

THE MSC BEAUFORT WIND AND WAVE REANALYSIS

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1. INTRODUCTION

Following the highly successful AES40 (Swail *et al.*, 2000) and MSC50 (Swail *et al.*, 2006) long-term wind and wave hindcast projects to develop climatologies of the North Atlantic Ocean (NAO), the Meteorological Service of Canada Beaufort (MSCB) project has been launched to apply many of the same hindcast analysis techniques to the Canadian Beaufort to produce a high-quality climatology. The first phase of this project, described here, addressed the period 1985-2005.

This project is a response to renewed interest in this basin in connection with planned offshore and near coastal resource development after a rather long period of dormancy. A number of studies of the operational and extreme climate of the region were undertaken and reported in the 1970s and 1980s; decades characterized by active exploratory drilling and associated wave measurement campaigns. For example, Murray and Maes (1986) summarized a number of studies of the extreme wave climate and found a wide spread in design values with 100-year return period significant wave heights varying from 4 m to 16 m.

In response to this uncertainty, a major hindcast study was carried out in the early 1990s for ESRF (Eid and Cardone, 1992; Eid *et al.*, 1992) that addressed a population of the 30-top-ranked (from the standpoint of potential wave generation) storms. Wind fields were developed from reanalyzed surface pressure fields produced by the Arctic Weather Center and augmented by manually generated kinematic analyses. Waves were hindcast with a well calibrated second-generation (2G) wave model

with shallow water physics included. Extremal analysis of the storm hindcast data, which reflected the actual synoptic ice edge associated with each event, yielded grid point specific extremes that varied from about 2 m very near shore to about 6 m in the most severe part of the study area. The study also included an assessment of the sensitivity of the wave climate to alternative probabilistic expressions of ice cover. A later study extended the same hindcast method to an additional population of 29 storms that might be responsible for extreme near shore erosion (MPL, 1993).

The study reported here adopts the approach of hindcasting a multidecade continuous period thereby producing a database from which both operational and extreme metocean statistics may be derived. For accurate extremes, it was still found to be necessary to apply intensive reanalysis of the wind fields for a subset of storms that drives the extreme wave conditions. For the continuous periods outside the major storm events, statistical corrections were applied to the NCEP/NCAR Global Reanalysis (NRA). Weekly dynamic updates of ice edge information for wave modeling were based on high-resolution Canadian Ice Service data. Application of Oceanweather's (OWI) 3rd generation wave model was made on a 28km grid covering much of the open waters of the Arctic and nested to a 5 km grid within the Canadian Beaufort. Extensive validation using a series of MEDS wave measurements in water depths from 11 to 87m water depth was performed.

The Beaufort Sea poses a number of special challenges not encountered in the MSC NAO studies noted. Most notable are the scarcity of *in*

situ meteorological data including an almost total absence of transient ship reports and moored weather data buoys, and the highly variable and complex nature of the sea-ice cover. In addition, while it has been shown (Swail and Cox, 2000) that the NRA products provide a very nice starting point for specification of marine wind fields for NAO ocean response modeling, there are indications (Atkinson and Solomon, 2002) that the NRA products in the Canadian Beaufort are considerably less accurate as they stand. This paper describes current methods adopted to address these challenges and points the way to further approaches that may be applied to produce even more accurate forcing wind fields and resulting wave hindcasts.

2. WIND FIELD METHODOLOGY

The wind field analysis methodology of OWI has continued to evolve, though the approach is still faithful to the principles of kinematic analysis. In particular, new historical data sources and analysis tools not available prior to the 1990s have become available to aid in the process of wind field analysis. In MSC Beaufort, the wind fields were analyzed using OWI's Interactive Objective Kinematic Analysis (IOKA) system (Cox *et al.*, 1995). In this process, all available measured wind data are brought into a background field and assimilated at 6-hourly intervals with the guidance and input of an experienced kinematic analyst working through a graphical interactive tool called the Wind WorkStation (WWS). For Beaufort Sea storm analysis, where it is rare to have the aid of offshore *in situ* marine wind measurements, it is especially important to first transform the coastal weather station measurements of wind speed to effective over-water exposure at 10-meter elevation. The background field is taken from the 10-m surface wind-gridded product of the NRA project but the background winds are adjusted even before importation into WWS. Finally, the global QuikSCAT wind database provides a powerful tool to minimize systematic errors in the NRA fields as described in more detail below. Briefly, the steps involved in the wind analysis as applied to MSC Beaufort

storms were as follows: (1) utilize the QuikSCAT database to identify and correct systematic errors in the NRA winds within the domain of the ocean response models; (2) adjust coastal stations based on the station dependent overwater/overland transformation ratios derived from station surface roughness and anemometer height; (3) import marine and adjusted coastal winds into the WWS together with adjusted wind observations from transient ships; (4) apply IOKA/WWS with a level of effort of several hours of interactive work per storm to carry out a kinematic reanalysis of the wind field at no greater than 6-hour intervals.

2.1 QuikSCAT/NRA Wind Correlations

The NRA wind fields were extracted from the master file of NRA winds as processed previously by OWI to provide effective neutral 10-m wind speed (the neutral wind speed normalizes the wind speed to neutral thermal stratification, air-sea temperature difference equals zero, so that ocean response models do not have to account for stratification; see Cardone *et al.* 1990) and then sorted by NRA grid box for all 142 NRA grid boxes in the Beaufort Sea, as shown in Figure 1. The comparative analysis consists of forming a matched QuikSCAT/NRA dataset for each box. To account for the asynoptic nature of the satellite data, the NRA 6-hourly winds straddling a satellite observation are linearly interpolated in time to the hour nearest the time of the satellite observation. Given the time-matched dataset in each box over the overlapping data sample, the analysis proceeds to compare the two datasets using Oceanweather's TIMESCAT program for various stratifications of the matched pairs. The basic stratifications are all months combined and wind direction quadrant defined as follows:

045-135 degrees
135-225 degrees
225-315 degrees
315-045 degrees
All directions combined

The directional bin is based on the NRA wind direction. TIMESCAT generates two types of

statistics. The first type consists of standard difference statistics on the matched data pairs of wind speed and direction including mean difference, RMS difference, standard deviation of the difference, scatter index and correlation coefficient. This type of comparison emphasizes the skill (or lack thereof) with which the NRA wind fields simulate the true time and space varying winds. The second type of comparison is applied to wind speed only and involves the exceedance distributions computed separately from the NRA and QuikSCAT data but using only data contained in the matched dataset. Specifically, the probability distributions of the NRA and QuikSCAT wind speeds are compared in terms of “quantile-quantile” scatter plots. This plot is produced as follows. First, the non-exceedance distribution of wind speed is computed for the NRA and QuikSCAT data separately. Then a scatter plot is constructed between the NRA and QuikSCAT unit percentile values from 1% through 99%, sometimes extended in tenths to 99.9%. This type of comparison emphasizes the systematic differences between the NRA and the true winds within the stratification addressed. If the q-q plot shows a linear relationship between the distributions then a simple correction algorithm for the systematic effects shown on the q-q plots is provided by the regression line through the data points. There are fewer than 500 comparisons per box available after combing all seasons and directions. The regressions on the q-q plots all indicate that the NRA wind speeds tend to underestimate the QuikSCAT winds and presumably the true wind speeds, especially for the “southerly” and “easterly” (from which) wind direction quadrants. In consequence, the NRA wind speeds were increased accordingly. NRA wind directions were also adjusted by applying the mean difference in wind direction returned for each stratification and grid point by TIMESCAT.

2.2 Sample Storm Wind Field

Figure 2 shows an example of a WWS display, for one time step only, in the storm of August 2003 at 00:00 UTC. The display shows all of the data referred to by the analyst to carry out the kinematic analysis of the wind fields including

the adjusted NRA winds, digitized kinematic analysis, sea level isobars, ship reports and land station winds for all land stations available. The hindcast of a typical storm simulated about a one-week period, though the most intensive part of the kinematic analysis focused on about 72 hours centered on the time of maximum storm impact in the area of interest. The analyst carried out a kinematic analysis through the addition of a kinema domain in which isotachs of surface wind speed (in red) were directly input using a tablet drawing device. All active data were assimilated into the background field using an objective analysis algorithm that operates on the field of scalar wind speed to define the analyzed wind speed, and separately on the zonal and meridional components of the wind to define the field of wind direction. The workstation also interpolated the wind fields in space and time as required by the coarse and fine wave models.

3. WAVE MODELING METHODOLOGY

3.1 MSC Beaufort Implementation of OWI-3G

The wave model applied in the MSC Beaufort was the same third generation wave model (OWI-3G) as used in the original AES40/MSC50 hindcasts (see Swail *et al.* 2006 for the most recent description of the model). Like the AES40/MSC50, boundary spectra along the southern boundary of the basin model were supplied from the GROW (Global Reanalysis of Ocean Waves) hindcast which applied a 2nd generation wave model on a global grid (Cox and Swail, 2001). Inscribed in the MSC Beaufort coarse 28km model grid is the fine domain 0.05 by 0.15 degree (approximately 5.2 km) shallow water implementation of the OWI-3G model (Figure 3). This regional grid represents 3442 active grid points.

Bathymetry for the MSC Beaufort basin and fine domain model were supplied from two basic sources. The GEBCO (General Bathymetric Chart of the Oceans) digital atlas (2003 edition) provided water depths for most of the basin wide hindcasting. This source data is a gridded product with resolution of 1-minute covering the global oceans. Depths for the fine grid as well

as overlapping regions of the coarse grid were supplied from the Canadian Hydrographic Service (CHS) archive. Coverage of the CHS bathymetry is shown in Figure 4; little smoothing was required at the CHS /GEBCO boundary as both datasets were found to be consistent.

