HINDCASTING WAVE CONDITIONS ON THE NORTH AMERICAN GREAT LAKES

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1. INTRODUCTION

A long-term hindcast of wave conditions on Lake Ontario, one of the North American Great Lakes, has recently been completed, as a part of an overall assessment of shoreline erosion and lake level regulation on the lake (Eberhardt and Eryuzlu, 2004). A key objective of the hindcast development was the prediction of wave conditions around the perimeter of the lake for a minimum time period of 40 years, as the hindcast waves were subsequently employed to numerically simulate sediment transport. Coastal erosion and sediment processes on the Great Lakes are strongly linked to lake water levels, which exhibit some relatively long-term (measured in decades) cycles of variation.

Lake Ontario is the smallest of the five Great Lakes, having a length of approximately 310 km and an average width of 85 km. The average depth of the lake is 86 m and the maximum depth is 244 m, as may be noted in Figure 1. Larger waves on Lake Ontario are mainly produced by large scale synoptic extratropical weather systems (referred to as winter storms) and, to a somewhat lesser degree, by meso-scale systems in summer. The general direction of movement of weather systems over Lake Ontario is from west to east, consistent with the general circulation of the atmosphere in the mid-latitudes.

The hindcast was conducted using a second generation spectral wave model, and employed a unique methodology for wind field development, as described below. The hindcast results were validated against historical long-term wave buoy measurements.

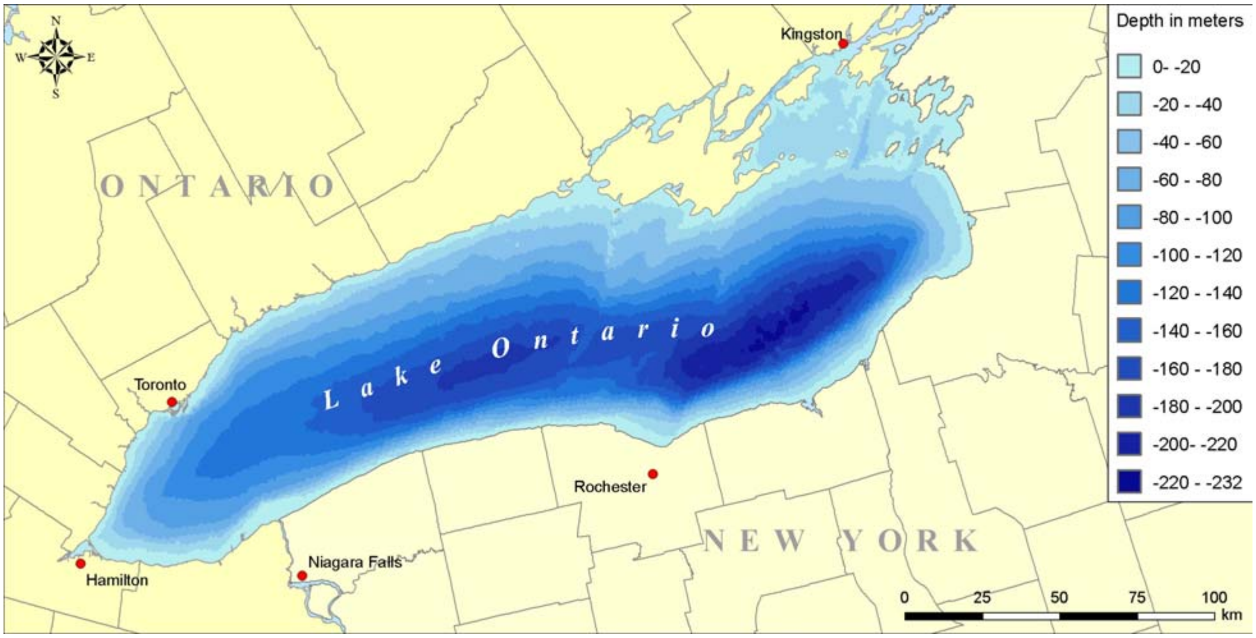

Figure 1 Location Plan for Lake Ontario

2. PREVIOUS WAVE HINDCAST INVESTIGATIONS

Previous wave hindcasts for Lake Ontario include those done by Resio and Vincent (1976 a, b) for the U.S. Army Corps of Engineers, the Ontario Ministry of Natural Resources (1988a, b and c) and the Wave Information Study by Rienhard et al. (1991) for the U.S. Army Corps of Engineers.

Resio and Vincent, in their studies, described a comprehensive numerical hindcast procedure for the Great Lakes. This hindcast was also the first attempt within the Corps of Engineers to use a numerical scheme for wave calculations instead of the standard empirical /analytical approach. Resio and Vincent used wind data for a sixty-nine year period (1907-1975) to hindcast storm events. They classified storm events as days with average wind velocities over the lake of 25 knots or above, as recorded by ship's anemometers. The results from these studies, which were tabulated as return period statistics, were used in design criteria at hindcast sites along the US coastline.

The Ontario Ministry of Natural Resources developed, as part of a Shoreline Management Plan, a wave climate database for the Great Lakes in the province of Ontario. For that study, a two-dimensional wave prediction model was utilized which was originally developed by Donelan (1977) and later modified by Schwab et al. (1984). Gridded wind fields interpolated over the lake from several land-based stations were used as input to the hindcast. Computed wave fields were calibrated against short-term recorded wave data at four locations. The wave database covered the period from 1964 to 1983.

The US Army Corps of Engineers completed a wave hindcast for thirty-two locations along the U.S. shoreline of Lake Ontario for the period 1956-1987 under the Wave Information Studies Program. A second-generation hindcast model, WISWAVE, was employed, using an input grid at 16 km resolution. The wave model was driven by means of measured winds from six land-based stations surrounding the lake. The winds were interpolated over the grid at 3-hr intervals using an inverse distance interpolation routine with a r^{-3} spatial weighting function, where r is the distance from the land station to the overwater grid point of interest. The model results were calibrated with measured wave data at two locations, with adjustment in wind speeds performed based on statistical comparison of wave heights and periods. Final validation was completed using two years of recorded wave data at two locations on the lake, Main Duck Island and near Toronto. Ice effects were not included in the hindcast.

The present hindcast differs from the earlier investigations of Lake Ontario wave climate in the following respects.

- The hindcast covered a longer time-period (40 years from 1961-2000) and utilized a much higher resolution (3 km) input/output grid.

- Wind data from a greater number of meteorological stations were used in the present study than in earlier work. Winds were interpolated at hourly intervals over the grid using the state-of-the-art Natural Neighbor Interpolation Technique (described below). Objective wind calibration procedures were also applied to both land based and buoy wind stations.

