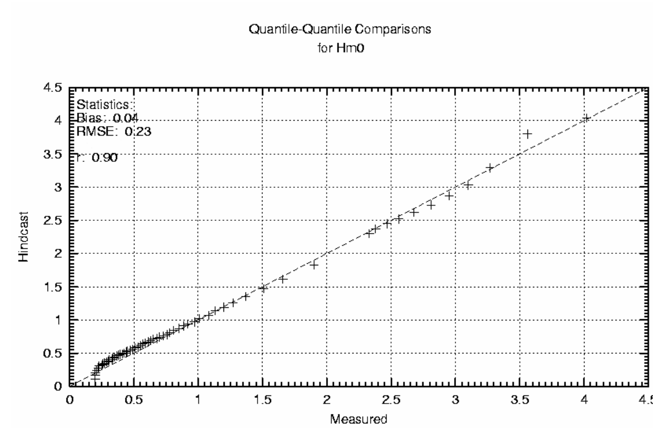
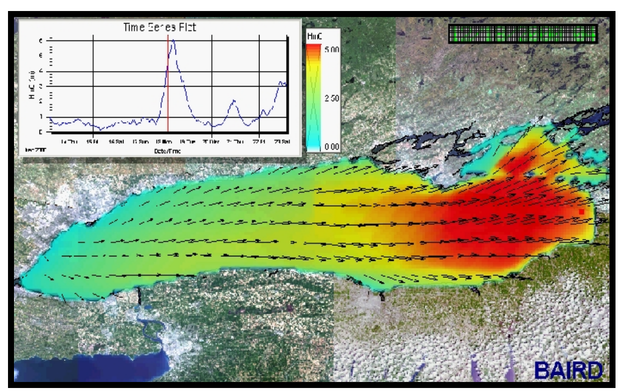
International Joint Commission and USACE





Lake Ontario WAVAD Hindcast for IJC Study

October 2003

10389.02

This report has been prepared by:

W.F. BAIRD & ASSOCIATES COASTAL ENGINEERS LTD.
1145 HUNT CLUB ROAD, SUITE 500
OTTAWA, ONTARIO
K1V 0Y3
CANADA

For further information please contact
Dr. Douglas Scott at 613-731-8900 or dscott@baird.com

TABLE OF CONTENTS

International Joint Commission *1*

1.0 INTRODUCTION 1

1.1 Previous Studies 1

2.0 OVERVIEW OF THE PRESENT STUDY 3

3.0 CLIMATIC CONDITIONS AROUND LAKE ONTARIO 5

4.0 AVAILABLE DATA 7

4.1 Meteorological Data 7

4.2 Buoy Data 17

4.3 Water Temperature 23

4.4 Ice Cover 23

5.0 WAVE MODEL 26

6.0 METHODOLOGY 29

6.1 Data Assembly 29

6.2 Pre-processing of Wind Data 29

6.2.1 Data Consistency Check 29

6.2.2 Initial Overland-Overlake Wind Adjustments 30

6.2.3 Conversion to 10 m Elevation 30

6.3 Final Wind Field Adjustment 31

6.4 Interpolation of Wind Data to WAVAD Grid 32

6.5 Wave Model Grid Setup 33

7.0 MODEL RESULTS AND VALIDATION 34

7.1 Comparison of WAVAD Model Output with Observed Data 35

8.0 FINAL WAVE SIMULATION FOR THE 40 YEAR PERIOD 46

9.0 SUMMARY AND CONCLUSIONS 50

REFERENCES 51

APPENDICES

I WIND FIELD ADJUSTMENT FOR TORONTO INTERNATIONAL AIRPORT

II WIND FIELD ADJUSTMENT FOR PETRIE ISLAND

III COMPARISON OF WIND SPEEDS (WITH AND WITHOUT BUOYS)

IV WAVE MODEL VERIFICATION - WITH C45135 BUOY

V WAVE MODEL VERIFICATION - WITH C45139 BUOY

VI COMPARISON OF WAVAD RESULTS WITH AND WITHOUT BUOY WINDS

VII COMPARISON OF WAVAD RESULTS (11 METEOROLOGICAL STATIONS)

1.0 INTRODUCTION

The International Joint Commission (IJC) is undertaking a comprehensive five year study to assess and evaluate the current criteria used for regulating water levels on Lake Ontario and in the St. Lawrence River. A series of Technical Work Groups (TWGs) were formed to investigate water level impacts on the multiple and diverse users groups affected by regulation, including: riparian land owners (coastal), the natural environment, recreational boating, hydro electric power generation, commercial navigation and municipal/industrial water uses. The Coastal TWG is investigating water level impacts on the following Performance Indicators (PI): erosion, flooding, existing shoreline protection structures, beach access, regional sediment budgets and barrier beaches. In addition to time series water levels, accurate historical wave data is required to model and predict impacts to these Coastal PI.

The objective of this study is to develop a 40 year hourly wave climate database for Lake Ontario, using the years 1961 to 2000 as the reference period. The overall study concept was developed in consultation with ERDC (Engineering Research and Development Centre) as part of the WIS (Wave Information Study) program. The technical part of the program was created with the assistance of Bob Jensen of Coastal Hydraulics Laboratory (CHL) and David Schwab of GLERL (Great Lakes Environment Research Laboratory of NOAA).

1.1 Previous Studies

Previous wave hindcasts for Lake Ontario include those done by Resio and Vincent (1976 a, b) for the U.S. Army Corps of Engineers and by a number of Canadian firms for 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. They also employed a suitable formulation to use measured overland winds to estimate overlake winds. 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 69 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 Canadian hindcasts were developed for the Ontario Ministry of Natural Resources as part of a Shoreline Management Plan designed to satisfy the need for a wave climate database for the Great Lakes in the province of Ontario. For this study, a two dimensional wave prediction model was utilized which was originally developed by Donelan (1977), and

Hudson and Donelan (1978), at the Canada Centre for Inland Waters (CCIW) and modified by Schwab et al. (1984). Gridded wind fields interpolated over the lake from several land-based stations were used. The overlake wind was estimated using the formulation given by Philips and Irbe (1978), which considers stability class and monthly air water temperature difference. Median bi-weekly ice cover was also considered (6/10 coverage or greater assumed to be land). Computed wave fields were calibrated against recorded wave data at Main Duck Island and Toronto (1972), with visual assessment of time series plots (hindcast vs. recorded) to select the best model wind stress factor (gamma = 0.08) and spreading factor (0.5 (+/-90 degrees)). Model results were validated with recorded data at Cobourg and Kingston (1973). For Lake Ontario, the wave database covers the period from 1964 to 1983. The grid size and number of archived stations are specific for each lake and were selected to provide an accurate representation over the lake with the minimum number of sites. Because of damage during previous storms from shoreline erosion at existing and proposed developments, these stations were considered priority sites by the Ministry of Natural Resources and Conservation Authority.

Rienhard et al. (1991) have completed a wave hindcast for 32 locations along the shoreline of Lake Ontario for the periods 1956-1987 under the Wave Information Studies Program for the U.S. Army Corps of Engineers. They used a 10 mile square grid covering the entire lake. The measured winds from land stations surrounding the lake were converted to an elevation of 10 m after being adjusted for the effects of air-water temperature differences and the land water interface. The winds were then interpolated over the grid at 3-hr intervals. Model results were calibrated with measured wave data at Cobourg and Kingston (1972) with adjustment in wind speeds based on statistical comparison of wave heights and periods. Model results were verified with recorded wave data at Main Duck Island and Toronto. Ice cover data were compiled using the database of GLERL. Due to the low percentage of ice coverage experienced in Lake Ontario during a normal winter, the effects of ice cover were felt to be insignificant. Thus, ice effects were not included in the Lake Ontario hindcast. Though the hindcast of Rienhard et al. (1991) was more reliable than that of earlier studies, their study also suffered from the following shortcomings. Only data from six land based stations for wind field generation were used, and simple transformation and tuning methods were applied. A simple inverse distance interpolation routine with a r^{-3} spatial weighting function was used to interpolate winds for the region over the lake, where r is the distance from the land station to the overwater grid point of interest. Both wave model grid resolution (10 mile) and the resolution of the frequency and direction bins were coarse. Model results were validated only with two years of data at two locations, and the study also suffered from a lack of comparison with measured winds.

2.0 OVERVIEW OF THE PRESENT STUDY

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

- The 40 year hindcast period covers the years from 1961-2000. The total number of archived stations is 307, which enables us to cover the entire shoreline of Lake Ontario with a grid resolution of 3 km. (Previous studies used 16 km resolution.)

- Wind data from a greater number of meteorological stations were used in the present study than in earlier work. The quality of wind data in the 1980's and the 1990's is far better than in the earlier decades. Winds were interpolated at hourly intervals over the grid using the state-of-the-art Natural Neighbor Interpolation Technique. Advanced 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, model results were validated against two multi-year sets of wave buoy measurements, as well as against data from various shorter term buoy deployments.

This report summarizes the development of a 40 year wave hindcast for Lake Ontario. The main tasks undertaken during the course of this study are as follows.

- An assessment of available meteorological, wave, ice and water temperature data for Lake Ontario. Data sources are assembled and listed by station and time.

- The following environmental data from Environment Canada, National Data Centre (NOAA) and GLERL were acquired and assembled.

  - Hourly meteorological record, which includes wind speed, wind direction and air temperature.

  - Daily ice coverage data from 1973 to 2000 and climatological data prior to 1973.

  - Water temperature data.

- Wave data (spectral and summary wave data).

- Available data were assembled into a uniform format suitable for the software used in the hindcasting process. Various quality control tests were applied to the data. The daily data sets were interpolated on an hourly basis and combined with the other data.

- The bathymetric grid for the wave model was developed and tested with different resolutions.

- Spatially and temporally varying wind fields for the wave model grid were developed using a natural neighbor interpolation technique pioneered by GLERL.

- Various adjustments to the wind field were made so that the wind fields were statistically and geographically consistent over Lake Ontario.

- Completion of a final 40 year (1961-2000) wave field simulation. Data were archived at 307 locations along the entire perimeter of Lake Ontario.

3.0 CLIMATIC CONDITIONS AROUND LAKE ONTARIO

Lake Ontario is the smallest of the five Great Lakes of North America, having a length of 311 km and an average width of 85 km. The average depth of the lake is 86 m and the maximum depth is 244 m. The wave regime in Lake Ontario is mainly produced by large scale synoptic extra-tropical 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 mid latitudes. Super-imposed upon this is a meridional component (i.e. either north to south or south to north). It is the track of the weather system that mainly determines the local geographical area in the lake where wave generation occurs. The intensity of the wind field associated with the weather system determines the wave spectrum (wave amplitude and period).

Recent intense wave regimes in Lake Ontario are related to significant climate change that is happening over the Great Lakes of North America in general, and the lower Great Lakes area in particular (Sousounis, 2002).

The Canadian Meteorological Service (Lewis, 1987) defines a storm over the Great Lakes as a weather system that produces wind speeds greater than 48 knots (88 kph). Such systems are mainly of two types: extensive synoptic scale systems (severe storms during winter) and summer squall and thunder storm activity. The strong winds and waves generated by the summer weather systems are much shorter in duration. Most of the events outside the summer months of June, July and August are attributable to migrating low pressure systems (of the extra-tropical type), although adjacent high pressure systems often contribute greatly to the formation of a strong pressure gradient, and hence strong wind fields.

Summer weather systems that produce strong winds over Lake Ontario are meso-scale systems such as squall lines and thunderstorms. On rare occasions, a hurricane from the Gulf of Mexico could travel as far as Lake Ontario and still give rise to strong winds (for example, Hurricane Agnes).

Five different seasons are identified for the Great Lakes from the point of view of wind fields.

1) Winter-January, February and March. Freeze-up of the lakes and the connecting waterways.

2) Spring-April and May. Transition period. Decline in cyclone activity.

3) Summer-June, July and August. Most cyclonic storms track to the north of the Great Lakes. Localized storm events are caused mostly by convective and squall line activity.

4) Early fall-September and October. Transition period. Gradual increase in cyclone activity and decline in convective activity.

5) Late fall/ Early winter-November and December. Period of maximum instability. Water-air temperature difference is maximum, leading to deepening of cyclones over the Great lakes.

These storms could be categorized based on the source region or area of genesis. The following eight types are identified: Alberta Low, Colorado Low, Texas Low, Gulf Low, Hatteras Low, Lakes Low, Northwestern Low and Pacific Low.

As can be seen from Figure 3.1, Gulf Lows and Hatteras Lows do not influence Lake Ontario, at least in generating strong wind fields.

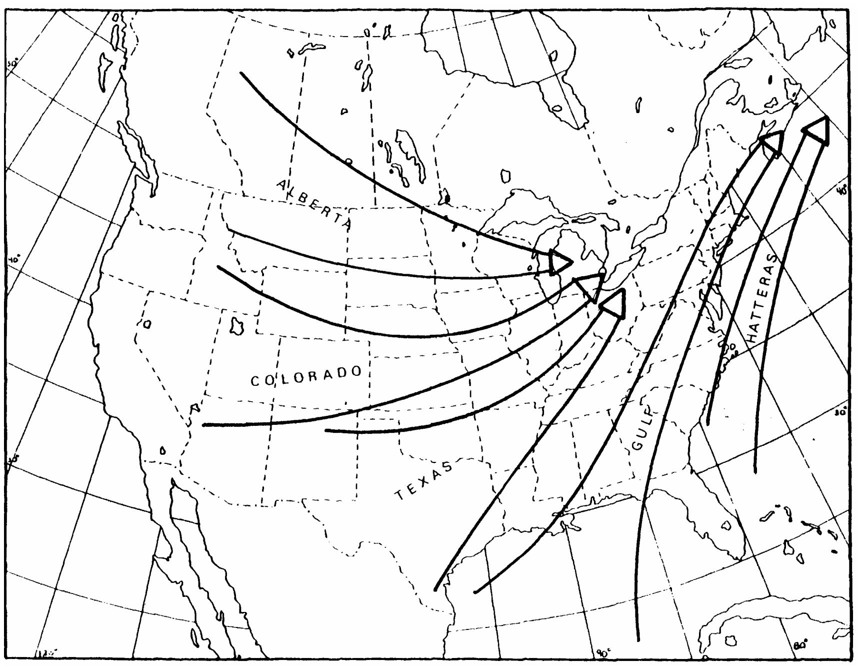


Figure 3.1 Storm Tracks Over the Great Lakes (Lewis, 1987)

4.0 AVAILABLE DATA

The prediction of waves in Lake Ontario largely depends upon the local meteorological conditions around the lake. The most important input to the model is accurate and representative wind data. It is generally accepted that the best method to obtain the climatology of winds over a bounded water body such as Lake Ontario is to use all available wind records at shore stations supplemented with any offshore buoy data. Validity, quality and availability of data were considered in the selection of land stations along Lake Ontario. In general, long-term stations have good quality data compared to that of automatic and short-term stations which suffer from gaps in the recorded data. This section of the report describes the input data for the following parameters: wind field, wave regime, water temperature, and ice cover.

4.1 Meteorological Data

Section 3.0, which describes the general climatology of the Great Lakes system, shows that strong wind fields capable of generating intense waves in Lake Ontario can exist year round due to two different source mechanisms: extra-tropical weather systems during winter and convective meso-scale systems during summer. However, it is generally recognized that the wave regimes generated by the large synoptic scale systems in winter are geographically more extensive and also could be more intense than the wave regimes produced by the convective systems.

The meteorological data are obtained from two main sources. Data for the Canadian stations are obtained from the Meteorological Service of Canada (MSC) and data for the USA stations are obtained from National Data Centre (NDC), NOAA. MSC has collected and compiled an extensive database of historical meteorological data containing wind speed, direction, sea level pressure, temperature and cloud cover for the period 1960 to 2000. The quality of the wind speed data varied in both space and time because the data were recorded with different instruments for different periods. Figure 4.1 shows the location of the meteorological stations around Lake Ontario and Figure 4.2 shows the stations used in the final analysis of this study. Figure 4.3 provides the number of meteorological stations available each year during 1961 to 2000. Prior to 1975, data from only 10 to 15 stations per year are available.

The primary task was to assemble the data into a standard format. Section 6.0 describes in detail the different methodologies used to achieve the assembly of these data. Tables 4.1 and 4.2 give a complete list of the Canadian and US meteorological stations along the shoreline of Lake Ontario. After analyzing available wind data, twenty-eight stations (including two buoys) were finally chosen for the wave hindcast. Table 4.3 summarizes data availability for each station and indicates those which were selected for the hindcast. These selected stations were also presented visually in Figure 4.2.

