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COMPARISON OF WAVE CLIMATE MODELS

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MANAGEMENT PERSPECTIVE

Whether used to estimate wave conditions for design of structures or for environmental considerations such as shore erosion or sediment resuspension and transport, simple wave prediction models have found increasing use by coastal engineers. The ability of several commonly used models to estimate wave conditions at specific sites is examined in this report, and generally, was found to be wanting, particularly in the critical area of wave direction. Environmental managers charged with assessing shoreline development projects will have to await future model refinement to be able to put their unqualified trust in the results of wave prediction models.

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PERSPECTIVE GESTION

Les ingénieurs spécialistes des côtes utilisent de plus en plus des modèles simples de prévision des vagues pour évaluer les conditions de vagues, que ce soit aux fins de la conception de structures ou pour des raisons environnementales comme l'érosion des rives ou la remise en suspension et le transport des sédiments. Le présent rapport étudie la capacité de plusieurs modèles couramment utilisés à estimer les conditions de vagues à des sites donnés; dans l'ensemble, ces modèles ont présenté des lacunes, surtout en ce qui concerne l'aspect crucial de la direction des vagues. Les gestionnaires de l'environnement chargés d'évaluer les projets de mise en valeur des rives devront attendre que les modèles de prévision des vagues deviennent plus raffinés pour pouvoir avoir pleinement confiance en leurs résultats.

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ABSTRACT

Wave estimates from several simple one-dimensional and one two-dimensional parametric numerical wave prediction models are compared to wave data from various sites on the Great Lakes and the Gulf of St. Lawrence. The one-dimensional models use various algorithms based on steady state wave prediction relations and provide wave information at one site only. The two-dimensional model solves the momentum balance equation for the whole water body. In most cases, wind data are available from overwater sensors at or near the site for which the wave predictions are made. Generally, all of the model results exhibited considerable scatter. The one-dimensional model incorporating the wave direction algorithm developed by Donelan (1980) was marginally superior, in particular in its ability to estimate direction. The two-dimensional model was not appreciably superior when assessed against data at a single site. None of the models could be considered satisfactory for use in predicting shoreline evolution where the results are sensitive to correct direction measurements.

RÉSUMÉ

On compare ici les estimations de vagues tirées de modèles paramétriques de prévision numérique des vagues (plusieurs modèles simples unidimensionnels et un modèle à deux dimensions) aux données de vagues recueillies à divers sites des Grands Lacs et du golfe du Saint-Laurent. Les modèles unidimensionnels font appel à divers algorithmes reposant sur les relations de prévision des vagues à l'état d'équilibre et ne fournissent d'information sur les vagues que pour un site. Le modèle à deux dimensions résout l'équation du bilan de la quantité de mouvement pour l'ensemble de la masse d'eau. Dans la plupart des cas, on dispose de données de vent recueillies par des capteurs sur l'eau au site pour lequel on fait des prévisions, ou à proximité. Règle générale, les résultats de tous les modèles montrent une dispersion considérable. Parmi les modèles unidimensionnels, celui qui intègre l'algorithme de direction des vagues mis au point par Donelan (1980) s'est révélé légèrement supérieur, en particulier dans sa capacité à prévoir la direction. Pour ce qui est du modèle à deux dimensions, il n'était pas nettement supérieur aux autres après comparaison de ses résultats avec les données d'un site unique. Aucun de ces modèles ne saurait être considéré comme satisfaisant pour prévoir l'évolution du trait de côte quand les résultats dépendent de mesures correctes de la direction.

1.0 INTRODUCTION

Numerical wave prediction models are now used routinely by consulting engineers, government agencies and universities to produce estimates of site specific wave climates. A wave climate is a data set consisting of values of wave height, period and direction for a particular location over a specified time interval, usually months or years, at a regular time step, typically one to six hours. For most engineering applications, measured wave climates are seldom available at a site under investigation over a sufficient time interval, but adequate wind climates are often available at the site or at a nearby site. Therefore, numerical wave prediction models are used to hindcast wave climates from recorded wind data, typically over time intervals of five to 20 years.

In Canada, several different one-dimensional models are being used to predict deep water wave climates. While these models lack the sophistication of two-dimensional spectral models, they have found an important niche for studies at specific sites where the cost of running large two-dimensional models is not warranted. The one-dimensional models are simple, inexpensive, and use input data from only one meteorological station. To date there has been no rigorous comparison of these models. Typically model predictions are checked against whatever limited measured data are available at or near the site being investigated, and empirical adjustments are made to them or to the input wind data to 'tune' the model results to the measured data (the most common adjustment being to increase the wind speed values to account for the difference between overland and overwater wind speeds). However, these measured data usually do not include wave direction information, so there have been almost no comparisons of the models' capabilities to predict wave direction. Furthermore, the effect of incorporating the empirical wave direction results of Donelan (1980) into these models has not been assessed. In this study, the capability of several of these one-dimensional models to estimate wave height, period, and direction is examined.

In addition, a two-dimensional wave model (Donelan 1977) was adapted to run as a wave climate model over time periods of years. Results from this two-dimensional model are compared with those from several one-dimensional models.

Previous studies have examined the ability of several empirical relations to predict wave conditions under quasi steady-state meteorological conditions (See, for example, Bishop 1983). The thrust of this study is to examine models that use steady-state equations which also incorporate empirical relations to make the models quasi-dynamic, that is, to adjust to changing wind speed and direction, and, in addition, compare their output to that of a two-dimensional model. Hindcasts are compared to several data sets from the Laurentian Great Lakes and the Gulf of St. Lawrence, most of which have wave direction data. In addition, very long hindcasts were made with four models for one site on the Great Lakes where there were no field data, but, nevertheless the outputs of the models could be compared.

2.0 The Models

Two one-dimensional models were used on all the available data sets, PHEW (Fleming et al. 1984, see also Fleming and Pinchin 1986), and Hindwave (Hawkes 1987). For comparison of the long wave climate, two other models, one from Public Works Canada and one from Baird and Associates both based on work by Baird and Glodowski (1978), were run for this study by colleagues. In addition the two-dimensional WAWSP model (Donelan 1977) was used on some data sets.

2.1 The PHEW Model

The PHEW (Parametric Hindcasting of Effective Waves) model, developed by Philpott Associates Coastal Engineers Ltd. is designed to use any steady-state wave prediction equations that accept wind speed, direction and duration, and fetch length as inputs. Throughout this study two were used, the SMB relations (Bretschneider 1973), and the Donelan relations (Donelan 1980).

The PHEW model contains a procedure to handle varying wind conditions built around the steady-state model, and is described in detail by Fleming et al.

(1984). A brief description follows.

The basic feature is that sequences of wave generation are always defined by backstepping through time. The effective wave condition at any given time step is assumed to be made up of two components, from a generated wave and a decayed wave. The generated wave is produced by the present wind field and the decayed wave by an earlier wind field. Both are described by a characteristic height, and period, and the deep water back-azimuth direction. The larger of the two waves is called the **dominant** wave. The effective wave is then defined as the root mean square value of the generated and decayed heights with period and azimuth of the dominant wave.

The direction of a generated wave component is taken to be the mean of the wind directions over the time steps required to generate that wave. The direction of the decayed wave is equal to the direction of the dominant wave at the time step immediately preceding the commencement of the decay.

For our comparisons with field data, the fetch lengths used in PHEW were determined in the following way. Straight line fetches at increments of one degree were established for each site, using 2 km grid bathymetry files available at NWRI, and then running average fetches (±15°) were computed for each degree of azimuth. The running averages were used in the wave prediction equations. For the long wave climate done for Stoney Creek on Lake Ontario, a table of fetch values provided by Public Works Canada was used.

The generated wave at a given time step is the maximum wave hindcasted over a preceding time interval that is limited either by an empirically determined maximum or by a rapid change in wind direction. Typical values are a maximum backstepping time of two days, or a change in wind direction of 45° or more. On the other hand, a wave decay sequence is started when a calm is encountered, or, when backstepping in time, an abrupt change in wind direction is encountered. A linear decay is applied to the height of the dominant wave.

The two steady-state models used are the well known SMB model and the newer Donelan model. The main attraction of the SMB model is that it has been used with considerable success for a long time. A major disadvantage is that it assumes the wave direction to be the same as the wind direction. It is a matter of common experience that, where there is a strong fetch gradient with azimuth, the wave direction is biased towards the direction of longer fetch. Donelan formalized this experience into his steady state equations, so that his predictions account for fetch gradient and purport to predict more realistic wave directions. Some runs were made with a hybrid version of the SMB model, in which the wave direction and fetches were computed according to the Donelan algorithm.

In the course of this work, the computed significant period from the SMB model and the peak period from the Donelan model are both assigned to the peak period. The Donelan model computes it directly. As for the period from the SMB model, various comparisons with field data suggest that its significant period can be equated simply to the peak period (Bishop et al. 1989), or can be increased slightly (Bretschneider (1970) suggests 1.06, Goda (1985) suggests 1.05) to estimate peak period.

2.2 The Hindwave Model

The Hindwave model is a proprietary numerical procedure developed by Hydraulics Research Limited, Wallingford (Hawkes 1987). The system operates in two parts.

The first part, which estimates the height, period, and direction of the waves for given wind conditions at specified speed and direction intervals and specified durations at a particular location, computes the wave directional spectrum (at 10° intervals), and then uses a weighted average (cosine squared) spreading function to determine the total spectrum (we did not adjust the power of the cosine although a higher power such as 6 works better for narrow fetches (Hawkes, personal communication)). The mean JONSWAP equation (Hasselmann et al. 1973) is used for the one-dimensional spectral estimate for each direction component. The component spectra are then summed using the procedure described by Seymour (1977). The fetches for each site were taken from the moving-average fetch tables at 10° increments determined by the PHEW program, so that the fetch estimates of the two programs were as similar as possible.

The second part of the Hindwave procedure is to apply a wind climate to the table established above to determine the wave conditions for a particular point in time, the winds are back-averaged vectorially for the appropriate duration categories of part one, and the largest wave conditions are selected from the set of wave height values.

2.3 PWC and Baird Models

For the comparison of the long wave climate at Stoney Creek, Lake Ontario, we had access to data sets generated by two other hindcast models, one from Public Works Canada (PWC), and one from Baird and Associates. Using twelve years of wind data from the Toronto Island Airport, wave climates using all the models were computed for Stoney Creek, near the west end of Lake Ontario.

The procedures used by PWC and Baird are both based on the procedure developed by Baird and Glodowski (1978). The overall approach taken in these models is similar to that of the PHEW model. This model uses a backstepping procedure to determine the wave conditions when the wind direction is from a given sector. When the wind moves to a new sector, these waves are decayed, and new wave values computed. The resultant waves are defined by taking the square root of the sum of squares of actively generated and all the decaying waves. Both use the SMB relations as described by Bretschneider (1973). Over the years, both models have been altered in some ways by the respective users. The most significant difference between these two models and the PHEW and Hindwave models is a factor of 1.25 that has been applied to the predicted significant wave period to estimate values of the peak period.

2.4 The WAWSP Model

The WAWSP (Wave and Wind Stress Prediction) model was developed to predict both wind stress and waves over the whole surface of an enclosed water body (Donelan 1977). In brief, the model solves the local momentum balance and the wave field at each grid point is represented by two 'characteristic' wave trains, one 'active' wave train roughly in the direction of the wind and one 'fossil' wave train left behind by a rapidly changing wind field. The wave field is parameterized in terms of the JONSWAP spectrum. It was adapted to run in a wave climate mode for this study.

The original model has also been adapted for use as a forecasting tool (Schwab et al. 1984b) and is now used routinely to forecast waves on the Great Lakes.

3.0 Field Data

A number of data sets were used to test the models, primarily from the Great Lakes, but also including two cases from the Gulf of St. Lawrence (figure 1.). Where possible, data containing wave direction information were used. Overwater wind data were available for all of the data sets.

3.1 Lake Erie

Two data sets from Lake Erie were used. One was collected in 1979, when the NWRI wave direction buoy (Skafel and Donelan 1983) was deployed off Pointe-aux-Pins from August to October, at N42 07 19, W82 03 26, in 20 m of water. Bursts of data of 20 minute duration sampled at two samples per second were collected every 6 hours and analysed to yield the characteristic wave height, peak period and mean direction. Wind data were available from a nearby meteorological buoy. The other wind and wave data set was collected in September and October 1981 by the NOAA Great Lakes Environmental Research Laboratory (Schwab et al. 1984a) at a tower in the central basin located at N42 03 18, W80 28 30, in 14 m of water. Wave spectra were calculated for 10 minute records sampled at two samples per second every hour and summarized in terms of characteristic height, peak period and mean direction.

3.2 Lake Ontario

Three data sets from Lake Ontario were used. The first two, collected in 1972, were from Waveriders deployed by the Marine Environmental Data Service, Fisheries and Oceans Canada. They were located off Toronto at N43 31 00, W79 19 00 in 55 m of water (April to December), and off Main Duck Island at N43 47 45, W76 49 39 in 70 m of water (April to November). Wind data were collected at nearby buoys as part of the International Field Year on the Great Lakes (IFYGL) programme. Characteristic wave height and peak wave period data are available at hourly intervals, based on time series approximately seventeen minutes long sampled at one sample per second. The third data set was collected using a capacitance wave staff at the NWRI Offshore Research Tower from June 1976 to July 1977. Wind data were also recorded at the tower. The tower is located at N43 16 06, W79 45 36 in 12 m of water. Characteristic height and peak period data are available for all records, but only limited wave direction data were collected during specific events (see Donelan et al. 1985).

3.3 Lake St. Clair

Data from a pressure transducer were collected in Lake St. Clair from October to November, 1985 at N42 22 04, W82 31 50, in 5.5 m of water. Approximately 4.3 minutes of data were collected every hour at 2 samples per second, and the surface elevation spectra computed from the pressure data using a Fourier transform technique, and these were reduced to characteristic height and peak period data. Wind data were collected at the same tower that housed the pressure transducer.

3.4 Gulf of St. Lawrence

The NWRI wave direction buoy was deployed at two sites in the gulf, as part of the Canadian Coastal Sediment Study (Skafel 1985). In 1983 it was deployed off Pte-Sapin, New Brunswick from July to November at N46 57 30, W64 43 20 in 16.5 m of water. In 1984 it was deployed off Stanhope, Prince Edward Island from September to November at N46 26 48, W63 06 00 in 14.6 m of water. Data were collected for 26 minutes four times per day at two samples per second, and summaries of characteristic height, peak period, and mean direction tabulated. Wind data were also collected on the buoy.

4.0 Model Results

The results of the models were examined in a variety of ways. Where the measured data were for short periods of time (a month or two), the time series were graphed for visual comparison. For these short records and some of the longer ones the predicted heights, periods, and directions were compared to the corresponding measured values. For these plots, two conditions were applied. First, only cases with measured heights greater than 0.3 m were included (0.2 m in the case of Lake St. Clair because of the shorter fetches), to avoid light, variable wind conditions. Second, only deepwater waves were shown because all models assumed deep water. Deepwater was defined, using the measured data, as $d/L_0 > 0.3$, where d is the water depth and L_0 is the deep water wavelength defined by the peak period. The solid lines on these comparison diagrams represent perfect agreement with the measured data. The dashed lines on the height diagrams are the 95% confidence limits (see Bishop and Donelan 1988).