- An improved second-generation spectral wave model was used for the wave hindcast. Several sensitivity tests were performed to select the optimum parameters such as grid resolution, number of frequencies and directional bins.

- The extent of ice cover over Lake Ontario (gridded ice data from 1973-2000 and seasonally averaged data prior to this) was compiled and its effects were included in the wave model.

- Prior to preparing the final hindcast, the model results were validated against two multi-year sets of wave buoy measurements, as well as against data from various shorter term buoy deployments.

3. AVAILABLE WAVE DATA

Historically waves have been measured on Lake Ontario at a number of locations, as shown in Figure 2 and summarized in Table 1. Many of the deployments were relatively short term and occurred in the mid-1970's. Two of the most important datasets in terms of the hindcast validation were the long term data from buoys C45135 (1989-present) and C45139 (1991-present), located at the eastern and western ends of the lake, respectively. It is important to note that there was a considerable change in the type of buoy utilized after 1996, when the three metre diameter buoys were changed to twelve metre diameter Discus buoys. The larger buoys do not respond appropriately to the short period wave conditions prevalent on Lake Ontario. The later data were not used in the hindcast validation.

More recently, a directional wave buoy, 45012, has been deployed in central Lake Ontario by the US National Atmospheric and Oceanographic Administration (NOAA). The data from this buoy were not available at the time of the preparation of the hindcast.

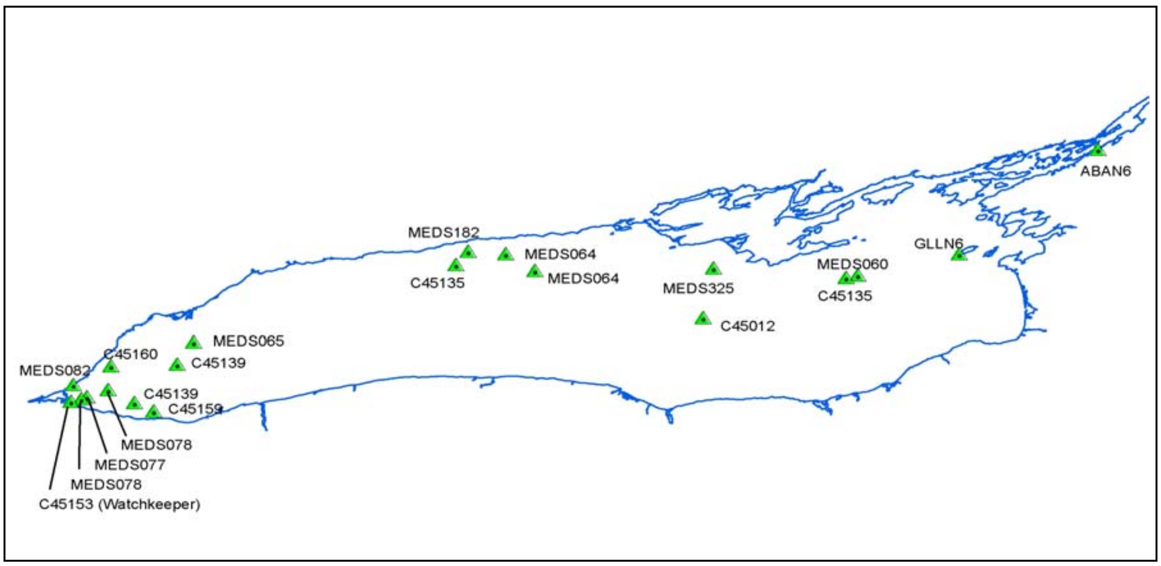

Figure 2. Historical Wave Measurement Locations on Lake Ontario

Table 1. Summary of Historical Wave Measurements Available in Public Domain

ID	Latitude	Longitude	Start Date	End Date
MEDS060	43.8	76.83	19/04/1972	21/11/1972
MEDS064	43.82	78.04	12/04/1972	05/12/1972
MEDS064	43.89	78.15	29/03/1973	12/12/1973
MEDS065	43.52	79.32	11/03/1792	06/06/1973
MEDS074	46.11	76.58	25/07/1973	01/11/1977
MEDS077	43.29	79.72	04/06/1976	30/11/1978
MEDS078	43.32	79.64	04/06/1976	16/06/1976
MEDS078	43.28	79.74	26/06/1976	26/08/1976
MEDS082	43.34	79.77	31/10/1972	15/12/1973
MEDS182	43.90	78.29	06/05/1982	17/11/1982
MEDS325	43.83	77.37	30/05/1994	13/10/1995
C45135	Varies	Varies	09/08/1989	Present
C45139	43.4	79.45	05/15/1991	Present
45012	43.62	77.41	03/2002	Present
C45153	43.27	79.78	30/08/2002	Present
C45159	43.23	79.47	02/06/2002	Present
C45160	43.42	79.63	02/06/2002	Present

4. HINDCAST WIND FIELD DEVELOPMENT

Wind data from buoy and land-based observing stations were used as the basis for hindcast wind field development. Consideration was given to the use of data provided by various atmospheric models (e.g. NCEP Re-analysis dataset, GEM, Eta..); however, these datasets suffered from either insufficient spatial resolution or insufficient temporal coverage.

The meteorological data were obtained from the Meteorological Service of Canada (MSC) and the US National Data Centre (NDC), NOAA. The numbers and locations of the observing stations varied in time, and an initial screening was completed to determine the most suitable stations to use in the hindcasting process, based on recording history, site exposure and other factors. Figure 3 shows the locations of the twenty-eight stations (including two buoys) selected for use as input to the hindcast, while Figure 4 indicates the number of meteorological stations operational each year during the 1961 to 2000 hindcast period. It may be noted that the numbers of stations increased significantly in the mid-1970’s, which had an impact on hindcast accuracy.

Once assembled, the following operations were then performed on the recorded meteorological data:

- Data consistency checks were carried out to ensure that the data fell within reasonable limits, for missing data, etc.

- An initial overland to overlake adjustment on wind speed and direction was performed based on Resio and Vincent (1976) for the land-based observations. This overland/overlake correction was applied based on selected directional octants from which the wind was originating.

- Conversion of the wind speed to an equivalent 10 m reference level, based on Businger et al. (1971) and considering air-water temperature difference. For this process, the average monthly lake wide basin water temperature data were compiled from the results of a GLREL Hydrological model (Croley, 1989). The monthly water temperatures were further interpolated into daily water temperatures.