3.2 Ice Edge

In the OWI-3G model grid point locations with greater than 50% ice concentration are considered as land with no wave generation and/or propagation. In the MSC Beaufort the ice edge was allowed to change on a weekly basis which allowed better representation of the changing ice conditions during the transition periods. In Canadian waters, the Canadian Ice Service (CIS) supplied a high-resolution ice concentration dataset that spanned the period 1971 to present (Table 1). Since the CIS data were typically weekly, the time period of all ice data were binned and averaged to the available CIS times. Figure 5 shows a comparison of the ice edge analysis that included the CIS data in Canadian waters and GFSC/DMSP ice data in other areas to complete the ice edge field across the entire coarse domain. A blend of the two ice sources was required since the CIS data did not cover the entire domain of the 28km model.

Table 1 Ice concentration data sources

Source	Frequency	Coverage	Date Range
GFSC	Daily	Full	Nov 1978- Dec 2000
DMSP	Daily	Full	Jan 2001- Present
CIS NetCDF	Weekly	Canadian Waters	Jan 1971- Present

4. VALIDATION

During the early 1980s, there were a series of Marine Environmental Data Service (MEDS) buoys deployed in the ice-free period in the

Canadian Beaufort. MEDS measurement locations are shown in Figure 6 and Table 2. This dataset is comprised of 12 buoys (26 deployments) over the 1981-1986 period and archived hourly wave parameters in water depths ranging from 11 to 71 meters. Since much of the MEDS data was obtained previous to the hindcast period of 1985-2005, individual months previous to 1985 were run for validation applying the same methodology.

Selected wave height and period timeseries comparisons are shown in Figure 7 for MEDS buoys 196 (87 meter depth) and 201 (59 meter depth) in 1982. Nearly all the MEDS data show the same missing data periods during each open-water season. The comparison shows both under and over estimation of the modeled vs. measurements, but overall the hindcast reflects the measured day-to-day and storm conditions.

Overall statistics of the wave hindcast are detailed by buoy in Table 3 and show a mean wave bias of 4 cm and underestimation of the mean wave period of just 0.41 seconds. Scatter indexes (SI) are larger (42%) than in the MSC50 (31%) due in part to the larger uncertainties in the wind fields and to the low mean measurement (0.99 meters) applied in the calculation of SI (standard deviation/mean measurement). A quantile-quantile comparison of wave heights (Figure 8) shows some overestimation at the larger percentiles (85-99.9%) of a few centimeters but overall the comparison is very linear. This comparison removed station 165 (1986 data) since this dataset exhibited strange behavior during storm conditions.

A peak-to-peak analysis which compares wave measurements during storm conditions is shown in Figure 9. Individual storm peaks with significant wave heights greater than 2 meters are matched with hindcast peaks within a 3-hour window. When the resulting dataset of 32 storm peaks are compared, they show a mean wave height difference of -22 cm and wave period difference of -1.05 seconds (underestimation of the hindcast). SI is 23% for wave height in storm conditions with a mean peak measurement of just 2.45 meters.

5. HINDCAST PRODUCTS

The Beaufort hindcast was run for the continuous period of 1985-2005 (21 years) and produced an hourly archive of wind and wave parameters at all points as well as wave spectra at select points archived over the fine domain model (Figure 10). Hindcast output was then subjected to extremal analysis and computation of a wind and wave atlas. These derivative products, along with the point-sorted archive of model output, were combined into a single USB drive of hindcast products (see Figure 11 for the products main menu).

Mean wind speeds and wave heights are shown for the ice-free period of June-November in Figure 12 and 13 from the wave atlas. The atlas includes mean, median, 90th percentile, 99th percentile, standard deviation, and 3 exceedence levels expressed graphically for both winds and waves. The 99th percentile winds and waves for September are shown in Figure 14. Anomalies from the 1985-2005 reference period are also computed for the mean, 90th and 99th percentiles. Results are time stratified for the entire period (1985-2005), all months, as well as individual months and individual years.

A peaks over threshold analysis was performed using the 1985-2005 point-sorted archive. A peak is defined as any event that is greater than the minimum significant wave height threshold, and must be separated from any other peak by at least 48 hours. The threshold for a wave height peak was taken as ½ the maximum value at each grid point. All peaks were processed using the Gumbel (Gumbel, 1958) extremal distribution at each individual grid point; no spatial smoothing was applied. Figure 15 shows the resulting 25-year return period for winds (above) and significant wave height (below). No limit was placed on the wave height in shallow water for this analysis, thus results in shallow water may exceed breaking criteria at some return periods.

6. SUMMARY

This study describes a 21-year wind and wave hindcast produced for the Canadian Beaufort. *In*

situ observations have been used to evaluate the wind and wave hindcast. The hindcast compares well against available wave measurements not only in terms of bias and scatter, but over the entire frequency distribution out to and beyond the 99th percentiles of waves.

The next steps in this project are to extend the continuous hindcast both backwards and forwards in time to cover the period 1971 to present (coincident with the CIS high resolution sea ice data). Additional validation using *in situ* data from the earlier period and more recent satellite altimeter observations also represent an important extension of the work.

In the future a goal is to investigate the possibility of running a combined wind, wave and storm surge model for the Canadian Beaufort. Concerns here revolve around the quality of the wind fields, bathymetry, and land surface elevation data, as well as sufficient validation data of water levels. Another potentially promising possibility is using satellite SAR wind products to investigate small scale variability in the Beaufort Sea wind fields, especially close to the coast.