The ability of the models to reproduce storm events is compared in more detail in the following way. Storm events in the summary time series of measured data were identified by a maximum in wave height (The size of the maximum varied from site to site, and is indicated in the text, below). The corresponding maximum in the model time series was found (several hours lead or lag was permitted). The number of occurrences, for each model, in which the model height fell within the 95% confidence limits of the measured height was determined. Similarly, the number of occurrences of the model wave direction within ±20° of the measured direction was found. Tolerances on period are difficult to establish (see,for example, Bishop and Donelan 1988), so that the model results that were within ±20% of the peak period for each storm were considered acceptable. In this fashion it was possible to compare, in tabular form, the relative performance of the models.

Finally, the longer records (greater than six months), notably for Lake Ontario, could only be examined practically by way of summary statistics. The percentage frequencies of occurrence of the waves in terms of height, period and direction classifications are presented in tabular form.

4.1 Lake Erie

Times series of the wave periods, heights, and directions for the 1979 data collected off Pte-aux-Pins are shown in figures 2a and 2b along with the hindcasted results. In general the models all identify storm events, in the sense that significant increases in measured wave height were also predicted by the models. Typically the heights of storms were overpredicted, and the corresponding periods tended to be underpredicted. The major variations in direction are tracked, but not closely. There appears to be a phase lag in the model results, but it is hard to quantify because the field data were reported only every eight hours.

Deepwater characteristics are compared to the measured data in figures 3a through 3o. Figures 3a to 3e show comparisons of height. The impression from the time series that the models overpredict is correct except for the WAWSP-8 km grid model, which tends to underpredict. Figures 3f to 3j show the period comparisons, where there is underprediction except for the WAWSP-32 km grid model and the Hindwave model, which have distributions that are more evenly scattered about the measured values. Figures 3k to 3o show the direction estimates. All models reproduce the broad features of the direction measurements, but none do so with good accuracy.

The ability of the models to reproduce storm events with wave heights greater than 0.66 m is summarised below.

Numbers of acceptable heights, periods and directions:

	PHEW-SMB	PHEW-Don.	Hindwave	WAWSP-8km	WAWSP-32km
No. of storms: 29					
H_{mo}	4	2	8	2	7
T_p	17	9	23	7	17
Mean Dir'n	17	18	23	17	20

(H_{mo} is the characteristic wave height defined as four times the variance of the surface displacement, and T_p is the period of the peak of the spectrum).

On the basis of this comparison, the Hindwave model performed the best, followed by the WAWSP-32 km grid model. The WAWSP-8 km grid model had the worst results.

The time series of the 1981 data collected on the GLERL tower are shown along with the model results in figures 4a and 4b. All storms were predicted, although most of the heights and periods were overestimated. All major wave direction changes were followed except on October 11 and 26-27, but these correspond to very low wave height events.

All of the deepwater data greater than 0.3 m in height are compared to the measured data in figures 5a to 5r. Heights tend to be overestimated and periods show considerable scatter. The direction estimates tend to be turned clockwise relative to the measured data; this tendency is also shown in the results of Schwab et al. (1984a) using a model similar to the WAWSP model with a 5 km grid.

The ability of the models to predict storms with measured heights greater than 1.5 m is shown in the following table.

Numbers of acceptable heights, periods and directions:

	PHEW-SMB	PHEW-wave[1]	PHEW-Don.	Hindwave	WAWSP-8km	WAWSP-32km
No. of storms: 6						
H_{mo}	4	3	5	4	5	4
T_p	6	6	6	5	4	4
Dir'n	2	2	3	2	0	2

[1] PHEW-SMB model with wave fetches.

The PHEW-Donelan model had the best results, followed by the PHEW-SMB and Hindwave models. The WAWSP-8 km model reproduced the wave heights well, but had the poorest direction results.

4.2 Lake Ontario

Summary tables for the 1972 data are presented in tables 1 and 2 in terms of wave height and period classes. The predicted conditions all follow the same general patterns as the measured data. In terms of height the PHEW-SMB wave fetch and WAWSP-32 km grid models tend to overpredict, while the Hindwave model consistently underpredicts the larger waves. There is a general tendency to underpredict the occurrences of long periods, although Hindwave and WAWSP-32 km grid and PHEW-SMB wave fetch models do well for the Main Duck data set.

The model results were compared to the 1972 Waverider data in terms of the wave height and period at the peaks of storms with measured heights greater than 1.5 m.

The Main Duck Island results are summarised below.

Numbers of acceptable heights, periods:2

	PHEW-SMB	PHEW-wave	PHEW-Don.	Hindwave	WAWSP-32km
No. of storms: 14					
H_{mo}	8	4	6	6	7
T_p	14	13	12	11	13

In terms of height, the PHEW-SMB model had the best performance, followed closely by the WAWSP-32 km grid model, and then the PHEW-Donelan and the Hindwave models. The PHEW-SMB model had the best record and the Hindwave model had the poorest record in predicting periods. The direction predictions of the models were all in reasonable agreement with each other. This may be due to the fact that nearly all the storms had wind directions approximately coincident with the longest fetch direction.

The model results for the Toronto site are summarized below.

Numbers of acceptable heights, periods:

	PHEW-SMB	PHEW-wave	PHEW-Don.	Hindwave	WAWSP-32km
No. of storms: 12					
H_{mo}	6	1	3	4	7
T_p	11	11	11	9	12

The WAWSP-32 km grid model had the best record for heights, followed closely by the PHEW-SMB model. The PHEW-SMB with wave fetches was the worst. The WAWSP-32 km grid model had the best record in predicting periods. As with the Main Duck results, there was generally reasonable agreement among the modelled directions, although there were more cases of markedly different values.

The PHEW-SMB, PHEW-Donelan and Hindwave models were compared to wave height, period, and limited direction data collected on the NWRI Research Tower from 1976 to 1977. The height and period data sets are presented in summary form in table 3, which shows the percentage frequencies of occurrence for height and period classes. The PHEW-Donelan model predicts the low wave height events the best, and the PHEW-SMB model is the worst. On the other end of the scale, all of the models miss the large wave height tail of the distribution, the Hindwave model being the worst, and the PHEW-SMB being the best. In terms of period, none of the models predicted the short periods well. Similar to the height data, the models missed the long period tail of the distribution, the PHEW-Donelan model being the worst, and the Hindwave model being the best. The direction results for selected data are compared to the measured values in figure 6. The general trend of the measured data is predicted by the models, with the PHEW-Donelan perhaps being the best.

In addition, a site near the western end of Lake Ontario, near Stoney Creek, was the subject of a wave hindcast for a different project, using the PWC model. Advantage of this was taken to generate hindcasts using the other models listed in the previous section, so that the models could be compared for a very long time series. The site was at N43 17, W79 42. A time series of hourly wind speed and direction from the Toronto Island Airport weather office for the period from 1974 to 1985 was used, allowing a 12 year period to be hindcast.

These data sets are most easily compared in summary form. Table 4a shows the percentage frequencies of occurrence for all directions, broken down into wave height and wave period classes. For wave height, the Hindwave, PHEW-Donelan and WAWSP-32 km models show the most nearly calm conditions, while the PHEW-SMB(wave fetch) model shows the least. On the other hand the PHEW-SMB(wave fetch) model shows significantly more occurrences of moderate conditions (1.0 to 1.5 m heights).

In terms of wave period, the Hindwave results show much fewer occurrences of calm conditions. The results from the PWC and the Baird models show a marked bias towards longer periods. Both these models use the SMB equations, with the periods multiplied by 1.25, whereas the PHEW-SMB model does not adjust the periods.

This site experiences the largest wave conditions for winds from the NE to E. Accordingly waves from this sector are shown in more detail: the percentage frequencies of occurrence for all waves are shown in Table 4b, and for heights greater than 1 m and for periods longer than 3 s in Table 4c. The PWC and Baird models produced similar results, as might be expected because they have the same origin. The other one-dimensional models have somewhat similar height summaries, with the notable exceptions of the 67.5° bin for the Hindwave model and the 22.5° bin for the PHEW-SMB(wave fetch) model; the period summaries are also similar with the same exceptions plus the relatively small sample in the 90° bin for the PHEW-SMB model.

The WAWSP-32 km grid model clearly produces much different results than the one-dimensional models. In Table 4b, the WAWSP model had the fewest waves in the 67.5° and 90° bins, and substantially more in the 112.5° bin. The results are similar in Table 4c, for the larger waves.

While all of the models used identical wind input, the WAWSP model used different fetch data: it is designed to accept fetch information only from a digitized bathymetry file of the lake, from which the shoreline is located. The bathymetry file contains data at a spacing of 2 km; this was reduced to a spacing of 32 km in the runs for this comparison. The reason for selecting the larger spacing was for economy of computing time.

To test the sensitivity of results to the spacing of the points in the WAWSP model, additional runs were made with spacings of 8 and 16 km. Only a short interval using January to April 1979 winds was used for these runs because of the increase in computing time required with the smaller spacing. The data are plotted in figure 7. For NE storms (for example, days 12 to 15) the 32 km model shows results with waves coming from a more clockwise direction, but all three have similar heights and periods. Examination of the digitized lake shape for the respective spacings reveals that the 32 km spacing representation reduces significantly the northerly fetches for the Stoney Creek site compared to the other two, while the easterly fetches are relatively unchanged, and the SE fetches increased somewhat. This distortion of the fetches appears at least partially responsible for the different wave direction results compared to the one-dimensional models.

Another result that was unique to the WAWSP-32 km grid data was that there was a much higher occurrence of relatively large waves from the SSW and SW compared to the one-dimensional models. This feature is also evident in Figure 7, on April 7, where both the 16 and 32 km grid models have larger waves than the 8 km grid model. This can be explained simply, at least qualitatively. The model automatically locates the site at the nearest grid mid-point resulting in minimum fetches of 4, 8, and 16 km for the 8, 16 and 32 km models respectively. Accordingly, the 8 km spacing gives superior results for the short fetch situations. For comparison, the minimum fetch used by the one-dimensional models for this site is about 5 km, which is close to the minimum possible fetch with the WAWSP 8 km grid model, but much smaller than the minimums for the other two WAWSP configurations.

4.3 Lake St. Clair

The times series of the data from Lake St. Clair and the hindcasts are shown in figure 8a and 8b. All of the models identified all storms. However, the storms out of the W to NW (longer fetches) tended to be underpredicted in terms of both height and period, while storms from the N to E (shorter fetches) were more closely predicted, although the decaying parts of the storms were overpredicted. The measured direction data were only available for selected times and are not shown on the time series, however the model directions are plotted and show considerable spread in the results.

All deepwater data with heights greater than 0.2 m are compared to the measured values in figures 9a to 9o. The best height data from the one-dimensional models appears to be from the PHEW-Donelan model, while the most scatter is found in the Hindwave data. The WAWSP-8 km grid model has the tightest distribution overall. The period data are considerably more scattered, with the best overall being the PHEW-Donelan model. The PHEW-Donelan model reproduces the directions the best, although all models have some values that are in considerable error.

The ability of the models to predict storms for measured wave heights greater than 0.8 m was compared in the same way as the Lake Erie results and the results are summarised below.

Numbers of acceptable heights, periods and directions:

	PHEW-SMB	PHEW-Don.	Hindwave	WAWSP-4km	WAWSP-8km
No. of storms: 7					
H_{mo}	2	6	5	4	5
T_p	5	6	7	7	6
Mean Dir'n	3	6	4	4	2

The PHEW-Donelan model had the best height estimates, correctly predicting six of the seven storms, followed closely by the Hindwave and, surprisingly, the WAWSP-8 km grid model. The Hindwave and WAWSP-4 km models had the best record for periods. The best direction performance was shared by the PHEW-Donelan model, and the worst were by the PHEW-SMB and WAWSP-8 km models.

4.4 Gulf of St. Lawrence

The PHEW models and the Hindwave model were tested against the Gulf data. All the deepwater data for heights greater than 0.3 m are compared to the measured data in figures 10a to 10i for Pte-Sapin. The PHEW-Donelan model predicts the heights best, while the PHEW-SMB model overpredicts, and the Hindwave model underpredicts for Pte-Sapin and has very scattered results for Stanhope. All three models underpredict the periods at longer values. Although there is considerable scatter in the direction estimates, the PHEW-Donelan model appears to be the best.

The reproduction of storms events greater than 0.9 m at Pte-Sapin is shown in the following table.

Numbers of acceptable heights, periods and directions:

	PHEW-SMB	PHEW-wave	PHEW-Don.	Hindwave
No. of storms: 4				
H_{mo}	1	0	2	0
T_p	4	3	4	2
Dir'n	0	1	1	2

The deepwater data for Stanhope (heights greater than 0.3 m) are shown in figures 11a to 11i. The PHEW-SMB model has the best height results; the PHEW-SMB model overestimates at higher values; the Hindwave model results are virtually uncorrelated with the measured data. All of the models have poor period performance, although the PHEW-Donelan results are a little more closely related to the measured data. The direction results are best for the PHEW-Donelan model, and worst for the Hindwave model.

The best heights are from the PHEW-Donelan model, the best periods from the PHEW-SMB wave fetch model, and the best directions from the Hindwave model. The latter, however did poorly in terms of height and period. None did well in terms of direction.

The reproduction of storms events greater than 0.9 m is shown in the following table.

Numbers of acceptable heights, periods and directions:

	PHEW-SMB	PHEW-wave	PHEW-Don.	Hindwave
No. of storms: 2				
H_{mo}	0	0	0	1
T_p	2	2	2	1
Dir'n	0	2	2	1

With only two storms to examine, little can be said of the relative performance for storms, except that none of the models predicted both storms.

5.0 Discussion

The quality of the hindcasted waves is dependent foremost on the quality of the available wind data. For all of the measured wave data sets in this study there were corresponding overwater wind data sets collected at or near the site. Where the wind was not measured at 10 m elevation, it was corrected to 10 m assuming stable conditions. Neither the wind data nor the models were 'tuned' in any way to make the results correspond better to the measured data.

The remaining most likely source of difficulty with the wind data is that the wind variability over the whole generating area is not represented. However, the one-dimensional models used in this study can only use one wind time series, so that extra wind records would only be useful if a single representative wind field were computed. The WAWSP model on the other hand is capable of using wind data from an array of sites, although this was not done for these comparisons. In this study, Lake St. Clair was the smallest lake, so that variable wind conditions would likely be of least concern and the Gulf of St. Lawrence was the largest water body, so that the variable winds would likely degrade the predicted waves the most.

5.1 Wave Height

First the predicted wave height versus measured wave height data, as shown in the comparison diagrams, are considered. All results for all data sets show scatter beyond the 95% confidence limits, in some cases substantially beyond. Some results also show a marked bias. Overall the PHEW-SMB model tends to overpredict the wave heights, and the PHEW-Donelan model is relatively unbiased, showing some over and some underprediction. The Hindwave model has less bias than the PHEW-SMB model, but shows more scatter. The WAWSP model tended to produce results of similar quality to the one-dimensional models. In more detail, for the Lake Erie 1979 data set, the PHEW-SMB, and Hindwave models overpredict; the WAWSP-8 km model underpredicts, the PHEW-Donelan and WAWSP-32 km model are the least biased, although the PHEW-Donelan model underpredicts for higher waves, and the WAWSP-32 km model has a lot of scatter.

For Lake Erie 1981, all overpredict at larger heights, the one-dimensional models more so than the WAWSP. The WAWSP-8 km model clearly gives the best results. It is interesting to note that Schwab et al. (1984b) based their acceptance of their version of the WAWSP model primarily on its good performance against this measured data set.