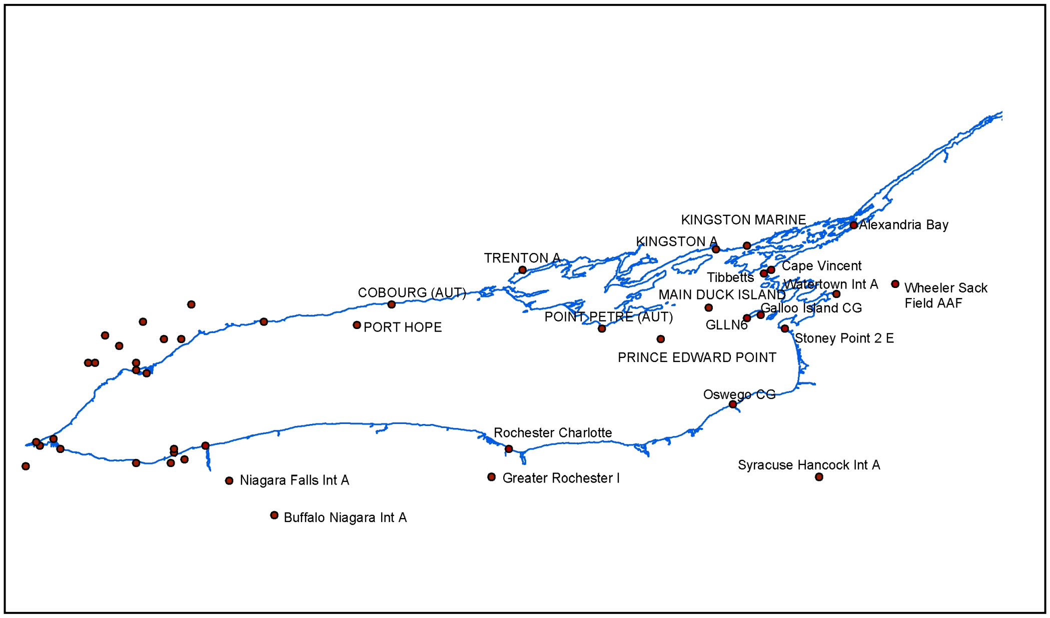


Figure 4.1a Map Showing Meteorological Station Locations Along Lake Ontario

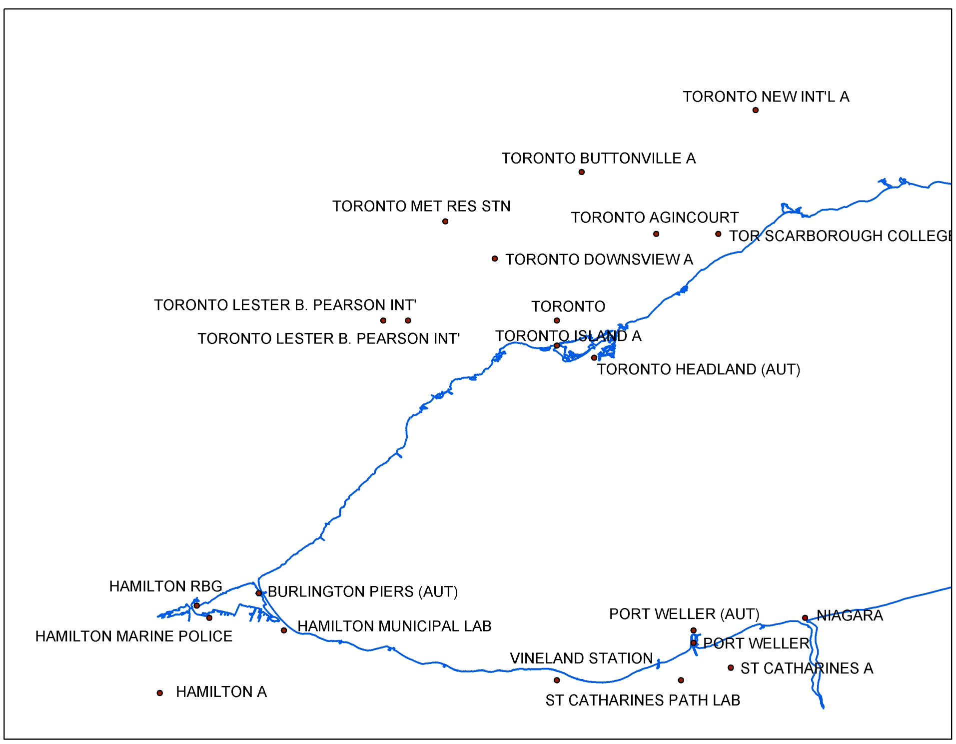


Figure 4.1b Close-up of the Map of Meteorological Stations Along Western End of Lake Ontario

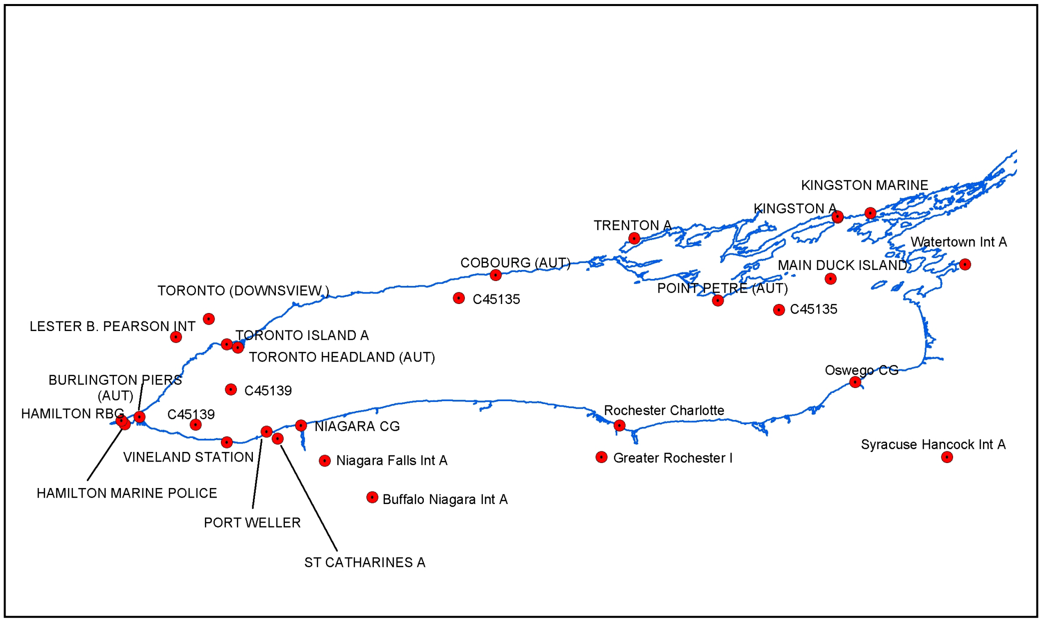


Figure 4.2 Map Showing Final Stations Considered for Wave Hindcast

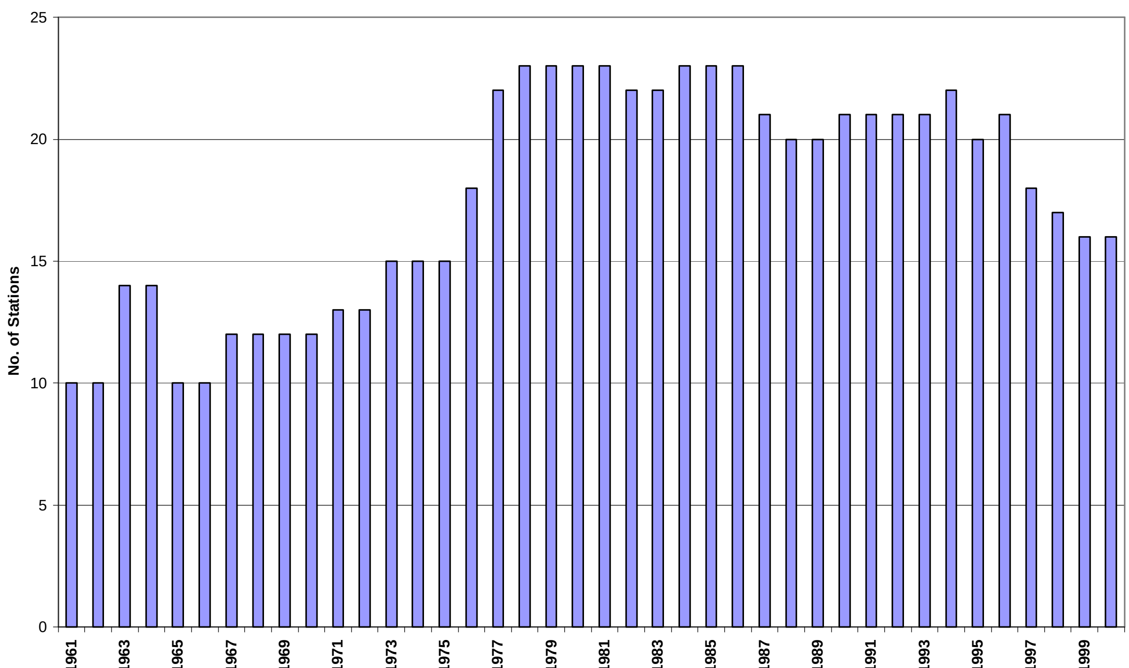


Figure 4.3 Number of Meteorological Stations per Year

Table 4.1

List of Canadian Meteorological Stations along Lake Ontario

Station Id	Station Name	Province	TC ID	Latitude	Lat	Min	Longitude	Long	Min	Elev.(m)	Start	End	Synoptic	Hourly	Temp	Precip.	Rate of Precip	Wind	Soil Temp	Evap	Sunshine	Radiation	Ozone	Upper Air	Snow	Tower	Air Quality	Nipher	Region
6104146	KINGSTON A	ONT	YGK	44.217	44	13	76.600	76	36	93	5/1/1967	present		D	X	X	X				S				@			N	O
6104153	KINGSTON MARINE	ONT	KMAR	44.233	44	14	76.450	76	27	107	5/1/1960	10/1/1967			@	@		B											O
6104ADF	KINGSTON (AUT)	ONT	KAUTO	44.217	44	13	76.600	76	36	93	5/1/1978	8/30/1988	H	G															O
6136699	PORT WELLER	ONT	WWZ	43.233	43	14	79.217	79	13		4/1/1967	present						@											O
6136699	PORT WELLER (AUT)	ONT	WWZ	43.250	43	15	79.217	79	13		4/1/1972	11/1/1982		H															O
6137287	ST CATHARINES A	ONT	YSN	43.200	43	12	79.167	79	10	98	6/1/1971	present		D	X	X	X											N	O
6137301	ST CATHARINES PATH LAB	ONT	YSN	43.183	43	11	79.233	79	14	99	2/1/1955	1/1/1962			@	@	X	B			S								O
6137301	ST CATHARINES CDA	ONT	YSN	43.183	43	11	79.233	79	14	99	1/1/1962	10/1/1964			@	X	X	B			S							N	O
6139145	VINELAND STATION	ONT	XVN	43.183	43	11	79.400	79	24	79	5/1/1958	12/31/1986			@	@	X	B	D		S								O
6151061	BURLINGTON PIERS (AUT)	ONT	WWB	43.300	43	18	79.800	79	48		1/4/1984	present																	
615105C	BURLINGTON (AUT)	ONT	WWB	43.300	43	18	79.800	79	48	78	5/1/1972	2/1/1976		H															O
6151684	COBOURG (AUT)	ONT	WNC	43.950	43	57	78.167	78	10	78	6/1/1972	present	H	H															O
6151968	DARLINGTON (AUT)	ONT	DAR	43.867	43	52	78.783	78	47	93	4/1/1972	11/1/1974		H															O
6153194	HAMILTON A	ONT	YHM	43.167	43	10	79.933	79	56	238	1/1/1970	present	X	D	X	X	X											N	O
6153264	HAMILTON MARINE POLICE	ONT	YHM	43.267	43	16	79.867	79	52	77	11/1/1953	3/31/1990			@	@		B											O
6153290	HAMILTON MUNICIPAL LAB	ONT	YHM	43.250	43	15	79.767	79	46	76	2/1/1960	11/1/1962						B											O
6153300	HAMILTON RBG	ONT	HRBG	43.283	43	17	79.883	79	53	102	7/1/1951	1/1/1997			@	X	X	B		A	S							N	O
6154820	MAIN DUCK ISLAND	ONT	MDIS	43.933	43	56	76.633	76	38	75	5/1/1959	9/30/1986			@	@		B											O
6156559	POINT PETRE (AUT)	ONT	WQP	43.833	43	50	77.150	77	9	79	5/1/1972	present	H	H															O
615672C	PORT HOPE	ONT	PH	43.850	43	51	78.333	78	20		7/25/1988	3/11/1991		H															O
615672C	PRINCE EDWARD POINT	ONT	PEP	43.783	43	47	76.867	76	52	74	3/11/1991	12/3/1992		H															O
6158350	TORONTO	ONT	YYZ	43.667	43	40	79.400	79	24		5/1/1959	5/1/1969		D	@	X	X		D		S	A						N	O
6158363	TORONTO AGINCOURT	ONT	TAGN	43.783	43	47	79.267	79	16	180	9/1/1952	1/1/1968			@	@		B											O
6158443	TORONTO DOWNSVIEW A	ONT	TDWN	43.750	43	45	79.483	79	29	198	9/1/1958	6/1/1982	X	D	@	X	X	U										N	D
6158578	TORONTO HEADLAND (AUT)	ONT	THEAD	43.617	43	37	79.350	79	21	87	4/1/1972	4/1/1998	H	H															O
6158665	TORONTO ISLAND A	ONT	YYZ	43.633	43	38	79.400	79	24	77	12/1/1962	12/8/1999	H	H															O
6158666	TORONTO IS A (AUT)	ONT	TAUTO	43.633	43	38	79.400	79	24	77	1/1/1970	6/11/1987		G															O
6158733	TORONTO LESTER B. PEARSON INT'	ONT	YTZ	43.667	43	40	79.633	79	38	173	6/1/1954	6/17/1999	X	X	X	X	X											N	O
6158733	TORONTO LESTER B. PEARSON INT'	ONT	YTZ	43.667	43	40	79.600	79	36	173	6/17/1999	present	X	X	X	X	X											N	O
6158740	TORONTO MET RES STN	ONT	TMET	43.800	43	48	79.550	79	33	194	9/1/1965	6/13/1988			@	@	B	B	D		S	K				X			H
6158749	TORONTO NEW INT'L A	ONT	YYZ	43.950	43	57	79.133	79	8	263	6/1/1973	3/1/1976		D	@	X	X	U		A								N	O
61587P6	TOR SCARBOROUGH COLLEGE	ONT	TSCA	43.783	43	47	79.183	79	11	130	7/1/1973	4/1/1980			@	@	X	B											O
6158875	TRENTON A	ONT	YTR	44.117	44	7	77.533	77	32	86	6/29/1959	4/1/1986	X	X	@	X	X							@	@			N	D
615HMAK	TORONTO BUTTONVILLE A	ONT	TBUT	43.867	43	52	79.367	79	22	198	5/23/1986	5/25/1998		X	X	X	X											N	O

Legend

Synoptic Observations

X Surface weather observations in a numerical code based on World Meteorological Organization regulations and exchanged world wide.

H Observations as above taken by an automatic station (various types).

Hourly Weather

X 24 hours per day.

D irregular observations, daily.

G Automatic station (various types) irregular, daily.

H Automatic station (various types) 24 hours per day.

Temperature

X Daily readings of maximum and minimum temperature (C).

Precipitation

X Daily values of liquid, freezing or frozen precipitation (drizzle, rain, snow, snow pellets, snow grains, ice pellets, hail and ice crystals) in mm.

Rate of Precipitation

X Tipping bucket rain gauge, hourly rainfall values and rate of rainfall in mm.

B mm and Fischer and Porter precipitation gauge, quarter hourly values and rate of precipitation in mm.

Wind

B Data processed from 45B autographic record, hourly total wind run in km/h and direction to 8 compass points.

U Data processed from U2A autographic record, hourly (short duration mean) wind speed in km/h and direction to tens of degrees.

Soil Temperature

D Morning values recorded for depths 5, 10, 20, 50, 100, 150 and 300 cm.

Evaporation

A Type A pan, daily values.

Sunshine

S Hourly values of bright sunshine.