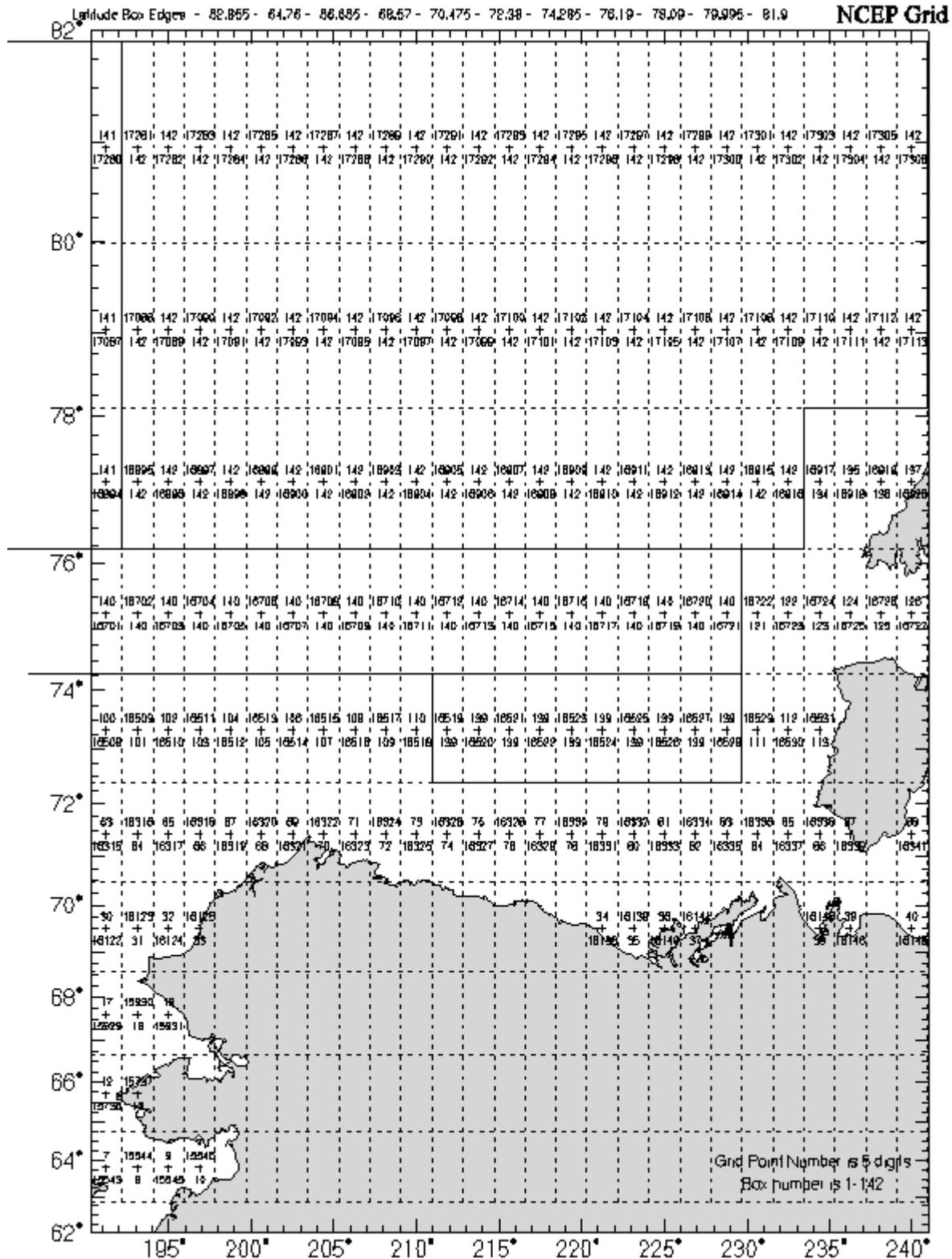
ACKNOWLEDGEMENTS

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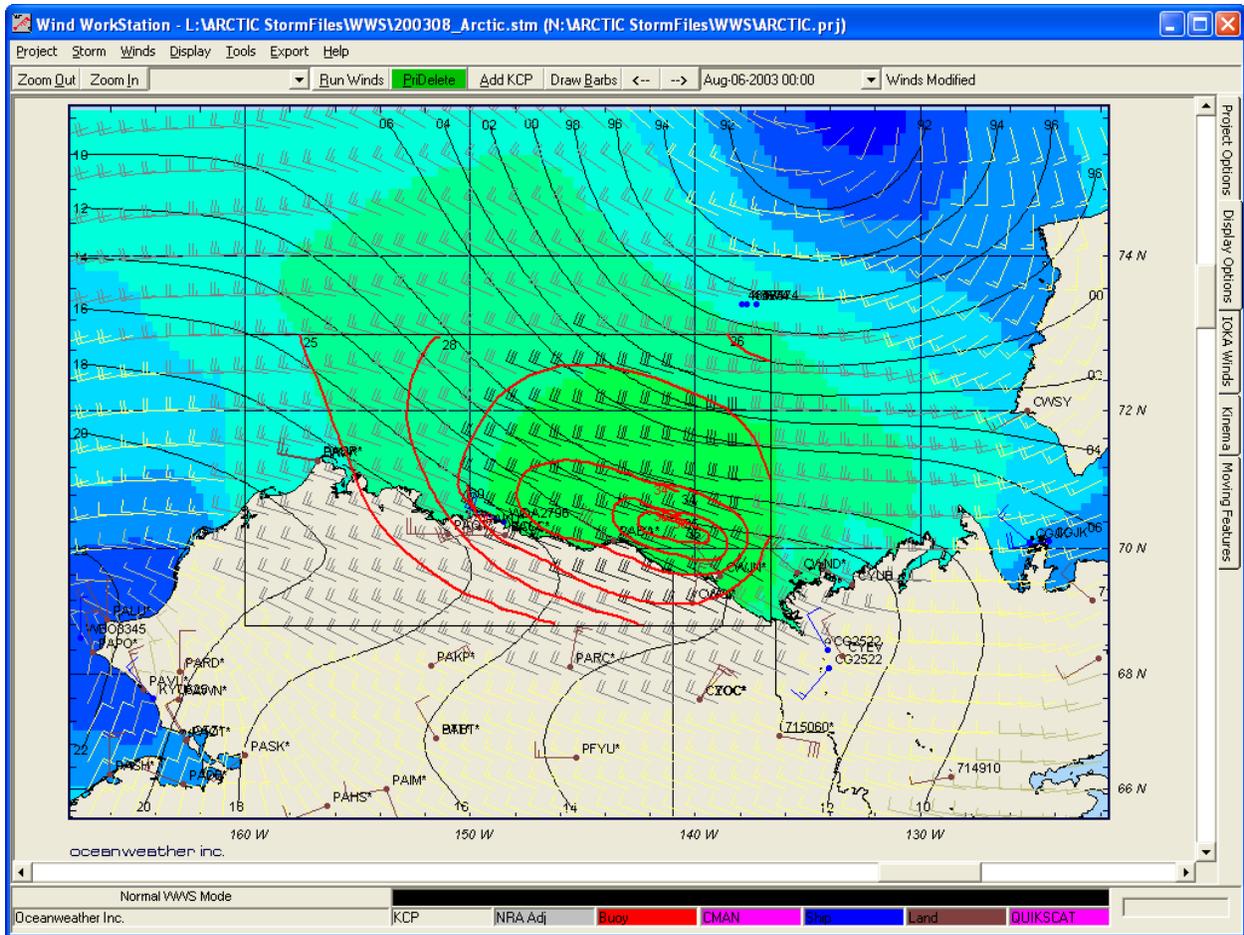
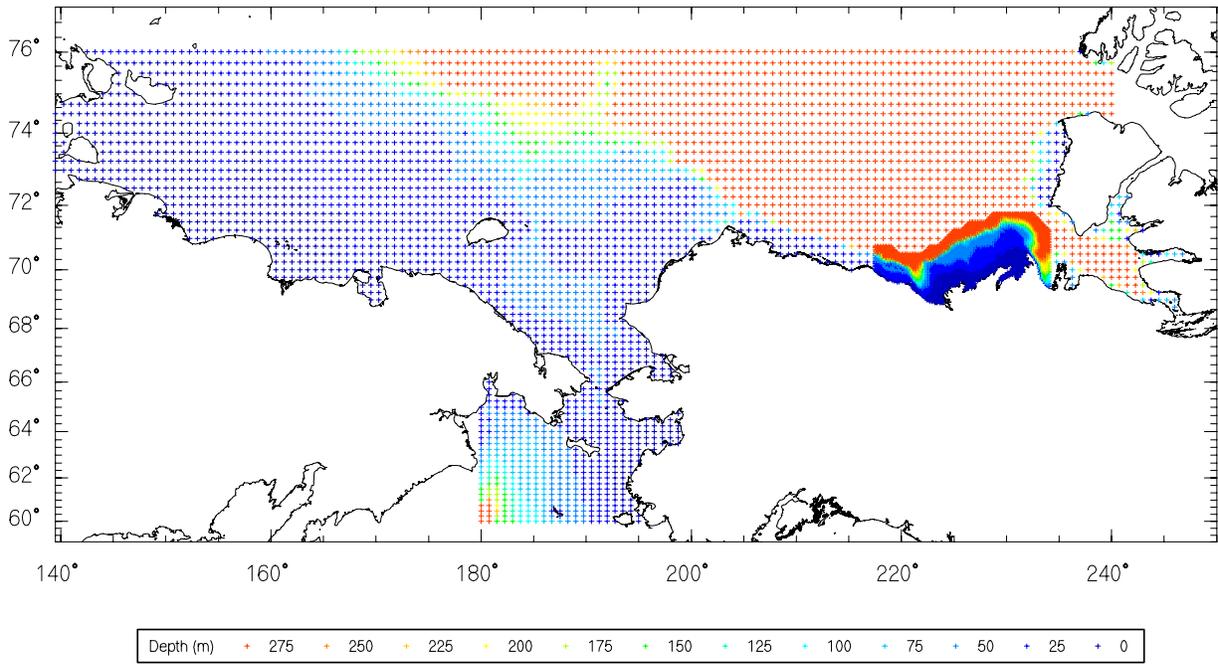


Figure 2 WWS Surface wind analysis (isotachs in knots) valid Aug-06-2003 00:00 UTC.

MSC Beaufort Coarse and Fine Domain



MSC Beaufort Fine Domain

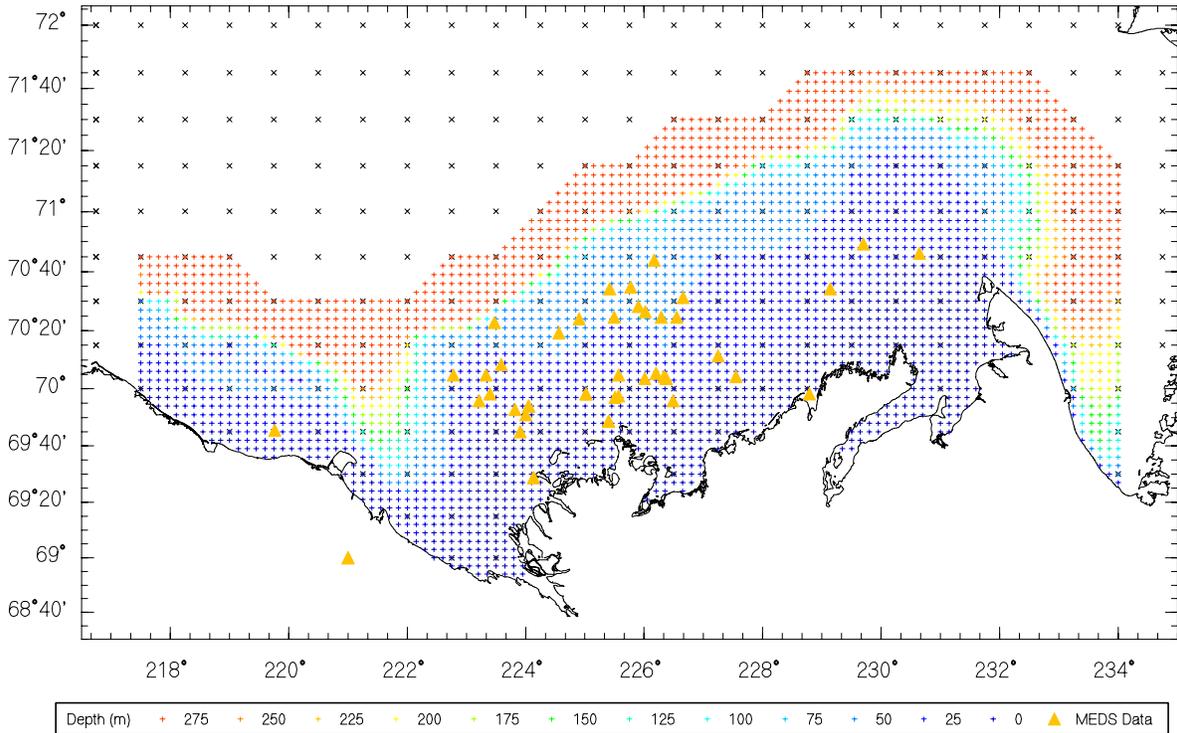


Figure 3 Beaufort 28 km coarse (top) and 5 km fine (bottom) wave model grids with depths (m) and MEDS validation locations.

