under specify very extreme sea states in a special class of storms characterized by resonant dynamic fetches or very long physical fetches and durations. The archive of GROW2000 consists of time sorted "fields" of 17 wind and wave variables at 3-hourly intervals at all grid points and time histories of full 2-D spectra at grid points at 5 degree latitude-longitude intersections.

## 3. HINDCAST SKILL THRESHOLDS

**Storm Peak Skill**. The skill of storm hindcasts that is necessary in order for a hindcast database to provide extrapolation of reliable sea state extremes for design has been demonstrated and achieved in hindcast model validation studies. For example, validation of the ODGP hindcast model against high quality wave measurements acquired in tropical cyclones and severe extratropical cyclones (Reece and Cardone, 1982) demonstrated that ODGP when driven by high-quality winds typically specifies peak significant wave height (SWH) at an arbitrary site in a storm with bias of less than 0.5 m, mean absolute error of less than 1.0 m and scatter index (SI) of 10-15% (SI= 100 x sd/avg where sd is the standard deviation of differences between hindcast and measured peak wave heights and avg is the average of measured heights in the validation population of heights; SI is also often expressed fractionally as sd/avg). The peak spectral period (TP) appeared to be specified with comparably small bias but with greater scatter. Since ODGP, the same hindcast methodology has been validated in a wide range of wave regimes including arctic and sub-arctic basins, mid-latitude NH and SH regimes, tropical cyclone regimes and subtropical regimes such as the Gulf of Mexico, South China Sea and Arabian Gulf (e.g. Cardone *et al.*, 1989; Swail *et al.*, 1992; Cardone and Ewans, 1992; Eid *et al.*, 1992). Oceanweather's 3G model (the alternative wave model physics of OWI3G is described by Khandekar *et al.* (1994) and Forristall and Greenwood (1998)) has also demonstrated excellent skill in both tropical and extratropical settings. Where OWI3G was used to validate hindcasts against many of the same storms used to validate ODGP as well as more recent storms measured by US and Canadian buoys the mean error in SWH and (TP) was found to be -.13 m (-.27 sec), the rms error .98 m (1.64 sec) and the scatter index 14% (15%). The skill seems to be invariant with wave height at least up to SWH of about 12 m, with a tendency to underestimate peak sea states in the most extreme storms in which SWH exceeds about 12 m. This under-specification in peak states was also observed with other wave models (Cardone *et al.*, 1996) and may be associated with one or more of the following possibilities: (1) wind speeds measured from buoys in high seas states, which feed into operational as well as kinematically reanalyzed wind fields may be biased low; (2) wave model growth reaches saturation prematurely (3) the source terms in wave models used for atmospheric input and wave dissipation, which are tuned even in 3G models, are being extrapolated beyond their applicable range; (4) spatially coherent small scale wind field features, such as rapidly propagating surface wind "jet streaks", which seem to be associated with several known occurrences of extreme storm sea states (Cardone *et al.,* 1996) are not resolved accurately in even the best wind fields. The concept of a fully developed sea continues to play a large role in wave models. In 1G and 2G models this limit to growth is usually explicitly invoked. In most 3G models, the dissipation source term is tuned such that when the model is driven by constant winds the detailed balance leads to an equilibrium or very slowly evolving spectrum at large fetch or duration. Resio *et al.* (1999) have shown that a rescaling of the reference wind speed in a fully developed spectrum formulation in terms of a dynamic reference height which increases with increasing wave height may explain the tendency of all models to underestimate extreme sea states. As noted above this revised scaling has been incorporated into ODGP2 for GROW2000.

Relatively few studies have been reported which compare model and measured directional spectra. For example, Jensen *et al.* (1995) compared WAM-4 hindcast and measured 2-D spectra at several data buoys off the US East Coast in two storm events (one tropical, one extratropical) in terms of mean wave direction and rms spreading. While generally good agreement was found for mean wave direction, systematic differences were often found for spreading. Forristall and Greenwood (1998) investigated the directional spread of various models as compared to measurements in both simple fetch and duration wave generation regimes and in tropical and extratropical storm hindcasts. To represent spreading, they adopted a measure based on second trigonometric moments of the wave spectrum which is equivalent to the square root of the "in-line variance ratio" defined by Haring and Heideman (1978). This ratio is an important measure of the wave load on an offshore structure. In comparisons of 2-D spectra from simulations of simple duration growth for a 20 m/s wind speed with various models and indications from measured data, Forristall and Greenwood show that the model spreading factors near the peak frequency of the model spectra differed little from each other but all models yield spreading factors less than (therefore too broadly spread) the measured spreading. In the tail of the spectrum, the WAM model has a lower spreading factor than the measurements, while the OWI3G agrees more closely with the data. The spreading exhibited by ODGP2 actually agreed best with the measured data, but this is not surprising because in that model the spreading is constrained to follow a prescribed empirical form. Forristall and Greenwood (1998) also found good agreement between modeled and measured spreading factors at two sites in the northern North Sea in a 5-year continuous hindcast made with OWI3G, but not so good agreement between hindcasts and measurements at a site in the northern Gulf of Mexico on the left side of the track of severe hurricane Opal (1995). Lower skill has also been seen in OWI3G and WAM hindcasts than of ODGP2 of the details of the 2-D spectra on the left side of tracks of tropical cyclones Frederic (1979) and Luis (1995).