As a final step in preparation of the wind data, the wind speeds from each available shore station were statistically compared to those measured at the closest buoy over the identical time period, and adjusted towards the buoy wind speeds. This adjustment was achieved on a station-by-station basis through creation of quantile-quantile plots of wind speed on a directional basis (compass octants), using data recorded over identical time periods. Wind speed factors, defined as the ratio of the overwater to overland wind speed, were derived as a function of the overland wind speed, and subsequently applied to entire wind speed time series at the station. In this manner, the land-based wind measurements were made statistically similar to the overwater measurements. It was inherently assumed in this process that the winds measured at the buoys were fully representative of overwater winds on Lake Ontario. For those meteorological stations not operational during the period of the buoy data, representative adjustments were applied based on nearby land-based stations.

An important consideration was the interpolation of the adjusted wind observations to the wave model grid. The observations varied significantly both spatially and temporally, and it was important that the selected interpolation technique adapt to these variations and provide a consistent overwater wind field representative of conditions on Lake Ontario. As well, the results of many spatial interpolation approaches, such as kriging and inverse distance weighting, require the appropriate selection of scale or calibration parameters, and a goal of the overall modeling process was to develop objective techniques for wind field derivation.

Based on these considerations, the Natural Neighbor Interpolation technique, as described in Sambridge et al. (1995), was utilized. This interpolation procedure has been successfully applied for a number of years by the Great Lakes Environmental Research Laboratory of NOAA (Beletzky and Schwab, 2001) to derive wind fields over the North American Great Lakes as forcing for hydrodynamic and wave models, and has been found to produce reliable, artifice-free results. Natural neighbour interpolation utilizes concepts from the field of computational geometry, such as Deulaunay triangulation, to derive interpolated values by finding weighted averages, at each interpolation point, of the values associated with that subset of the observation points which are natural neighbors of each interpolation point.

Natural neighbor interpolation has the following mathematical advantages:

- The original data (observation) values are recovered exactly at the data points.

- The interpolation is entirely local (every point is only influenced by its natural neighbor nodes).

- The derivatives of the interpolated function are continuous everywhere except at the data points.

In terms of the wind field generation, this approach has advantages in that the methodology addresses temporal variation in the observation points (the Deulaunay triangulation varies on an hour by hour basis, using the available data) and is a robust technique for addressing interpolation of clustered observation stations.

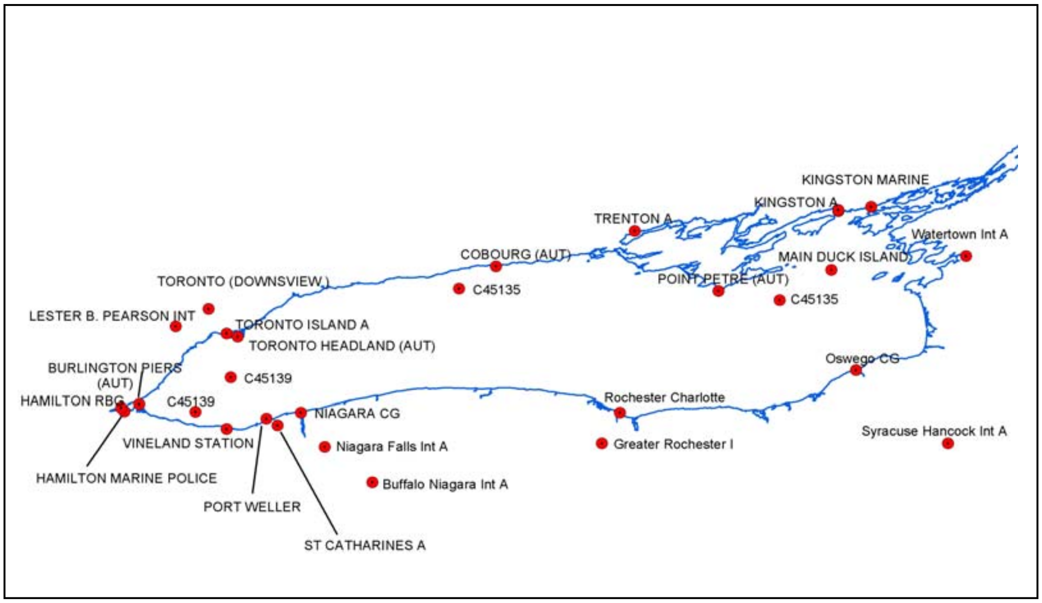

Figure 3. Map Showing Final Stations Utilized in Wave Hindcast

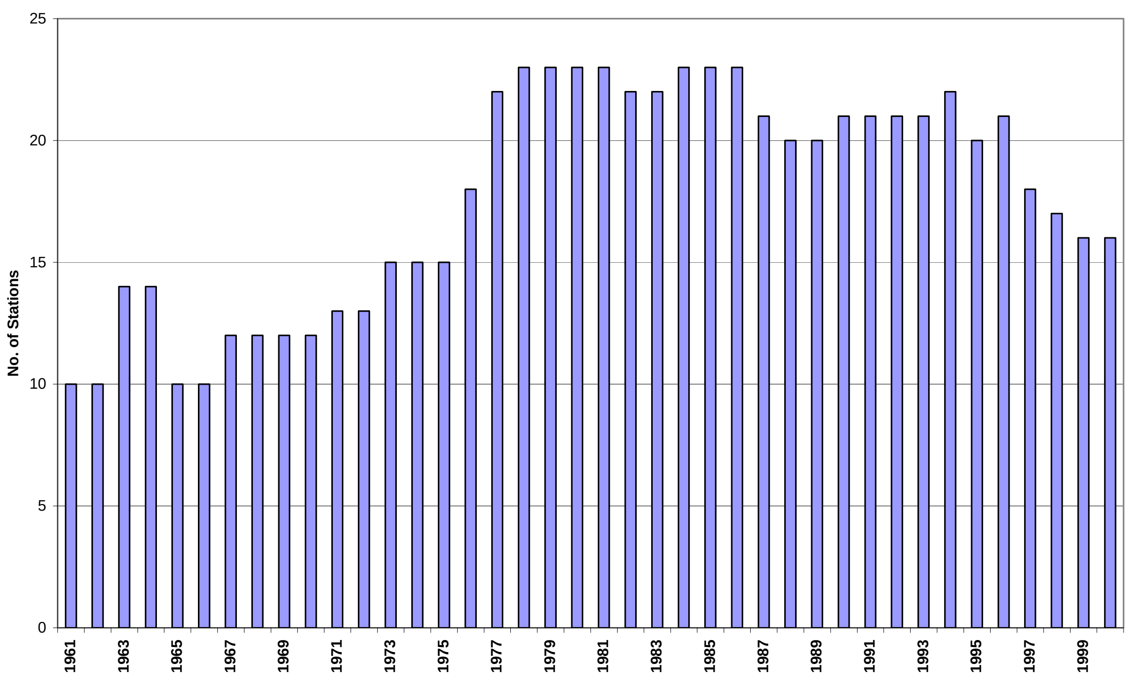

Figure 4. Number of Meteorological Stations per Year of Hindcast

5. THE WAVE MODEL AND ITS SETUP

The WAVAD model, as summarized in Resio (1981) and Resio and Perrie (1989), was used for the wave generation modeling carried out in this study. WAVAD is a second generation (2G) spectral wave model that maintains an equilibrium between the wind source and non-linear wave energy flux with an assumed f^{-4} shape for the wave spectrum. The non-linear wave interactions are represented as a momentum flux to the forward face (frequencies less than spectral peak) of the spectrum based on a constant proportion of the energy transferred out of the mid-range frequencies. Wave-wave interactions also transfer energy to the high frequency region of the spectrum where it is assumed that energy is lost due to breaking processes.