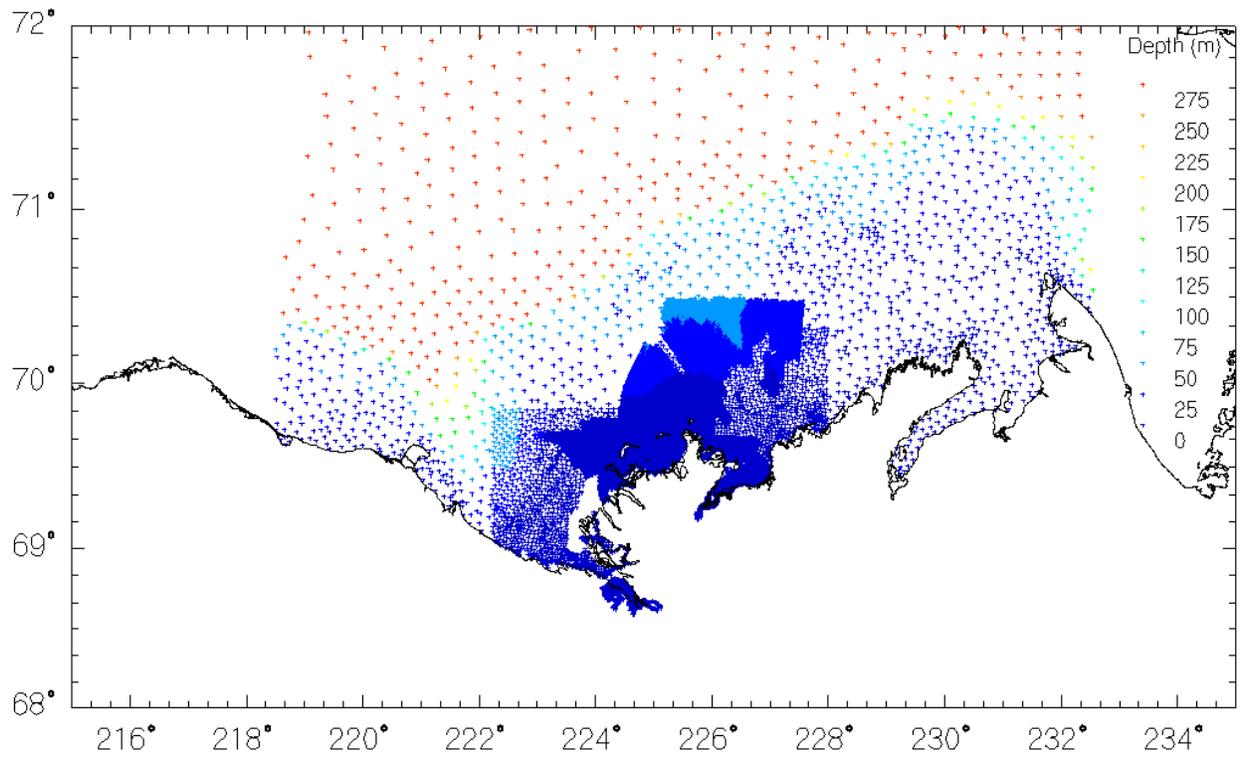


Figure 4 Depth measurements provided by CHS for use in the Beaufort wave model.

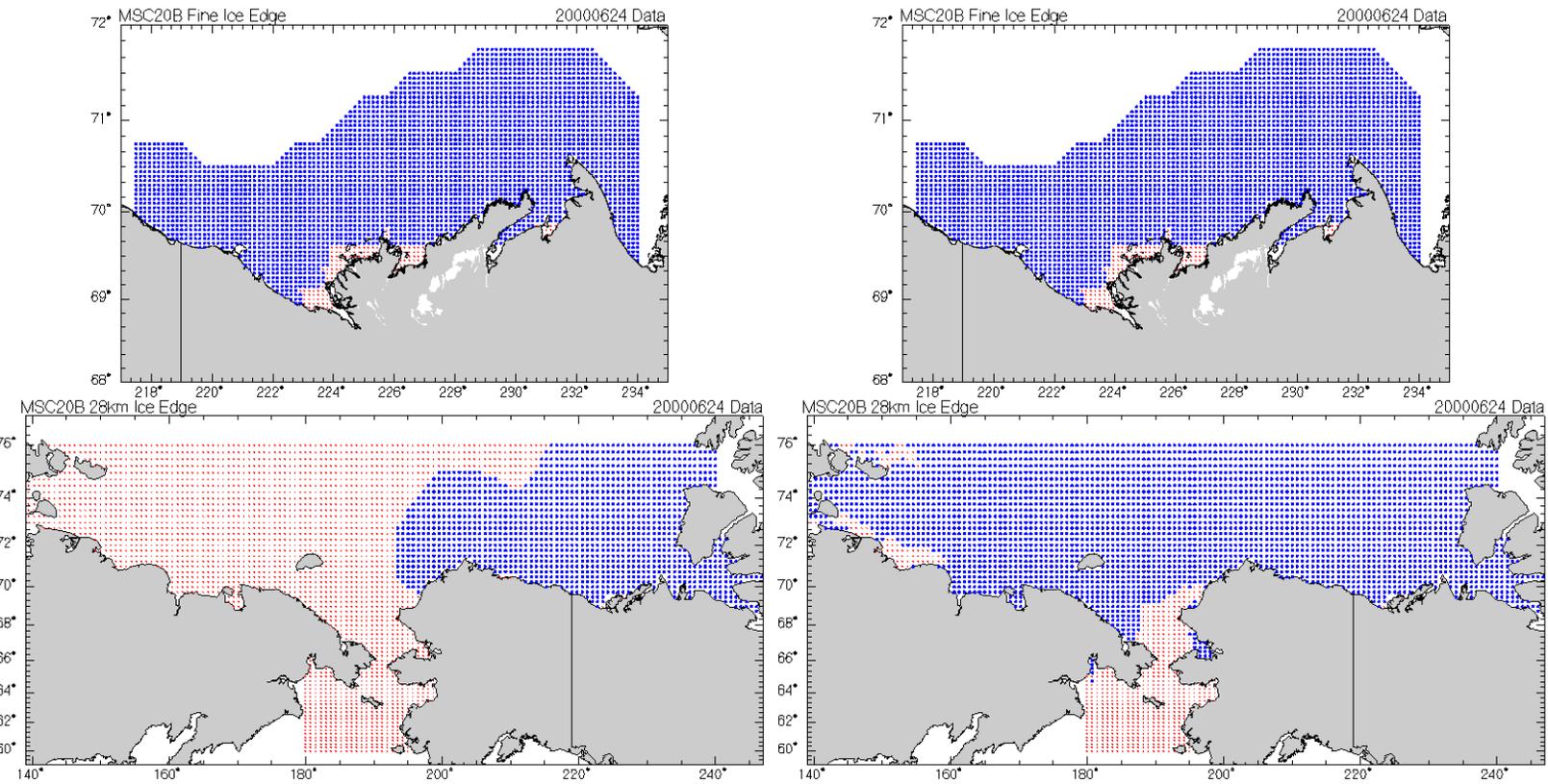


Figure 5 Comparison of weekly ice edge (blue represents greater than 50% concentration) valid June-24-2000 from the Canadian Ice Service (left) and final blended ice edge (right) from multiple ice data sources on the MSC Beaufort course and fine model domain