**Skill in Continuous Hindcasts**. The recent SWADE hindcast study carried out using data acquired off the US East Coast (Cardone *et al.*, 1995b) demonstrated that where surface wind fields are specified using kinematic reanalysis techniques which take advantage of the enhanced data coverage in areas of dense buoy and/or offshore platform measurement arrays (e.g. off the east and west coasts of North America and in and around the North Sea), well calibrated wave models may specify the evolution of SWH with negligible bias and scatter near the lower limit set by accuracy and sampling variability in the wave measurements. It is not yet as clear that the details of the 2-D spectrum and hence mean or peak spectral wave period or wave direction and angular spreading of waves are as well simulated. Within the core of the dense SWADE buoy array, the SWH scatter index (SI) found of 14% is unprecedented for continuous hindcasts. However, the mean negative error of about 0.4 seconds in peak period is apparently a real characteristic of this hindcast and may be caused by use of 3G wave model physics. Errors in hindcasts validated against wave measurements over the larger area comprising the SWADE and NOAA buoy arrays increased to levels (SWH SI of 18%-25%) probably more typical of continuous hindcasts of mid-latitude extratropical weather regimes in the open ocean with kinematically reanalyzed winds. Errors were generally larger (SWH SI 26%-40%) when the same hindcast was repeated with wind fields produced operationally at major analysis centers at the time (October, 1990). This study suggests that an acceptable skill level for continuous hindcasts is represented by SWH SI in the range of 18-25% and bias of less than 0.5 m. More recent validation studies have added hindcast-measured parameter distributional comparisons as a skill measure, usually in terms of SWH quantile-quantile scatter plots (Cox *et al.*, 1999).

## 4. CRITICAL EVALUATION OF NRA BASED HINDCASTS

A comprehensive validation of the AES40 hindcast against in-situ wind and wave measurements at data buoys and against wind speed and SWH measurements from ERS1/2 and TOPEX satellite altimeters is reported at this workshop by Swail *et al.* (2000). Basin-wide 100-year extremes of wind speed, SWH, associated TP and maximum wave height were also reported. Against the best science quality measurements, namely 213,724 comparisons at US and Canadian buoys, the mean difference (bias), SI and correlation coefficient (CC) between AES40 and buoy SWH were found to be .10 m, 23% and .93 respectively. For the same comparison data base, a quantile-quantile scatter plot comparison of SWH height over the range of cumulative non-exceedance probability of 1% to 99% showed a near linear match and average difference of only 0.10 m at all sites. The satellite comparisons (over 3 million data pairs were used over the whole basin) were found to be quite consistent with the in-situ comparisons with bias, SI and CC of -.01m, 22% and .93 respectively. Spatial maps of these difference measures derived from the satellite comparisons exhibit very good consistency in skill at these levels over virtually all parts of the AES40 hindcast domain. Storm peaks are also well specified as reflected in the close match between 100-year extremes derived from the top-40 peaks of the AES40 hindcast and extremes developed from previous detailed storm hindcast studies. Table 1 compares 100-year SWH at several such locations, including a location (West of Shetlands) in the most severe part of the North Atlantic and several sites off the East Coast of North America. Extremes in all of these areas are dominated by extratropical cyclones. The extremes match closely in all areas with differences within the expected sensitivity of the extrapolation process to details such as peak threshold and fit uncertainty (the AES40 extremes are based upon the GUMBEL distribution fitted with the method of moments; see Swail *et al.*, 2000).

Table 1. Comparison of 100-Year Significant Wave Height (m) from AES40 Hindcast and Dedicated Site-Specific Studies.

| **Area** | **Study** | **AES40** |
|---|---|---|
| West of Shetlands | 18 | 17 |
| Hibernia, Grand Banks | 15 | 15 |
| Scotian Shelf Deep | 13 | 14 |
| Georges Bank Deep | 13 | 14 |

Thus we may conclude that AES40 provides a data base for the specification of SWH normals and extremes in all regions of the North Atlantic dominated by extratropical weather to a level of accuracy comparable to that provided by dedicated site-specific hindcast studies. AES40 also provides reasonable estimates of extremes in regions dominated by tropical cyclones, though no public domain estimates from detailed hindcast studies were available for comparisons with the AES40 extremes here. However, we may legitimately ask: is the AES40 SWH wave climate specified with the minimum uncertainty possible especially in areas subject to “extreme storm seas” (SWH > 12 m) and are the other integrated properties of the spectrum important for engineering applications such as TP, directional spreading and ‘swell’ content specified with comparable accuracy? Until this question is answered in the affirmative, and it cannot at this time, AES40 may be considered to be a state-of-the-art hindcast but perhaps not quite yet the “final answer” for the North Atlantic.