For Lake St. Clair 1985, the PHEW-SMB model overpredicts; the PHEW-Donelan and Hindwave models don't have much bias, although the Hindwave results have considerable scatter. The WAWSP models are best, the 8 km version outperforming the 4 km version, as evidenced by the reduced scatter (a surprising result because the smaller grid would be expected to give a better result).

All the models showed considerable scatter for the Pte-Sapin data. The PHEW-SMB model tends to overpredict, the Hindwave model underpredicts, and the PHEW-Donelan model has the least bias.

For the Stanhope data, the PHEW-SMB and -Donelan models overpredict, the first more so than the second. The Hindwave model results appear to have very little correlation to the measured data.

The wave heights for the longer Lake Ontario tests were examined in terms of summary statistics. The PHEW-SMB model reproduces the distribution quite well for the two data sets from 1972. The PHEW-SMB wave fetch and WAWSP-32 km grid models both overpredict for the Main Duck Island data set, but only the former overpredicts for the Toronto data. On the other hand, the Hindwave model does not predict data in the higher ranges for either data set.

The Lake Ontario 1976/77 measured height data have occurrences to values as great as 3.5 to 4.0 m (0.07 %), and the measured periods to the 8 to 9 s class (0.31 %). In contrast, the predicted data do not have occurrences at these large values. The results from the PHEW-SMB model most closely resemble the measured data with data missing only from the highest 'bin'. The next best is the PHEW-Donelan results, missing the two top bins, and the worst is the Hindwave results, missing the top three bins (table 3).

For the Lake Ontario 1974-85 hindcasts (there are no measured data), the distributions are similar at low wave heights, but show variation in the occurrences of large heights. The PHEW-SMB model has the largest waves (0.01 % in the 4.0 to 4.5 m class), and the Hindwave model has the smallest (nothing greater than 3.0 m). The PWC and Baird models give similar results to the PHEW-SMB model, as might be expected, because they all use the SMB relations. The pattern of occurrences is similar to the above three data sets where there are measured data.

From the summary comparisons, it would appear that the PHEW-SMB model most closely reproduced the wave height occurrences, particularly for large waves, and that the Hindwave model consistently underpredicts the occurrence of large waves.

5.2 Wave Period

The comparison diagrams showing predicted and measured wave period are discussed first. In general, there is more scatter in the results than shown by the wave height data.

In the Lake Erie 1979 comparison, all but the Hindwave results tend to underpredict. For the 1981 Lake Erie data, the PHEW models have little bias, whereas the Hindwave model results tend to be a little high, and the results from the WAWSP models are low. Overall the comparisons are quite good, considering the coarseness with which the measured data were reported (See figures 4j to 4m).

The 1985 Lake St. Clair measured periods are reproduced best by the PHEW-Donelan model, and worst by the Hindwave model which shows the largest scatter, although there is not a lot to choose between the data sets. An unexpected result is that the WAWSP-8 km grid data appear to have less scatter than the 4 km grid data.

The predicted results from all the models for Pte-Sapin and Stanhope tend to be under the measured results.

The wave periods for the longer data sets for Lake Ontario are compared in terms of the summary statistics, which show the percentage frequencies of occurrence of wave periods in one second interval bins.

The 1972 Lake Ontario measured data do not show any occurrences for periods under two seconds because the Waverider outputs were sampled at one Hertz, so that the distributions of short periods cannot be compared. At longer periods it is evident that the models do not predict the distribution of the longest periods found in the measured data, the PHEW models being the worst, and the Hindwave being the best.

The 1976-77 Lake Ontario periods are not predicted particularly well at the shorter periods; above three seconds the Hindwave model produced the best results. None of the models predict the periods in the 8 to 9 second group. It should be noted that the measured periods are determined from the time series of the surface elevation using a method developed by Donelan (1976), which is not as accurate a method as the spectral methods used for the other data sets.

There are no measured data with which to compare the model data for the long runs at Stoney Creek in Lake Ontario, 1974 to 1985. If the hindcast comparison is restricted to the longer periods which are of more engineering importance, it can be seen that the PWC and Baird models contain data up to the 9 to 10 second bin, whereas all the others stop at the 8 to 9 second bin. Of the latter, the Hindwave model has the most occurrences in that group. Referring to the above comparisons to measured data from Lake Ontario where the Hindwave reproduced the measured data the best, one is left with the impression that in this comparison, the PWC and Baird models are probably overestimating the occurrences of long periods,and the PHEW models are underestimating these occurrences.

5.3 Wave Direction

Accurate estimates of wave direction are of crucial importance for successful operation of sediment transport models, prediction of harbour responses, and the descriptions of other coastal processes. For example, Kamphuis (1989) points out that small inaccuracies in wave direction can result in substantial errors in predicted longshore sediment transport. Nevertheless, accurate prediction of wave direction remains elusive. Holthuijsen and Smith (1988) examined estimates of wave direction for the North Sea obtained from several models, including synoptic models used by the British Meteorological Office and the Royal Netherlands Meteorological Institute. They found that the best results, obtained with the synoptic models, still had errors of about 15°, for waves greater than 1.5 m (and are worse for smaller waves).

The ability of the various models to estimate wave direction is examined in more detail in this section. The direction predictions are best compared to the measured data by examining the comparison diagrams. In general the predictions exhibit quite a large amount of scatter relative to the measured data. If an overall best predictor had to be chosen from the one-dimensional models, the PHEW-Donelan model appears to have a slight edge. The smaller grid size version of the WAWSP model was superior to the large grid size for any data set, but the WAWSP model did not show a distinct superiority over the one-dimensional models. Some case by case comparisons follow.

For the Pte-aux-Pins data set, Lake Erie, 1979, the Hindwave model produced the best results. All of the models had a slight counterclockwise bias. The 1981 Lake Erie data set was reproduced best by the Hindwave model, followed by the WAWSP models, the 8 km grid version being better than the 32 km version. All models had a slight clockwise bias. This rotation means that in the range from 0 to 50° the model directions are predicted to be from longer fetches, while in contrast waves from the longest fetch (270°) are modelled to be from shorter fetches (>270°). The PHEW-Donelan model results show definite banding: most of the measured directions from 0 to 90° are estimated at about 70°; most of the measured directions from 200 to 300° are estimated at about 270°. These two predicted directions correspond reasonably well with the maximum fetches for easterly and westerly winds (see Figure 1a), so the fact that these predicted wave directions are biased to these directions may be the result of the direction algorithm used by Donelan (1980).

The 1976-77 Lake Ontario results were reproduced best by the PHEW-Donelan model, although all models were biased clockwise for directions greater than 300°.

The measured directions for Lake St. Clair were predicted quite well by all of the models for values less than about 180°. Above about 300° there was a tendency for all the predictions to be biased clockwise. Because of the difficulty in establishing the true measured values from 200 to 300° (Skafel and Donelan, personal communication), no comparisons are made in that range.

The Pte-Sapin data were relatively poorly estimated, the scatter being the worst of all the data sets. The predicted data sets tended to be turned counterclockwise for directions less than about 120°, and clockwise over 200°. The scatter and bias were least for the PHEW-Donelan model. Fleming et al. (1986), using a hybrid method incorporating the SMB equations for period and height and the Donelan method for direction, also found improved results for direction over the normal direction method used for SMB. The Stanhope comparisons were limited by the small data set. The waves were clearly onshore, and the results of the PHEW-SMB and Hindwave models appear to have a counterclockwise bias. The PHEW-Donelan results agree reasonably well with the measured directions.

6.0 Concluding Remarks

The one-dimensional models are in fact very simple models of complicated processes, and to expect them to perform well in a variety of situations is perhaps asking too much. As pointed out by Baird et al. (1986), they all contain, largely empirical, procedures to adapt steady-state equations to varying wind speed and duration, procedures to estimate fetches, and procedures to calculate decay. It is well recognized that these models do not handle swell at all, and for this study, the measured wave data sets did not contain cases of swell. However, with the exception of Lake St. Clair, all of the water bodies in this study have dimensions of several hundreds of kilometres, so that the homogeneity of the wind fields becomes an issue. Lack of homogeneity in the wind field means that these models are being applied outside their domain of validity, as was the case in the study by Holthuijsen and Smith (1988). Nevertheless, from a practical point of view, wind data is not often available over the whole generating area, and these types of models have been used successfully at many sites in Canada (See Baird et al. 1986). The two-dimensional model (WAWSP) is capable of accepting multiple wind time series, but they were not readily available for this study.

All that being stated, the models are still able to provide useful estimates of wave climates. In terms of their relative merits, the overall best one-dimensional model is the PHEW-Donelan model, because of its slightly superior wave height and direction estimates. It does appear to underpredict the wave periods slightly, where the Hindwave model performed rather better.

The two-dimensional model (WAWSP) does not show any distinct superiority to the one-dimensional models when assessing the waves at one site. However, it does provide data for the whole water body at the same time, at considerable cost in computation time relative to the one-dimensional models. Furthermore, if the grid size is not chosen carefully for the two-dimensional model and is too large, unexpected results await the unwary user.

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References

Baird, W.F. and C.W. Glodowski. 1978. Estimation of Wave Energy Using a Wind Wave Hindcast Technique. Proc. Int. Symposium on Wave and Tidal Energy, Canterbury, England, F3: 39-54.

Baird, W.F., Readshaw, J.S. and O.J. Sayao. 1986. Nearshore Sediment Transport Predictions, Stanhope Lane, P.E.I. Canadian Coastal Sediment Study, Report No. C2S2-21, National Research Council of Canada.

Bishop, C.T. 1983. Comparison of Manual Wave Prediction Models. J. Waterway, Port, Coastal, and Ocean Engineering, American Society of Civil Engineers, 109(1):1-17.

Bishop, C.T., Donelan, M.A. and K.K. Kahma. 1989. Shore Protection Manual's Wave Prediction Reviewed. National Water Research Institute, Contribution No. 89-91, Burlington, Ontario.

Bishop, C.T. and M.A. Donelan. 1988. Waves and Wave Forecasting. In: Civil Engineering Practice - Geotechnical/Ocean Engineering, P.N. Cheremisinoff, N.P. Cheremisinoff, and S.L. Cheng (eds.), Technomic Publishing Co., Inc., Lancaster, PA, 3:653-695.

Bretschneider, C.L. 1973. Prediction of Waves and Currents. Look Laboratory, Univ. of Hawaii, Report. 3(1):1-17.

Donelan, M.A. 1976. A Method for the Automatic Measurement of Wave Frequency. J. of the Fisheries Research Board of Canada, 33(10):2318-2322.

Donelan, M.A. 1977. A Simple Numerical Model for Wave and Wind Stress Prediction. National Water Research Institute, Burlington, Ontario.

Donelan, M.A. 1980. Similarity Theory Applied to the Forecasting of Wave Heights, Periods and Directions. Proc. Canadian Coastal Conference, National Research Council of Canada, pp. 47-61.

Donelan, M.A., Hamilton, J. and W.H. Hui. 1985. Directional Spectra of Wind-generated Waves. Phil. Trans. R. Soc. Lond. A315: 5: 509-562.

Fleming, C.A., Philpott, K.L. and B.M. Pinchin. 1984. Evaluation of Coastal Sediment Transport Techniques, Phase 1: Implementation of Alongshore Sediment Transport Model and Calibration of Wave Hindcasting Procedure. Canadian Coastal Sediment Study, Report No. C2S2-10, National Research Council of Canada.

Fleming, C.A., and B.M. Pinchin. 1986. Evaluation of Estimation Techniques. Proc. Internat. Conf. on Measuring Techniques of Hydraulics Phenomenon in Offshore, Coastal and Inland Waters, BHRA, The Fluid Engineering Centre, pp. 189-202.

Fleming, C.A., Pinchin, B.M. and R.B. Nairn. 1986. Evaluation of Coastal Sediment Transport Techniques, Phase 2: Comparison with Measured Data. Canadian Coastal Sediment Study, Report No. C2S2-19, National Research Council of Canada.

Goda, Y. 1985. Random Seas and Design of Maritime Structures. Univ. of Tokyo Press, Japan. 323p.

Holthuijsen, L.H., and D.R. Smith. 1988. An Evaluation of Model Estimates of Ocean Wave Directions. Ocean Engng., 15(2): 127-137.

Hawkes, P.J. 1987. A Wave Hindcasting Model. In: Advances in Underwater Technology, Ocean Science and Offshore Engineering, 12: Modelling the Offshore Environment. Society for Underwater Technology, London.

Kamphuis, J.W. 1989. Sediment Transport Modelling: Sensitivity to Incident Wave Direction. Proc. XXIII Congress, IAHR, Ottawa: C285-C292.

Liu, P.C., Schwab, D.J. and J.R. Bennett. 1984. Comparison of a Two-dimensional Wave Prediction Model with Synoptic Measurements in Lake Michigan. J. Of Physical Oceanography 14(9): 1514-1518.

Schwab, D.J., Bennett, J.R., Liu, P.C. and M.A. Donelan. 1984a. Application of a Simple Numerical Wave Prediction Model to Lake Erie. J. Geophysical Research, 89(C3): 3586-3592.

Schwab, D.J., Bennett, J.R. and E.W. Lynn. 1984b. A Two-dimensional Lake Wave Prediction System. Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan.

Seymour, R.J. 1977. Estimating Wave Generation on Restricted Fetches. J. Waterway, Port, Coastal, and Ocean Division, American Society of Civil Engineers, 103(2):251-264.

Skafel, M.G. 1985. Offshore Wind and Wave Data, CCIW Wave Direction Buoy. Canadian Coastal Sediment Study, Report No. C2S2-14, National Research Council of Canada.

Skafel, M.G., and M.A. Donelan 1983. Performance of the CCIW Wave Direction Buoy at ARSLOE. IEEE J. of Oceanic Engineering, OE-8(4): 221-225.

Venkatesh, S., Donelan, M.A., Graber, H., Liu, P., Schwab, D. and M. Skafel. 1988. Finite Depth Wind Waves - A Preliminary Analysis of Data from a Field Study on Lake St. Clair. American Meteorological Society Annual Meeting, Preprint Volume.