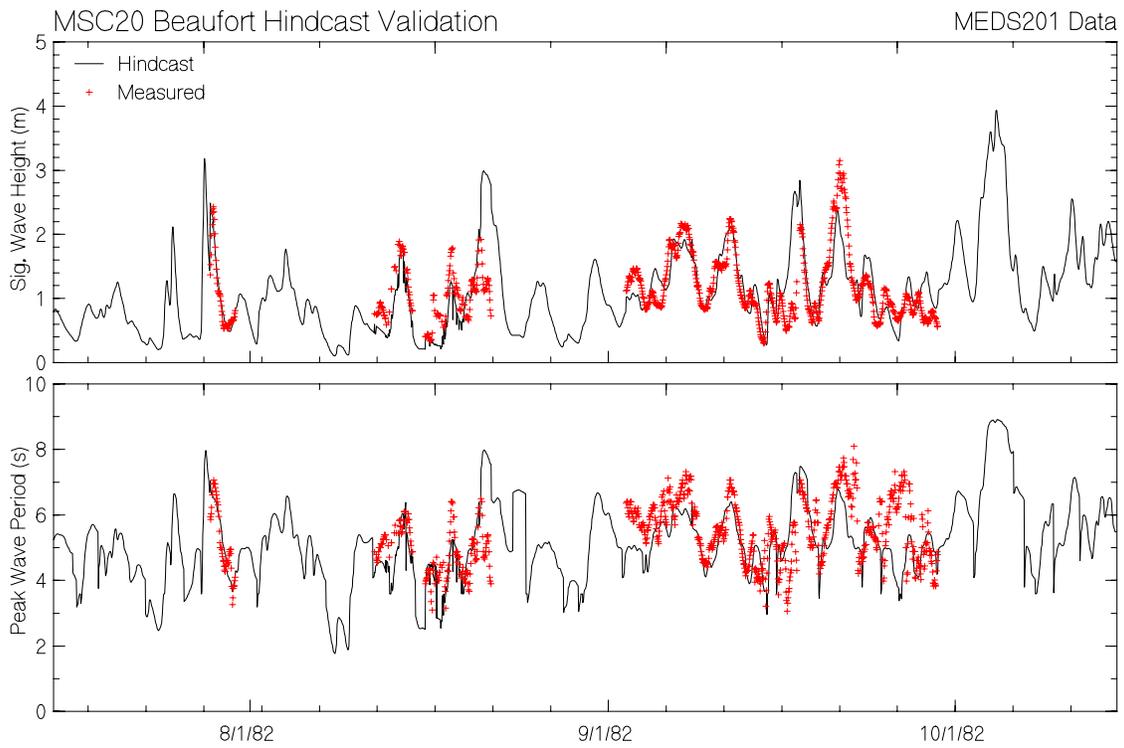
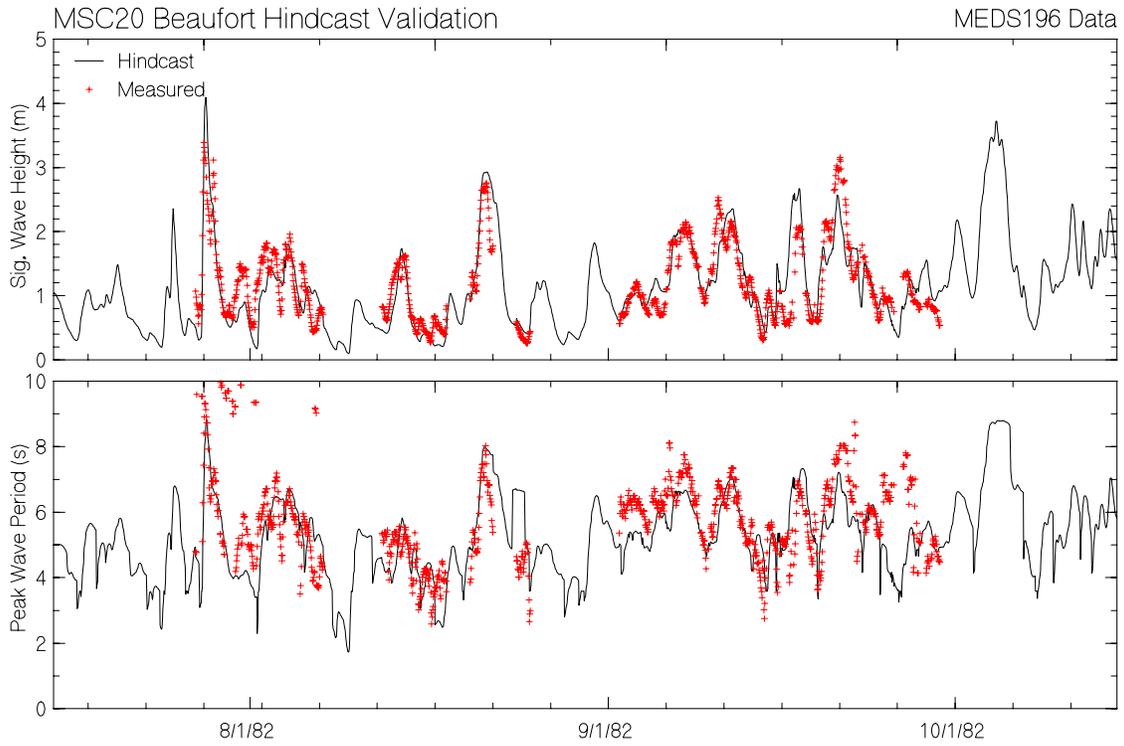


Figure 7 Timeseries comparison of measured (red) and hindcast (black) wave heights and periods at MEDS 196 (top) and 201 (bottom)

Table 3 Wave statistics by buoy

Hindcast Period : 01-JAN-1982 00:00:00 to 01-JAN-1988 00:00:00

	Station	Grid Point	Number of Pts	Mean Meas	Mean Hind	Diff (H-M)	RMS Error	Stnd Dev	Scat Index	Ratio	Corr Coeff
Sig Wave Ht (m)	MEDS196	0	1045	1.20	1.19	-0.01	0.39	0.39	0.32	0.50	0.83
Wave Period (s)	MEDS196	0	1045	6.59	5.34	-1.25	4.43	4.25	0.65	0.37	-0.12
Sig Wave Ht (m)	MEDS200	0	106	0.63	0.67	0.04	0.41	0.41	0.66	0.47	0.42
Wave Period (s)	MEDS200	0	106	4.47	4.44	-0.02	1.86	1.86	0.42	0.42	0.14
Sig Wave Ht (m)	MEDS201	0	1080	1.08	1.12	0.04	0.48	0.48	0.44	0.49	0.63
Wave Period (s)	MEDS201	0	1080	5.19	5.05	-0.14	1.09	1.08	0.21	0.41	0.51
Sig Wave Ht (m)	MEDS202	0	54	0.79	0.51	-0.28	0.48	0.38	0.49	0.20	0.58
Wave Period (s)	MEDS202	0	54	4.63	4.23	-0.41	1.25	1.18	0.26	0.44	0.54
Sig Wave Ht (m)	MEDS204	0	1104	0.99	0.90	-0.08	0.34	0.33	0.34	0.41	0.75
Wave Period (s)	MEDS204	0	1104	5.15	4.74	-0.41	1.00	0.92	0.18	0.32	0.63
Sig Wave Ht (m)	MEDS205	0	1130	0.90	0.91	0.01	0.31	0.31	0.35	0.52	0.79
Wave Period (s)	MEDS205	0	1130	4.90	4.76	-0.14	0.95	0.94	0.19	0.43	0.64
Sig Wave Ht (m)	MEDS207	0	39	0.67	0.77	0.10	0.83	0.82	1.22	0.44	-0.38
Wave Period (s)	MEDS207	0	39	7.32	4.37	-2.95	7.98	7.42	1.01	0.31	0.28
Sig Wave Ht (m)	MEDS208	0	85	0.72	0.71	-0.01	0.61	0.61	0.85	0.51	0.10
Wave Period (s)	MEDS208	0	85	5.51	4.26	-1.25	4.20	4.01	0.73	0.39	0.20
Sig Wave Ht (m)	MEDS209	0	263	0.64	0.80	0.16	0.42	0.39	0.62	0.58	0.71
Wave Period (s)	MEDS209	0	263	4.14	4.07	-0.07	1.46	1.46	0.35	0.52	0.31
Sig Wave Ht (m)	MEDS265	0	342	1.07	1.32	0.24	0.47	0.40	0.37	0.78	0.77
Wave Period (s)	MEDS265	0	342	5.40	5.51	0.10	1.27	1.27	0.23	0.59	0.51
Sig Wave Ht (m)	WEL123	0	127	0.60	0.51	-0.09	0.32	0.30	0.50	0.28	0.68
Wave Period (s)	WEL123	0	127	4.58	3.58	-1.00	3.59	3.45	0.75	0.30	-0.09
Sig Wave Ht (m)	WEL165	0	432	1.01	1.38	0.37	0.63	0.52	0.51	0.73	0.77
Wave Period (s)	WEL165	0	432	5.43	5.50	0.08	1.39	1.39	0.26	0.51	0.51
Sig Wave Ht (m)	Combined	0	5807	0.99	1.03	0.04	0.42	0.42	0.42	0.51	0.73
Wave Period (s)	Combined	0	5807	5.35	4.94	-0.41	2.35	2.31	0.43	0.41	0.24