Next, we explore how closely GROW and its refinement GROW2000 approach, on a global basis, the skill of AES40 at least with regard to SWH. Cox and Swail (2000) include a comprehensive validation of the GROW hindcast against in-situ wind and wave measurements at data buoys and against wind speed and SWH measurements from ERS1/2 and TOPEX satellite altimeters. The evaluation of GROW2000 is underway and only preliminary results are given here with more complete results to be presented at the workshop itself. For the highest quality measured data, namely 453,750 comparisons over all US and Canadian buoys, the SWH bias, SI and CC were found to be .10 m, 27% and .90 respectively. These statistics (and similar statistics for smaller buoy groupings) indicate only a relatively small deterioration of these skill measures in GROW in the deep water areas off the east and west coasts of North America, in the central Bering Sea and Gulf of Mexico, relative to that achieved off the east coast by AES40. However, the regional SWH distributional comparisons for GROW showed less linearity than the AES40, suggesting biases which vary systematically from region to region in certain SWH ranges. For example, near Hawaii and west of Chile, GROW SWH is biased low in the 10%-99% (percentiles) by up to 1 m, while in the Gulf of Mexico and western Caribbean GROW SWH is biased high by up to 1 m in the same probability range. In NH mid-latitudes, GROW appears biased high by up to 0.5 m in the 25 – 75% range.

Cox and Swail (2000) include altimeter comparisons stratified over broad regions (NH extratropics, SH extratropics and tropical belt (20N-20S)). These difference statistics showed little variation when averaged over broad regions. For all regions combined (8,662,504 comparisons), the bias, SI and CC were -.04 m, 24% and .89, which are again only slightly less skillful than AES40. The altimeter comparison database allows resolution of the skill measures spatially over regions as small as one grid point box. Figure 1 shows the SWH bias (hindcast – altimeter) so computed as contoured in 0.25 m intervals (dashed lines negative, solid lines positive). The bias is less than 0.25 m over virtually the entire North Atlantic and North Pacific and generally varies between +0.50 m and - 0.50 m in the SH. The narrow belt of -0.25 m to -0.50 m bias along the northern border of the Southern Oceans which extends around the globe near 30 S is confirmed in in-situ comparisons using a NOAA buoy moored west of Chile. Cox and Swail (2000) speculate that this bias pattern may reflect a small deficiency of SH swell. Figure 1 also gives the global bias distribution based on the GROW2000 hindcast. GROW2000 virtually eliminates the positive bias seen in GROW on both sides of the Aleutian and Kurile island chains and the small chains and larger islands which define the Caribbean basin. This is a logical result of the greater resolution of GROW2000. The positive bias of GROW is also reduced along the Antarctic ice edge, probably a result of both the greater model resolution and the more accurate ice edge specification of GROW2000. Over other regions the spatial distribution and magnitude of the bias is little changed between GROW and GROW2000. However, this is not to say that hindcasts are equivalent in these regions. In general GROW2000 SWH is more energetic than GROW because of the inflation of NRA wind speeds, the revised P-M wind scaling and the explicit assimilation and resolution of tropical cyclones. For example, Figure 2 compares the GROW (upper) and GROW2000 (lower) monthly maximum SWH for a typical month (October, 1998). The peaks of SWH in the several severe storms in the SH "roaring forties" are 20-30% greater in GROW2000 than in GROW. The signatures of tropical cyclones are also indicated in GROW2000 (and absent in GROW) in the western Caribbean (Hurricane Mitch), off the west coast of Mexico and in the vicinity of the Philippines Islands. The systems in the Chukchi and Beaufort Seas are resolved in GROW2000 and absent in GROW, a result again of more accurate ice specification.

One area where one would expect a definite bias in GROW and possibly GROW2000 relative to AES40, is in specification of storm peaks and derivative return period extremes. In Figure 3, we compare 100-year SWH extremes computed from GROW with extremes derived in detailed hindcast studies with kinematically reanalyzed winds. The GROW extremes are based upon fits to the top-ranked 40 events over 40 years using the GUMBEL distribution and method of moments fitting. This process is comparable to the method used in the detailed basin studies. The points on this plot represent 15 widely separated areas distributed over the following basins: North Atlantic Ocean, Gulf of Mexico, South Atlantic Ocean, North Pacific Ocean, Bering Sea, Sea of Okhotsk, South China Sea, Southern Ocean. These comparisons are restricted to extremes associated with non-tropical cyclones. The smallest extreme on this plot (3.8 m) is associated with pure southwest swell offshore Nigeria (Cardone *et al.*, 1995a). The largest extreme on this plot (18 m) is associated with West of Shetlands (Archer, 1999/2000). The correlation between the GROW and the "studies" extremes is remarkable (CC = .99) and as expected the GROW extremes are biased low. The bias is –1.5 m in an absolute sense and about 12% as a percentage. It is expected that extremes from GROW2000, when similarly analyzed, will yield comparably skillful extremes with less bias. For example, Figure 4 compares GROW2000 and altimeter wind speed and SWH in terms of scatter plots, difference statistics and q-q plots in the northeast North Atlantic west of Shetlands, where we would expect the hindcast to be quite good, and Figure 5 gives the same for a grid points in the Tasman Sea west of central New Zealand where skill is much more challenging to achieve. However, we find that at both sites the scatter index is 23% or less, the overall bias is less than 0.5 m and the match at the 99 percentile between model and altimeter SWH is within 0.1 m. The matches in wind speed at the same percentile are not very close, with the model greater than the altimeter, but this is largely a result of the saturation of altimeter wind speeds above about 15 m/s.