Radiation

A Global solar radiation RF1.

K Global solar radiation RF1, Sky radiation RF2, Reflected solar radiation RF3 and Net radiation RF4.

Tower
X

Nipher
N nipher snow measurement in mm water equivalent.

Region
H AES Downsview
O Ontario

Table 4.2

List of US Meteorological Stations along Lake Ontario

	Station	Province	TC ID	Latitude	Lat	Min	Longitude	Long	Min	Elev.(m)	Start	End
WBAN_14733	Buffalo Niagara Int A	NY	BUF	42.933	42	56	78.733	78	44	214.9	7/1/1929	present
WBAN_14733	Niagara Falls Int A	NY	IAG	43.100	43	6	78.950	78	57	178.3	6/1/1951	present
WBAN_04724	Greater Rochester I	NY	ROC	43.117	43	7	77.683	77	41	182.9	5/1/1930	present
WBAN_14768	Syracuse Hancock Int A	NY	SYR	43.117	43	7	76.100	76	6	125	7/1/1929	present
WBAN_14771	Watertown Int A	NY	ART	44.000	44	0	76.017	76	1	98.1	5/1/1929	present
WBAN_94790	Alexandria Bay	NY	26B3	44.330	44	20	75.950	75	56	84.1	10/1/1972	present
	Cape Vincent	NY	CPV	44.110	44	7	76.330	76	20	136.9	1/1/1980	31/12/1981
COOP_303119	Galloo Island	NY	GLLN6	43.883	43	53	76.450	76	27	78.9	7/1/1969	31/8/1974
	Galloo Island CG	NY		43.900	43	54	76.383	76	23	7.9	10/1/1972	12/31/1972
	Niagara	NY	13G	43.260	43	16	79.040	79	4	78.9	7/1/1947	present
	Oswego CG	NY	28G	43.460	43	28	76.520	76	31	75	7/1/1950	present
	Oswego CG Lightboat	NY	28G	43.467	43	28	76.517	76	31	n/a	?	present
26G/WBAN_14700	Rochester Charlotte	NY	26G	43.260	43	15	77.600	77	36	75.9	6/1/1950	present
COOP_308290	Stoney Point 2 E	NY		43.833	43	50	76.267	76	16	76.2	7/1/1969	present
	Tibbetts	NY		44.100	44	6	76.367	76	22	4.9	10/1/1972	12/31/1973
WBAN_14715/GTB	Wheeler Sack Field AAF	NY		44.050	44	3	75.733	75	44	214	1/1/1942	present

Table 4.3
List of Meteorological stations showing year data was available

	Station	Province	Start	End	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
✓	KINGSTON A	ONT	5/1/1967	present								x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✓	KINGSTON MARINE	ONT	5/1/1960	10/1/1967	x	x	x	x	x	x	x	x																																	
✗	KINGSTON (AUT)	ONT	5/1/1978	8/30/1988																			x	x	x	x	x	x	x	x	x	x	x												
✗	PORT WELLER	ONT	4/1/1967	12/1/1970								x	x	x	x																														
✓	PORT WELLER (AUT)	ONT	4/1/1972	present													x	x	x	x	x	x	x	x	x	x	x																		
✓	ST CATHARINES A	ONT	6/1/1971	present												x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✗	ST CATHARINES PATH LAB	ONT	2/1/1955	1/1/1962	x	x	x																																						
✗	ST CATHARINES CDA	ONT	1/1/1962	10/1/1964			x	x	x																																				
✓	VINELAND STATION	ONT	5/1/1958	12/31/1986	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x														
✓	BURLINGTON PIERS (AUT)	ONT	1/4/1984	present																									x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✗	BURLINGTON (AUT)	ONT	5/1/1972	2/1/1976													x	x	x	x	x																								
✓	COBOURG (AUT)	ONT	6/1/1972	present													x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✗	DARLINGTON (AUT)	ONT	4/1/1972	11/1/1974													x	x	x																										
✗	HAMILTON A	ONT	1/1/1970	present											x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✓	HAMILTON MARINE POLICE	ONT	11/1/1953	3/31/1990	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x										
✗	HAMILTON MUNICIPAL LAB	ONT	2/1/1960	11/1/1962	x	x	x																																						
✓	HAMILTON RBG	ONT	7/1/1951	1/1/1997	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			
✓	MAIN DUCK ISLAND	ONT	5/1/1959	9/30/1986	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x														
✓	POINT PETRE (AUT)	ONT	5/1/1972	present													x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✗	PORT HOPE	ONT	7/25/1988	3/11/1991																													x	x	x	x									
✗	PRINCE EDWARD POINT	ONT	3/11/1991	12/3/1992																																x	x								
✗	TORONTO	ONT	5/1/1959	5/1/1969	x	x	x	x	x	x	x	x	x	x																															
✗	TORONTO AGINCOURT	ONT	9/1/1952	1/1/1968	x	x	x	x	x	x	x	x	x																																
✓	TORONTO DOWNSVIEW A	ONT	9/1/1958	6/1/1982	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x																		
✓	TORONTO HEADLAND (AUT)	ONT	4/1/1972	4/1/1998													x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
✓	TORONTO ISLAND A	ONT	12/1/1962	present			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✗	TORONTO IS A (AUT)	ONT	1/1/1970	6/11/1987											x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x														
✓	TORONTO LESTER B. PEARSON INT'	ONT	6/1/1954	6/17/1999	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✓	TORONTO LESTER B. PEARSON INT'	ONT	6/17/1999	present																																									x
✗	TORONTO MET RES STN	ONT	9/1/1965	6/13/1988						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x												
✗	TORONTO NEW INT'L A	ONT	6/1/1973	3/1/1976														x	x	x	x																								
✗	TOR SCARBOROUGH COLLEGE	ONT	7/1/1973	4/1/1980														x	x	x	x	x	x	x	x																				
✓	TRENTON A	ONT	6/29/1959	4/1/1986	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✗	TORONTO BUTTONVILLE A	ONT	5/23/1986	5/25/1998																											x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Table 4.3 Continued…

	Station	State	Start	End	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
✓	Niagara Falls Int A	NY	6/1/1951	Present	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✓	Greater Rochester I	NY	5/1/1930	Present	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✓	Syracuse Hancock Int A	NY	7/1/1929	Present	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✓	Watertown Int A	NY	5/1/1929	Present	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✗	Alexandria Bay	NY	10/1/1972	Present													x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✗	Cape Vincent	NY	10/1/1972	7/31/1979													x	x	x	x	x	x	x	x																					
✗	Galloo Island	NY	7/1/1969	8/31/1974										x	x	x	x	x	x																										
✗	Galloo Island CG	NY	10/1/1972	12/31/1972													x																												
✓	Niagara	NY	7/1/1947	Present	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✓	Oswego CG	NY	7/1/1950	Present	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✗	Oswego CG Lightboat	NY	?	Present																																									
✓	Rochester Charlotte	NY	6/1/1950	Present	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✗	Stoney Point 2 E	NY	7/1/1969	Present										x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✗	Tibbetts	NY	10/1/1972	12/31/1973													x	x																											
✗	Wheeler Sack Field AAF	NY	1/1/1942	Present	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
✓	C45135		9/8/1989	Present																														x	x	x	x	x	x	x	x	x	x	x	x
✓	C45139		5/15/1991	Present																																x	x	x	x	x	x	x	x	x	x
✗	45012		Mar, 2002	Present																																									
✗	ABAN6		July, 1992	Present																																	x	x	x	x	x	x	x	x	x
✗	GLLN6		Sept, 1983	Present																							x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

4.2 Buoy Data

Waves have been measured in Lake Ontario using buoys at twelve locations, as shown in Figure 4.4 and listed in Table 4.4. There are several inconsistencies in the recorded wave and wind data. The period and duration of the parameters varied considerably. The buoys are usually removed during winter (November to March). The long-term data are biased due to the lack of recorded winter storms that often produce the largest and most severe wave conditions. There was a considerable change in the type and pay loads of the two long-term buoys (C45135, C45139) after 1996. Initially, data were recorded by 3 m diameter buoys from 1988 to 1996. However, after 1996 the data were recorded by large 12 m Discus Buoys which do not respond well to short period wave conditions.

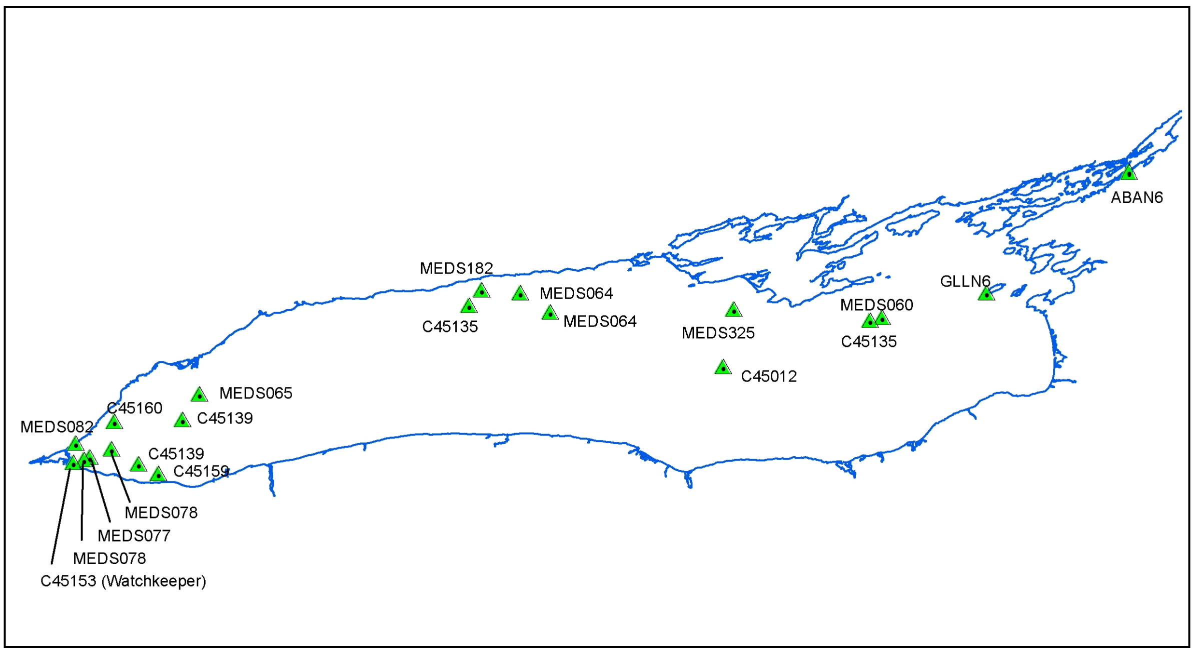


Figure 4.4 Map Showing Buoy Locations

Table 4.4

Buoy Locations

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
C45012	43.62	77.41	03/2002	Present
C45153 Watchkeeper	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
ABAN6	44.33	-75.93	07/1992	Present
GLLN6	43.89	-76.45	09/1983	Present

To understand the internal consistency of the wave regimes as recorded by Watchkeeper Buoys (3 m in diameter) and Discus Buoys (12 m in diameter), a comparison was made between the time series of significant wave height and period, generated from the observed records of both types of buoys (Figure 4.5), while deployed adjacent to each other. It can be seen that the Discus Buoy appears to significantly underestimate the wave heights and overestimate the wave periods. Therefore, only a qualitative comparison was attempted with these two data sets, and only the data for the period 1989 to 1996 was used in the final comparisons. The data from the other MEDS buoys were not considered because recorded data for these buoys were not long enough.

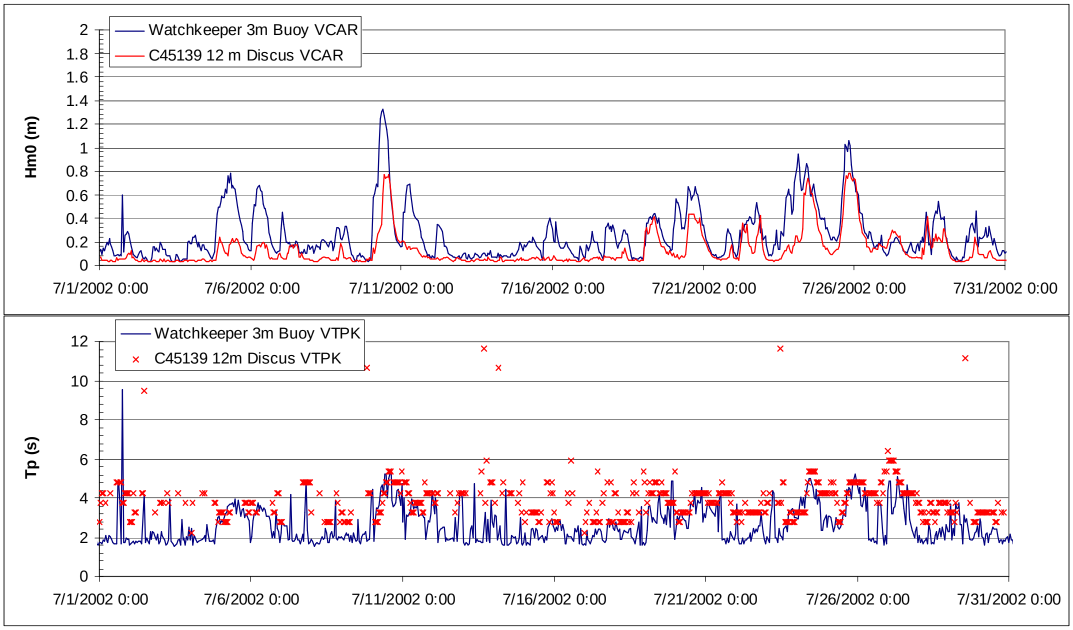


Figure 4.5 Time Series Comparison of Wave Data as Recorded by Watchkeeper Buoy and Discus Buoy

For the temporal period covering 1989 to 1996, Table 4.5 summarizes the average wave conditions for the buoys C45135 and C45139 which are located in the west and east ends of Lake Ontario respectively. Since at the latitude of Lake Ontario, the mid-latitude weather systems generally travel from west to east (with a meridional component) it is logical to expect higher amplitude waves at the eastern end of the lake. The maximum wave amplitude at the western end of the lake is less than 4 m, whereas at the eastern end, it is over 5 m. It can be seen from Tables 4.6 and 4.7 that the maximum wave periods at the western end are in the 8 to 9 second range, while in the eastern end, they are in the 9 to 10 second range.

Table 4.5

Summary of Wave Data from the Buoys used for Model Validation

Wave Data Source	Mean Hm0 (m)	Max. Hm0 (m)	Mean Tp (s)	Max. Tp (s)
C45135	0.71	5.12	3.78	12.8
C45139	0.48	3.53	1.06	12.8

Figure 4.6 shows the wave height exceedence of the buoys in Lake Ontario.

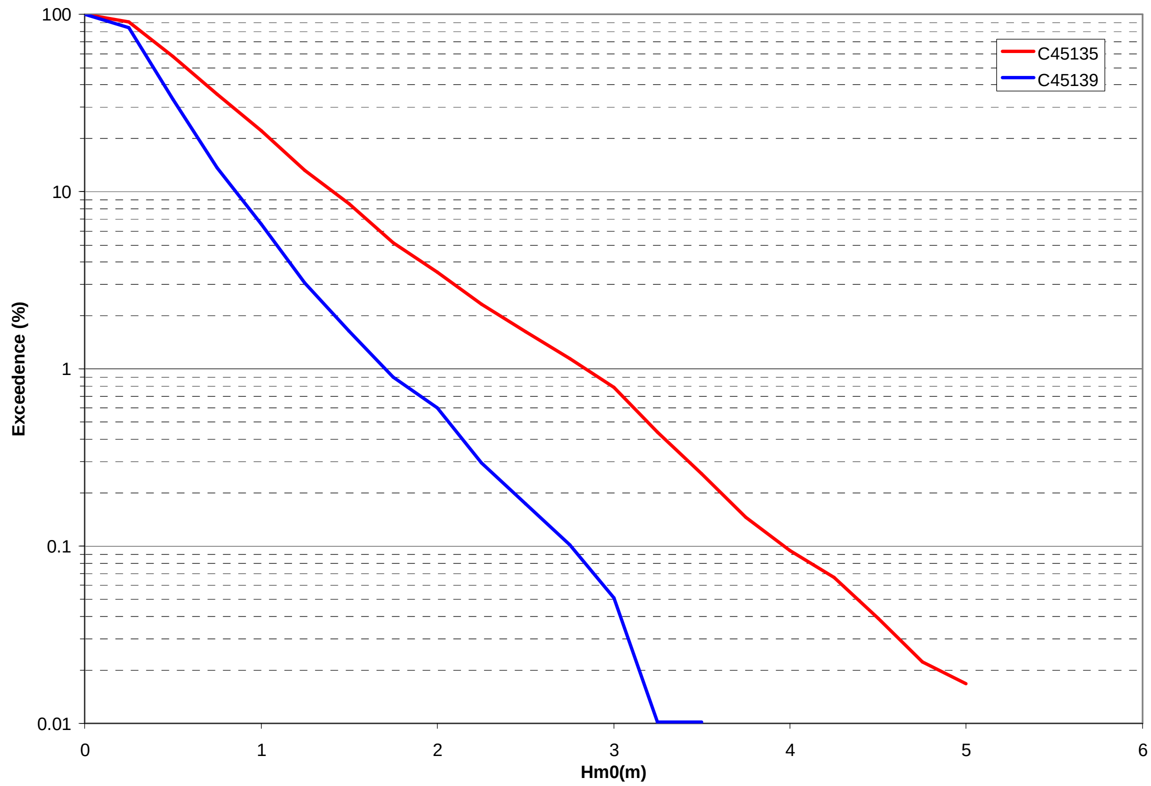


Figure 4.6 Exceedence of Hm0 for Buoys C45135 and C45139

Tables 4.6 and 4.7, respectively, show the scatter plots of data from buoys C45135 and C45139.