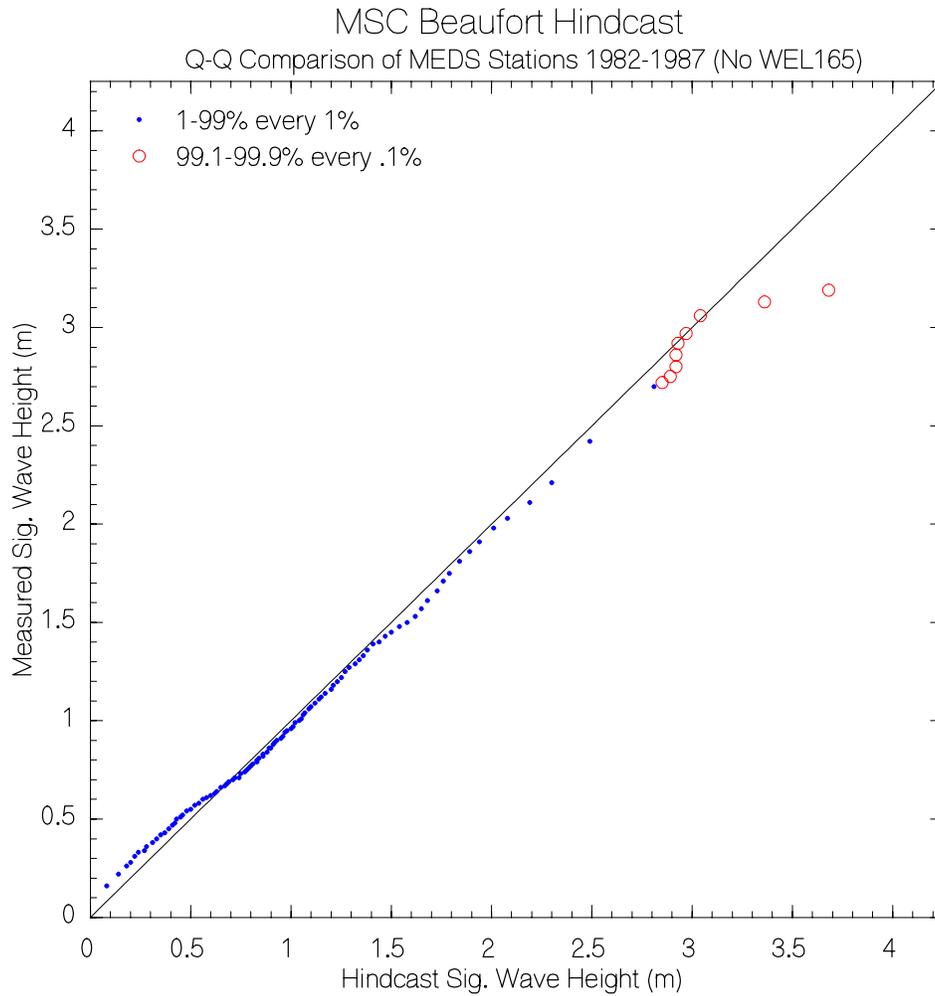
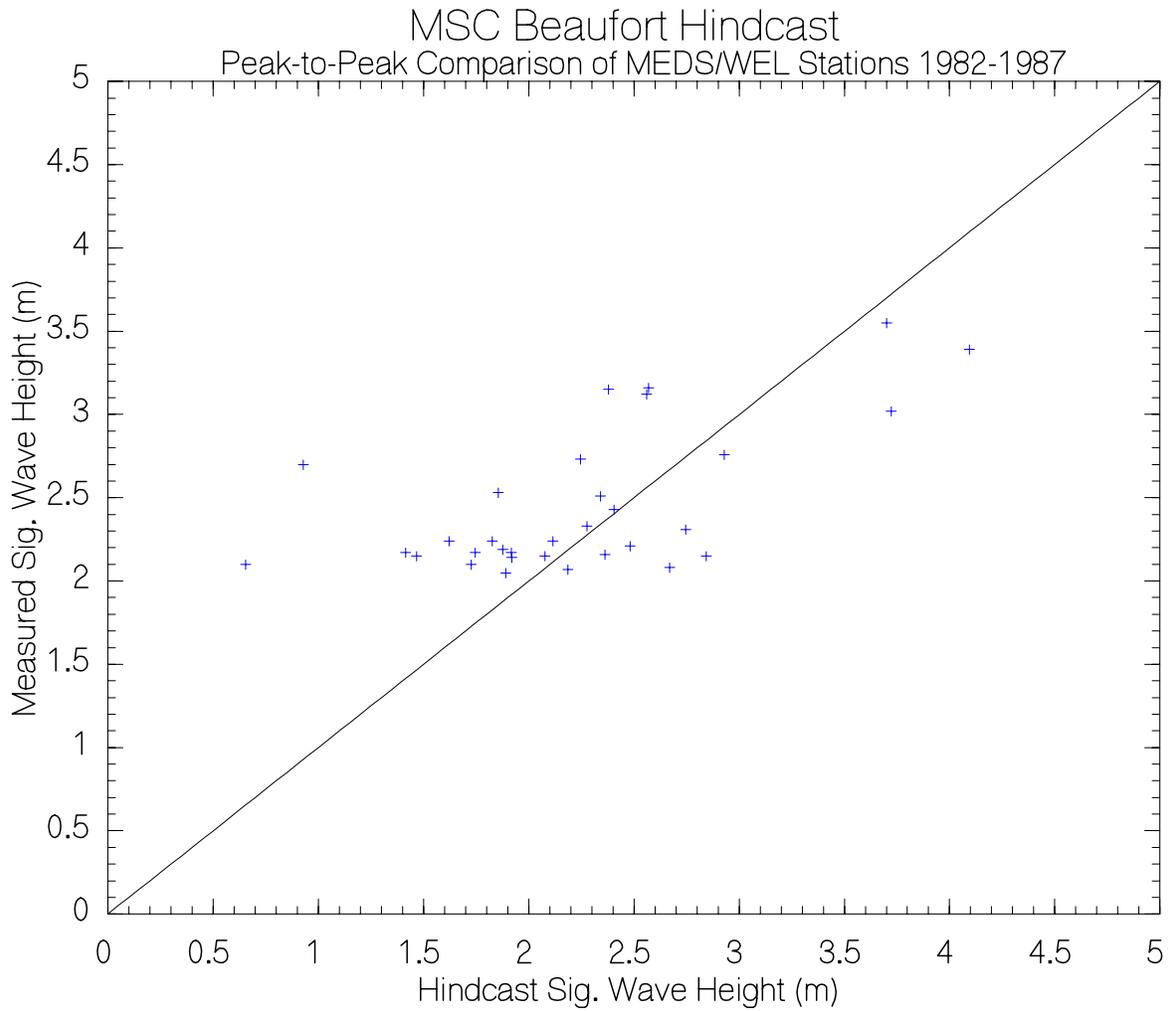


Figure 8. Quantile-Quantile comparison from 1 to 99% for combined *in situ* data vs. hindcast significant wave height (meters).



	Station	Grid Point	Number of Pts	Mean Meas	Mean Hind	Diff (H-M)	RMS Error	Stnd Dev	Scat Index	Ratio	Corr Coeff
Sig Wave Ht (m)	MEDS196	0	9	2.61	2.54	-0.07	0.50	0.49	0.19	0.44	0.67
Wave Period (s)	MEDS196	0	9	7.33	7.06	-0.27	0.58	0.51	0.07	0.44	0.76
Sig Wave Ht (m)	MEDS201	0	7	2.35	2.21	-0.14	0.43	0.41	0.17	0.14	0.26
Wave Period (s)	MEDS201	0	7	6.90	6.53	-0.36	0.60	0.48	0.07	0.14	0.22
Sig Wave Ht (m)	MEDS204	0	4	2.34	1.79	-0.55	0.56	0.11	0.05	0.00	0.95
Wave Period (s)	MEDS204	0	4	6.87	5.92	-0.95	1.02	0.39	0.06	0.00	0.84
Sig Wave Ht (m)	MEDS265	0	5	2.47	2.41	-0.05	0.45	0.44	0.18	0.60	0.85
Wave Period (s)	MEDS265	0	5	7.09	6.94	-0.16	0.64	0.62	0.09	0.40	0.82
Sig Wave Ht (m)	Combined	0	32	2.45	2.24	-0.22	0.60	0.56	0.23	0.31	0.63
Wave Period (s)	Combined	0	32	7.66	6.61	-1.05	4.11	3.98	0.52	0.31	-0.29

Figure 9 Peak to peak wave height scatter plot (top) and statistics for events > 2 meters (measured).
Note: Figure corrected from original version presented at conference.

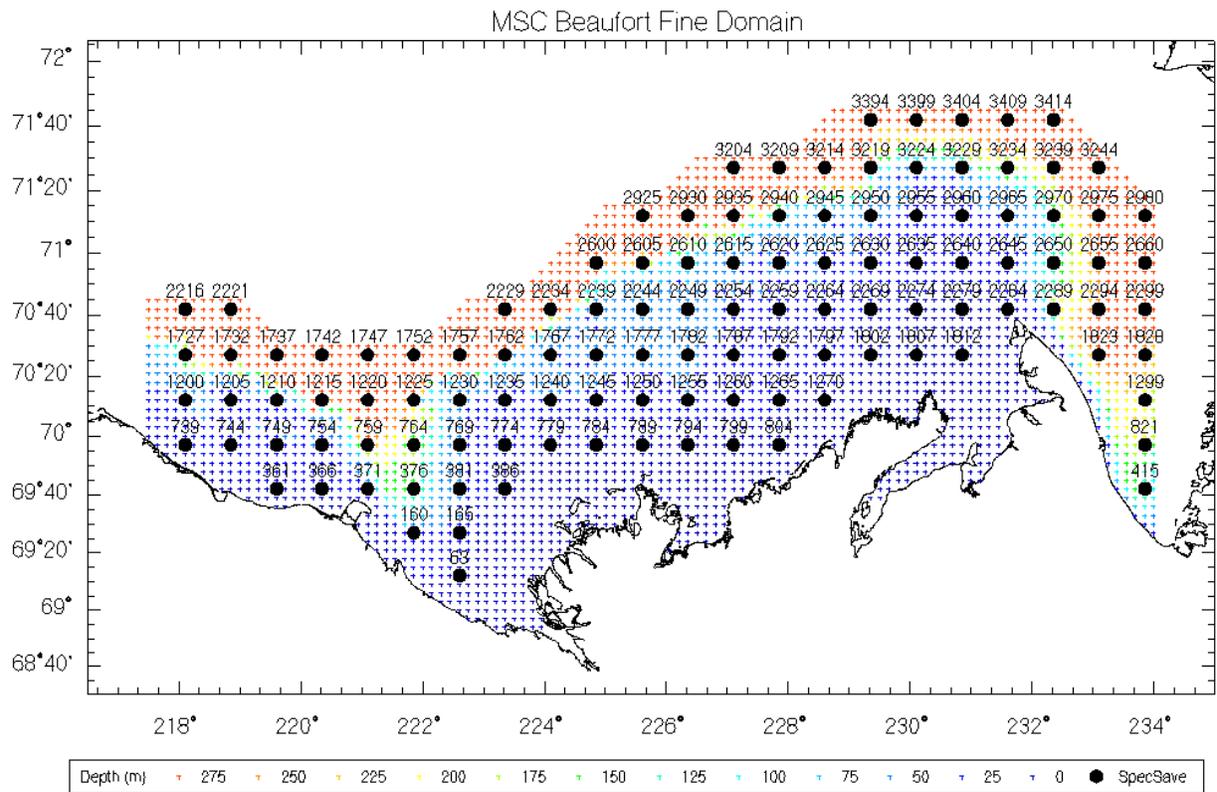
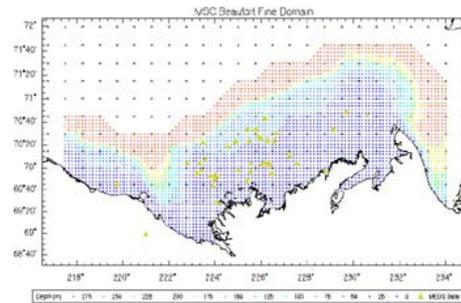


Figure 10 Beaufort wind and wave archive (locations colored by depth) and wave spectra (black) locations

MSC

Beaufort Wind and Wave Climatology

A 21-year continuous wind and wave hindcast
covering the period 1985-2005.