Inputs to the WAVAD model consisted of a regular grid defining the shoreline and bathymetry in the region of interest, as well as a spatially and temporally varying ice cover and wind field defined at the grid points. Output from the model included the spectral wave energy densities at all grid locations, from which standard parameters such as significant wave height (Hs), peak wave period (Tp), mean wave direction (MWD), peak wave direction and wave directional spreading were derived. Various sizes and resolutions of model grids were tested in the preliminary stages of this study and a 3 km grid was selected for the final hindcast. It was found from several sensitivity tests that a 3 km grid proved to be a good compromise for resolution as well as computational efficiency. The final numerical model grid (Figure 5) covered a domain extending from 76.08° W to 79.86° W and from 43.12° N to 44.254° N with a resolution of 0.027° (3 km). The bathymetry for Lake Ontario was derived from the NOAA GLERL topographic database.

Several sensitivity tests were conducted to assess frequency and directional bin resolution. Twenty-two frequencies (2.5 to 15 s) and twenty-four directional bins were chosen for the wave simulations, and a time step of 360 seconds was employed.

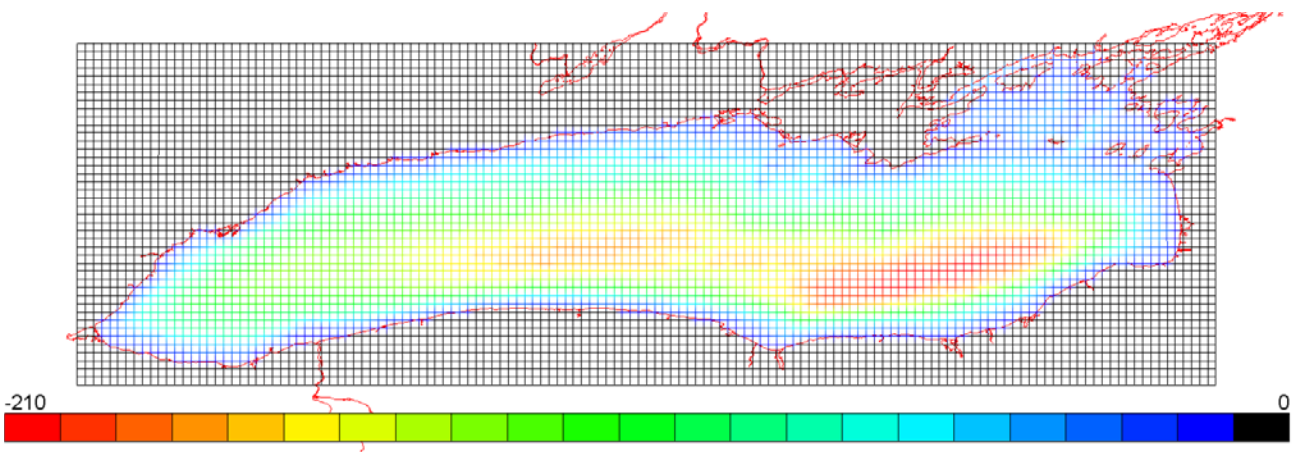

Figure 5 Wave Model Grid

Although Lake Ontario is never completely frozen, ice cover extends in the near shore and eastern part of the lake. For the present study, digital ice cover data from Great Lakes Environmental Research Laboratory (GLERL) were acquired. These data included 20-year (1960-1979) ice concentration climatology from a database developed by Assel et al. (1983) and polygonal digital ice data from 1973-2000 developed at GLERL.

The ice cover data considered for the study was categorized into two sets:

(A) Prior to fall of 1972 - ice climatology was utilized that provided average, minimum and maximum conditions twice a month.

(B) From fall of 1972 to spring 2000 - irregularly timed ice charts (typically two to three days apart) were utilized. An example of a typical ice cover chart is shown in Figure 6.

To incorporate these data into the WAVAD model, the data sets were read into a FORTRAN program to interpolate the data to the appropriate grid spacing and time increments for the model simulations. From the irregularly timed charts, daily values were interpolated. Since the first and last ice charts of the season typically showed a small amount of ice, it was decided that five days prior to the first, and five days following the last ice chart, it would be assumed that the lake was essentially ice free. Following a spatial interpolation routine, the result was a file containing the percentage of ice cover on each day, at each grid point. These data were then processed based on a threshold of thirty per cent. That is, wave energy at grid cells with values of ice coverage greater than 30 per cent were removed from the wave simulation. This was accomplished by preventing both wave generation and wave propagation in model grid cells above this ice threshold.