Table 4.6

Scatter Plot the for Buoy C45135

Wave Distribution By Height And Period (All Directions)
Location: C45135
Date Range: 08 Sep 1989 04PM to 31 Oct 1996 11PM
Season: All

Wave Height (m)	Wave Period (s) 0.0-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	9.0-10.0	10.0-11.0	11.0-12.0	Total	A (%)	C (%)
0-0.2															100.00
0.2-0.4			760	842	204	23		1	1				1831	26.80	100.00
0.4-0.6			48	719	338	38		1	1				1145	16.76	73.20
0.6-0.8			2	355	496	104	1			1			959	14.04	56.44
0.8-1.0			1	63	463	183	15			1			726	10.63	42.40
1.0-1.2				2	219	122	28		1				372	5.44	31.78
1.2-1.4				2	111	187	38	1					339	4.96	26.33
1.4-1.6				1	20	105	47	7		1			181	2.65	21.37
1.6-1.8			2	1	3	91	59	15					171	2.50	18.72
1.8-2.0			5	1		26	33	18					83	1.21	16.22
2.0-2.2				1	1	14	22	10	1				49	0.72	15.00
2.2-2.4						3	21	21	3				48	0.70	14.29
2.4-2.6			1	1		2	20	12	2				38	0.56	13.58
2.6-2.8				1	1		8	9	5				24	0.35	13.03
2.8-3.0							3	10	3	1			17	0.25	12.68
3.0-3.2			1				1	11	5	1			19	0.28	12.43
3.2-3.4							1	3	7				11	0.16	12.15
3.4-3.6								3	6				9	0.13	11.99
3.6-3.8									2				2	0.03	11.86
3.8-4.0									4				4	0.06	11.83
4.0-4.2									1	2			3	0.04	11.77
4.2-4.4															11.72
4.4-4.6									2				2	0.03	11.72
4.6-4.8															11.69
4.8-5.0										1			1	0.01	11.69
5.0-5.2															11.68
Totals			820	1989	1856	898	297	122	44	8			6034		
A(%)			12.00	29.11	27.17	13.14	4.35	1.79	0.64	0.12				88.32	
C(%)	100.00	100.00	100.00	88.00	58.88	31.72	18.57	14.23	12.44	11.80	11.68	11.68			

Meta Data

11.7% Calm Conditions (Wave Height<0 m and Wave Period<0 s)
Number of records this direction: 6832
Total records used in selected interval
(including calms and missing data): 20883
Missing data (not included in calculation): 14051
Wave height: Max: 5.12 Min: 0.20 Mean: 0.71
Wave period: Max: 12.80 Min: 0.00 Mean: 3.78

Legend

Row and column percentages have the following meanings:
A – based on records in this direction
C – percentage exceedance derived from 'A'
Frequencies of occurrence are reported in 'counts'

Table 4.7

Scatter Plot the for Buoy C45139

Wave Distribution By Height And Period (All Directions)
Location: C45139
Date Range: 15 May 1991 11AM to 29 Nov 1993 02PM
Season: All

Wave Height (m)	Wave Period (s) 0.0-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0	5.0-6.0	6.0-7.0	7.0-8.0	8.0-9.0	9.0-10.0	10.0-11.0	11.0-12.0	Total	A (%)	C (%)
0-0.1															100.00
0.1-0.2															100.00
0.2-0.3			7	177	141	19							344	3.50	100.00
0.3-0.4			1	66	144	22	2						235	2.39	96.50
0.4-0.5				23	154	37	1						215	2.19	94.10
0.5-0.6				18	119	51						2	190	1.94	91.91
0.6-0.7				17	105	58	2						182	1.85	89.98
0.7-0.8				13	45	55	7						120	1.22	88.12
0.8-0.9				13	52	67	17						149	1.52	86.90
0.9-1.0				2	42	71	15						130	1.32	85.38
1.0-1.1				2	31	66	16						115	1.17	84.06
1.1-1.2					20	46	23	1					90	0.92	82.89
1.2-1.3					17	48	28						93	0.95	81.97
1.3-1.4					7	22	22	1					52	0.53	81.02
1.4-1.5					4	18	15	1					38	0.39	80.49
1.5-1.6					2	9	9	3					23	0.23	80.11
1.6-1.7						15	12	1					28	0.29	79.87
1.7-1.8						5	11	2					18	0.18	79.59
1.8-1.9						3	6	1					10	0.10	79.40
1.9-2.0							9	4					13	0.13	79.30
2.0-2.1							5	7					12	0.12	79.17
2.1-2.2							6	6	1				13	0.13	79.05
2.2-2.3							2	4					6	0.06	78.91
2.3-2.4								3	2				5	0.05	78.85
2.4-2.5								3					3	0.03	78.80
2.5-2.6								3					3	0.03	78.77
2.6-2.7									1				1	0.01	78.74
2.7-2.8								1	2				3	0.03	78.73
2.8-2.9									2	1			3	0.03	78.70
2.9-3.0									1				1	0.01	78.67
3.0-3.1								2	1				3	0.03	78.66
3.1-3.2															78.63
3.2-3.3															78.63
3.3-3.4															78.63
3.4-3.5															78.63
3.5-3.6															78.63
Totals			8	331	883	612	208	43	10	1		2	2098		
A(%)			0.08	3.37	8.99	6.23	2.12	0.44	0.10	0.01		0.02		21.37	
C(%)	100.00	100.00	100.00	99.92	96.55	87.55	81.32	79.20	78.76	78.66	78.65	78.65			

Meta Data

78.6% Calm Conditions (Wave Height<0 m and Wave Period<0 s)
Number of records this direction: 9817
Total records used in selected interval
(including calms and missing data): 22300
Missing data (not included in calculation): 12483
Wave height: Max: 3.53 Min: 0.15 Mean: 0.48
Wave period: Max: 12.80 Min: 0.00 Mean: 1.06

Legend

Row and column percentages have the following meanings:
A – based on records in this direction
C – percentage exceedance derived from 'A'
Frequencies of occurrence are reported in 'counts'

4.3 Water Temperature

Average monthly lake wide water temperature data for Lake Ontario were compiled from the results of a GLREL Hydrological model (Croley 1989). Monthly water temperatures were further interpolated into daily water temperatures. The resulting daily lake wide average water temperature data was then used in the pre-processing program to check air-water temperature differences which are required for over lake wind computations. Figure 4.7 shows the monthly average lake temperature data for 1998 and 1999.

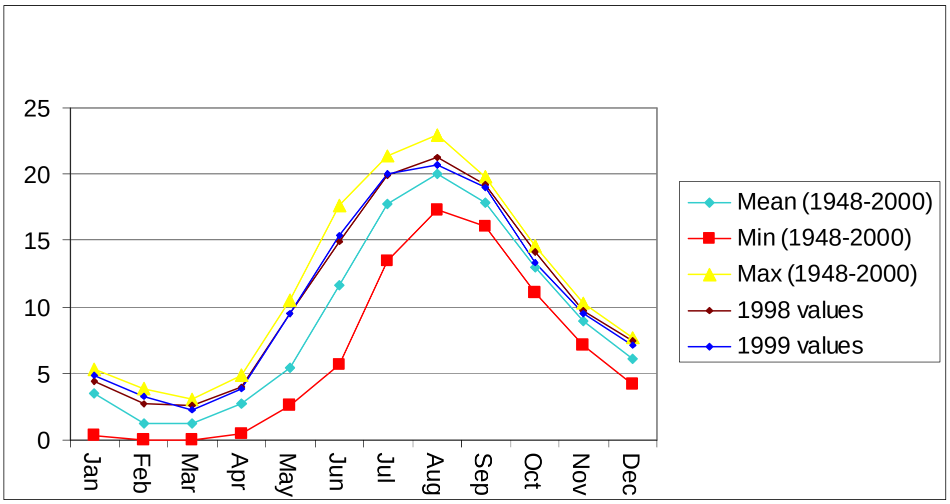


Figure 4.7 Modelled Monthly Water Temperature for 1998 and 1999

4.4 Ice Cover

Ice cover over the Great Lakes influences fisheries, coastal zone processes, lake levels, navigation and it also has an effect on wave generation in the lakes. Although Lake Ontario is never completely frozen, ice cover extends in the near shore and eastern part of the lake. It is important to consider effects of ice cover when developing an accurate wave climatology for the lake. For the present study, digital ice cover data from the Great Lakes Environmental Research Laboratory 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 previous ice data sets (1960 – 1979) were based on synoptic ice charts. The recent data were based on composite ice charts, and all other relevant information was available in digital form.

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

(A) Prior to fall of 1972 - ice climatology was obtained providing 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). An example of a typical ice cover chart is shown in Figure 4.8.

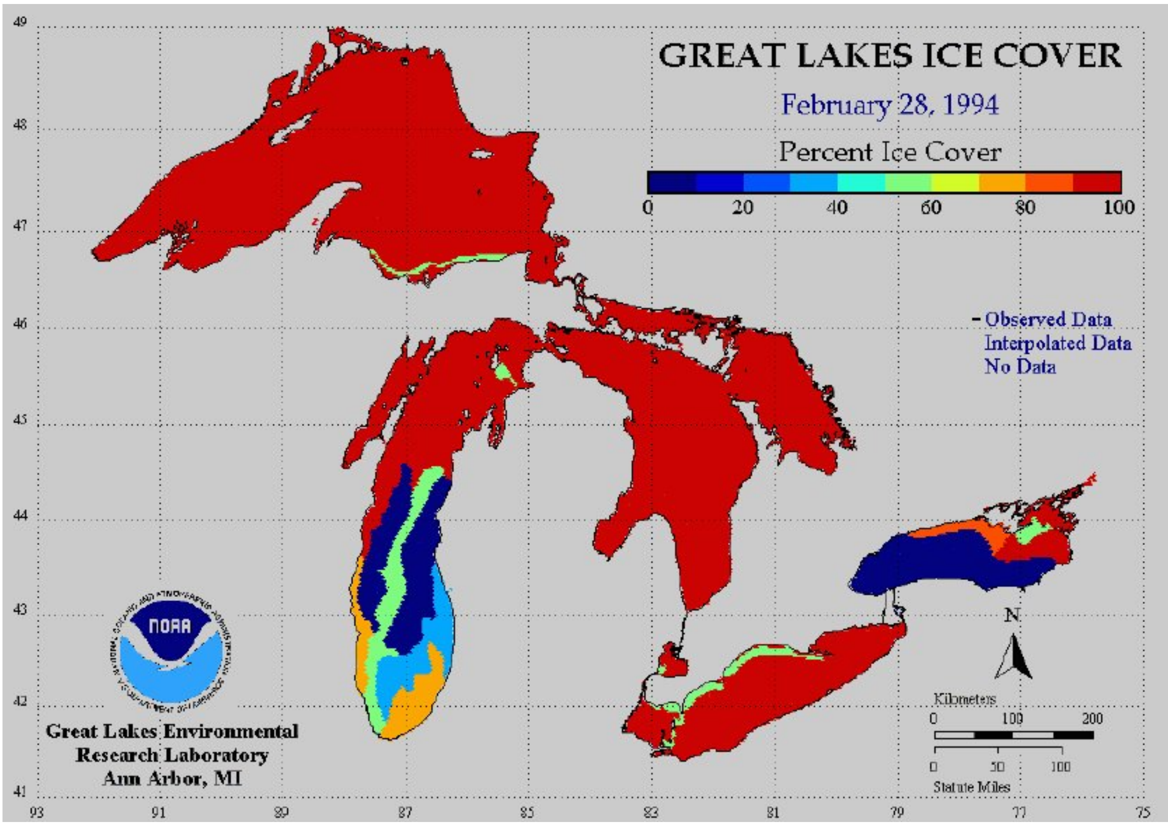


Figure 4.8 Great Lakes Ice Cover, Feb 28, 1994.

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. By making this assumption and inserting these assumed charts, interpolation at any time of the year was possible. 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 30 per cent, waves with values of ice coverage greater than 30 per cent being removed from the wave simulation. This was accomplished by preventing both wave generation and wave propagation in model grid cells above this ice threshold.

For the earlier data, the average ice climatology was synthesized into a daily data set in much the same manner as the irregularly spaced ice charts. Again, a threshold of 30 per cent was used to determine whether the grid cells would be included in the computation.

5.0 WAVE MODEL

The wave model used in this study was developed by Dr. Donald T. Resio of ERDC, CHL. It is described in detail in Resio and Perrie (1989). The model simulates wave growth, dissipation, and propagation in deep water. The modelled spectra are represented as fully two-dimensional in discretized frequency and direction band. Propagation effects and source-sink mechanisms are computed in terms of variations of energy levels in each of these frequency direction elements. All wave parameters, such as wave height, frequency of the spectral peak and mean wave direction are computed from these discrete elements. Wave growth is modelled through the transfer of energy from the wind to the sea surface. A part of this energy is converted to surface gravity waves and the remaining energy is transferred through wave-wave interactions from the midrange portion of the spectrum to both the forward face and high frequency regions. Equilibrium range is reached for a constant set of wind input. This is a state of the art spectral wave model based on a $\boldsymbol{f}^{-4}$ equilibrium range.

The model is based on the assumption that the wave field in a water body can be represented by the distribution of energy in discrete frequency and direction elements and the effects of refraction, shoaling and diffraction are insignificant in deep water. The change in energy in each element as a function of time at all specified points in the water body is determined by the radiative transfer equation.

$$\frac{\partial \boldsymbol{F}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{t},\boldsymbol{f},\theta)}{\partial \boldsymbol{t}} = \sum_{\boldsymbol{k}=1}^{\boldsymbol{n}} \boldsymbol{G}_{\boldsymbol{K}}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{t},\boldsymbol{f},\theta) + \overrightarrow{\boldsymbol{c}_{\boldsymbol{g}}}(\boldsymbol{f},\theta).\nabla \boldsymbol{F}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{t},\boldsymbol{f},\theta)$$

where F is the two dimensional spectral energy density of the element located on the water surface at point (***x,y***) at time ***t*** with frequency ***f*** and propagation direction θ, $\boldsymbol{G}_{\boldsymbol{K}}$ represents a number of functions that act as sources or sinks of energy. This equation is solved at each point in a square grid on the water body for successive intervals in time. The wind source term supplies energy to the sea surface and allows the wave spectrum to grow, and the wave-wave interaction term controls development of the spectrum.

The spectral density in the equilibrium range is given by:

$$\boldsymbol{n(k) = B' k^{-4}}$$

where $\boldsymbol{B'}$ is a constant with units time^{-1} and k is the wave number.

This model uses an upstream differencing method in which each frequency-direction element in the directional wave spectrum is propagated independently. This method is simple, stable and takes less execution time than any other higher order propagation scheme. A latitude-longitude grid is used in which propagation along meridians (or components of propagation along meridians) represents propagation along great circles.

Various source and sink terms in the model represent energy transfer from the atmosphere to the wave field, energy transfer among wave frequencies (wave-wave interactions), energy transfer from waves back to the atmosphere (swell propagating against the wind) and energy losses due to wave breaking in deep water.