<p>Ice Plots</p> <p>Weekly/Monthly ice data provided by the Canadian Ice Service</p>	<p>Validation</p> <p>Comparison with MEDS buoys</p>	<p>Wave Atlas</p> <p>Graphics and data analysis based on the wind and wave climatology</p>
<p>Wind and Wave Fields</p> <p>Synoptic sort (1-month, all points per file, gzipped)</p> <p>17 Archived Wind and Wave Fields Description</p>		<p>Wave Spectra Archive</p> <p>117 Archive Locations - gzipped by point</p> <p>Gif Image/CSV File of Archive Locations</p> <p>Spectra Description</p>
<p>Wind and Wave Timeseries</p> <p>Time sort (1 file per grid point, gzipped)</p> <p>17 Archived Wind and Wave Fields Description</p>	<p>OSMOSIS</p> <p>Requires OSMOSIS be installed on your PC</p>	<p>Extremes</p> <p>Gumbel and Weibull extremes computed by point</p>

Figure 11 Beaufort DVD-ROM archive main menu

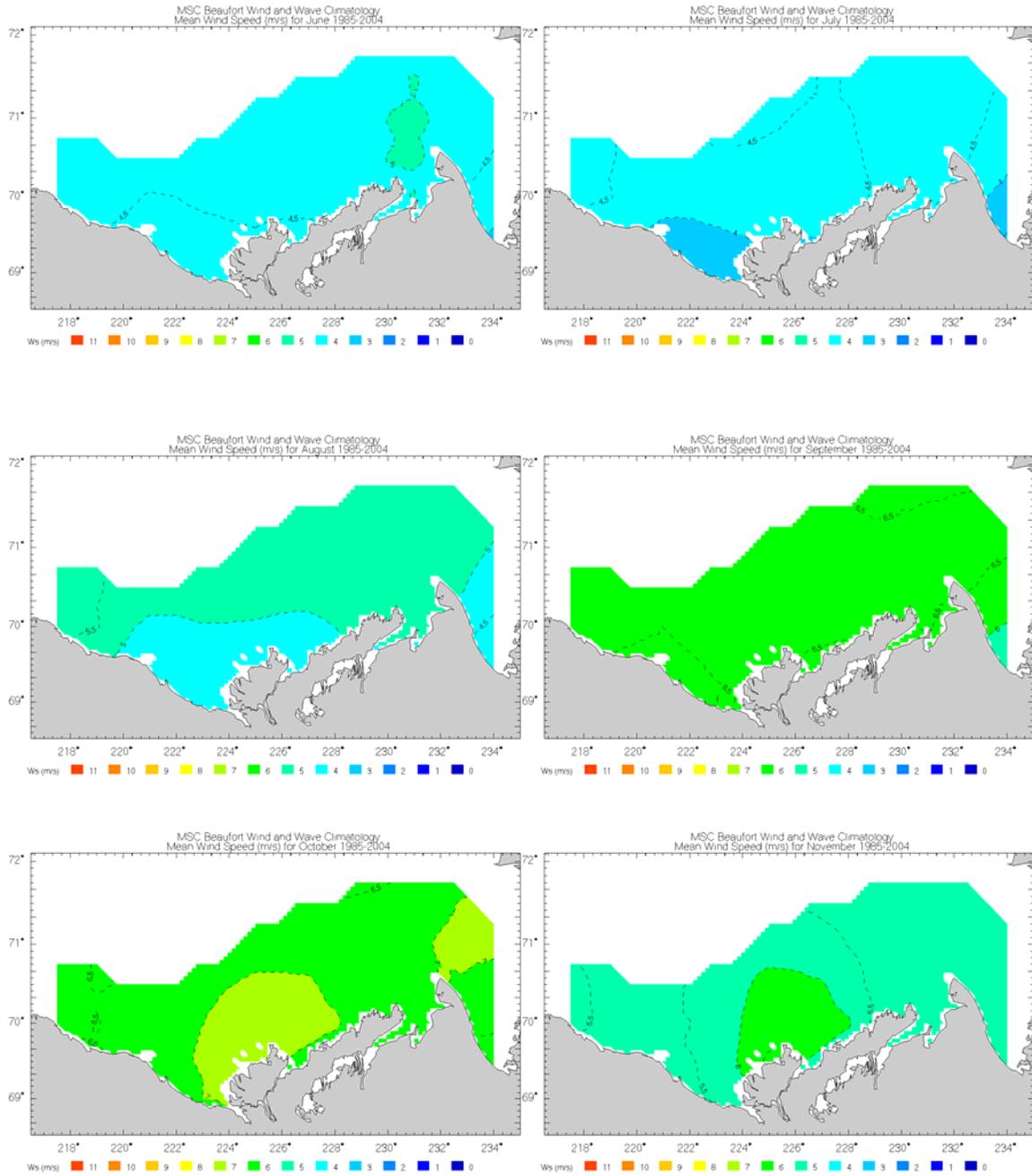


Figure 12 Mean monthly wind speeds (m/s) for June-November 1985-2005.

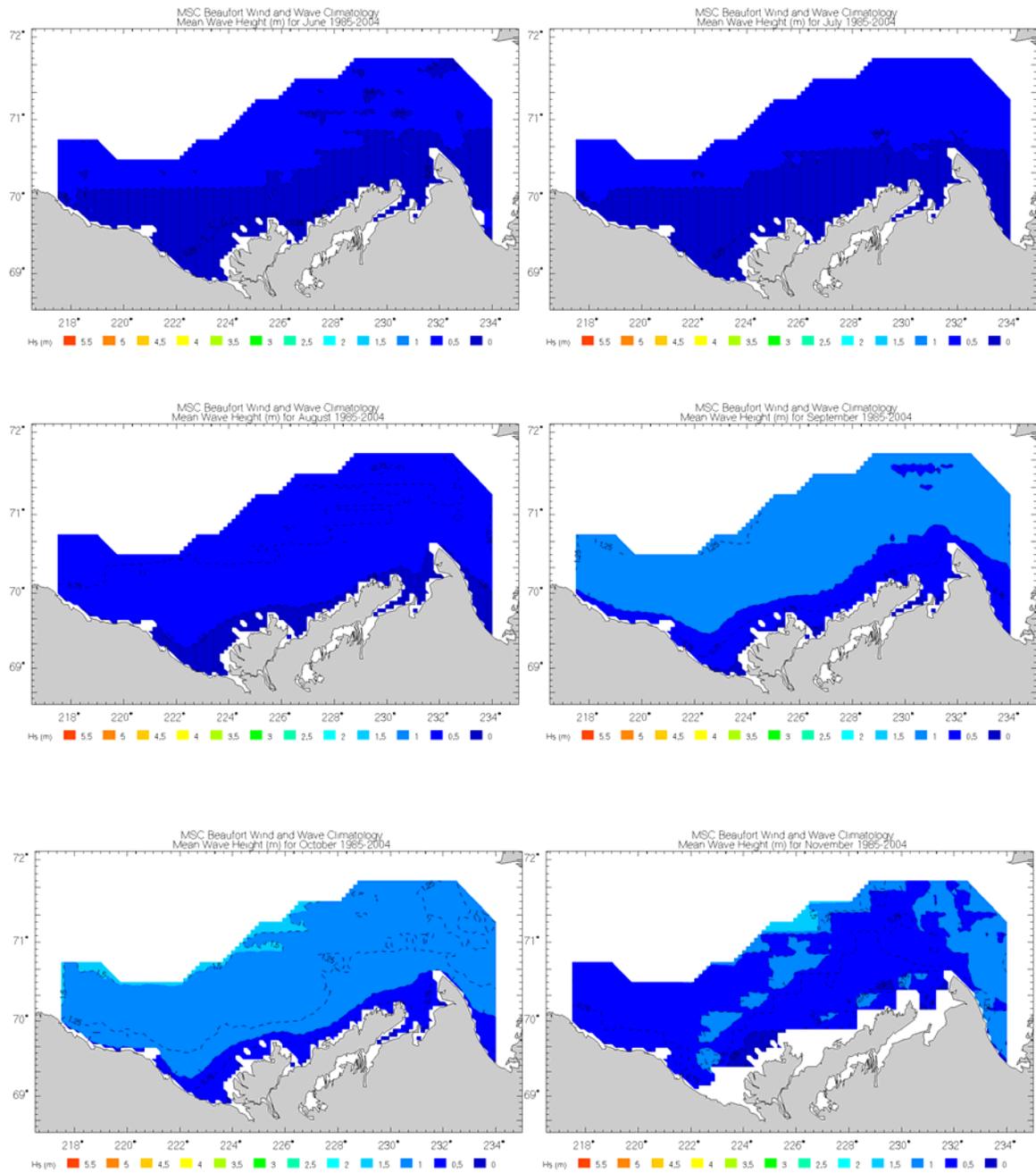


Figure 13 Mean monthly wave heights (m) for June-November 1985-2005.