TABLE 1

LAKE ONTARIO AT TORONTO 1972
% OCCURRENCES. ALL DIRECTIONS

H_{mo} (m)	Measured	SMB	PHEW Donelan	SMB wave fetch	Hindwave	WAWSP 32 km
0.0-0.5	61.99	63.16	71.98	58.08	55.88	70.06
0.5-1.0	24.25	26.17	21.71	28.87	34.93	22.18
1.0-1.5	8.32	7.64	5.10	8.30	7.01	5.46
1.5-2.0	3.43	2.21	0.57	3.16	1.54	1.61
2.0-2.5	1.02	0.22	0.33	0.73	0.34	0.20
2.5-3.0	0.67	0.20	0.31	0.33	0.30	0.38
3.0-3.5	0.31	0.40	0.00	0.44	0.00	0.10
3.5-4.0	0.00	0.00	0.00	0.09	0.00	0.00
4.0-5.0	0.00	0.00	0.00	0.00	0.00	0.00
T_p (s)						
0-1	0.00	5.56	7.91	3.82	0.66	2.56
1-2	0.00	20.01	19.58	17.69	3.64	28.84
2-3	38.05	42.52	45.71	40.51	39.52	38.38
3-4	29.32	20.85	19.18	24.40	36.10	21.17
4-5	19.40	8.63	5.83	8.92	14.50	6.07
5-6	9.62	1.74	1.11	3.55	2.68	2.20
6-7	2.36	0.34	0.68	0.63	1.25	0.37
7-8	0.93	0.35	0.00	0.49	0.63	0.39
8-9	0.27	0.00	0.00	0.00	0.00	0.00

TABLE 2

LAKE ONTARIO AT MAIN DUCK ISLAND 1972
% OCCURRENCES. ALL DIRECTIONS

H_{mo} (m)	Measured	SMB	PHEW Donelan	SMB wave fetch	Hindwave	WAWSP 32 km
0.0-0.5	54.77	43.50	50.72	37.84	32.48	57.11
0.5-1.0	31.32	36.82	38.71	36.35	45.59	30.86
1.0-1.5	9.24	14.92	8.11	17.07	17.27	7.76
1.5-2.0	2.92	3.26	1.81	4.23	3.85	2.80
2.0-2.5	1.17	1.21	0.52	3.20	0.80	0.81
2.5-3.0	0.58	0.30	0.12	0.95	0.00	0.53
3.0-3.5	0.00	0.00	0.00	0.26	0.00	0.10
3.5-4.0	0.00	0.00	0.00	0.10	0.00	0.20
4.0-5.0	0.00	0.00	0.00	0.00	0.00	0.00
T_p (s)						
0-1	0.00	2.15	2.86	1.09	0.34	1.64
1-2	0.00	12.09	10.18	9.36	1.80	19.71
2-3	29.67	31.98	35.41	29.30	16.44	34.93
3-4	34.53	33.49	36.91	33.59	38.66	27.35
4-5	24.81	16.04	12.28	18.33	29.26	11.20
5-6	8.75	3.41	1.83	6.14	10.02	3.52
6-7	1.75	0.82	0.52	1.86	1.82	1.30
7-8	0.39	0.00	0.00	0.32	0.66	0.34
8-9	0.10	0.00	0.00	0.00	0.00	0.02

TABLE 3

LAKE ONTARIO AT WAVES TOWER 1976/77
% OCCURRENCES. ALL DIRECTIONS

H_{mo} (m)	Measured	PHEW SMB	PHEW Donelan	Hindwave
0.0-0.5	93.2	87.36	93.30	90.43
0.5-1.0	5.85	10.71	5.07	6.95
1.0-1.5	0.49	0.70	0.73	1.56
1.5-2.0	0.16	0.38	0.30	0.44
2.0-2.5	0.15	0.65	0.57	0.61
2.5-3.0	0.04	0.15	0.02	0.00
3.0-3.5	0.04	0.05	0.00	0.00
3.5-4.0	0.07	0.00	0.00	0.00
T_p (s)				
0-1	28.70	10.91	11.59	0.69
1-2	35.74	27.96	46.43	46.50
2-3	16.87	54.40	35.05	34.48
3-4	10.06	4.55	3.59	10.71
4-5	5.31	0.92	1.12	5.07
5-6	1.81	0.32	0.95	1.50
6-7	0.77	0.90	0.29	0.56
7-8	0.45	0.03	0.00	0.49
8-9	0.31	0.00	0.00	0.00

TABLE 4a

LAKE ONTARIO AT STONEY CREEK 1974-85
% OCCURRENCE, ALL DIRECTIONS

H_{mo} (m)	PWC	BAIRD	HINDWAVE	PHEW SMB wind	PHEW Donelan wave	PHEW SMB	WAWSP 32 km grid
0.0-0.5	66.71	66.36	69.05	64.63	57.56	73.15	68.49
0.5-1.0	25.29	25.26	22.78	27.64	28.55	21.24	24.71
1.0-1.5	4.82	5.15	5.34	4.83	9.38	3.93	5.32
1.5-2.0	2.04	2.01	2.09	1.84	3.05	1.38	1.16
2.0-2.5	0.83	0.86	0.64	0.80	1.10	0.26	0.25
2.5-3.0	0.24	0.28	0.10	0.22	0.27	0.03	0.05
3.0-3.5	0.05	0.06	0.00	0.04	0.07	0.01	0.01
3.5-4.0	0.01	0.02	0.00	0.01	0.01	0.00	0.00
4.0-4.5	0.00	0.00	0.00	0.01	0.01	0.00	0.00
T_p (s)							
0-1	7.07	6.13	0.64	11.97	8.33	14.18	3.94
1-2	17.87	15.66	26.22	19.35	16.43	22.96	26.61
2-3	28.66	26.58	37.28	40.01	37.23	38.15	37.48
3-4	28.65	29.93	16.31	19.96	22.71	15.75	22.54
4-5	9.98	12.06	11.37	5.52	10.68	5.94	7.34
5-6	4.29	5.23	5.53	2.54	3.70	2.66	1.77
6-7	2.43	3.00	1.99	0.59	0.79	0.36	0.29
7-8	0.90	1.16	0.58	0.05	0.10	0.01	0.03
8-9	0.14	0.23	0.08	0.01	0.01	0.00	0.00
9-10	0.02	0.02	0.00	0.00	0.00	0.00	0.00

TABLE 4b

LAKE ONTARIO AT STONEY CREEK 1974-1985
% OCCURRENCE, ALL WAVES

16 Point Wave Direction Bin:	22.5°	45°	67.5°	90°	112.5°
PWC	2.6	2.6	7.4	18.0	4.9
Baird	2.4	3.1	7.1	18.0	5.3
Hindwave	6.2	4.5	12.8	17.2	1.6
PHEW-SMB-Windfetch	2.0	2.6	6.3	17.7	6.2
PHEW-SMB-Wavefetch	11.4	5.0	5.6	29.6	4.3
PHEW-Donelan	9.5	3.6	5.4	30.3	0.9
WAWSP-32 km	3.0	2.7	3.0	7.7	11.7

TABLE 4c

LAKE ONTARIO AT STONEY CREEK 1974 - 1985

% OCCURRENCE, $H_{mo} > 1$ m

16 Point Wave Direction Bin:	22.5°	45°	67.5°	90°	112.5°
PWC	0.16	0.46	2.73	4.04	0.25
Baird	0.13	0.61	2.71	4.09	0.26
Hindwave	0.05	0.33	4.68	3.09	0.00
PHEW-SMB-Windfetch	0.25	0.85	2.32	3.20	0.58
PHEW-SMB-Wavefetch	4.14	1.13	1.86	5.82	0.14
PHEW-Donelan	0.17	0.10	1.05	4.15	0.05
WAWSP-32 km	0.03	0.19	0.01	1.06	1.76
% OCCURRENCE, $T_p \geq 3$ s					
PWC	1.4	1.4	5.5	14.0	1.9
Baird	1.4	1.8	5.4	15.0	2.4
Hindwave	4.5	4.0	12.0	13.0	0.4
PHEW-SMB	1.1	1.8	4.4	8.8	2.2
PHEW-SMB-Wavefetch	8.4	2.9	4.0	14.8	0.8
PHEW-Donelan	3.1	1.3	3.3	15.0	0.5
WAWSP-32 km	0.5	0.6	1.0	3.3	5.8

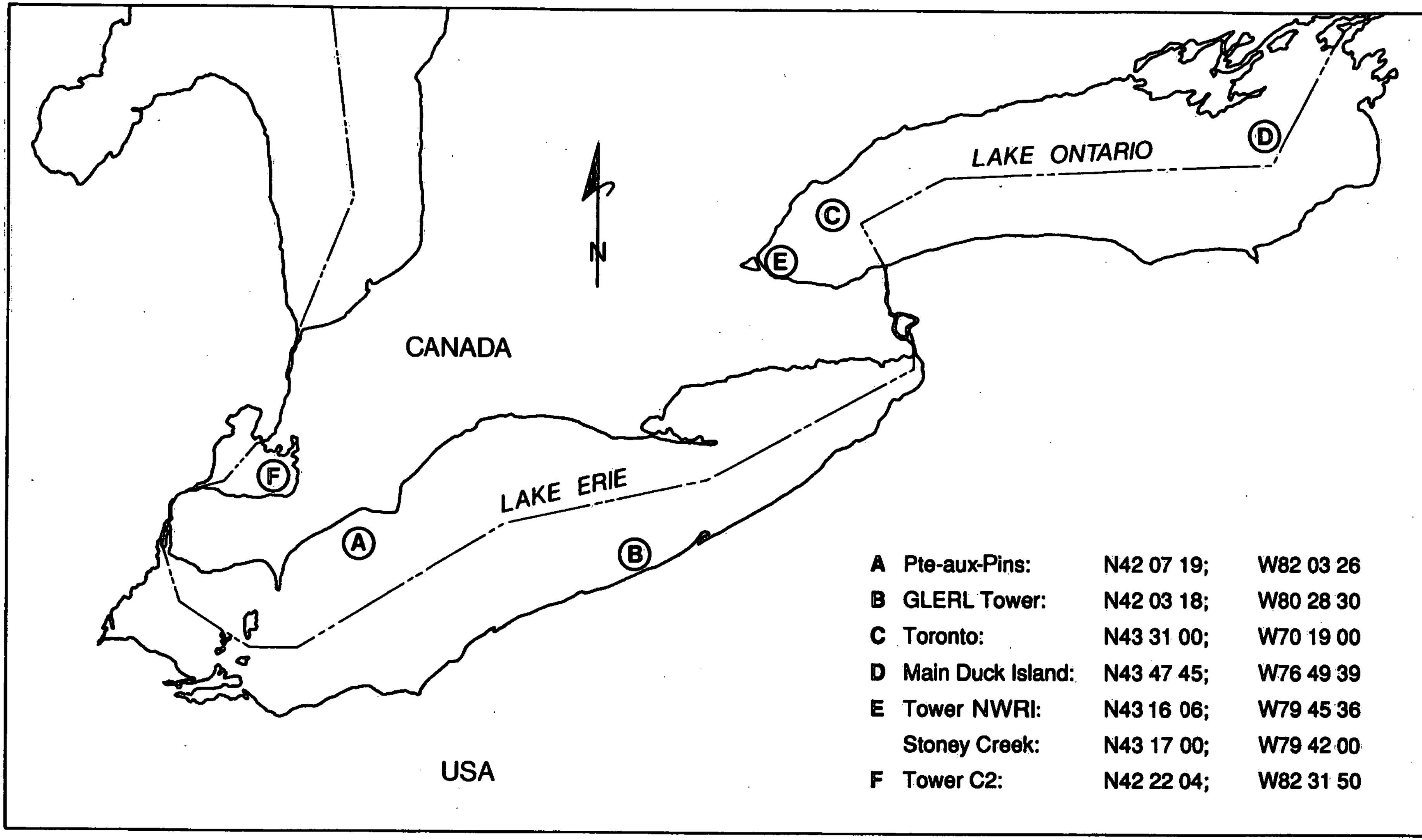

Figure 1a. Locations of sites on the Great Lakes.

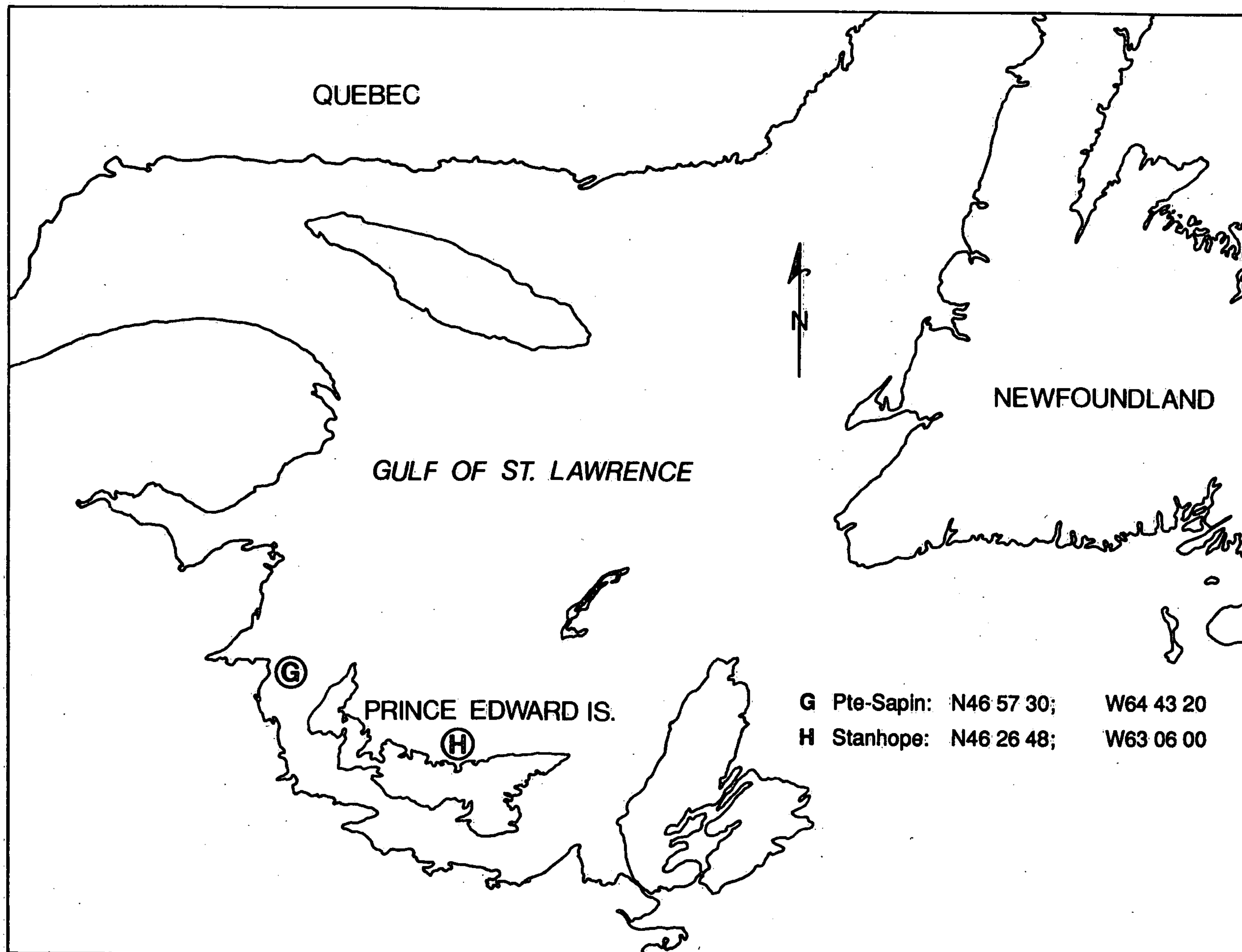

Figure 1b. Locations of sites on the Gulf of St. Lawrence.