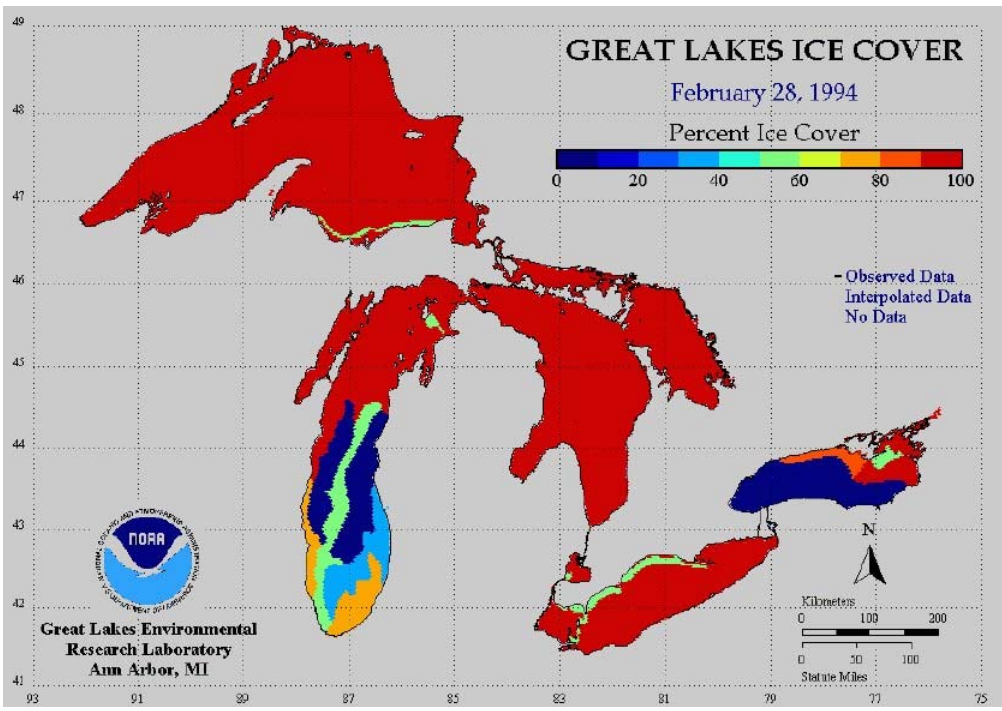

Figure 6. Great Lakes Ice Cover, Feb 28, 1994.
[Source: Great lakes Environmental Research Laboratory]

6. MODEL VALIDATION

An initial hindcast for the period 1989 to 1996 was carried out in order to validate the model based on direct comparisons between the WAVAD model results and the non-directional buoy data, C45135 and C45139, collected during this period. Since the C45135 buoy locations changed considerably, separate comparisons were made for different time periods. This buoy was located near to the northern shore in the central part of the lake during 1989-90, and subsequently moved to the eastern part of the lake during 1991-96. Buoy C45139 was located at the western end of the lake (Figure 2) and remained there during the period 1991-93.

Figure 7 shows a snapshot of wave conditions during February 1997, a period in which ice cover restricted wave growth and propagation at the northeastern end of the lake.

Figures 8 and 9 provide quantile-quantile and time series comparisons of the WAVAD results to buoys C45135 and C45139, respectively, while Table 2 summarizes the hindcast comparison statistics. Reasonable agreement was achieved in significant wave height while peak wave period was biased low in the comparisons at buoy C45139.