The energy input into the spectrum is given by:

$$\boldsymbol{S_W(f,}\ \theta)=\boldsymbol{B(f,}\ \theta).\boldsymbol{F(f},\ \theta)$$

where $\boldsymbol{B(f},\ \theta)$ is a function with units of time^{-1} given by

$$\boldsymbol{B}(\boldsymbol{f},\theta)=\boldsymbol{z}\left(\frac{\boldsymbol{uf_m}}{\boldsymbol{g}}\right)\boldsymbol{f}\cos(\theta_{\boldsymbol{wv}}-\theta_{\boldsymbol{wd}})$$

where f is frequency, z is a dimensionless constant, u is wind speed, $\boldsymbol{f_m}$ is peak frequency, g is acceleration due to gravity, $\theta_{\boldsymbol{wv}}$ is wave direction , $\theta_{\boldsymbol{wd}}$ is wind direction. The constant z is composed of the drag coefficient, the ratio of air to water density, and an empirical constant with a value between 0.16 and 0.24.

The nonlinear source term S_{NL} for the case of active wave generation is given by:

$$S\ (\boldsymbol{f},\ \theta)=[\hat{E}\ (f)|^{n+1}\ -\ \hat{E}\ (f)|^{n}]\Phi\ (\theta-\theta_0)$$

where $\hat{E}$ (f) is the estimated value of the one dimensional spectral density E(f), $\Phi\ (\theta-\theta_0)$

is an angular function , and θ_0 is the mean wave propagation direction. The fully developed sea can be modelled by:

$$\boldsymbol{T_m}\ |^{\boldsymbol{n}+1}=\boldsymbol{T_m}\ |^{\boldsymbol{n}}+\boldsymbol{p}\frac{\partial \boldsymbol{T_m}}{\partial \boldsymbol{t}}\Delta \boldsymbol{t}$$

where T_m is the peak period and p is given by

$p=1$ if $f_m > f_{PM}$

$=0$ if $f_m \leq f_{PM}$

and the fully developed peak frequency f_{PM} is given by

$f_{PM} = Z_c\ g/\ (2\pi\ u)$

Z_c being a dimensionless empirical constant.

Swell decay in this model is based on the concept of energy loss by non-linear fluxes. In this form, the total energy flux from the rear slope portion of the spectrum is estimated as:

$$\Gamma_{g} = \left[\frac{a_1 (2\pi)^9}{g^4} \right] E_0^3 f_m^9$$

where a_1 is a dimensionless empirical constant that ranges in value from 0.35 to 2.0. An explicit scheme is used to estimate the energy loss over the time step, and part of the energy is redistributed to the forward face of the spectrum.

6.0 METHODOLOGY

This section describes in detail the methodology for the hindcast of waves which included data assembly, data pre-processing, wind field adjustment and interpolation and wave model grid set up.

6.1 Data Assembly

In an initial step, the basic meteorological field data from MSC Canada and NDC (NOAA) were available in different formats and were converted to a consistent format for use in a pre-processing program.

6.2 Pre-processing of Wind Data

The pre-processing program basically checked for data consistency, applied overwater corrections to the wind data and converted all the wind data to a standard 10 m elevation except for buoy winds which were converted already to 10 m elevation. Overland wind speeds generally are smaller than overwater values because of the marked transition from higher aerodynamic roughness overland to much lower aerodynamic roughness overwater. This transition can be very abrupt so that wind speeds reported at coastal stations are often non-representative of conditions only a few kilometers offshore.

All parameters were checked for reasonable and seasonable limits. Wind and temperature were adjusted for overland/overlake effect, and converted to a common 10 m reference height. All parameters were checked against lake wide average values at each time step. Daily estimates of lake wide mean water temperature were utilized for overland/overlake adjustment and for reference height adjustment. Further details on the wind data processing are provided in the following sub-sections.

6.2.1 Data Consistency Check

The pre-processing program performed the following tasks:

- Only considered observations which were within the time frame of interest.
- Checked for reasonable and seasonable air temperatures.

- Calculated temperature difference between that of water and air if both air and water temperature were available.
- Checked for reasonable air-water temperature difference.
- Checked for zero wind speed. (Generally, most zero wind speeds indicate missing data. In this study, if the station wind speed was zero, it was assumed that the data was missing.)
- Checked for missing wind direction and excessive wind speeds.
- Checked for continuity of data availability at each station.
- Carried out "spike" checks to remove erroneous data.
- Removed data if the values deviated from the lake wide average by a given amount.

6.2.2 Initial Overland-Overlake Wind Adjustments

Overlake winds differ considerably from overland winds due to differences in frictional coefficients between land and water and atmospheric stability. When overlake winds are calculated from overland station data, the wind speeds need to be adjusted. Resio and Vincent (1976) applied an empirical relationship between overland and overlake winds, which is based on two empirical curves. One relates the overland-overlake wind speed ratio to the air-water temperature difference and the other relates overlake wind speed (Uw) to overland wind speed (U1). The overlake winds are calculated by multiplying the overland winds by a factor R, which is the ratio of the two wind fields. The R factor used in the wind conversion is dependent on the stability of the lower atmospheric layers and on the magnitude of the overland wind. The stability of the lower atmosphere is dependent on the difference between the upwind overland air temperature and water surface temperature. In the adjustment of the air temperature over the lake, an input parameter is the overwater fetch.

The pre-processing program applied overland/overlake correction to wind speeds and wind direction, based on selective input octants from which winds were originating.

6.2.3 Conversion to 10 m Elevation

The height at which wind speed may be observed varies from station to station and the measurements were reduced to a common 10 m reference level by means of mixing length theory, which assumes a logarithmic profile of the wind speed with height. The formulation utilized was based on Businger et al. (1971). The program can convert a measured wind speed at any height Z to an effective wind speed for any other height Z´ and can provide this as input to the model. Factors affecting the profile shape are the stability of the air column and the effective roughness length at the lake surface. This procedure works well within the planetary boundary layer provided the condition

$-1 \geq Z'/L \leq 1$ is met, where

Z' is the height of the wind observation (m)

L is the Monin-Obukhov length (m) and is approximated by

$$L = \frac{U^2 T_a}{g(T_a - T_w)\ln\left(\frac{z}{z_0}\right)}$$

and U is the measured wind speed at height z (m/s); T_a and T_w are, respectively, the air and water temperatures, z_0 is a roughness length given originally as 0.00459 $(0.04U)^2$ based on Charnok's (1955) form of $z_0 = au^2_* /g$. The roughness length varies according to Charnok's formula and the stability length (Monin-Obukhov length) varies according to the Businger-Dyer formulation. The constant in Charnok's formula was chosen so that under neutral conditions the drag coefficient is 0.0016 at the 10 m level.

6.3 Final Wind Field Adjustment

Wind fields over Lake Ontario were derived using shore station wind data. The quality of the computed winds depended upon the number of shore stations, their location and the quality of the recorded wind data. The major constraint in this study was the lack of reliable buoy wind data for comparisons throughout the hindcast period. As a final step in adjustment of the wind data, the wind speeds from the available shore stations were compared with that of buoy wind speeds for the same period and adjusted towards the buoy wind speeds, so that the average wind speeds over the lake were statistically similar. It was inherently assumed that the winds measured at the buoys were fully representative of overwater winds. During adjustment of the wind speeds, the directional variation of the wind speeds was taken into account.

For wind speed comparisons, Quantile-Quantile (Q-Q) plots were used. A Q-Q plot is a graphical technique for assessing whether two data sets are statistically equivalent. In this approach the quantiles (percentages of data points below a given wind speed value) were plotted against the quantiles of the second data set. If equivalent quantiles provide equivalent wind speed, the data sets are statistically similar.

The Q-Q plots of wind speeds measured at Toronto International Airport and at the Buoy C45139 are shown in Appendix I prior to and after adjusting the winds. It can be seen from the plots that except for the south east sector, winds were under-predicted when compared to the Buoy C45139 data. Q-Q plots after adjustment show that the wind speeds at both locations were statistically similar. It should be noted that wind speeds less than 4 m/s were ignored in the adjustment.

The Q-Q plots of wind speeds for Petrie Island and Buoy C45135 are shown in Appendix II. The wind speeds in the north east, east and south west directions were overestimated at Petrie Island and the winds from the north west direction are underestimated.

Using the wind field database that was prepared, wind data were extracted for the locations of the buoys in the lake, and a comparison was made with the winds recorded by the buoys. The results of these comparisons are shown in Appendix III. The Q-Q plots suggest that the wind adjustment procedure worked well, whether or not there was buoy data.

6.4 Interpolation of Wind Data to WAVAD Grid

There are only a few meteorological stations along Lake Ontario, which provide geographical and temporal data coverage. To interpolate data at irregular points in time and space on to a regular WAVAD grid, we used a Natural Neighbor Interpolation Technique described in Sambridge et al. (1995).

For interpolation schemes " Natural Neighbors" represent a set of closest surrounding nodes, whose number and position are well defined, and varies according to the local nodal distribution. One can think of "Natural Neighbors" about any point as a unique set of nodes that define the "Neighborhood" of the point. Natural Neighbor Interpolation is a weighted average of the functional values associated with data, which are natural neighbors of the point at which interpolation is being made. The weights are the natural neighbor coordinates of the interpolation location, with reference to the locations of those data.

Natural Neighbor Interpolation has the following advantages:

- The original function values are recovered exactly at the reference 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 reference points. This method helps interpolation of irregularly spaced data by using a spatial smoothing step with a specified smoothing radius. The nearest Neighboring technique assigns the value of the nearest measurement station to each point in the regular grid, similar to the Thiessen polygon weighting scheme.

- The spatial smoothing step replaces each value on the regular grid with the average value at all grid points within the specified smoothing radius.

In the Nearest Neighboring Technique, we also considered observations for up to three hours before the interpolation time to three hours after the interpolation time. In the Nearest Neighbor distance calculations, the distance from a grid point to the observation points is increased by the product of the time difference multiplied by a scaling speed. The interpolation scaling speed taken was 10 km/hr and the interpolation smoothing distance was 30 km. We found that the Nearest Neighbor Technique provided improved results when compared to those derived from the inverse power law or negative exponential weighting functions.

6.5 Wave Model Grid Setup

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) 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. Though a 5 km grid is computationally fast, it proved coarse and missed the finer details at the east end of the lake. A 2 km grid had much better resolution, but required considerable computational time. 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 6.1) 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 model bathymetry for Lake Ontario was derived from the GLERL topographic database. Figure 6.1 shows a plan view of the final numerical model grid with bathymetry. 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 simulation and a time step of 6 minutes was employed.

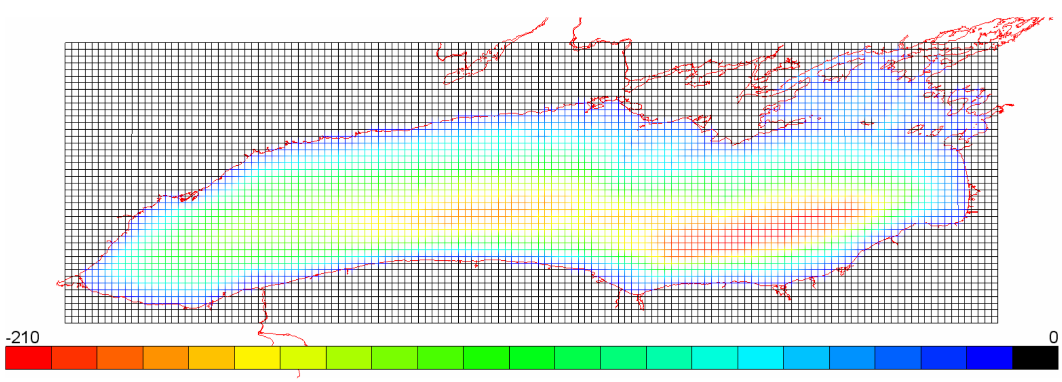
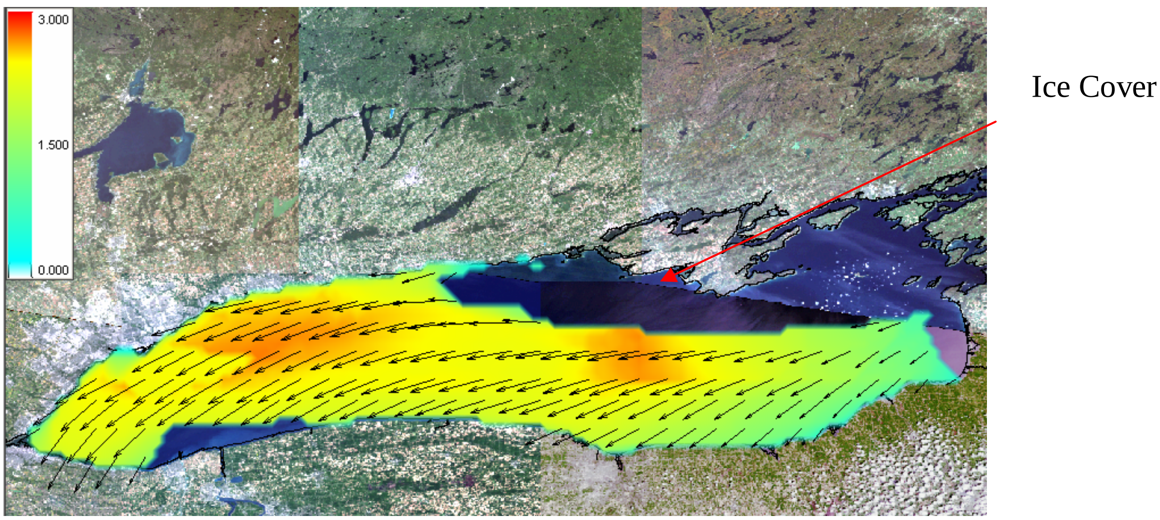


Figure 6.1 Wave Model Grid

7.0 MODEL RESULTS AND VALIDATION

An initial hindcast for the period 1989 to 1996 was carried out to validate the model. The model results are compared with the observed buoy data during this period.

Figures 7.1a and 7.1b, respectively, present snapshots of WAVAD output for wave conditions in the months of February and August for the year 1997. The colour contours represent the wave height over the model grid domain, ranging from 0 (mauve) to 3 metres (red). The vectors show the direction of wave propagation.



7.1a Snapshot of the Wave Field in February

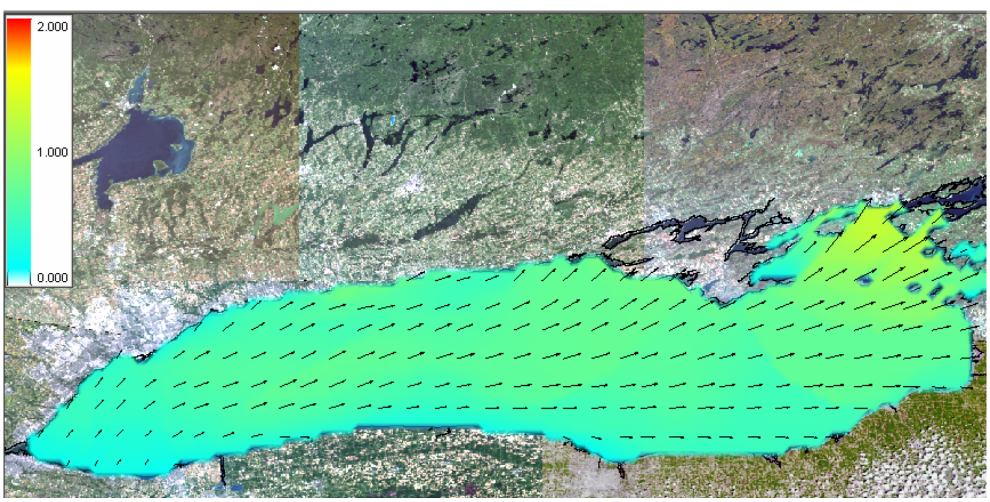


Figure 7.1b Snapshot of the Wave Field in August

Detailed summaries of the results, including the Q-Q plots and time series are provided in Appendices IV and V.

7.1 Comparison of WAVAD Model Output with Observed Data

To facilitate an initial assessment of the validity of the overall wave modelling approach (interpolation of winds and WAVAD hindcast model), the model results were compared to the previous non-directional wave buoy measurements in Lake Ontario. The results are summarized in Appendices IV and V.