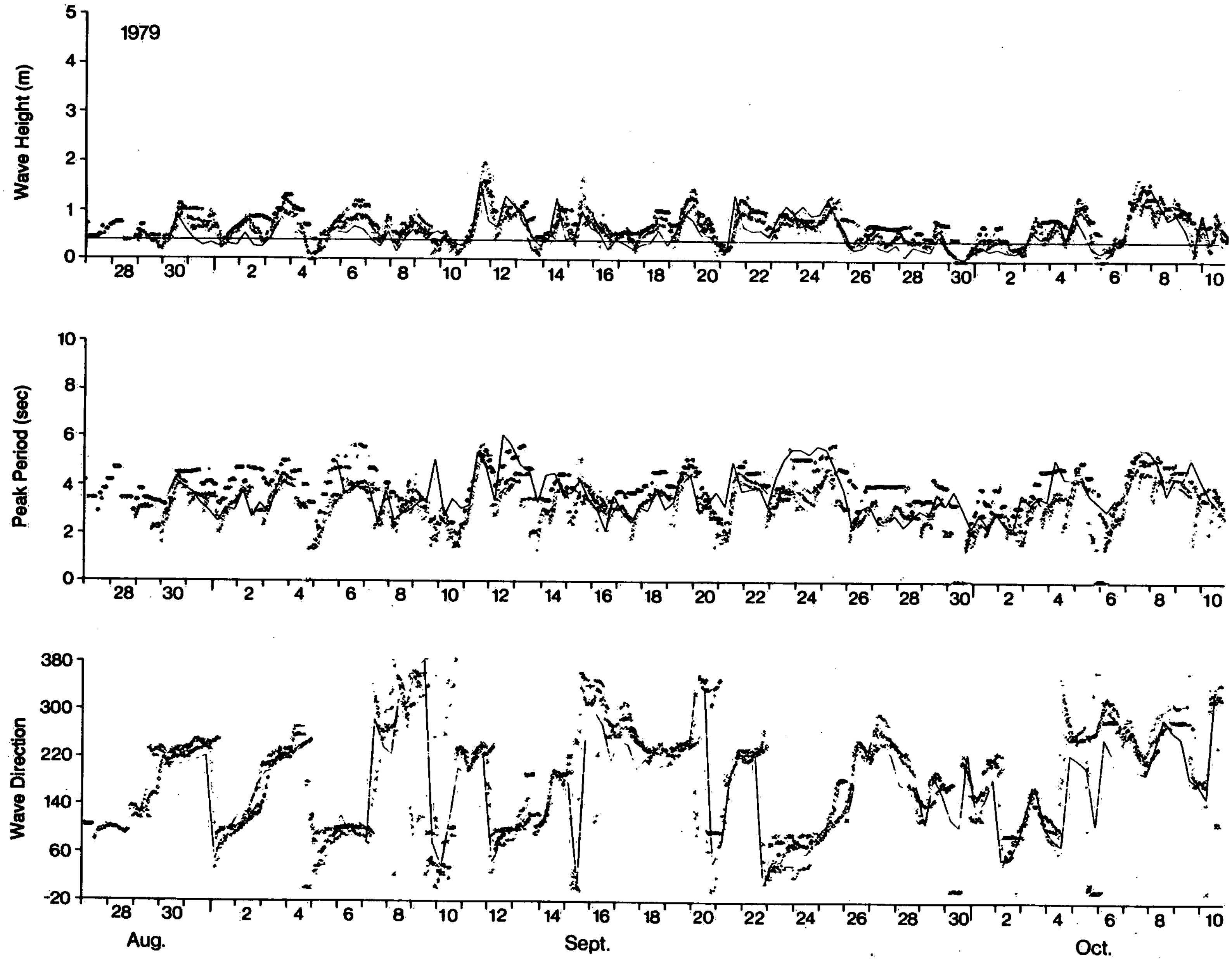

Figure 2a. Time series of measured and predicted waves off Pointe-aux-Pins. (— measured; ++++ PHEW-SMB; ×××× PHEW-Donelan; ◇◇◇◇ Hindwave.)

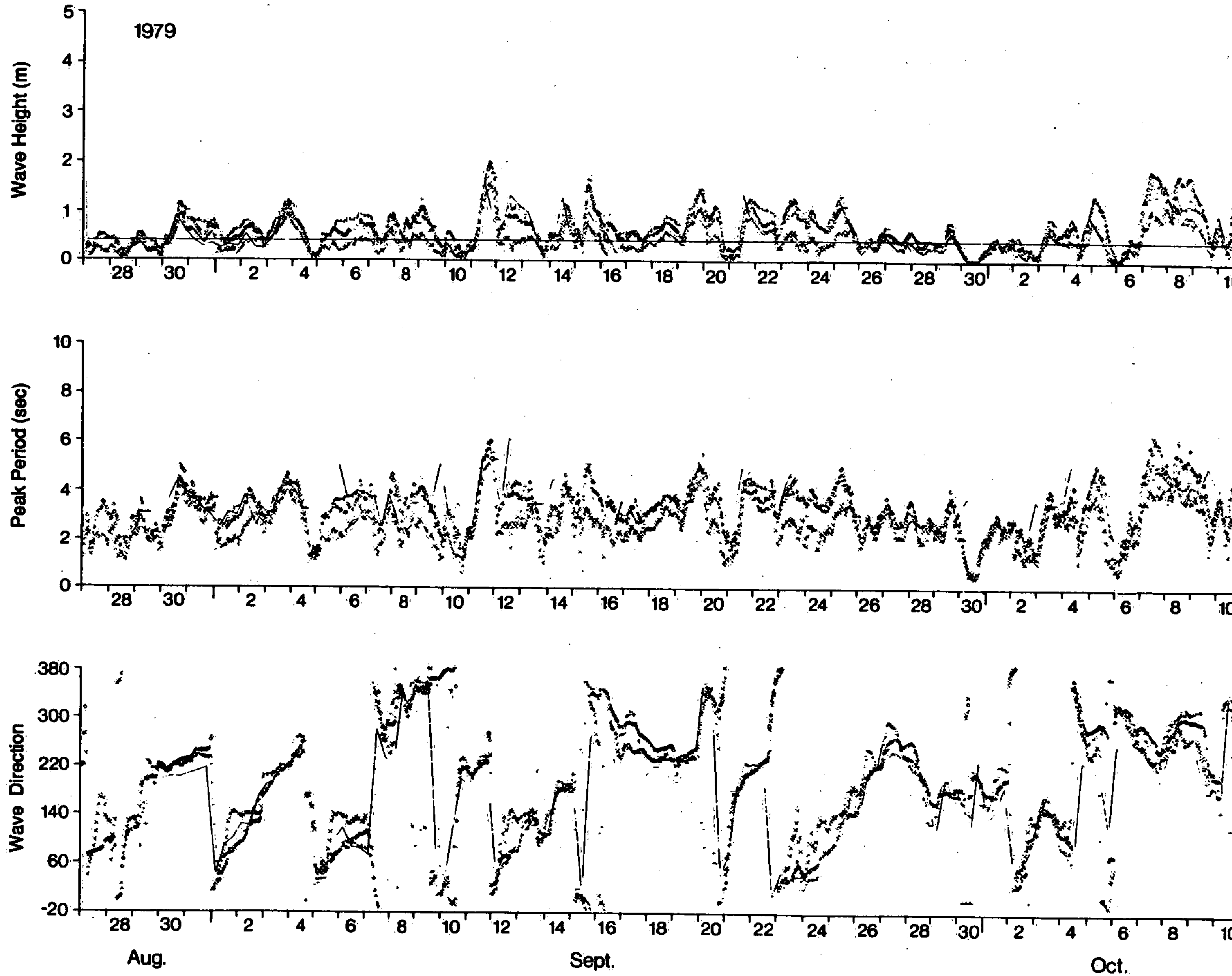

Figure 2b. Time series of measured and predicted waves off Pointe-aux-Pins. (— measured; ++++ PHEW-SMB; ×××× WAWSP 8 km grid; ◇◇◇◇ WAWSP 32 km grid.)

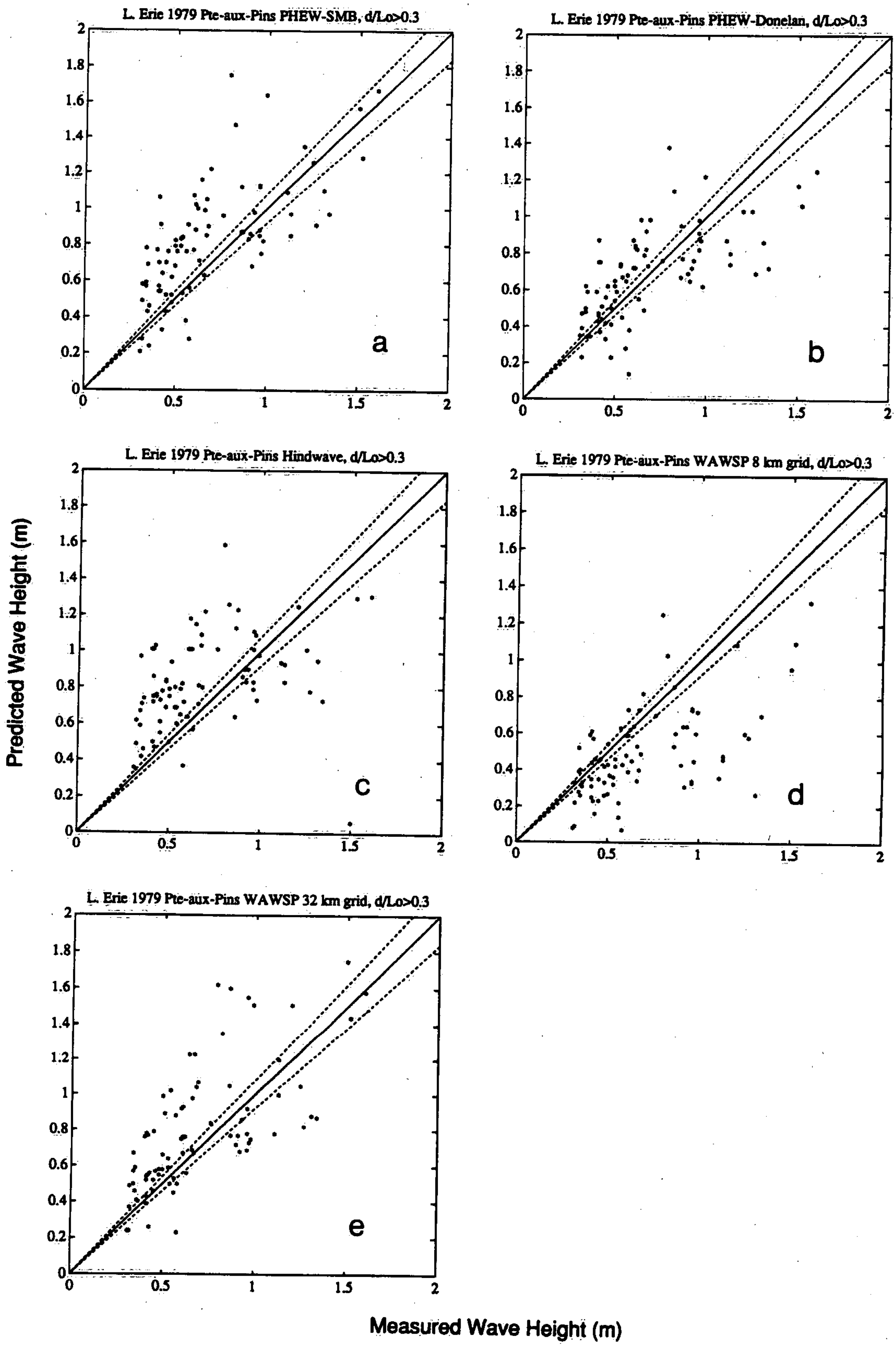

Figure 3. Comparison of predicted and measured wave parameters for Pointe-aux-Pins.