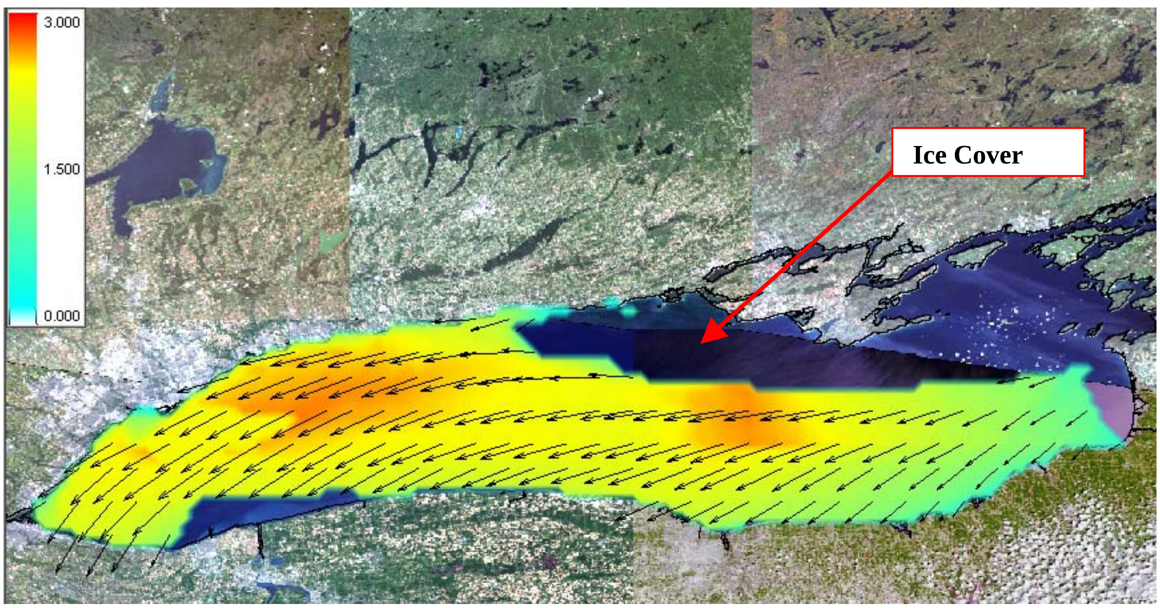

Figure 7. Snapshot of the Wave Field in February 1997

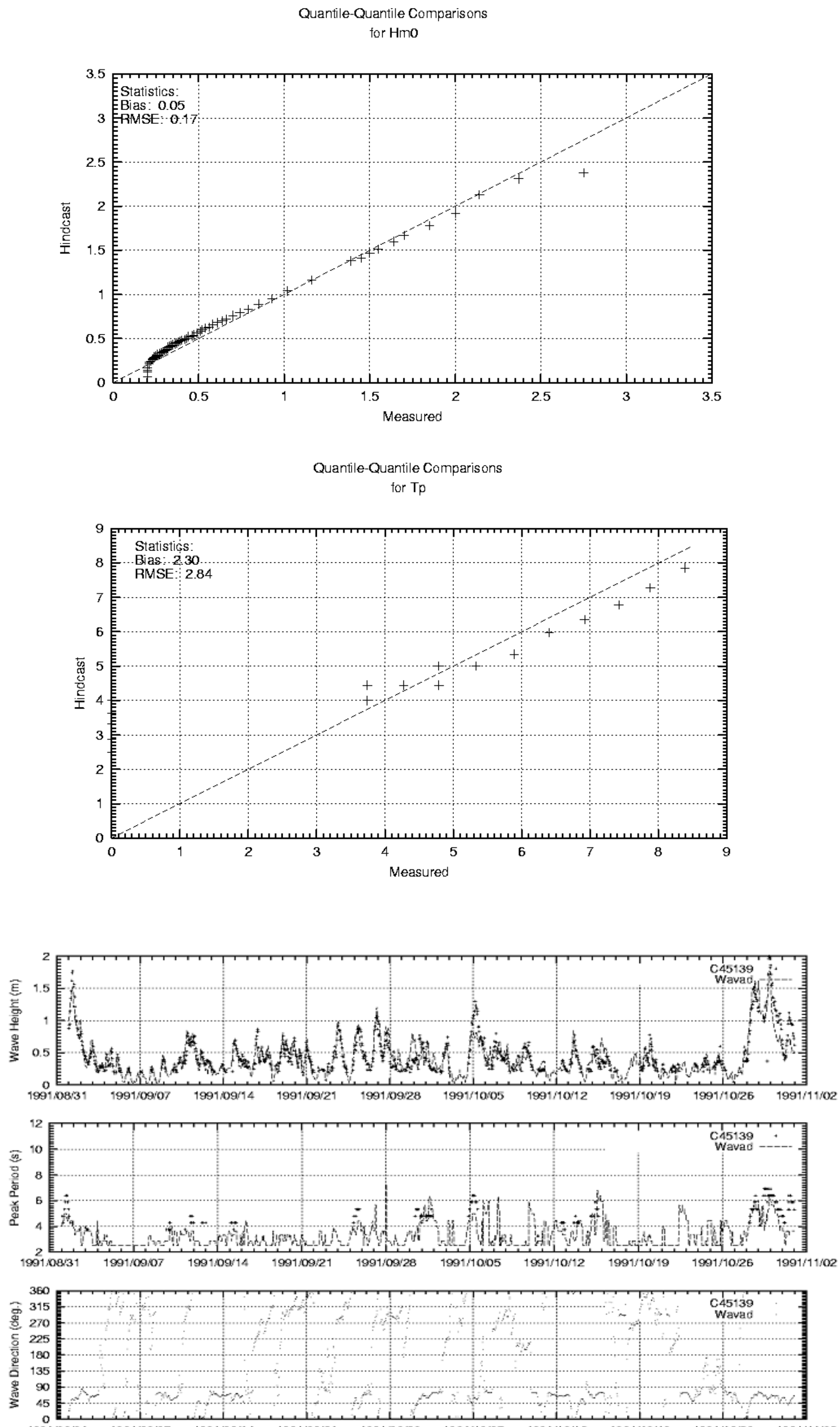

Figure 8. Quantile-Quantile (Hm0, TP) and Time Series Comparisons for Buoy C45135

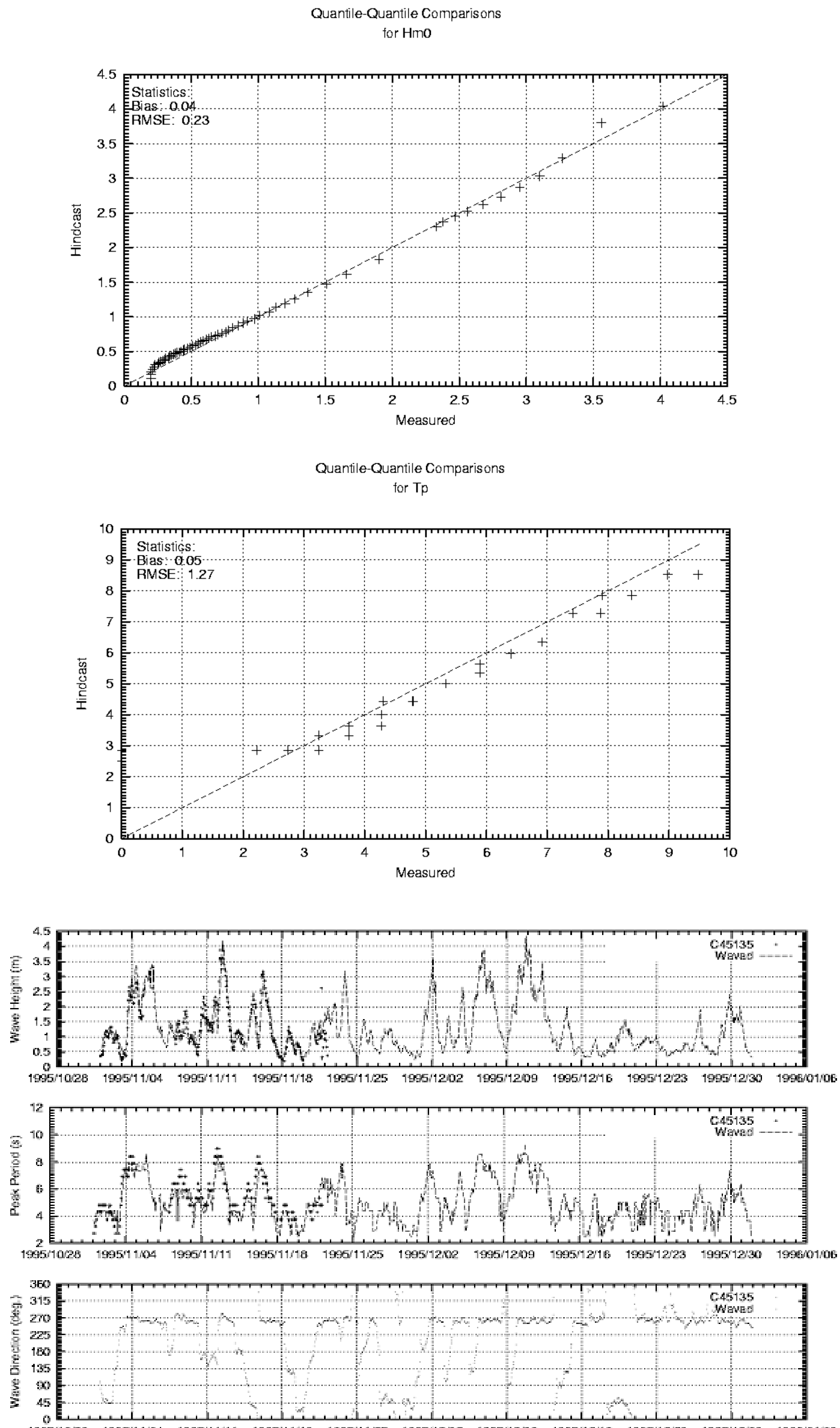

Figure 9. Quantile-Quantile (Hm0, TP) and Time Series Comparisons for Buoy C45139

Table 2. Summary of Comparison Statistics for the Hindcast

Buoy	Date	Hm0(m)			Tp (s)		
		Bias	***RMSE***	***Correlation***	***Bias***	***RMSE***	***Correlation***
C45139	1991-93	0.05	0.17	0.86	2.30	2.84	0.62
C45135	1989-90	0.03	0.22	0.92	0.06	1.61	0.64
C45135	1991-96	0.04	0.23	0.90	0.05	1.27	0.65

7. SENSITIVITY TESTS

Effect of Buoy Winds

An important consideration in the hindcasting process was the possible influence of the recorded wind data at the two long-term buoys, C45135 and C45139, on the wind field generation. As there are significant temporal gaps in the buoy coverage, it was important that the wind field derived from use of land-based observations alone be representative of wind conditions over the lake and that there not be large statistical differences in the quality of the wave climate if buoy winds were not available. The buoy influence was assessed through two means:

- Wind fields were interpolated using only the land-based observations and compared to actual recorded buoy winds during the same period. Excellent agreement was achieved.