## 5. CONCLUSIONS AND OUTLOOK

### 5.1 Conclusions

Are these latest continuous long term hindcasts based on NRA products the “final answer” to global wave climate specification? Not quite! But these products constitute considerable progress toward that ideal. With regard to specification of SWH normals and extremes in the North Atlantic Ocean, AES40 provides wave statistics accurate enough for most engineering purposes and a database ripe for mining in research on climate change and variability. Additional spatial and temporal resolution is required for the most accurate representation of tropical cyclones and of course higher resolution and shallow water physics are needed for near shore applications. Also, the issue of a possible bias of SWH in rare “extreme sea states” needs to be resolved. Finally, the period and directional properties of the seaway are probably not specified as skillfully and with as little bias as SWH and further improvements in these areas will depend at least in part on further improvement in wave model source term physics and propagation schemes.

The global hindcast products described provide remarkably skillful hindcasts of SWH on a global basis and estimates of normals and extremes, which compare well with those derived in dedicated local studies and (in the North Atlantic) from AES40. Extremes of SWH derived from GROW are biased low in general but the bias appears to be correctible through the use of local in-situ data sets (if available), altimeter data or, as a last resort, the linear regression indicated in Figure 3. So unbiased, GROW normals and extremes may be adequate for engineering applications involving planning and feasibility and initial assessments of global wave climate change and variability. However, we do not recommend the use of GROW derived extremes for final design. GROW2000 provides higher resolution global hindcast data at least as skillful as GROW and extremes with much less bias than GROW.

### 5.2 Outlook

**Wave Models**. Despite the great progress in wave modeling over the past two decades, several problem areas have been revealed mainly through the biases in 3G model specification of the wave heights in very high sea states, biases in specification of details of the 2-D spectrum such as TP and angular spreading in simple regimes, and larger errors in specification of 2-D spectra in more complicated wave regimes such as tropical cyclones. In fact, in some of these respects, well-tuned 2G models may outperform 3G models, the latter admittedly constrained by empirical rather than physical formulations for spectral shape. There is certainly a need for further refinement of the source terms for input and dissipation and more accurate numerical approximation of wave-wave interactions. Fortunately, there is a growing base of high-quality wind fields and measured wave data becoming available to wave modelers to allow testing of more physically based source terms, including data sets in a number of well documented extratropical and tropical cyclones and the new global wind data sets such as the NRA and modified NRA wind fields described in this paper. The international wave modeling community has, in fact, embarked on the development of a virtual wave model test bed facility that assembles the drivers for the standard tests and the above noted wind fields and measured wave data sets for the real test cases in a convenient form for alternative wave model evaluation. This facility will also include a standard package for the statistical evaluation of model performance.

**Convergence.** The continuous hindcast studies described in this paper point the way, say within the next five years, to a definitive hindcast of the time and space evolution of the global wave climate over the past fifty years, at least for deep-water open coast exposures. This “final” hindcast data set will have incorporated and be entirely consistent with available in-situ historical measured data sets and global satellite data sets. The data set will be free of bias in all properties of the 2-D spectrum of interest to the offshore industry such as SWH, TP, mean wave direction and wave directional spreading and correctly specify swell after propagation basin scale distances. However, it is unlikely that this database can be extended any further back in time, except for tropical cyclone extremes in limited areas. And since current design practices demand estimates of extremes for even rarer return periods (up to 10,000 years) additional research is needed to understand the influence of climate variability and trend on extremes estimated from only 50 years of history, and to define the possible physical constraints on storm intensities and ocean response which might place an upper limit on the extremes predicted by distributional extrapolations.

**Access.** The products of the earliest hindcast studies (e.g. ODGP, Hibernia) consisted typically of a hard-copy report containing a few tables of estimates of extremes of wave height and period for return periods up to 100 years at specific concession blocks of interest to the study sponsor. The earliest JIPs (e.g. ODGP, BSCOMP) included the derivation of extremes over larger areas and included delivery on 9-track tape of actual hindcast time series in bit-packed binary form. The most recently conducted JIPs, such as the SEAMOS and NESS updates, include derivation of extremes and normals at thousands of grid points in the study basin and delivery of digital files of the derivative products and all hindcast time series at all model grid points. All files are placed on CD-ROM and delivered together with access software for browsing and exporting of either derivative products or the hindcasts themselves. As the hindcast databases become even larger, such as produced for example by the AES40 study, it will be more convenient for the user to access the data base for the grid points needed at any given time over the Internet from a central server.