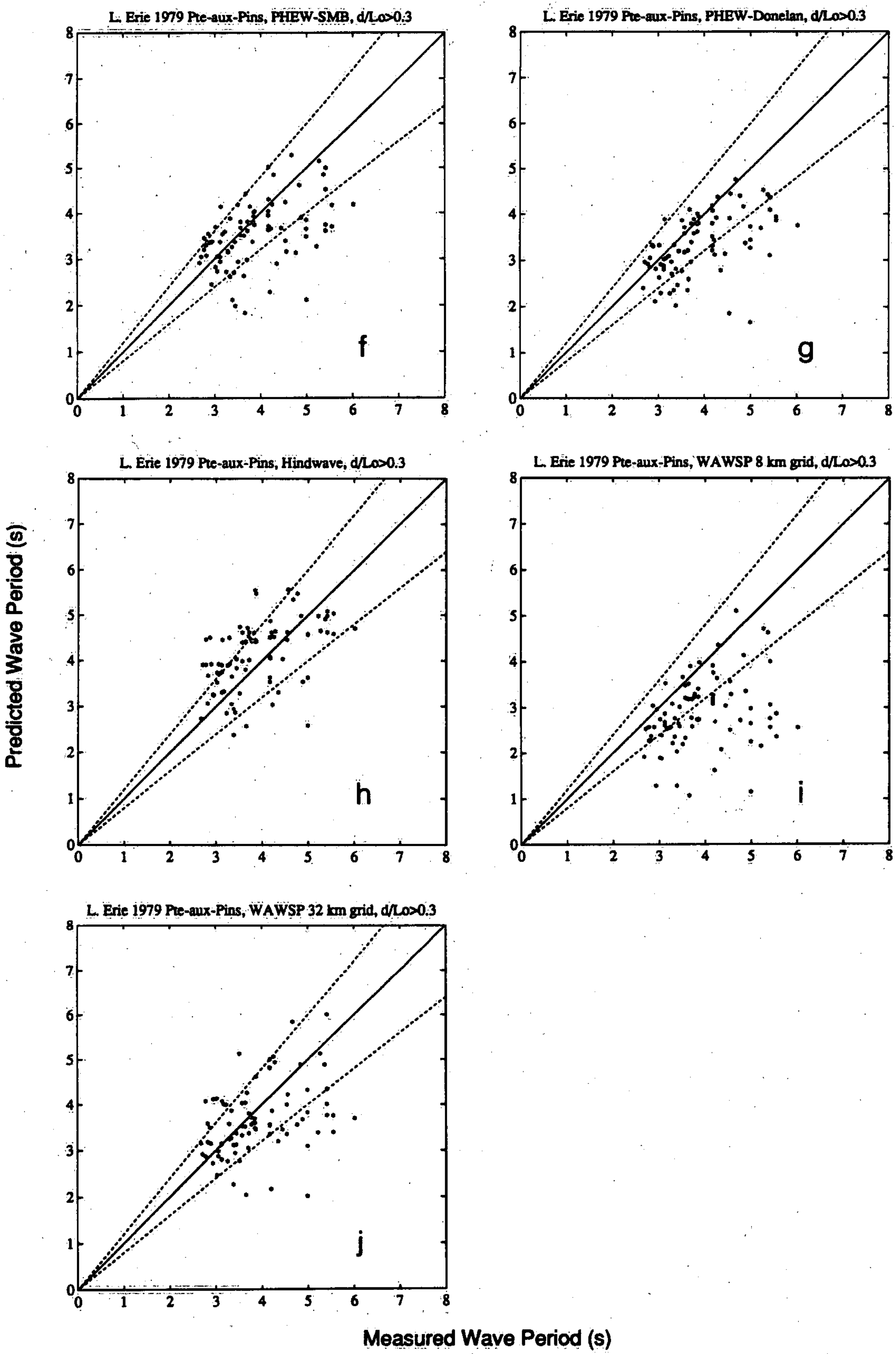

Figure 3 Continued

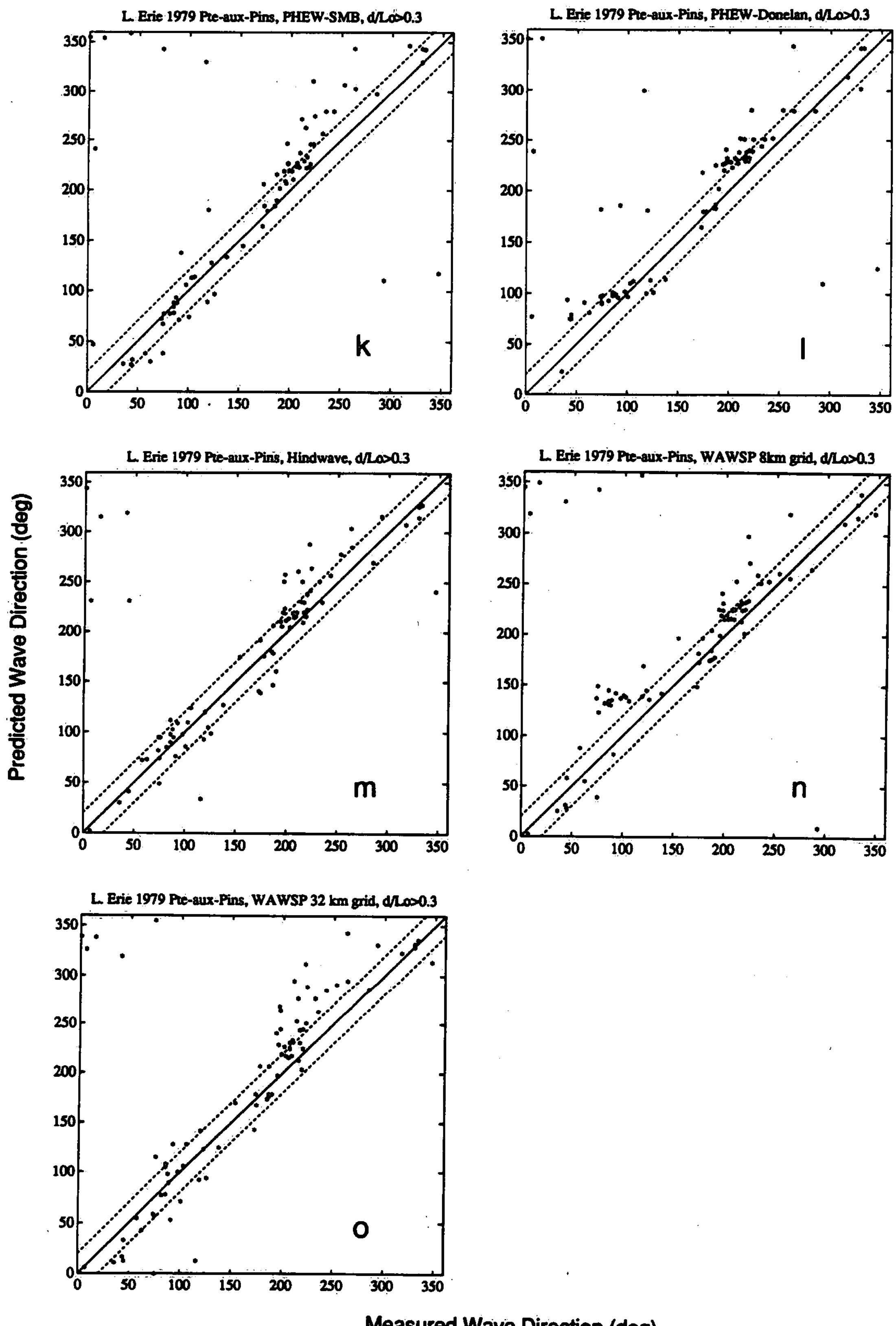

Figure 3 Continued

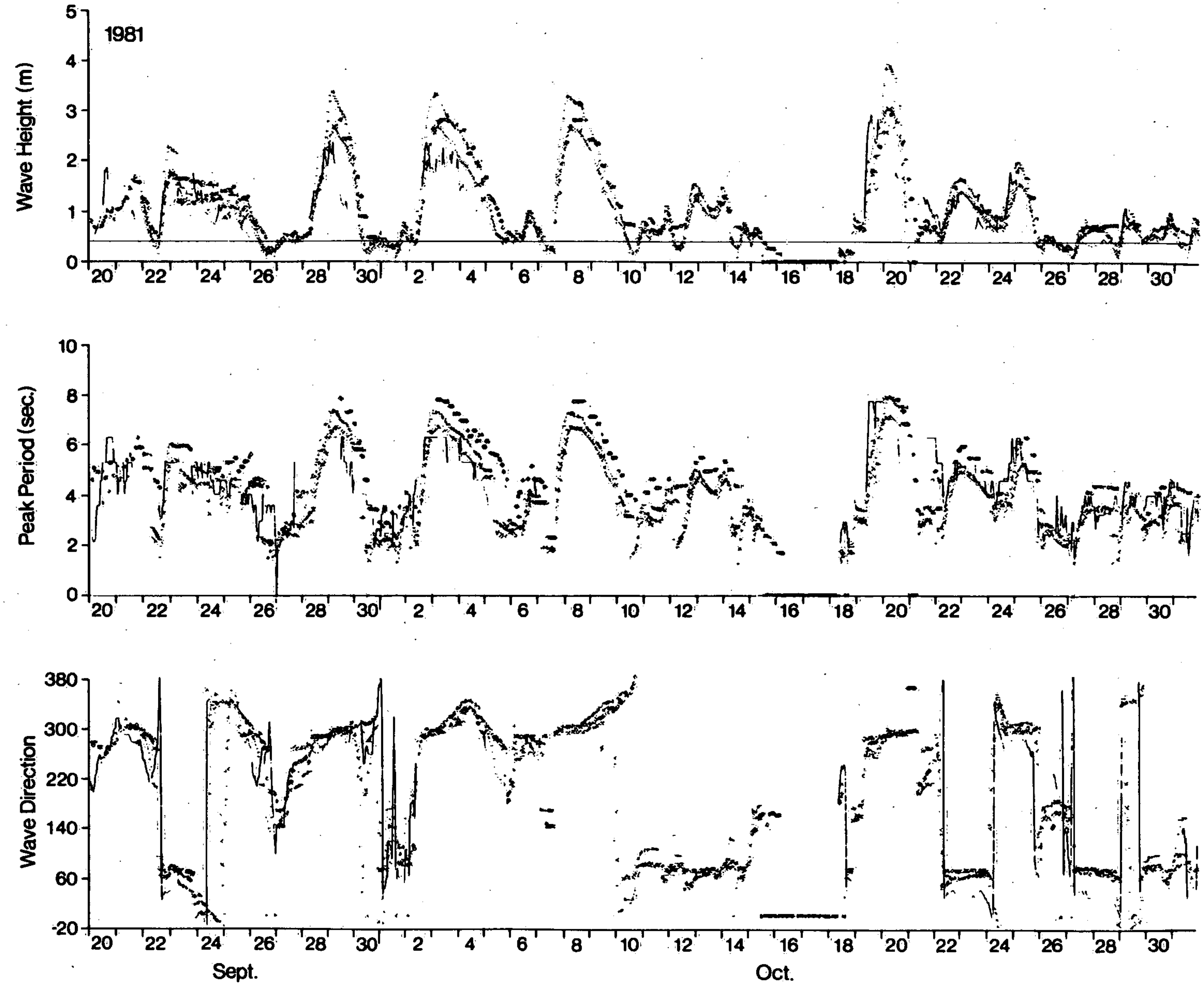

Figure 4a. Time series of measured and predicted waves at the GLERL tower. (— measured; ++++ PHEW-SMB; ×××× PHEW-Donelan; ◇◇◇◇ Hindwave.)

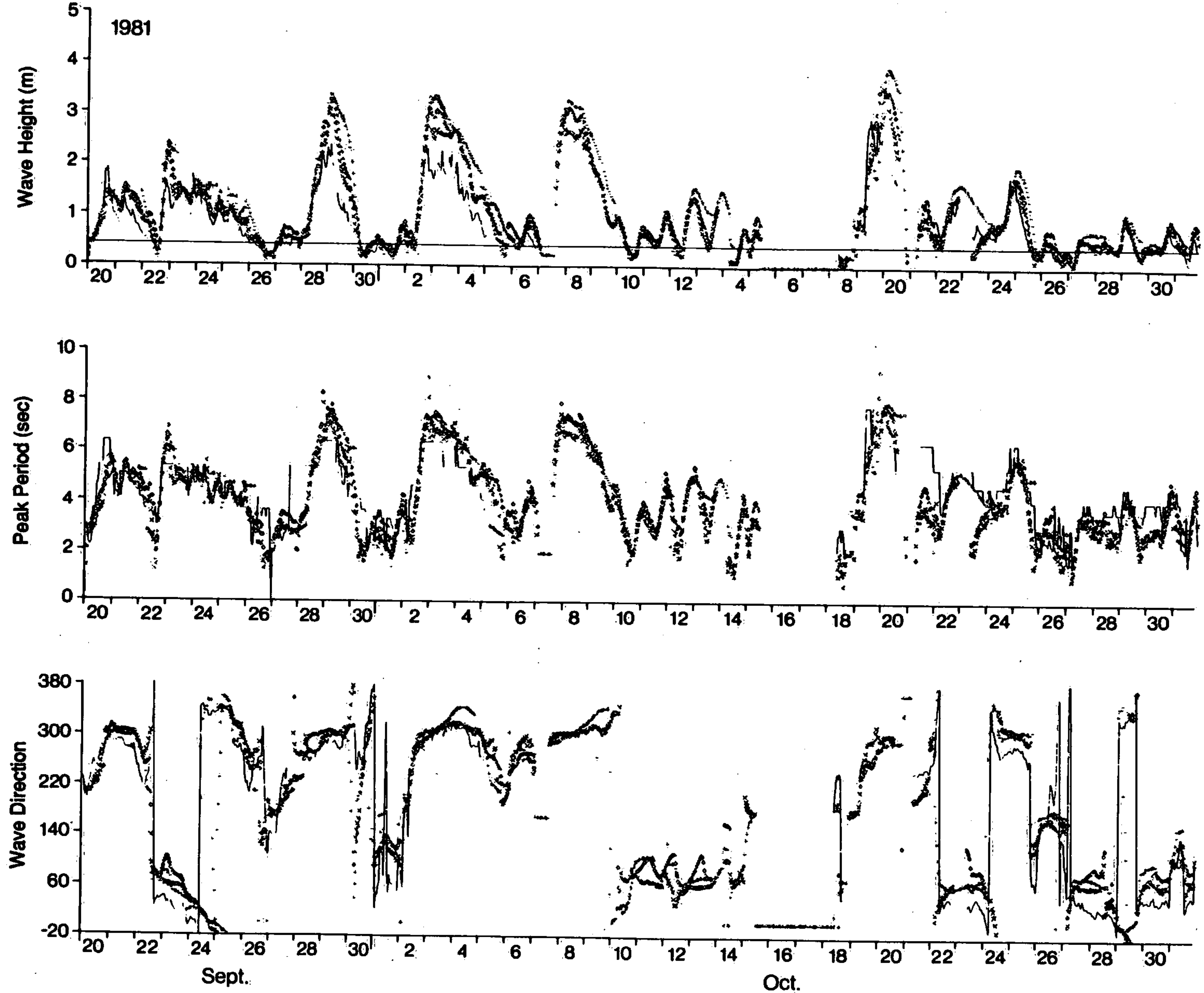

Figure 4b. Time series of measured and predicted waves at the GLERL tower. (— measured; ++++ PHEW-SMB; ×××× WAWSP 8 km grid; ◇◇◇◇ WAWSP 32 km grid.)

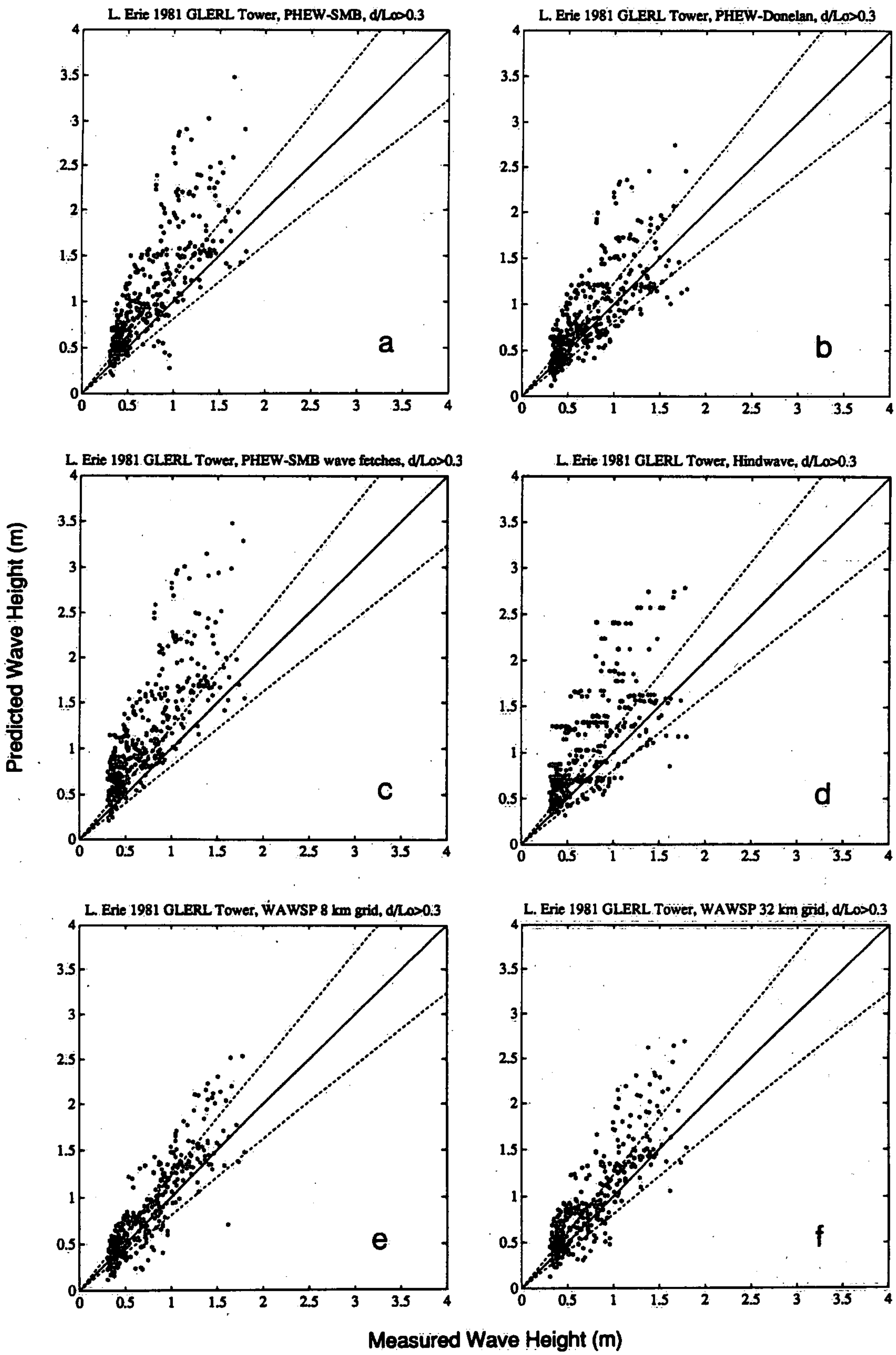

Figure 5. Comparison of predicted and measured wave parameters for the GLERL tower.