- A hindcast was performed using only wind fields derived from the land-based observations. Table 3 provides a summary of the comparison statistics for the two long-term buoys with and without the inclusion of buoy winds. It may be noted that there was only a small degradation in wave performance when the buoy winds were excluded.

Table 3. Summary of Hm0 Comparison Statistics With and Without Inclusion of Buoy Winds

Buoy	C45135			C45139		
	Bias	***RMSE***	***Correlation***	***Bias***	***RMSE***	***Correlation***
With buoys	0.04	0.23	0.90	0.06	0.17	0.87
Without buoys	0.02	0.27	0.85	0.08	0.19	0.86

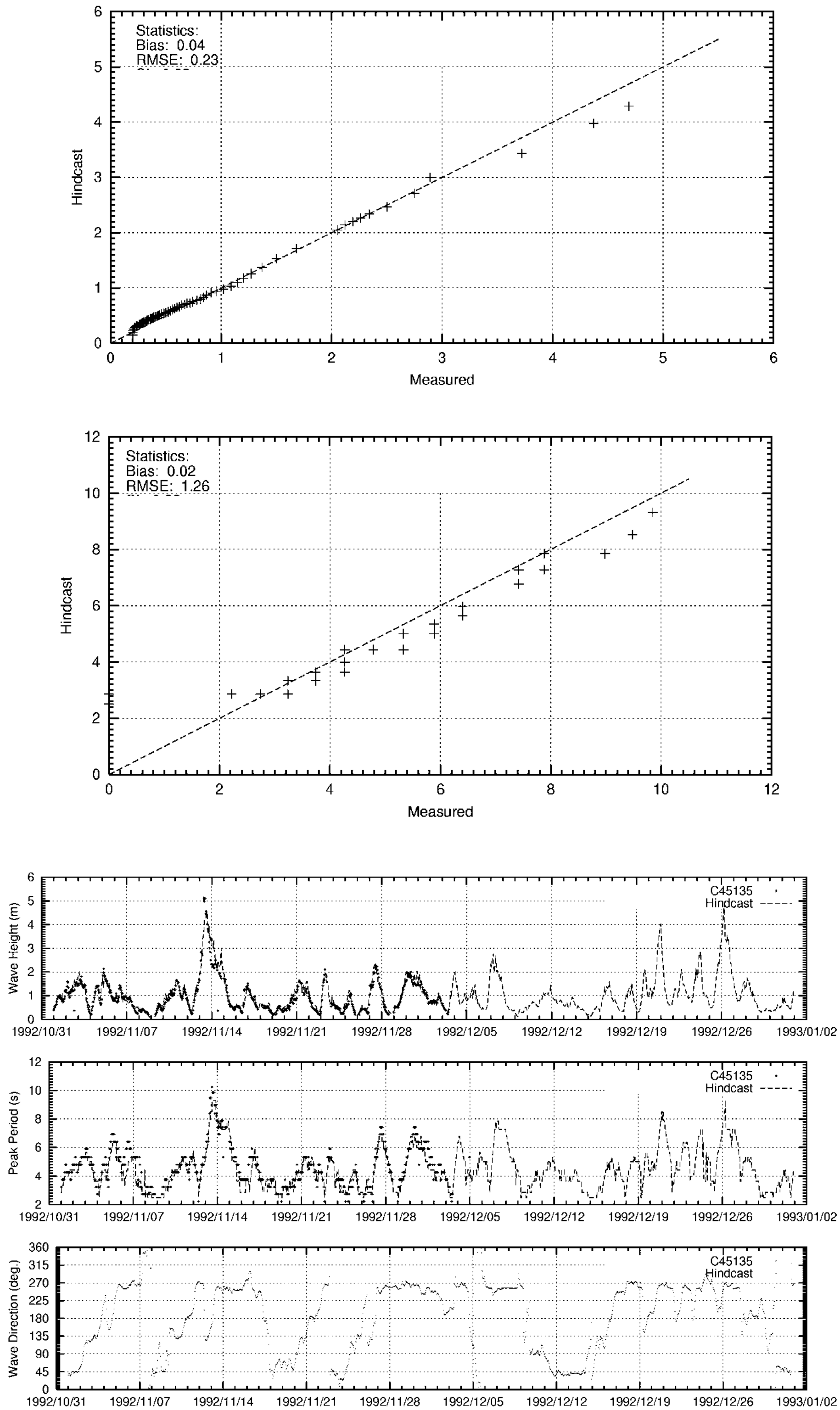

Figure 10. Quantile-Quantile (Hm0, TP) and Time Series Comparisons for C45135 (With Buoy Winds)