Direct comparisons were made between the WAVAD model results and the non-directional buoy data collected from 1989 to 1996. Since the C45135 buoy locations changed considerably, separate comparisons were made for different time periods. Buoy C45139 was located close to the western end of the lake (Figure 4.4) and remained there during the period 1991-93. On the other hand, Buoy C45135 was located closer to the northern shore in the central part of the lake during 1989-90 and then moved to the eastern part of the lake during 1991-96.

Visual inspection of the plots showed that while WAVAD consistently overestimated the observed wave heights, trends in the time series correlated well. Q-Q of Hm0 and TP and sample time series are shown respectively in Figures 7.2 and 7.3 for Buoys C45135 and C45139.

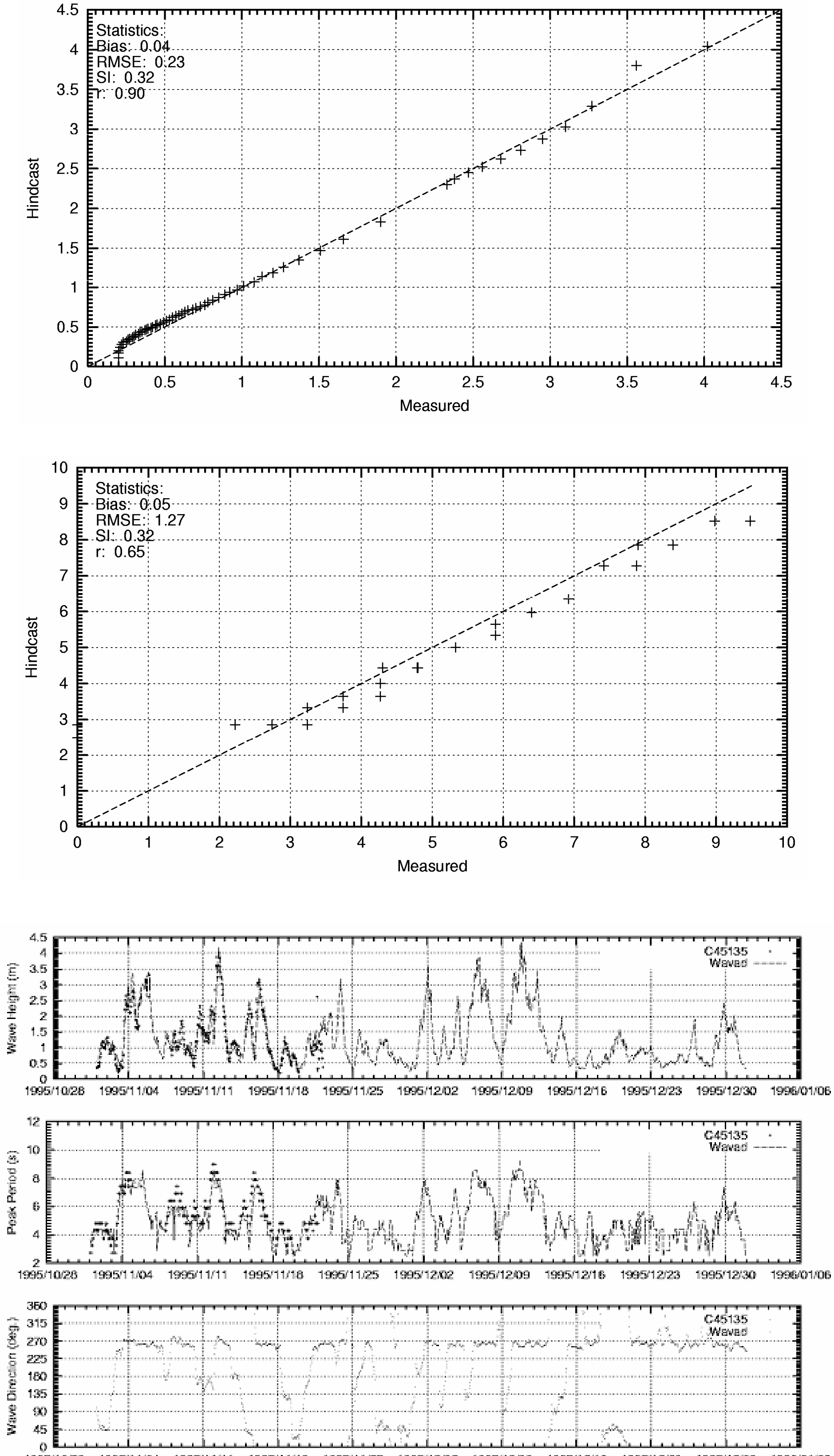


Figure 7.2 Q-Q (Hm0, TP) and Time Series Comparisons for Buoy C45135

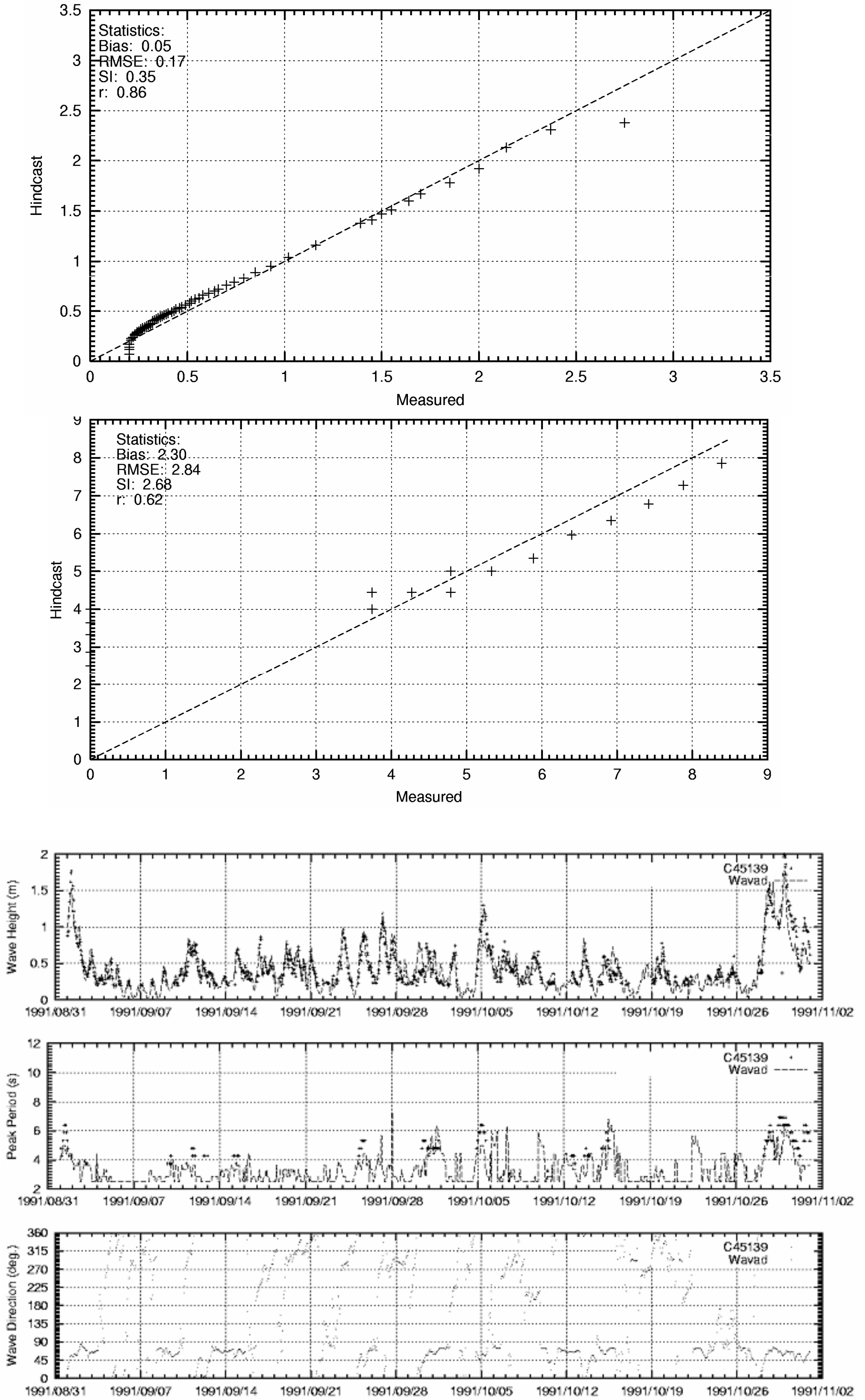


Figure 7.3 Q-Q (Hm0, TP) and Time Series Comparisons for Buoy C45139

Table 7.1 provides a summary of comparison statistics for the hindcast. Observed buoy wind data were available only from 1989 onwards.

Table 7.1

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

Overall, the WAVAD model performed much better in determining the wave amplitudes and not so well for the wave period. The correlation coefficients between the computed and observed wave amplitudes, varied from 0.86 to 0.92, which was deemed quite satisfactory.

On the other hand, the correlation coefficients for the wave period were not as good and the highest value was only 0.65. The better performance of the model for the computation of wave amplitudes was also reflected in the somewhat relatively lower values of bias and RMSE.

In order to assess the impact of the inclusion of buoy winds on the computed wave fields, numerical experiments were carried out with and without buoy winds and time series comparison of measured and sample hindcast wave fields are shown in Figures 7.4 to 7.7 and detailed time series comparisons are given in Appendix VI. It can be seen that the influence of the inclusion of buoy winds in the interpolated wind data over the lake is negligible.

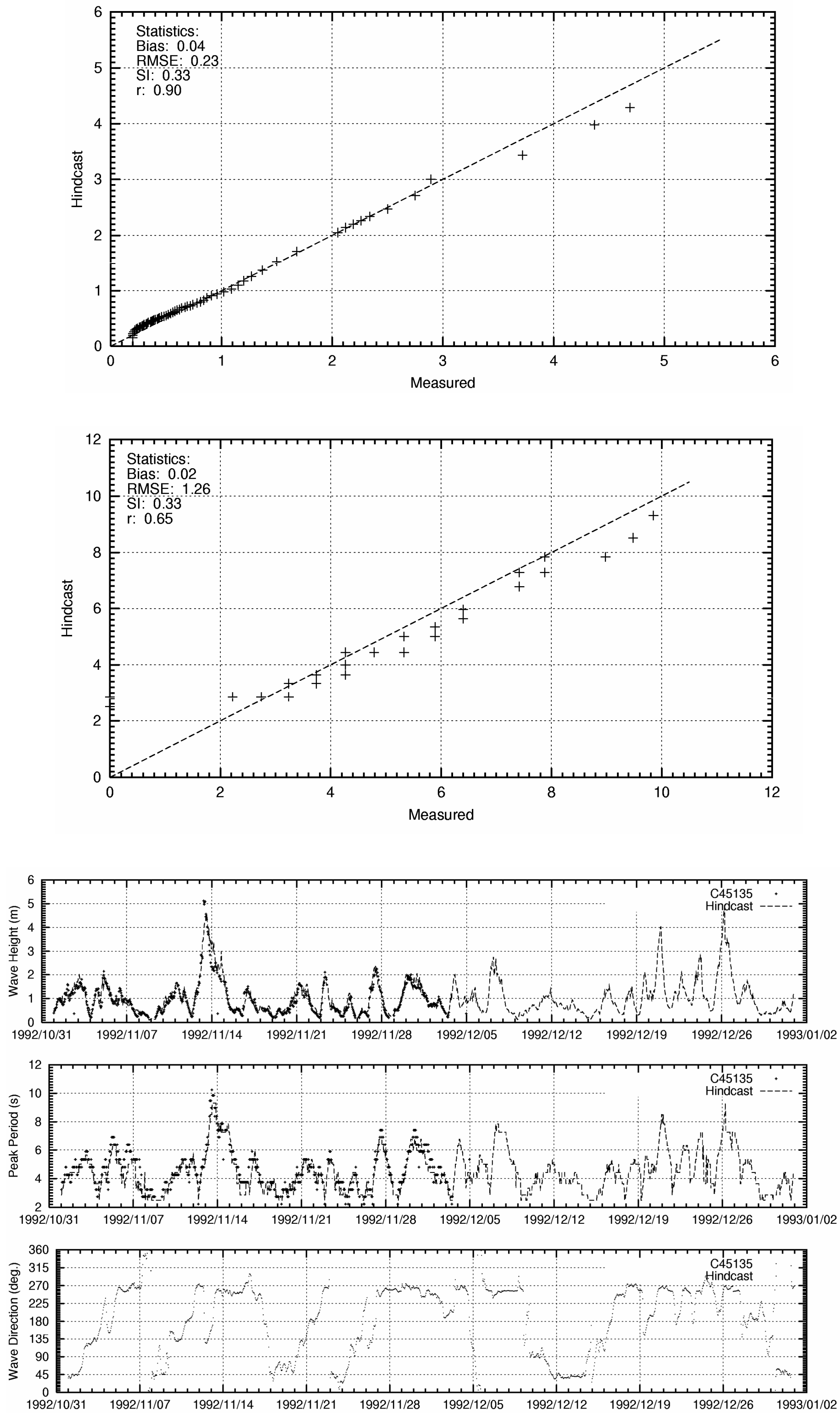
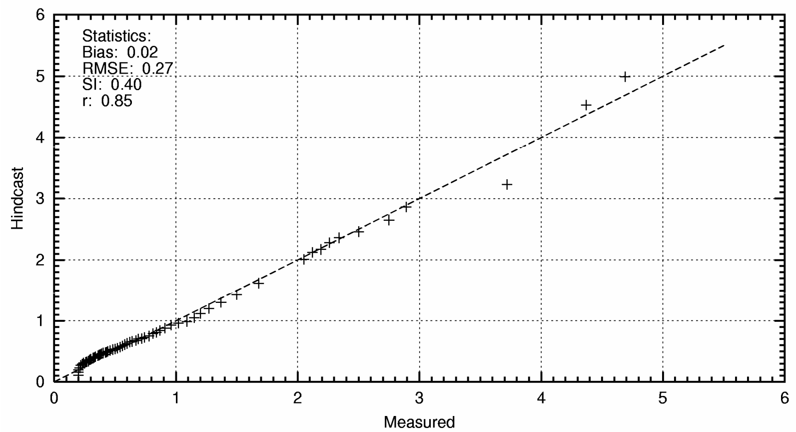
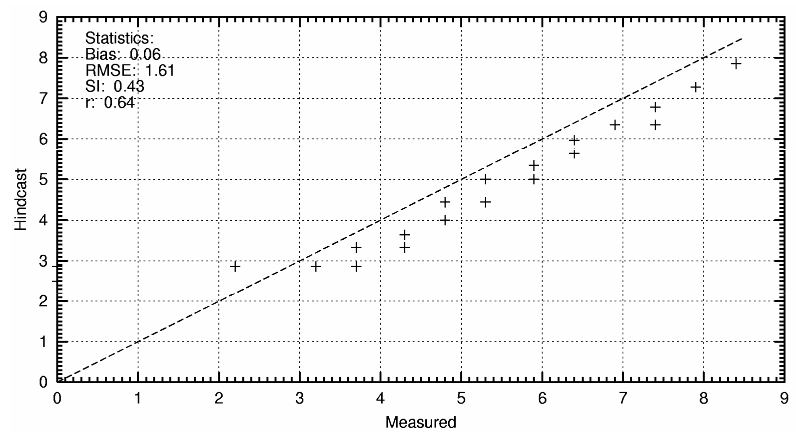


Figure 7.4 Q-Q (Hm0, TP) and Time Series Comparisons for C45135 (With Buoy Winds)





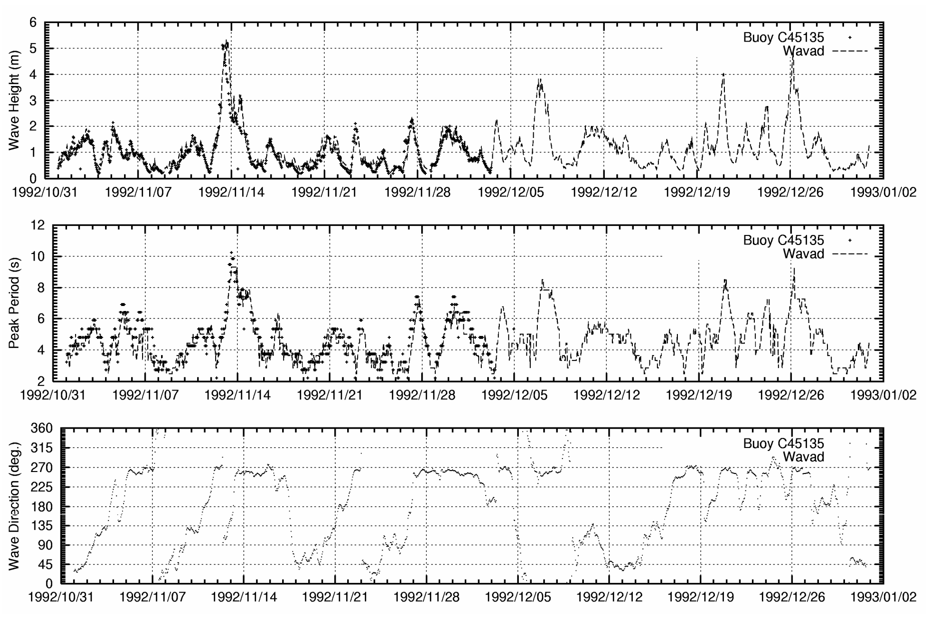


Figure 7.5 Q-Q (Hm0, TP) and Time Series Comparisons for C45135 (Without Buoy Winds)