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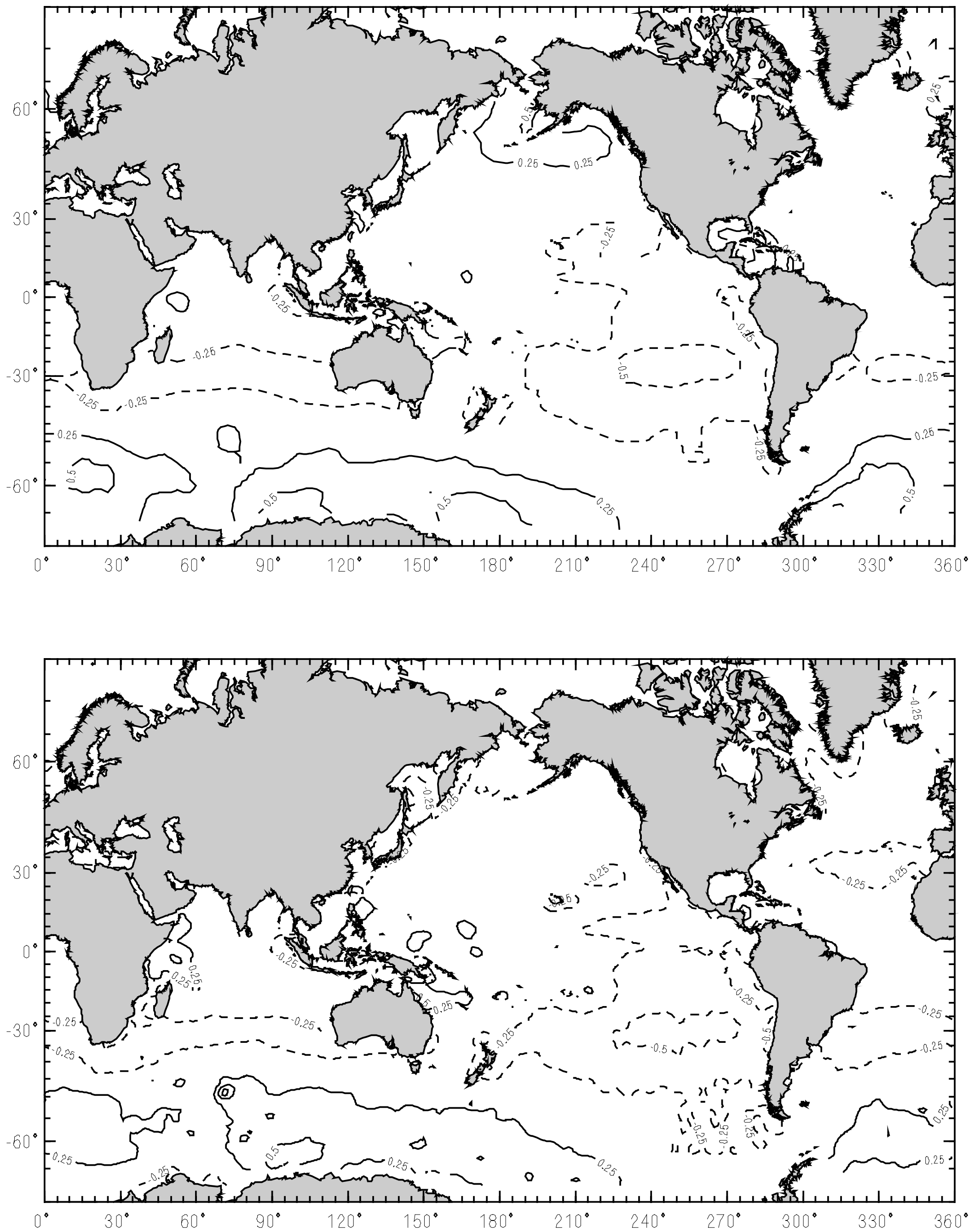


Figure 1. Average difference (hindcast-measured in meters) for GROW (top) and GROW2000 (bottom) vs. combined altimeter measurements for the period 1991-1998.