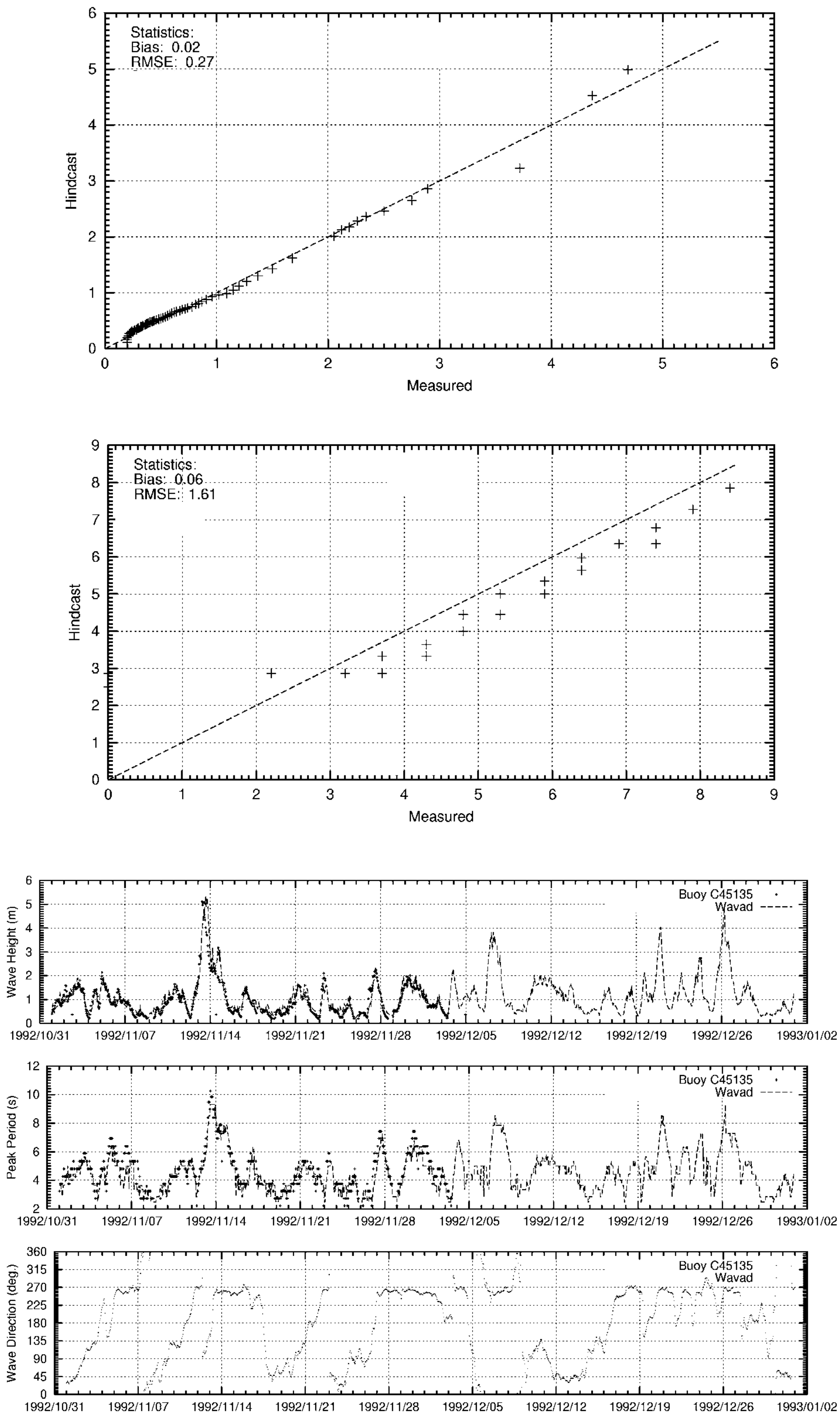

Figure 11. Quantile-Quantile (Hm0, TP) and Time Series Comparisons for C45135 (Without Buoy Winds)

Temporal Variation in Observations Density

In the 1960's, meteorological data were available at eleven stations as compared to twenty-three in the 1990's. In order to assess the potential impact of the reduced observation network on the hindcast accuracy, a one year period (1991) was simulated in the model using only wind input from only those original stations that existed in the 1960's. In this case, only the wind data from the original eleven stations that existed in the 1960's were used. The results of this simulation were compared to estimated wave conditions using all twenty-three stations. It was noted in these comparisons that there was a probability of over-estimation of waves at the eastern end of the lake and under-estimation of the waves in the western end during the earlier time period.

9. PRODUCTION SIMULATIONS

Once the model validation had been completed, a final wave simulation for a 40 year period (1961-2000) was carried out, with the results archived for hourly intervals at 307 different deep water locations around the perimeter of Lake Ontario.

Figure 12 shows the maximum significant wave height in the hindcast period for four locations around the lake, while Table 4 summarizes the key wave statistics for these locations. The largest estimated wave heights occurred at the east end of the lake, consistent with the dominant westerly winds and storm behaviour in this region.

Table 4. Summary of Wave Parameter Statistics

	Hm0 (m)		**Tp (sec)**	
	Maximum	**Mean**	**Maximum**	**Mean**
East end	6.23	0.62	11.06	3.49
South end	5.50	0.72	9.31	3.72
West end	5.85	0.51	10.27	3.22
North	4.66	0.50	10.27	3.26

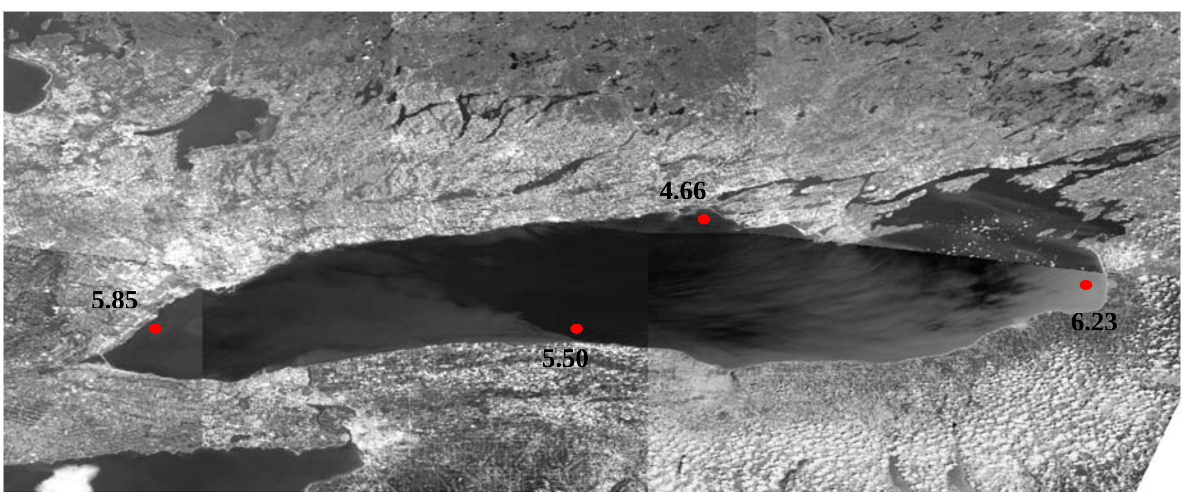

Figure 12. Maximum Hm0 (1961-2000) for Various Locations in Lake Ontario

10. SUMMARY

A long-term hindcast has been performed for Lake Ontario, covering a 40 year period from 1961 to 2000, with hourly results archived at 307 locations around Lake Ontario. The second-generation spectral wave model, WAVAD, was used for the hindcast, employing an input grid of 3 km resolution, which was significantly more detailed than previous hindcasting efforts on the lake. The influence of ice cover on wave generation was included in the hindcast, making use of polygon ice cover data for the period 1973-2000 and seasonally averaged data prior to this. The hindcast model was driven by wind fields derived largely from land-based meteorological data recorded at observing stations around the perimeter of the lake. A unique aspect of the hindcast was the use of objective procedures for wind field adjustment, based on statistical comparisons to available buoy winds, as well as the use of a natural neighbour scheme for interpolation of the observing station winds to the wave model grid.

Reasonable agreement was achieved in comparisons to the available long-term wave buoy datasets.

One potential area of improvement to the hindcasting process that will be explored in future efforts will be an improved representation of changes in wind direction from land-based observations to overwater winds. In addition, comparisons will be carried out with directional wave buoy data now available at one location in the lake.

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