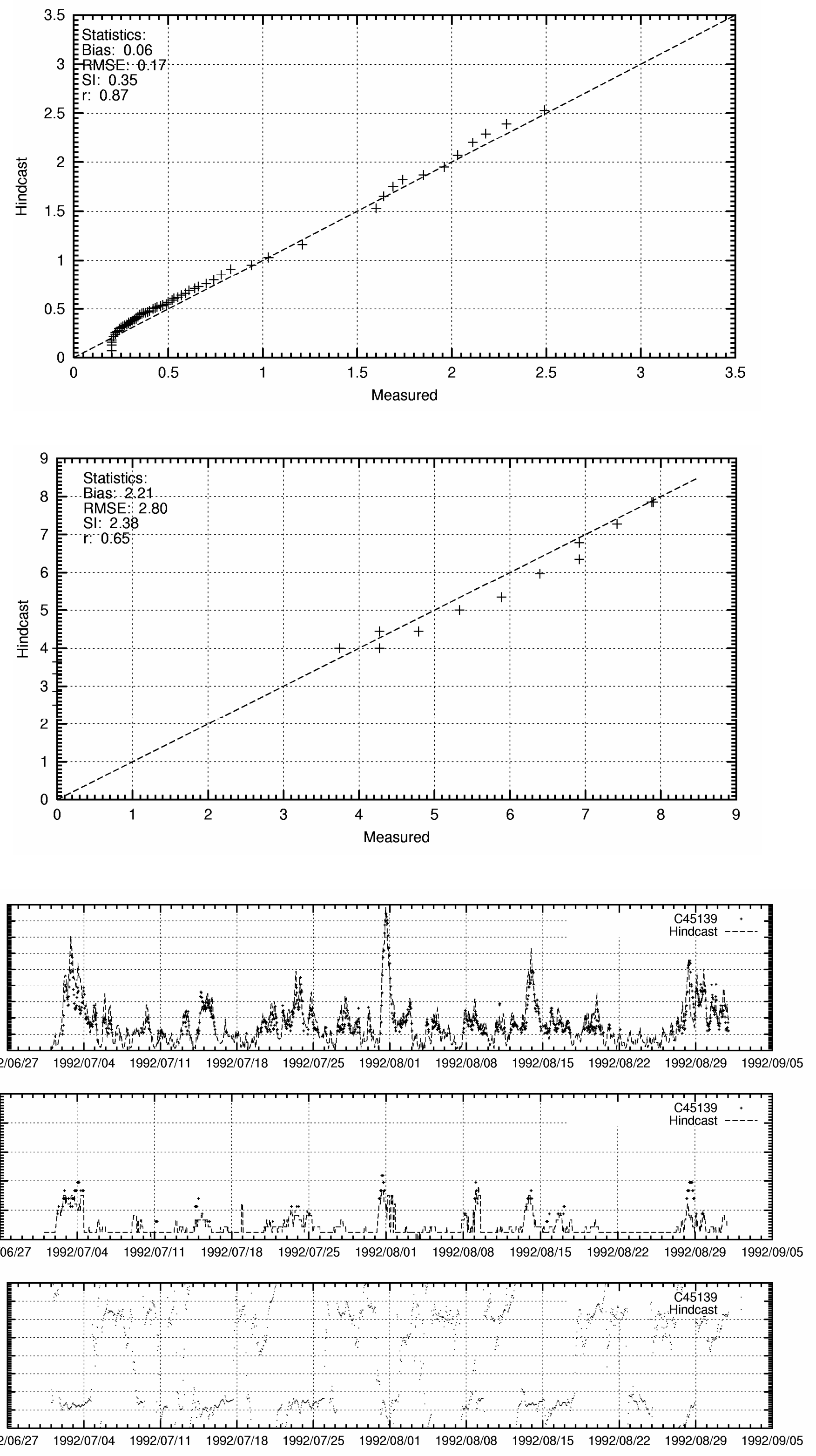


Figure 7.6 Q-Q (Hm0, TP) and Time Series Comparisons for C45139 (With Buoy Winds)

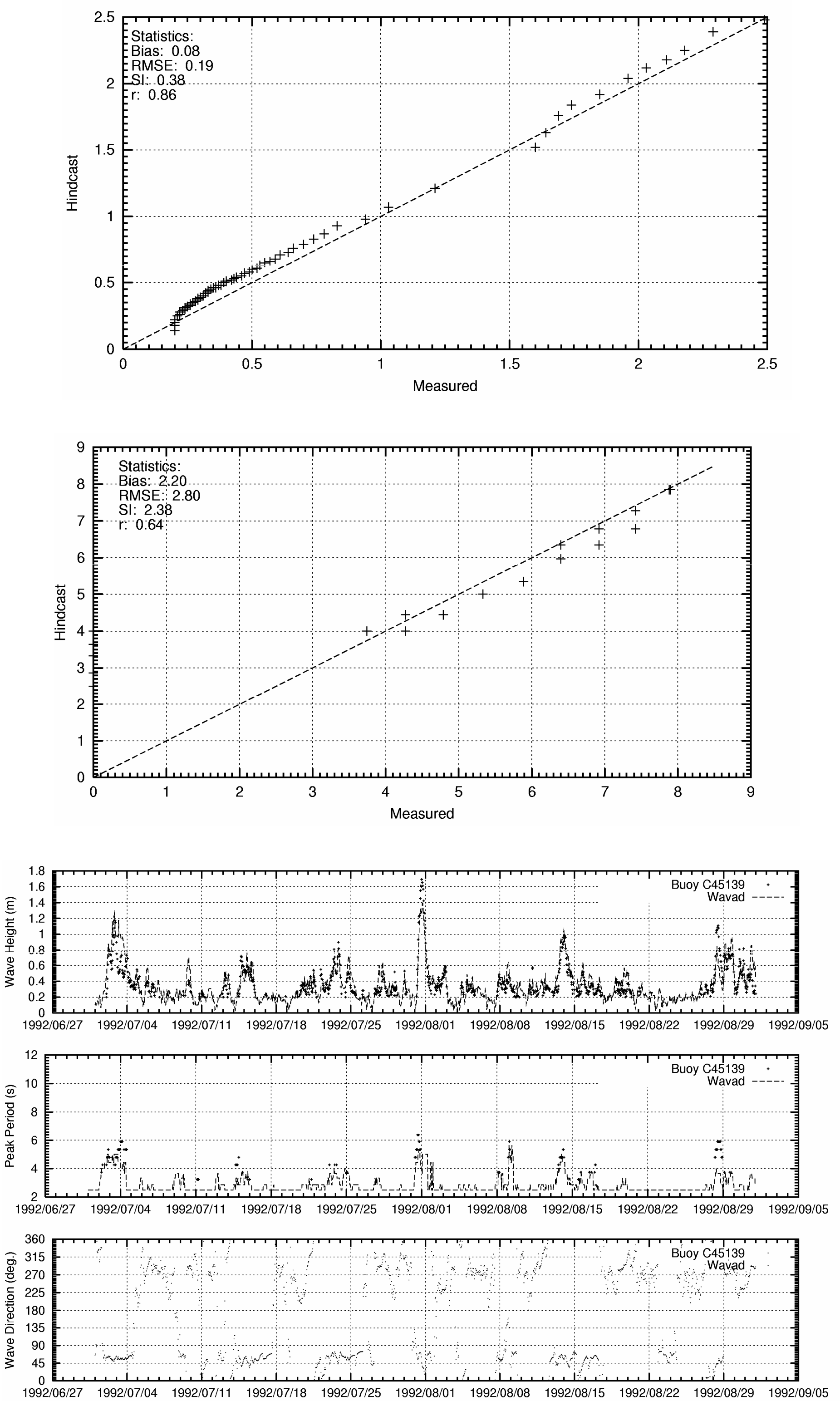


Figure 7.7 Q-Q (Hm0, TP) and Time Series Comparisons for C45139 (Without Buoy Winds)

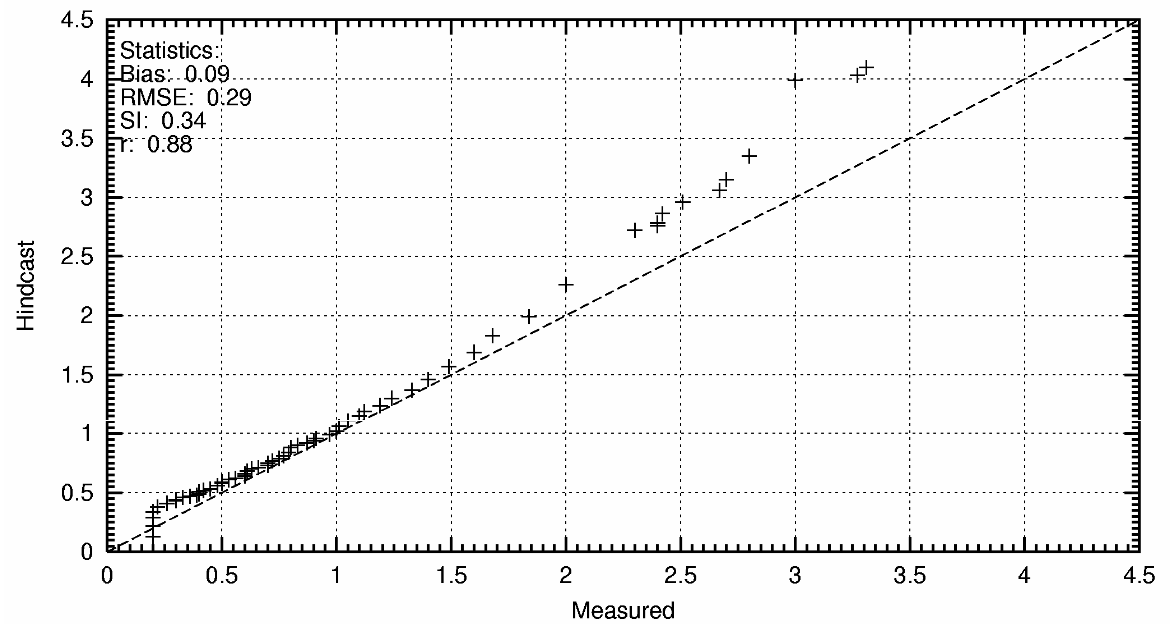
Table 7.2 provides a summary of the comparison statistics with and without the inclusion of buoy winds.

Table 7.2

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

In the 1960's, meteorological data were available at eleven stations compared to twenty-three in the 1990's. The impact of wind data on wave hindcast from the number of stations in a year is verified by modelling the wave field in the year 1991. In this case, only the wind data from the original eleven stations that existed in the 1960's were used. Figures 7.8 and 7.9 show the Hm0 - QQ comparison plots for the Buoys C45135 and C45139 respectively. It can be noted from these figures that there is a probability of over-estimation of waves at the east end of the lake and under-estimation of the waves in the west end during the earlier time period.



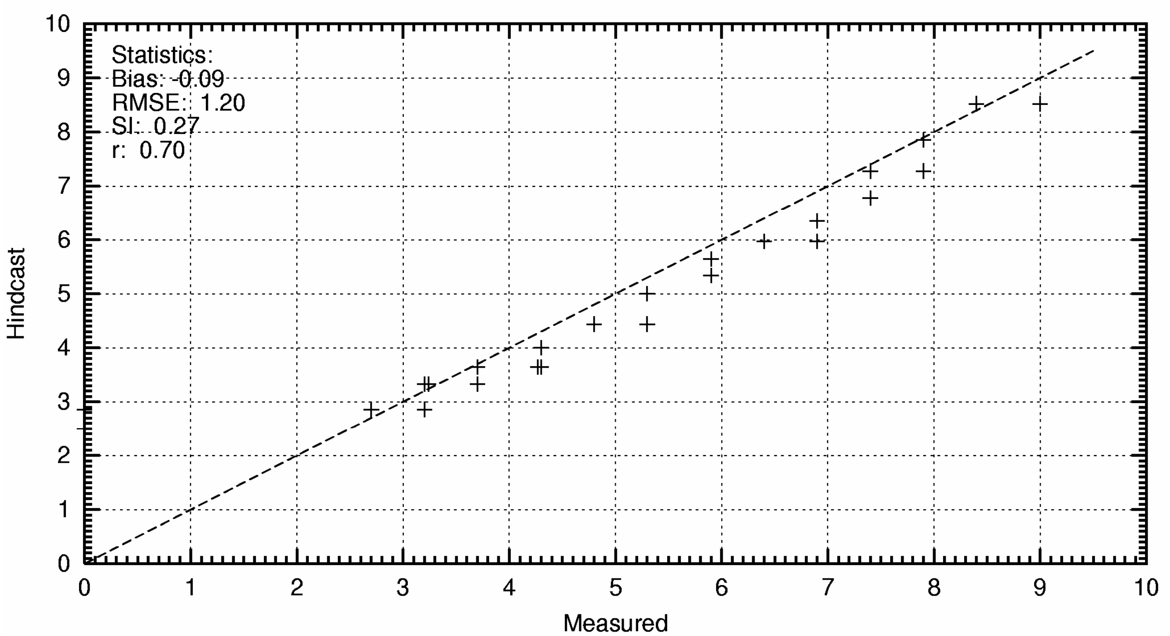
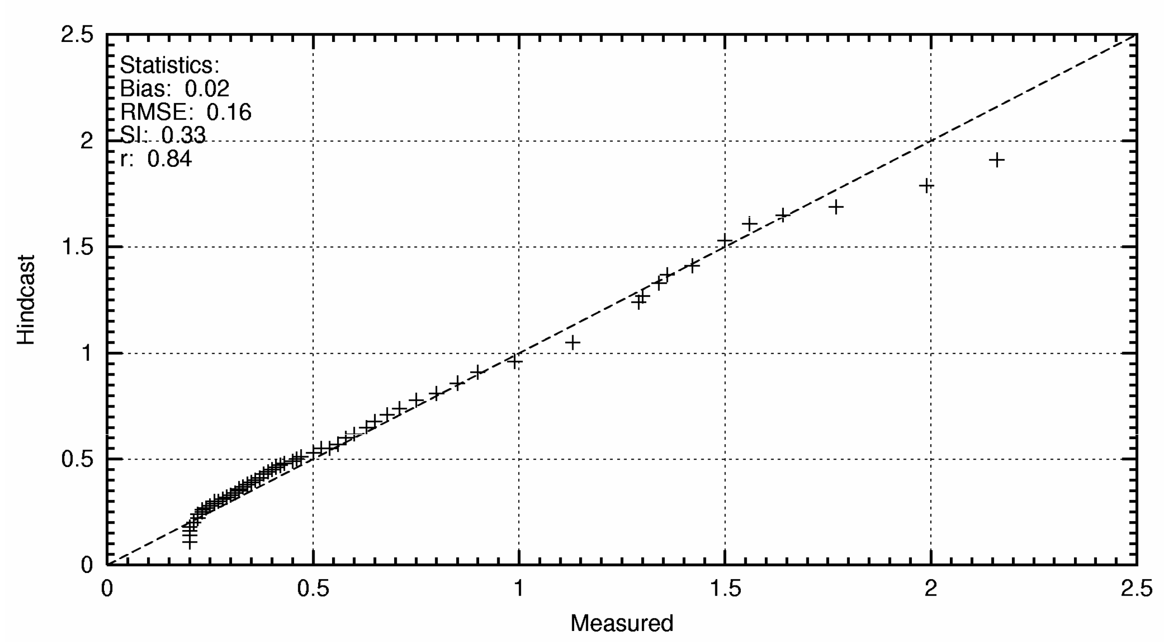