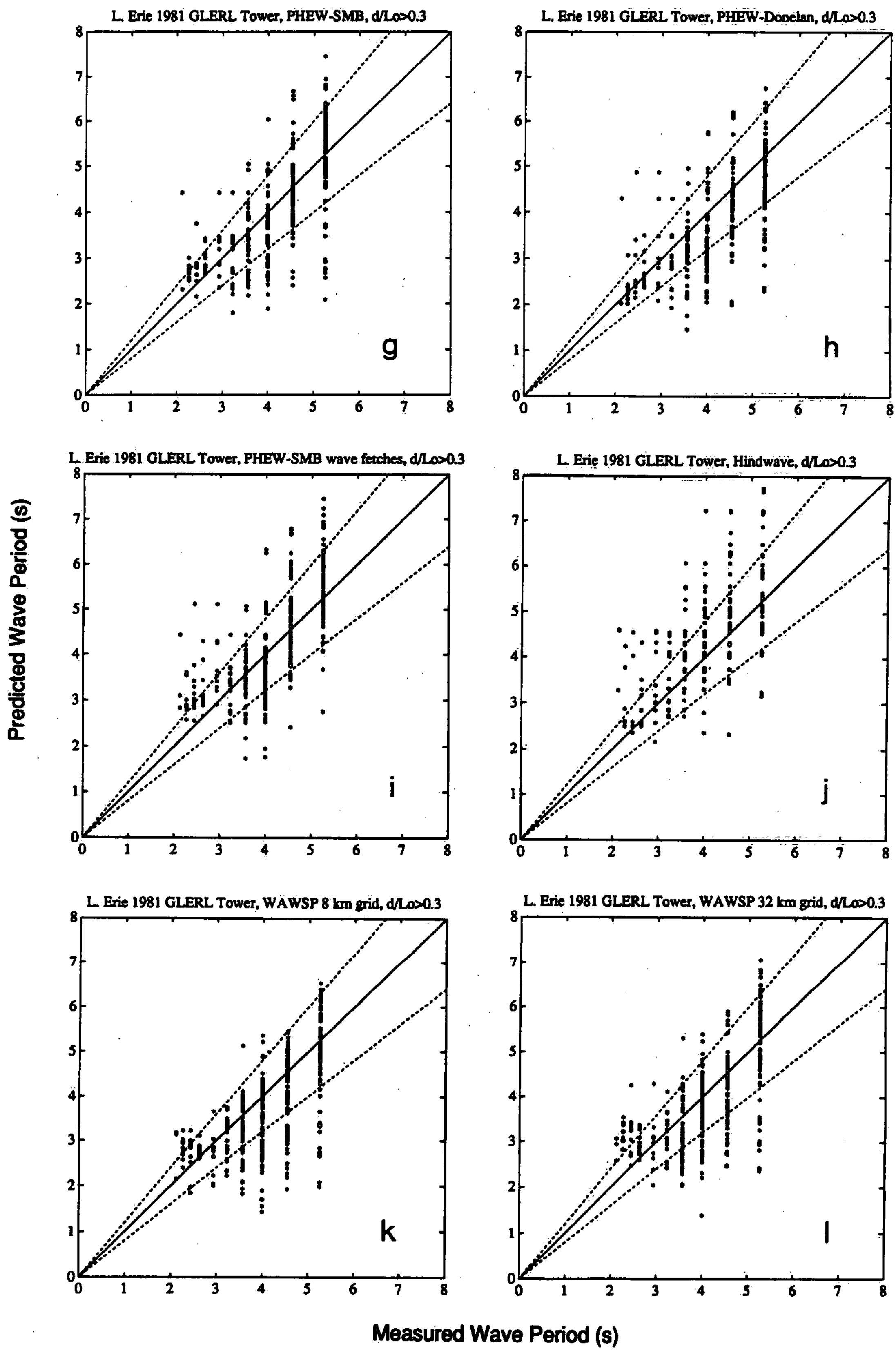

Figure 5. Continued

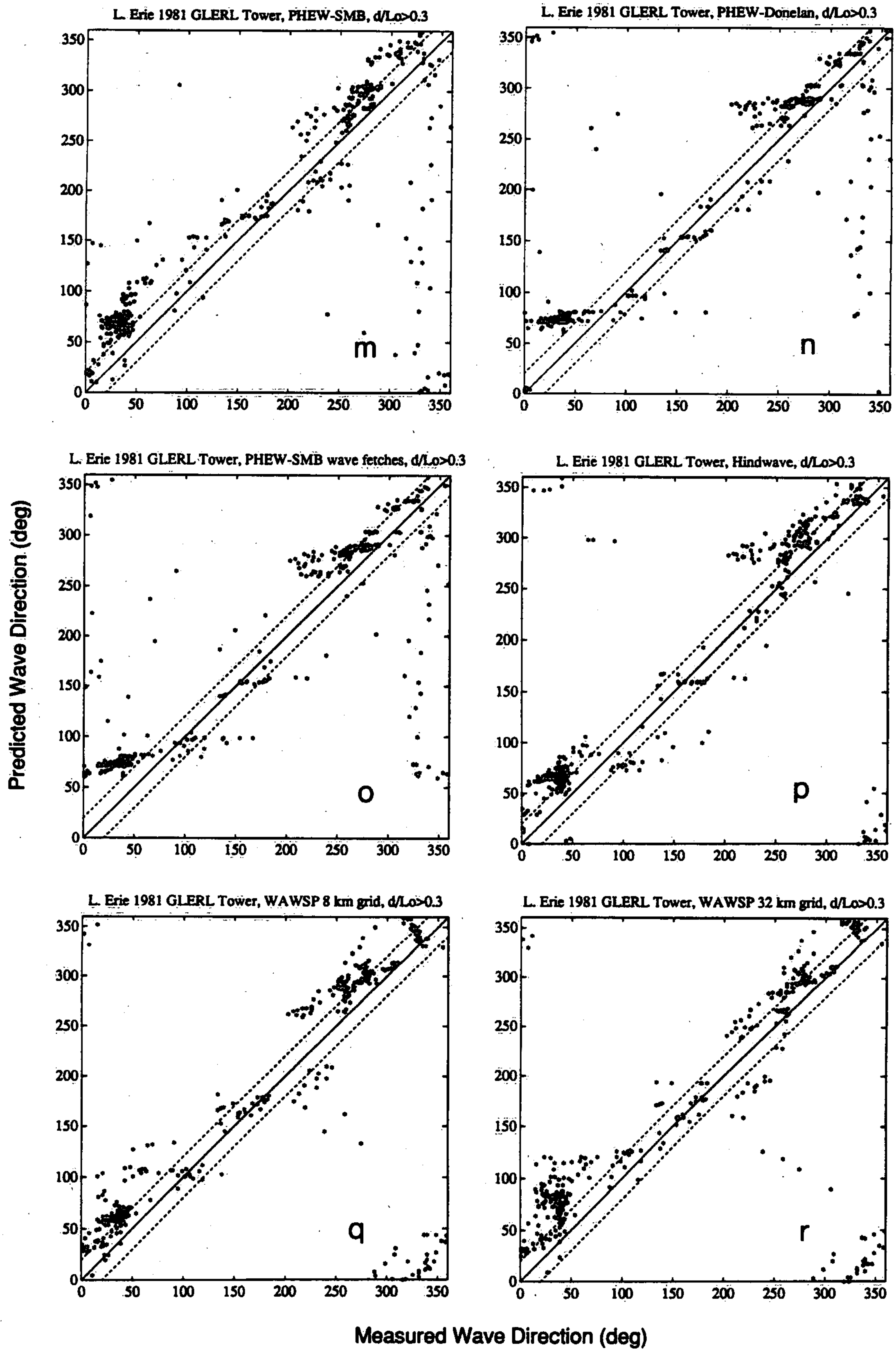

Figure 5. Continued

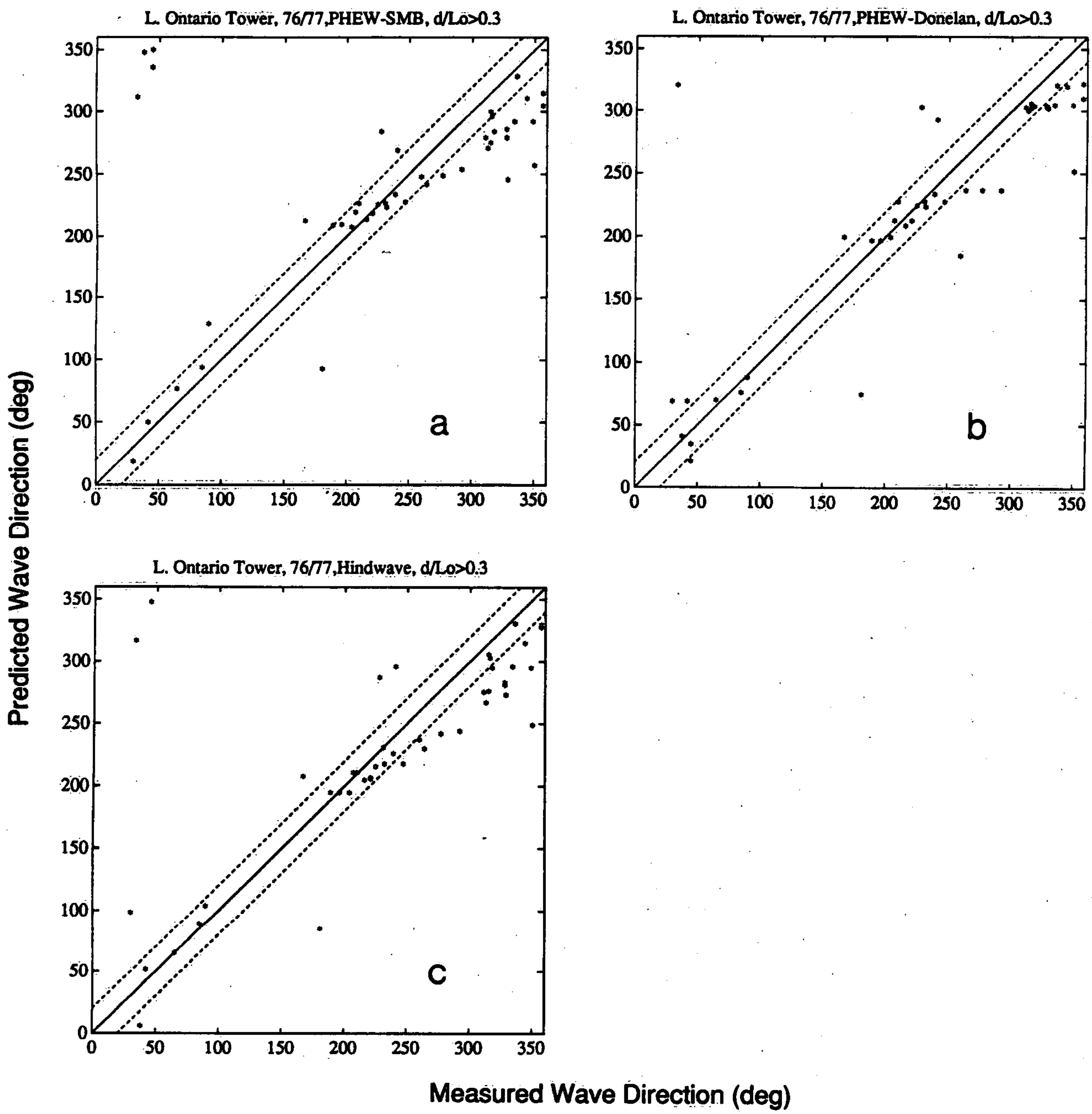

Figure 6 Comparison of predicted and measured wave parameters for the NWRI Research Tower.

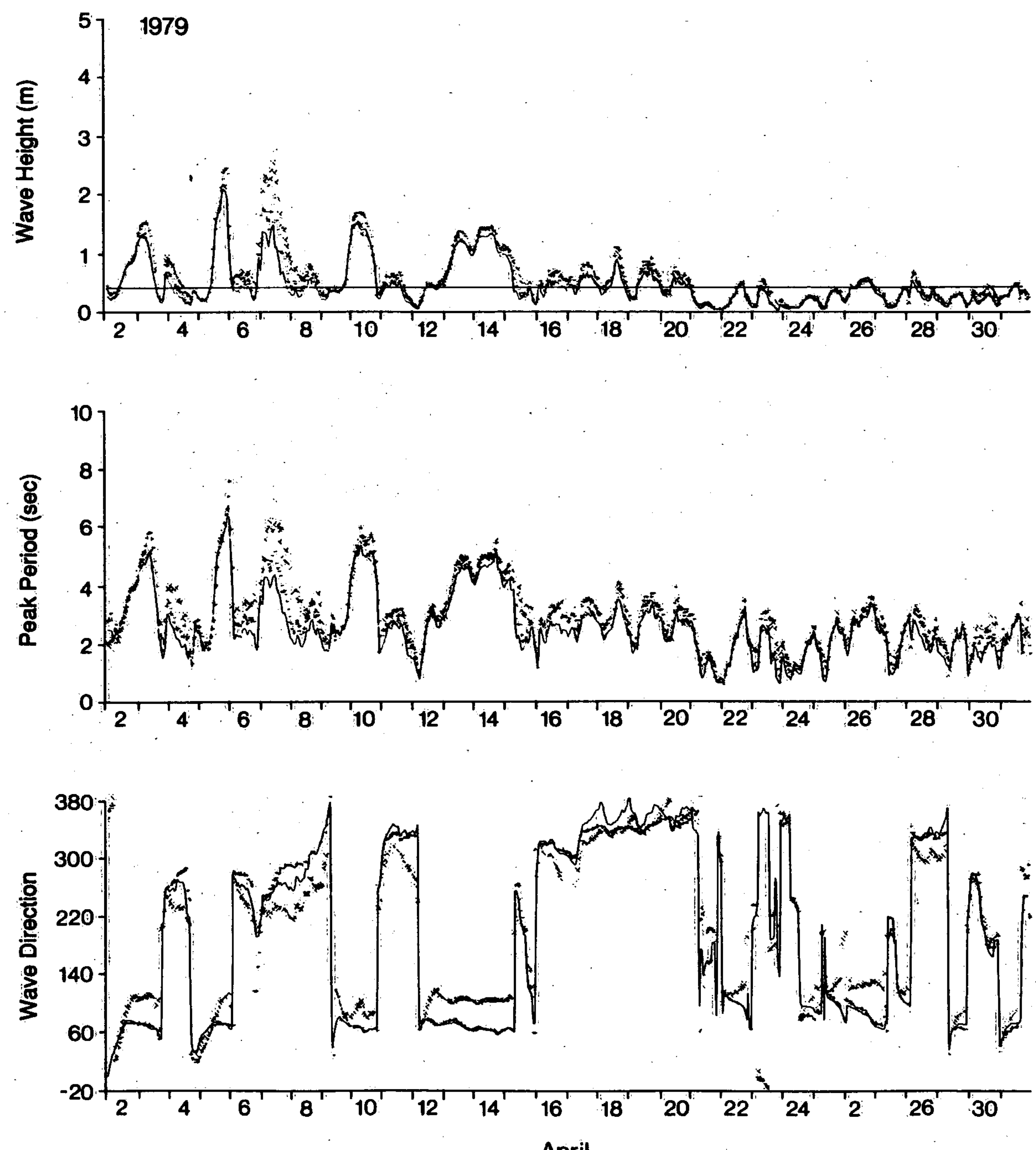

Figure 7. Time series of predicted waves off Stoney Creek using three different grid sizes in the WAWSP program. (— 8 km; ++++ 16 km; ×××× 32 km.)