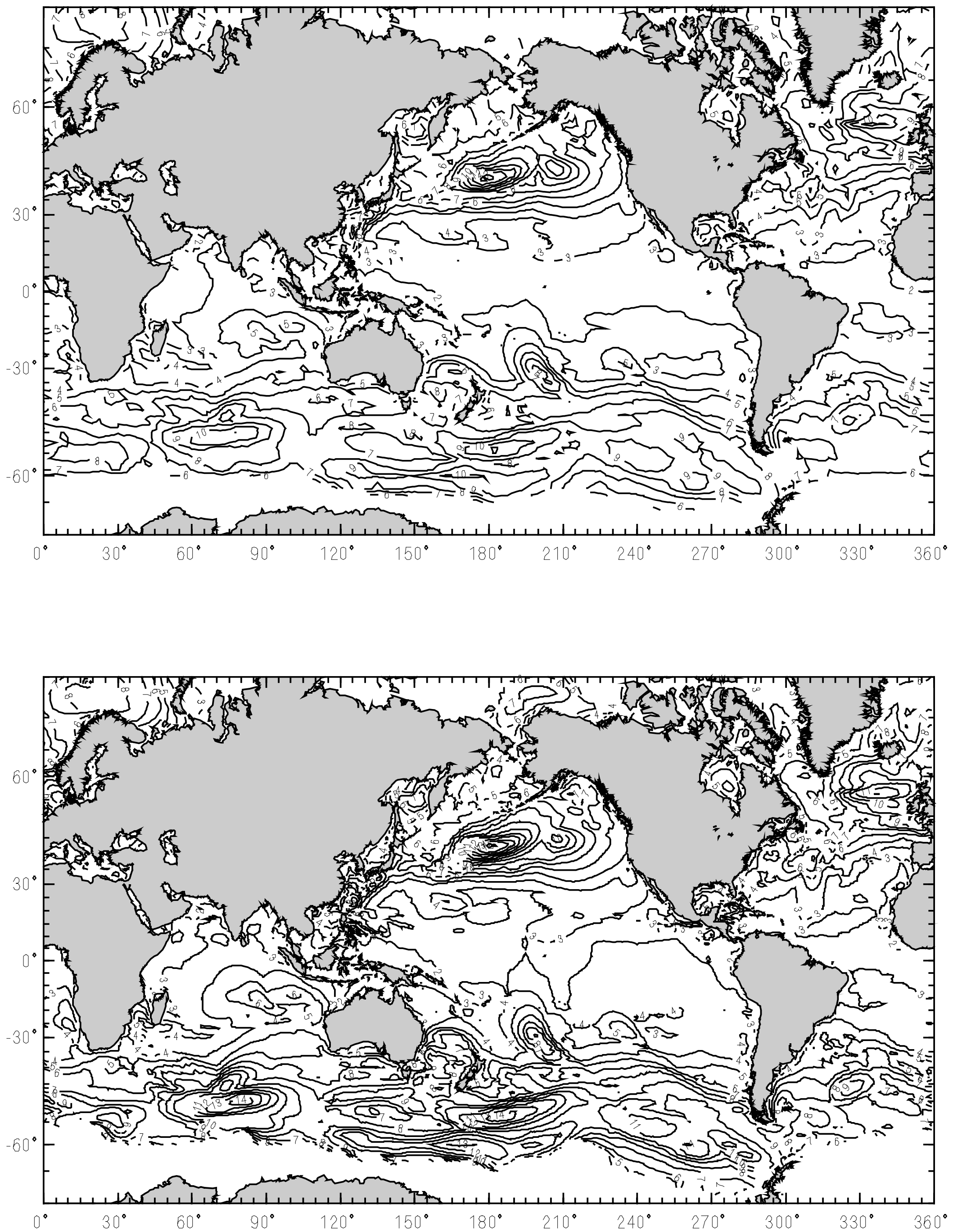
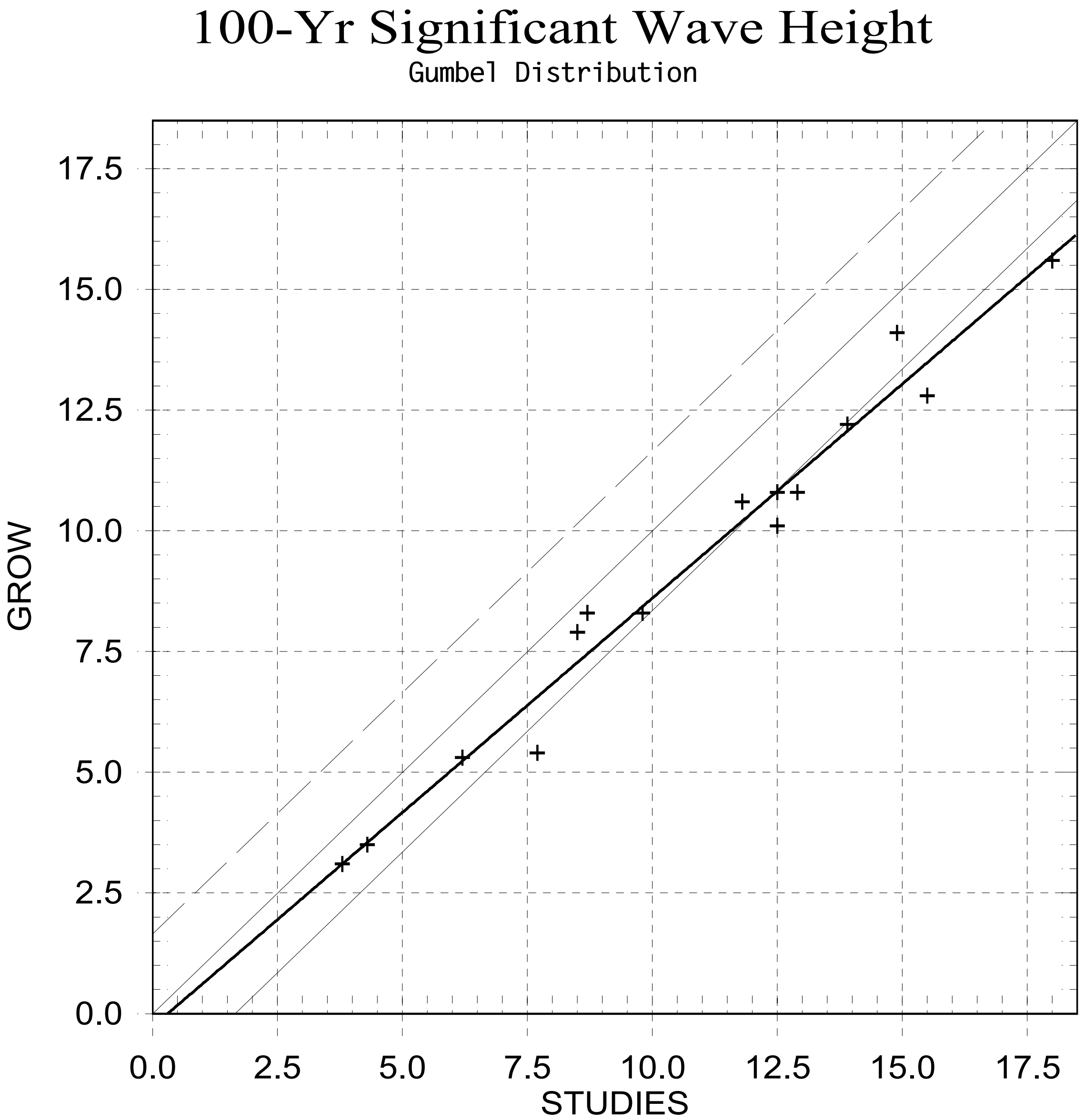