Figure 7.8 Q-Q (Hm0, TP) Comparison for C45135 for the Year 1991 (11 Meteorological Stations in 1960 are Considered for the Hindcast)



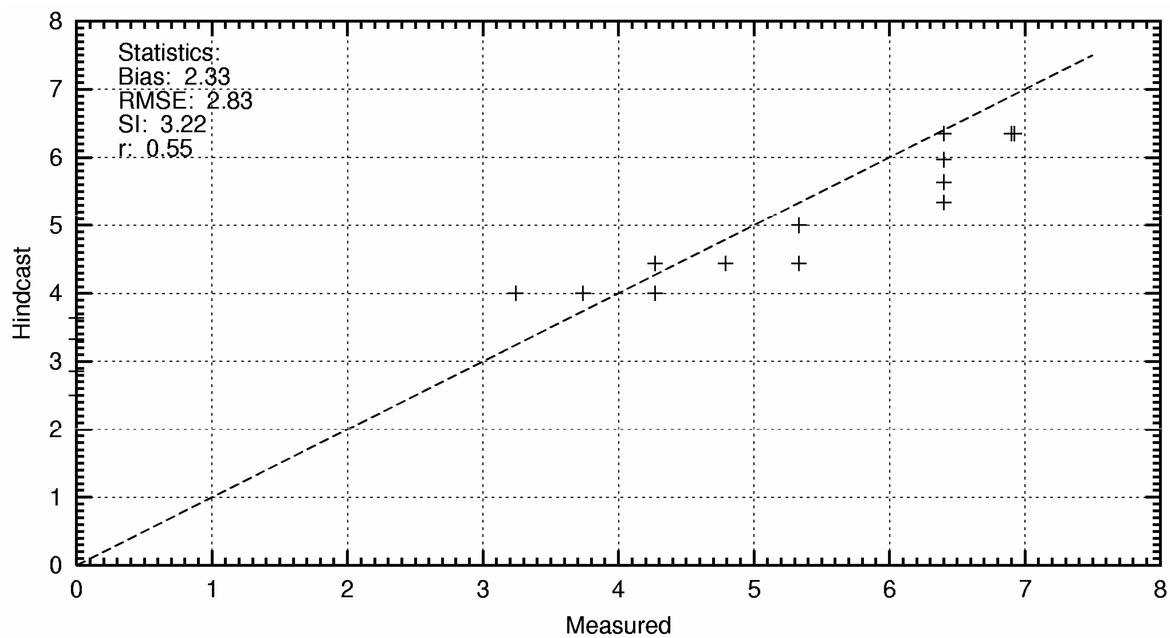


Figure 7.9 Q-Q (Hm0, TP) Comparison for C45139 for the year 1991 (11 Meteorological Stations in 1960 are Considered for the Hindcast)

8.0 FINAL WAVE SIMULATION FOR THE 40 YEAR PERIOD

Once the model validation was assessed, final wave simulation for a 40 year period (1961-2000) was completed. The summary of the wave climate at 307 locations (Figure 8.1) along the shore of Lake Ontario was stored in Baird time series format. Table 8.1 shows the sample header information and variables which are contained in each file. Each file contains wave parameters such as significant wave height, wave period, mean wave direction and wind speed at hourly intervals for the 40 year period.

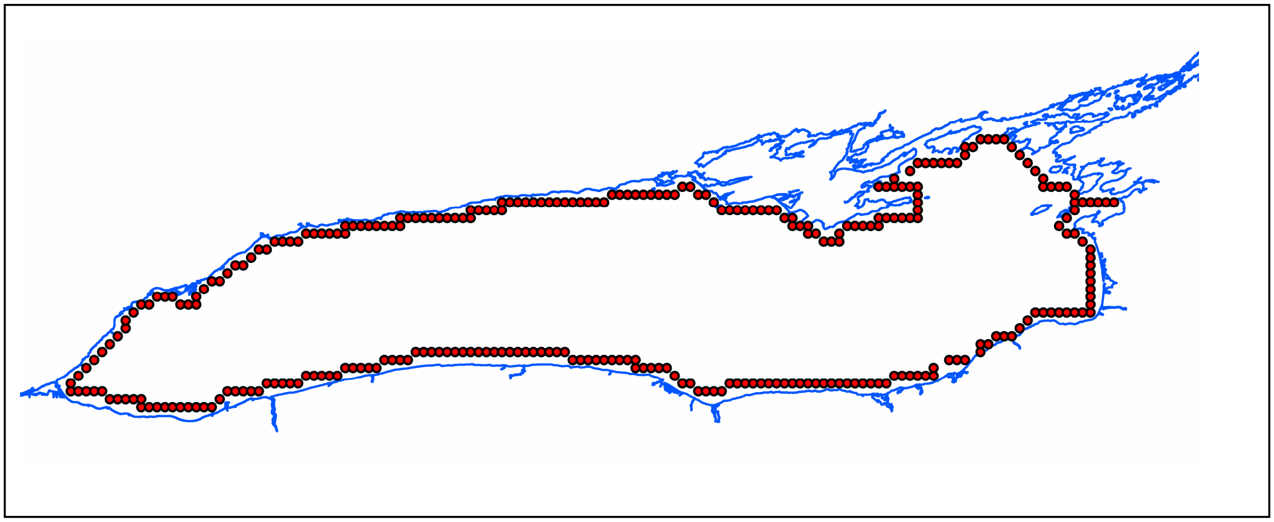


Figure 8.1 Locations Along the Shoreline of Lake Ontario, Where Wave Data Were Stored

Table 8.1

Header information in each file

```
#Version: 2.0
#Created: 2003 05 11
#Project: Lake Ontario Wave Hindcast
#Source:  From File: point_006.wv
#
#Model Grid Coordinates   14   5
#IJC Point Reference:   578
#Latitude: 43.23 N
#Longitude: -79.51 W
#Water Depth:  17.20 m
#Time Zone: UTC
#Starting Date: January 1, 1961 01:00
#Ending date: December 31, 2000 23:00
#Data Temporal Interval: 1 hour
#
#Wave Model Details:
#  Model Name:  WAVAD 2D Spectral
#  Author:  D. Resio, modified by Baird
#  Grid Resolution: 0.027 degrees (3 km)
#  Time Step: 360 seconds
#
#Contact Information:
#  Baird & Associates
#  Tel:   613-731-8900
#  www.baird.com
#  info@baird.com
#
#Comments:
#  This wind-wave hindcast was performed as one study element of the
#  International Joint Commission Lake Ontario - St. Lawrence River
#  Level Regulation Study.
#-------------------------------------
#Number of Data Types: 4
#HM0     m     -99.    S   Significant Wave Height
#TP      s     -99.    S   Peak Wave Period
#MWD     deg   -99.    a   Mean Wave Direction
#WSPD    m/s   -99.    S   Wind Speed
# -99 represents no data
#END
```

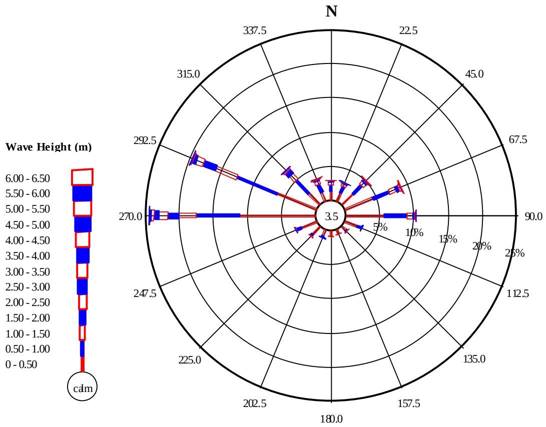
Use Disclaimer: This data was prepared by Baird for the Buffalo District United States Army Corps of Engineers and the International Joint Commission for a study on Lake Ontario Any use or reliance on this data by a third party is the responsibility of the third party. As such, Baird accepts no liability for damages, in whole or in part, suffered by a third party due to the application of the wave data for a use other than its original study purpose.

Figure 8.2 shows the wave rose plots for four locations along Lake Ontario, while Table 8.2 shows the key wave parameters for all four locations. It can be noted from the table that maximum and median wave heights at the west end of the lake, respectively, are 5.85 and 0.51 m. However, at the eastern end wave heights are greater than at the western end.

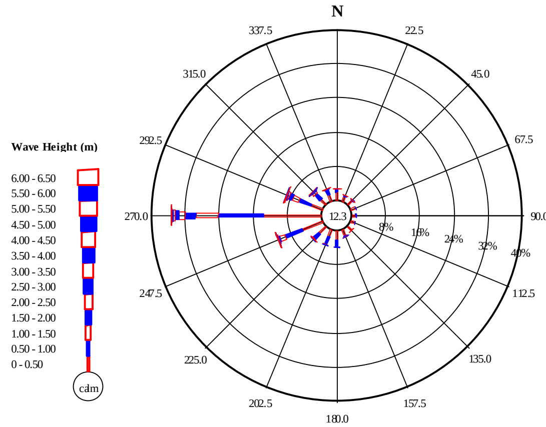
Table 8.2

Summary of Wave Parameter Statistics

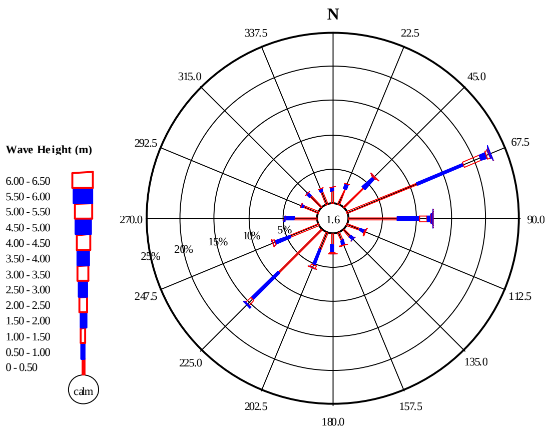
	Hm0 (m)		**Tp (sec)**	
	Maximum	**Mean**	**Maximum**	**Mean**
East end	6.23	0.62	11.06	3.49
South end	5.50	0.72	9.31	3.72
West end	5.85	0.51	10.27	3.22
North	4.66	0.50	10.27	3.26



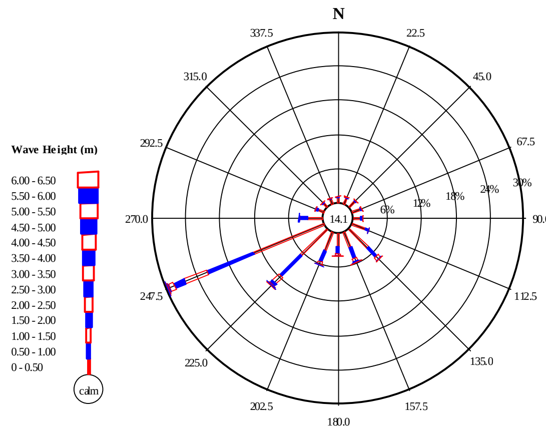
East end



South end



West end



North end

Figure 8.2 Wave Roses of Hm0 for Four Locations Along Lake Ontario

9.0 SUMMARY AND CONCLUSIONS

A unique wave data set has been developed in this study, covering a 40 year period from 1961 to 2000, with hourly values stored at some 307 locations around Lake Ontario, thus giving a 3 km resolution, as compared to a 16 km resolution in previous studies. In addition, wind data from a greater number of meteorological stations around the lake and data from offshore buoys were also used.

An improved second generation spectral wave model was used for the wave hindcast, and the wind data, which formed one of the inputs to the wave model, were interpolated using a sophisticated mathematical technique, known as the Natural Neighbor Interpolation.

Influence of ice cover on wave generation was studied, making use of polygon ice cover data for the period 1973-2000 and seasonally averaged data prior to this.

Other important features of this study included the incorporation of air-water temperature differences in the wind stress computation, and various adjustments to the wind field to arrive at a statistically and geographically consistent data set.

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

The unique wave data set developed in this study, which makes use of the best available data and has been interpolated through state-of-the-art mathematical techniques, should serve the various needs of the Lake Ontario community for several decades, especially if in the future, there are changes to the wave regime due to climate change.

REFERENCES

Assel, R.A., Quinn.H.H.,Leshkevich. G.A. and Bolsenga, S.J. (1983). Great Lakes Ice Atlas. GLERL contribution no. 299. Great Lakes Environmental Research Laboratory, Ann Harbor, Michigan.

Businger, J.A. , Wyangaard, J.C., Izumi, U., and Bradley, E.F. (1971). Flux-Profile Relationships in the Atmospheric Surface layer, Journal of the Atmospheric Sciences, Vol. 28, pp-181-189.

Charnok, H. (1955). Wind Stress on a Water Surface, Quar. Journal of Royal Meteorological Society, 81,pp 639-690.

Croley II , E. Thomas. (1989). Lumped Modeling of Laurentian Great Lakes Evaporation. Heat Storage and Energy Fluxes for Forecasting and Simulation. NOAA Technical Memorandum ERL GLERL-70.

Donelan. M.A. (1977). A simple numerical model for wave and wind stress prediction. Report. National Water Research Institute, CCIW, Burlington, Ontario.

Hudson, J. and Donelan M.A., (1978). The computational scheme of a numerical model for wave and wind stress prediction. Applied Research Division and Hydraulics Division, Canada centre for Inland Waters, Burlington, Ont. 1978.

Lewis, P.J. (1987). Severe Storms over the Great Lakes: A Catalogue summary for the period 1957 to 1985, Report No. 87-13, Canadian Climate Centre, Atmospheric Environment Service, Downsview, Ontario.

Ontario Ministry of Natural Resources. (1988a) Wave hindcast Database for Lake Erie and St. Clair, Sandwell Swan Wooster, Inc., Don Mills , Ontario.

Ontario Ministry of Natural Resources. (1988b) Wave hindcast Database for Lake Ontario and Lake Superior, MacLaren Plansearch Limited, Willowdale, Ontario.

Ontario Ministry of Natural Resources. (1988c) Wave hindcast Database for Ontario's Great Lakes: Lake Huron/Georgian Bay. Philpott Associates.

Phillips and Irbe. (1978). Lake to Land Comparison of Wind, Temperature and Humidity on Lake Ontario during the International Field Year for the Great Lakes (IFYGL). Canadian Climate Centre, Report CLI-2-77, AES, Downsview, Ontario.

Reinhard, Robin. D, Driver, David. B, Hubertz, Jon.M .(1991). Hindcast Wave Information for the Great Lakes: Lake Ontario. WIS Report 25. US Army Engineer Waterways Experiment Station.

Resio, D. and Perrie, W. (1989). Implications of an f^{-4} Equilibrium Range for Wind-Generated Waves, Journal of Physical Oceanography. Volume 19. pp. 193-204.

Resio, D. (1981). The Estimation of Wind-Wave Generation in a Discrete Spectral Model. Journal of Physical Oceanography. Vol. 11, No. 4.

Resio, D.T. and Vincent, C.L. 1976a. Design wave information for the Great Lakes; Report 2, Lake Ontario, Technical report H-76-1, US Army Engineer Waterways experiment station, Vicksburg, MS.

Resio, D.T. and Vincent, C.L. 1976b. Estimation of winds over the Great Lakes; Technical report H-76-12, US Army Engineer Waterways experiment station, Vicksburg, MS.

Sambridge, M., Braun, J., and H. McQueen, 1995. Geophysical parameterization and interpolation of irregular data using natural neighbors. International Journal of Geophysics, 122, 837-857.

Schwab, D.J., Bennet, J.R., Liu, P.C. and Donelan, M.A. (1984). Application of a simple numerical wave prediction model to Lake Erie, Journal of Geophysical Research, Vol. No. 89, No. c3,pp 3586-3592.

Sousounis, P.J., edited 2002. The Potential Impacts of Climate Change in the Great Lakes Region, Special Section, Journal of Great Lakes Research, Vol. 28, No. 4, 493-462.

APPENDIX I
WIND FIELD ADJUSTMENT FOR TORONTO INTERNATIONAL AIRPORT

APPENDIX II
WIND FIELD ADJUSTMENT FOR PETRIE ISLAND

APPENDIX III
COMPARISON OF WIND SPEEDS (WITH AND WITHOUT BUOYS)

APPENDIX IV
WAVE MODEL VERIFICATION WITH C45135 BUOY

APPENDIX V
WAVE MODEL VERIFICATION WITH C45139 BUOY

APPENDIX VI
COMPARISON OF WAVAD RESULTS WITH AND WITHOUT BUOY WINDS

APPENDIX VII
COMPARISON OF WAVAD RESULTS (11 METEROLOGICAL STATIONS)