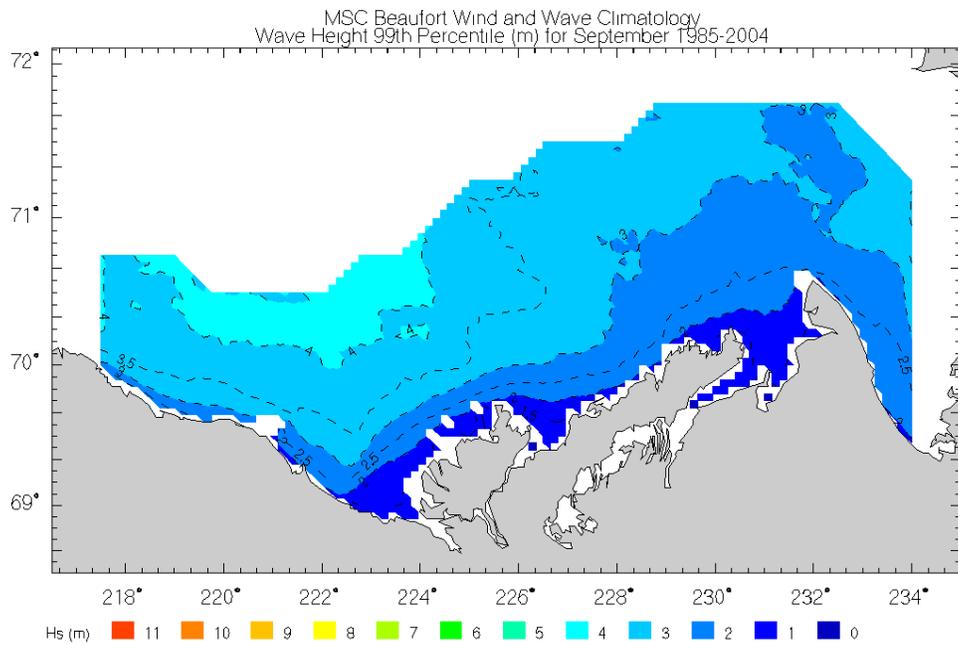
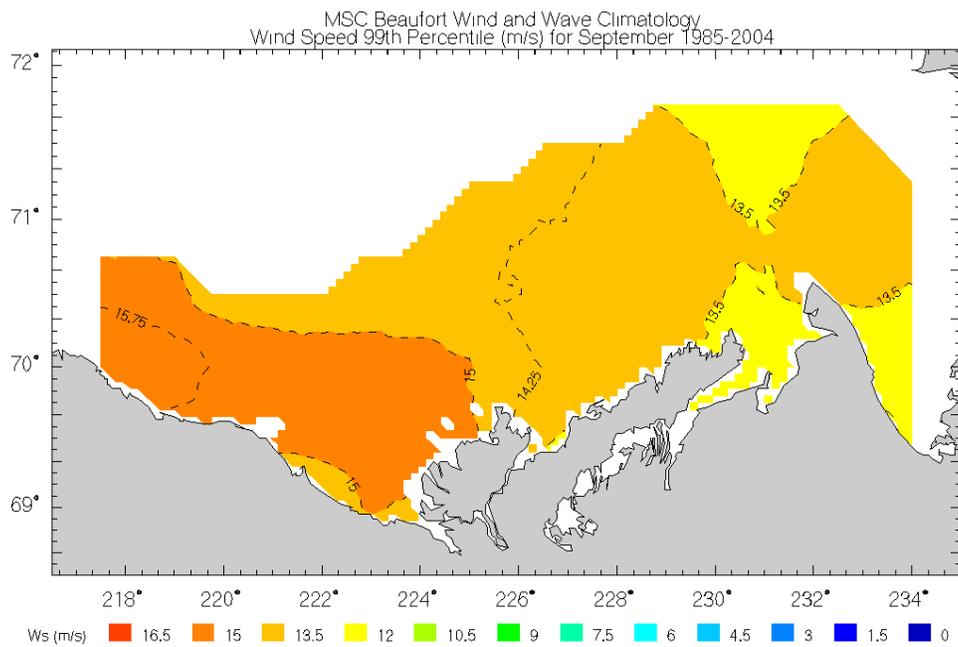


Figure 14 99th percentile winds (top, m/s) and wave heights (bottom, m) for September 1985-2005.

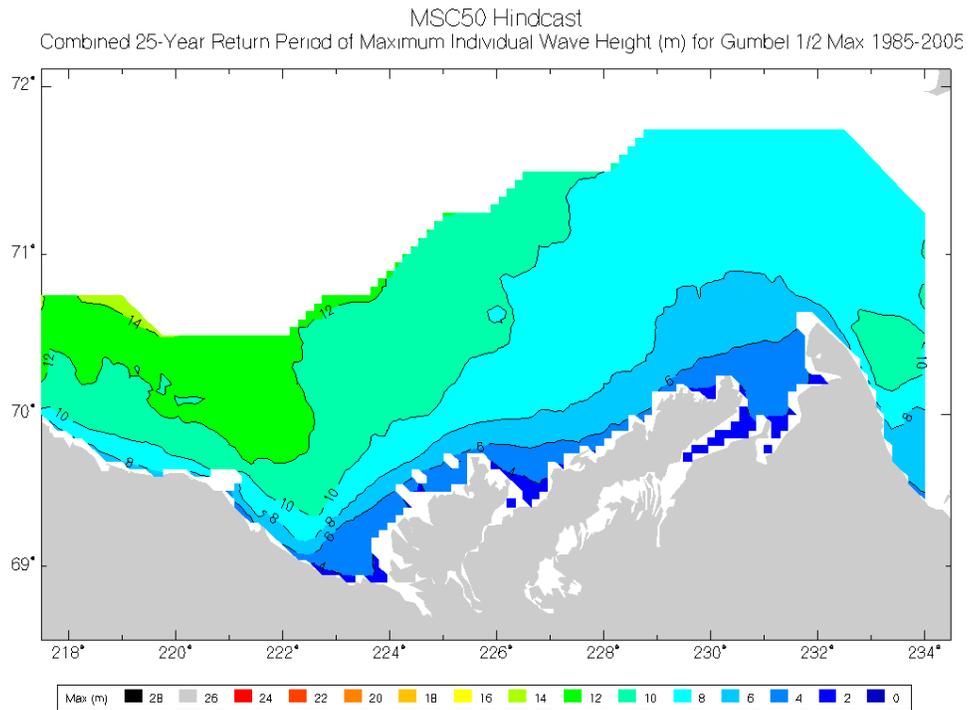
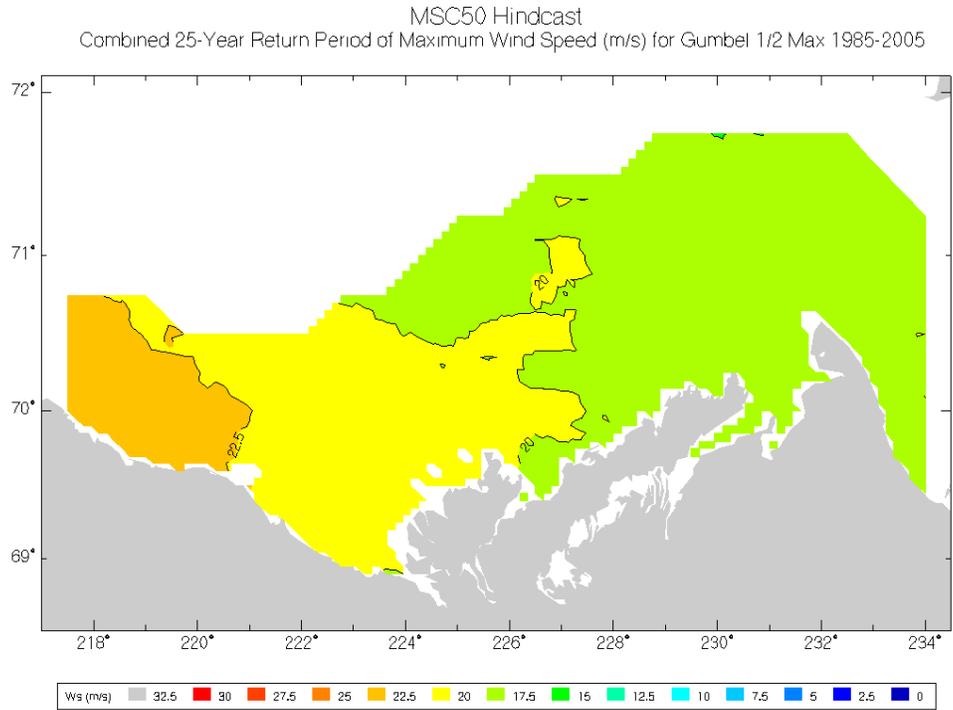


Figure 15 25-year computed wind speed (m/s, above) and maximum individual wave height (m, above) extremes.