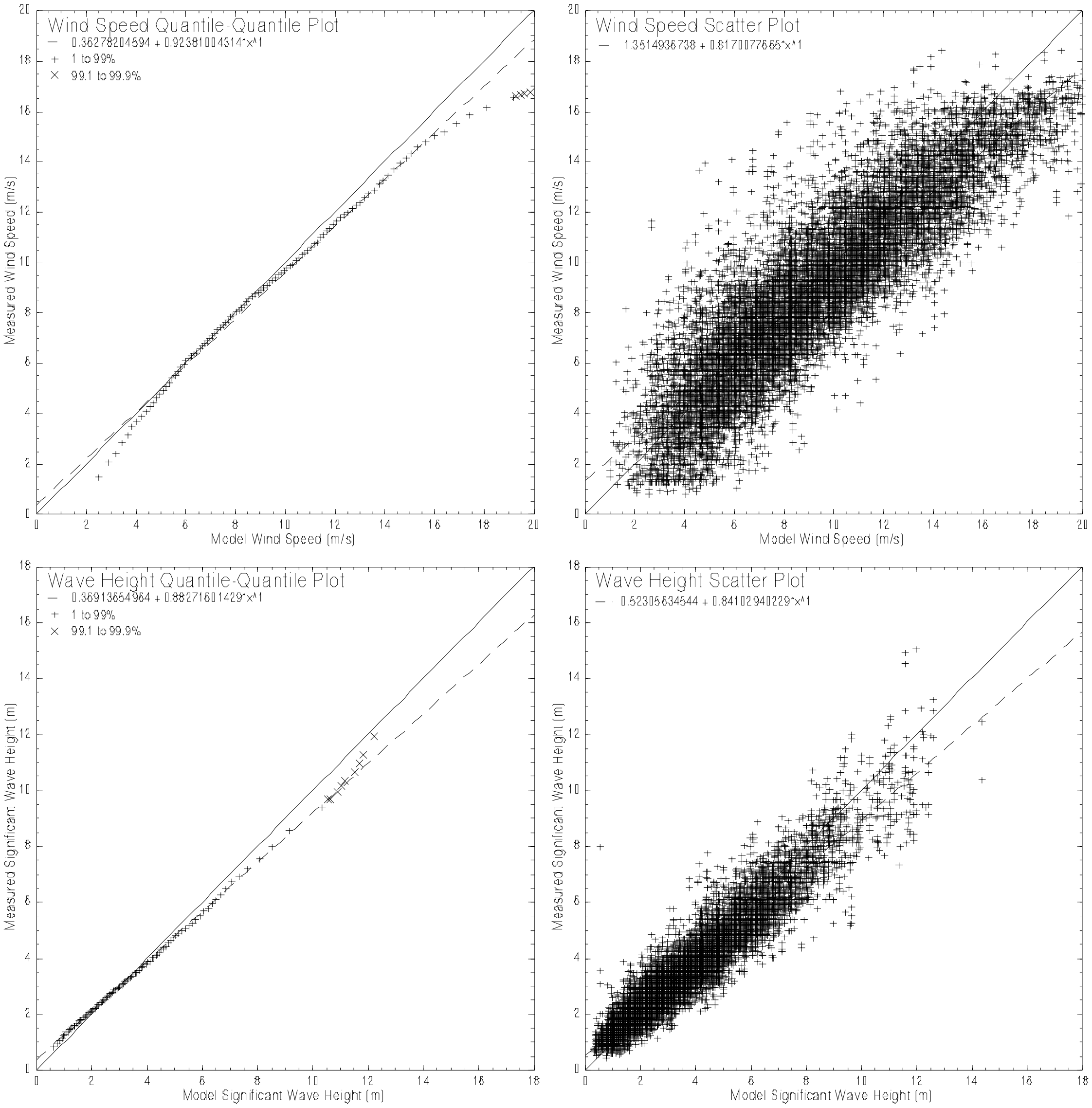


Figure 2. Maximum significant wave height (meters) hindcast for October 1998 for GROW (top) and GROW2000 (bottom).



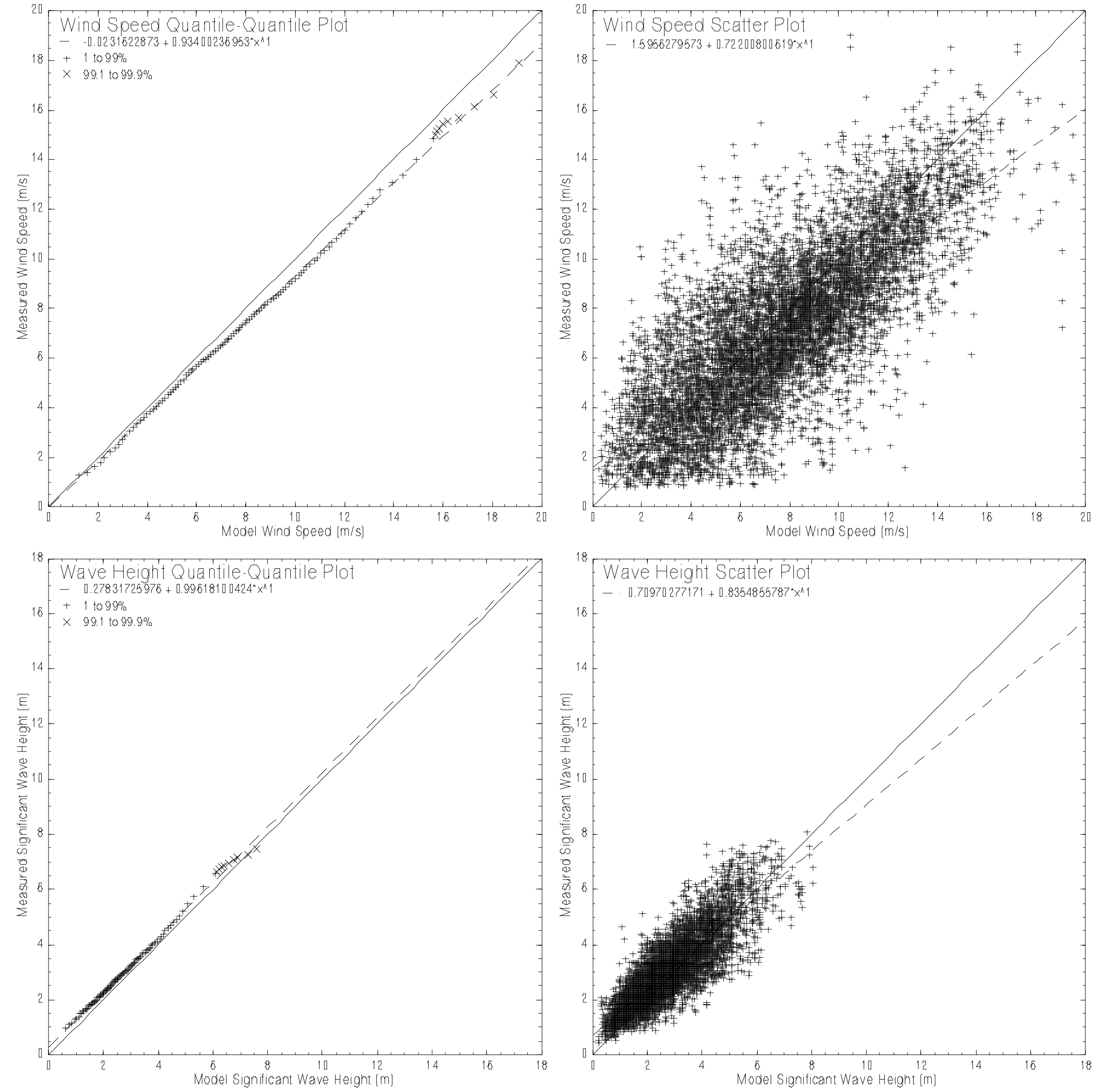
```
Best Fit: Y = 0.887X + -0.272
 Total Points:              15
 Mean X:                10.733
 Mean Y:                 9.253
 Mean Diff:             -1.480
 Root Mean Square:       1.655
 Standard Dev.:          0.740
 Scatter Index:          0.069
 Ratio:                  0.000
 Correlation Coeff:      0.987
```

Figure 3. Scatter plot of 100-year significant wave height extremes (meters) computed from GROW and dedicated hindcast studies.



| | Station | Grid Point | Number of Pts | Mean Meas | Mean Hind | Diff (H-M) | RMS Error | Stnd Dev | Scat Index | Ratio | Corr Coeff |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Wind Spd. (m/s) | Combined | 0 | 14383 | 9.03 | 9.40 | 0.37 | 1.86 | 1.82 | 0.20 | 0.61 | 0.89 |
| Sig Wave Ht (m) | Combined | 0 | 14543 | 3.51 | 3.55 | 0.04 | 0.71 | 0.71 | 0.20 | 0.49 | 0.94 |
| Wave Period (s) | Combined | 0 | 14340 | 7.41 | 7.38 | -0.03 | 0.95 | 0.95 | 0.13 | 0.45 | 0.86 |

Figure 4. Comparison of GROW2000 and ERS/Topex altimeter measurements at a 2.5 degree box surrounding 60.0N, 10.0W.



```
                                 Grid     Number     Mean     Mean      Diff     RMS    Stnd    Scat           Corr
                      Station    Point    of Pts     Meas     Hind     (H-M)   Error     Dev   Index   Ratio  Coeff
                      -------  --------  --------   ------   ------    ------   -----   -----   -----   -----  -----
Wind Spd. (m/s)    Combined          0      9483     7.11     7.63      0.53    2.30    2.24    0.32    0.62   0.77
Sig Wave Ht (m)    Combined          0      9526     2.96     2.69     -0.27    0.73    0.68    0.23    0.32   0.84
Wave Period (s)    Combined          0      9462     7.25     7.70      0.45    1.40    1.32    0.18    0.59   0.54
```

Figure 5. Comparison of GROW2000 and ERS/Topex altimeter measurements at a 2.5 degree box surrounding 40.0S, 170.0E.