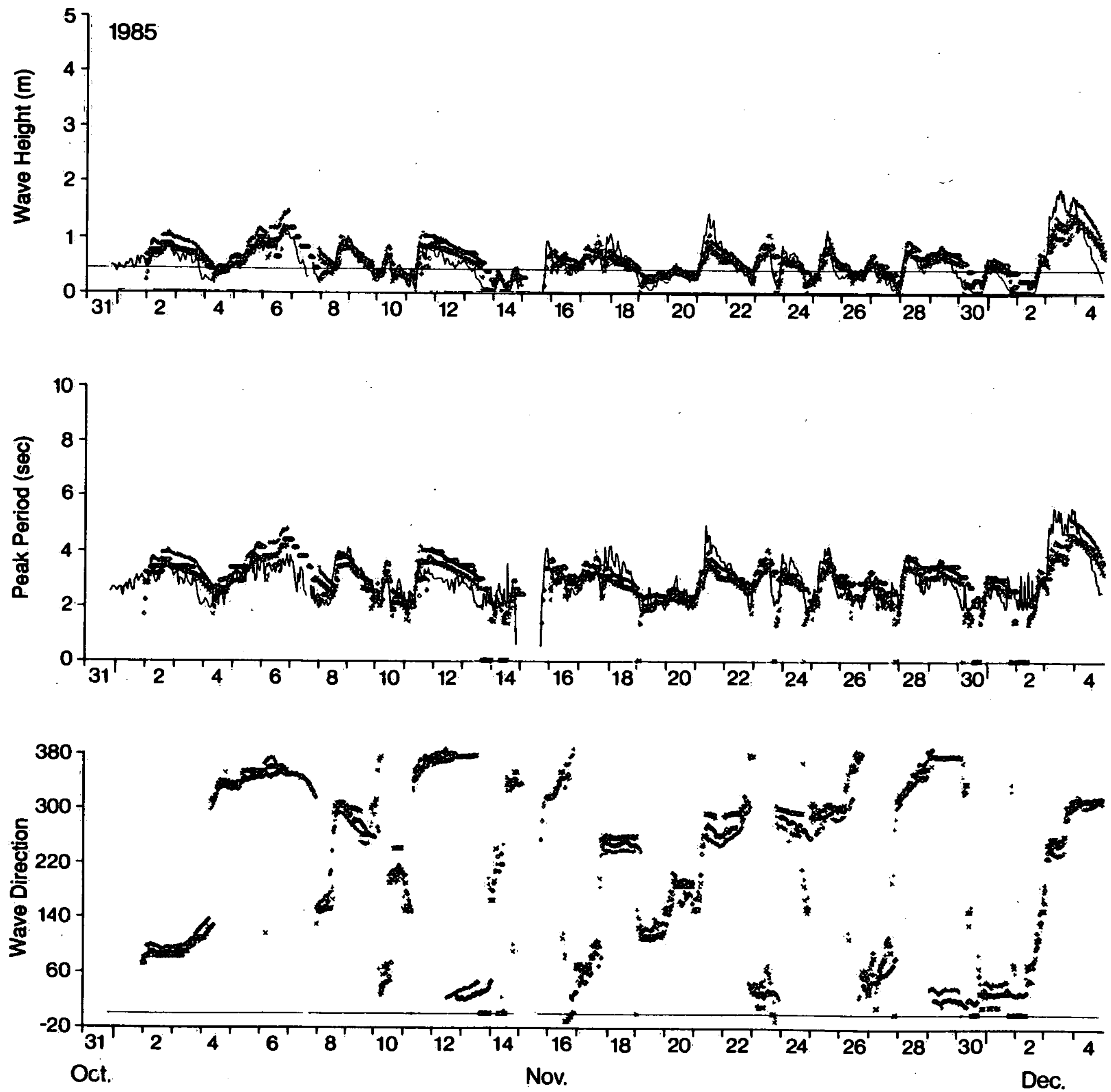

Figure 8a. Time series of measured and predicted waves in Lake St. Clair. (— measured; ++++ PHEW-SMB; ×××× PHEW-Donelan; ◇◇◇◇ Hindwave.)

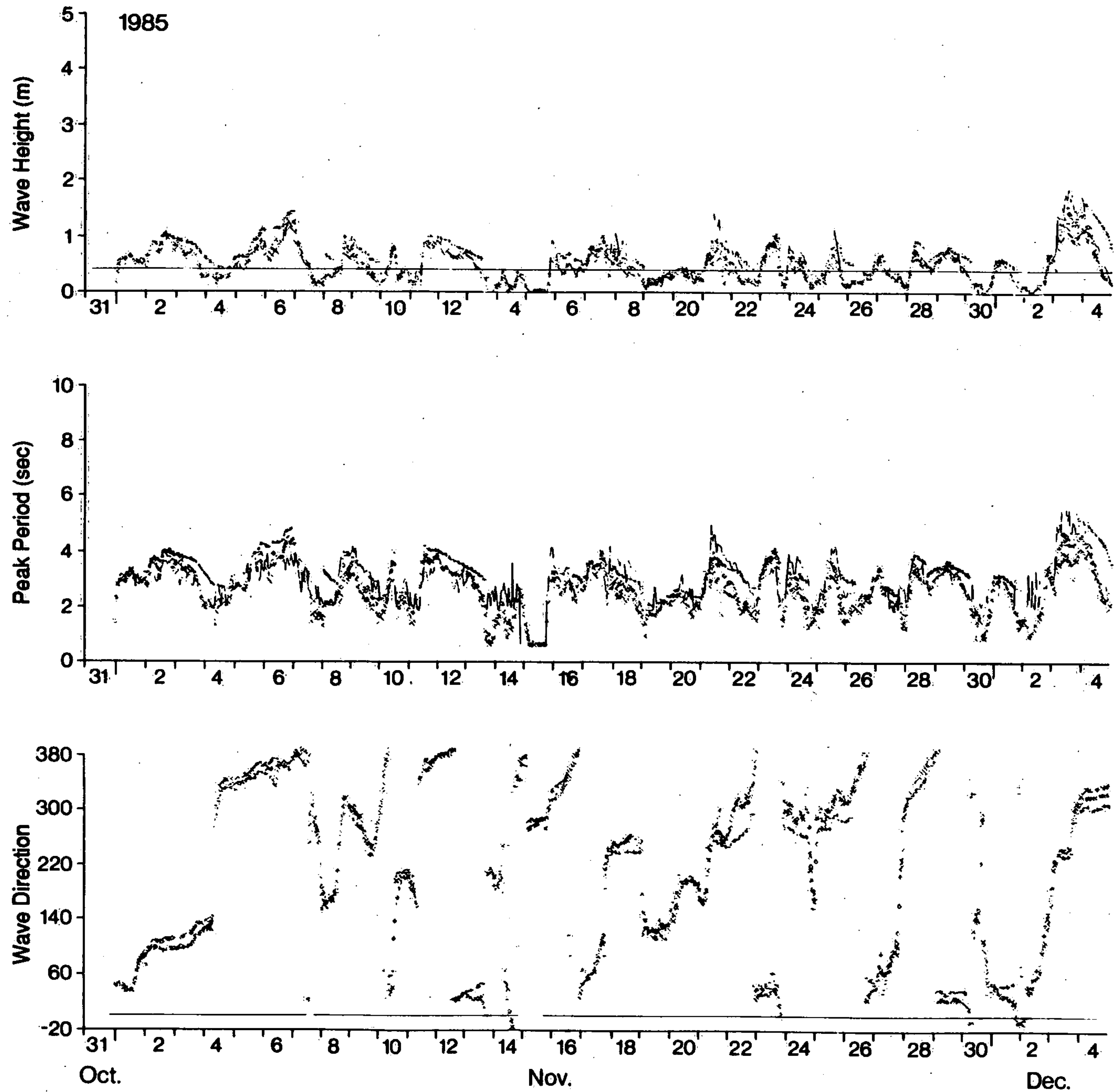

Figure 8b. Time series of measured and predicted waves in Lake St. Clair. (— measured; ++++ PHEW-SMB; ×××× WAWSP 4 km grid; ◇◇◇◇ WAWSP 8 km grid.)

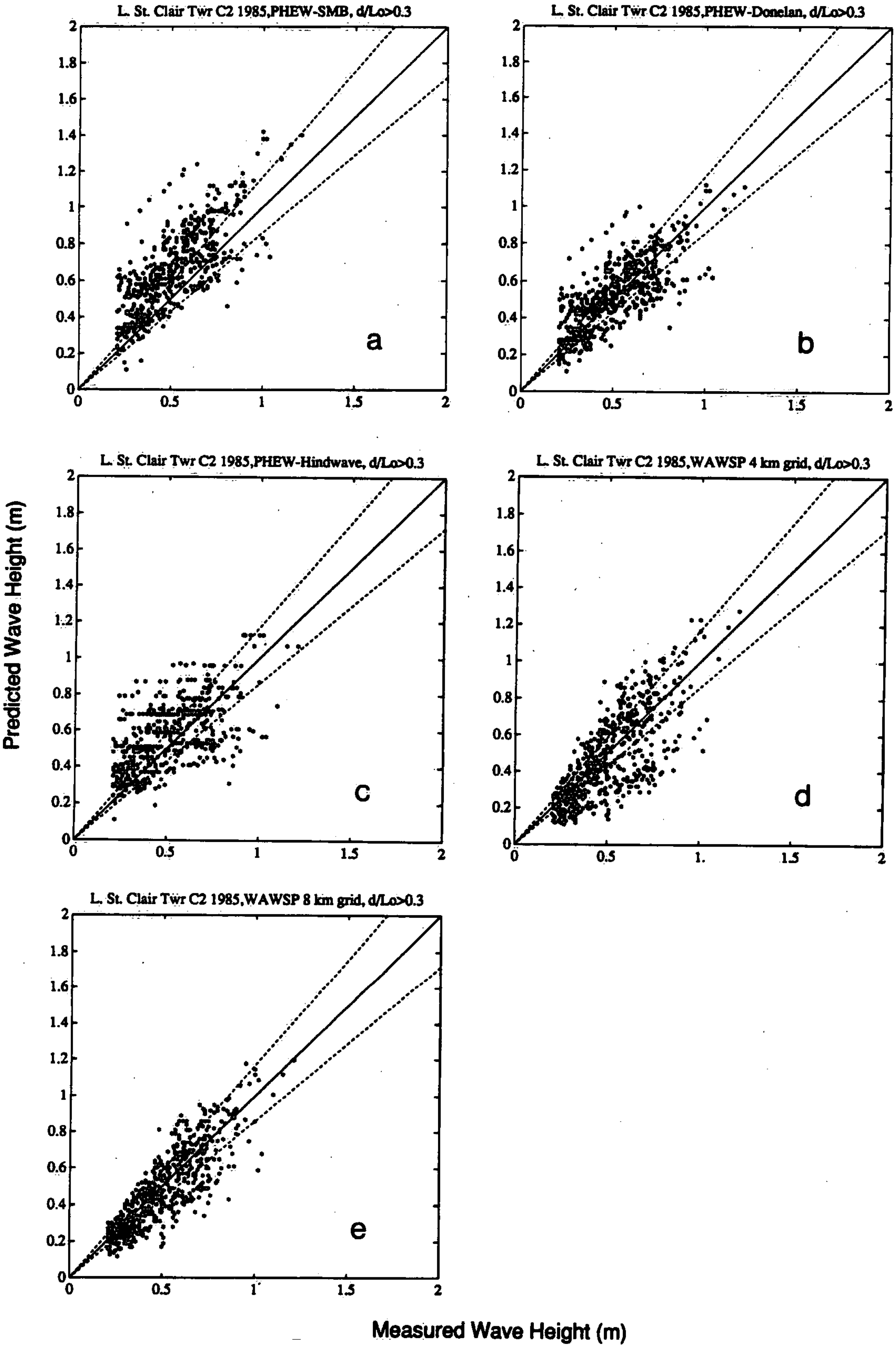

Figure 9. Comparison of predicted and measured wave parameters in Lake St. Clair.

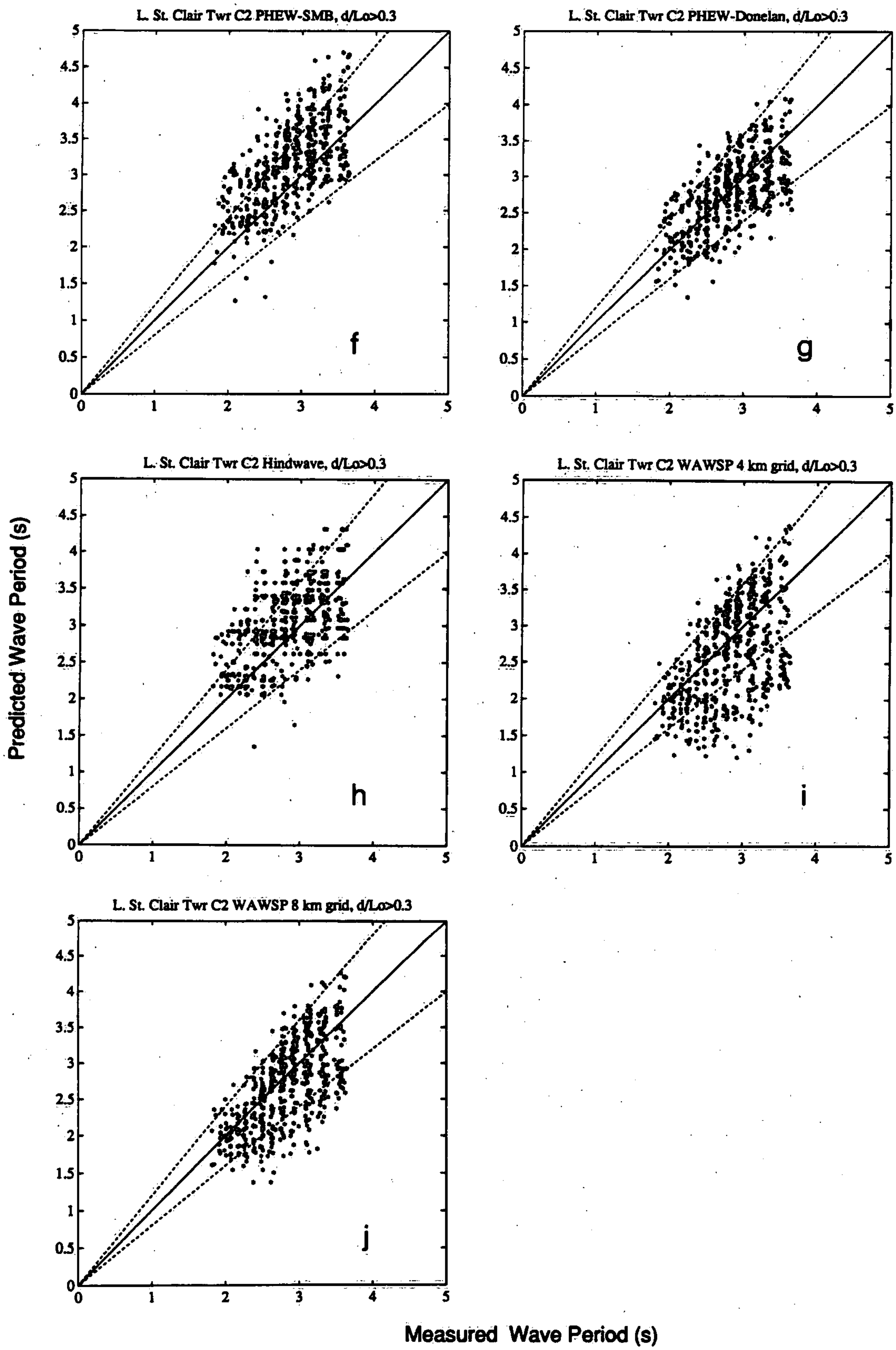

Figure 9. Continued

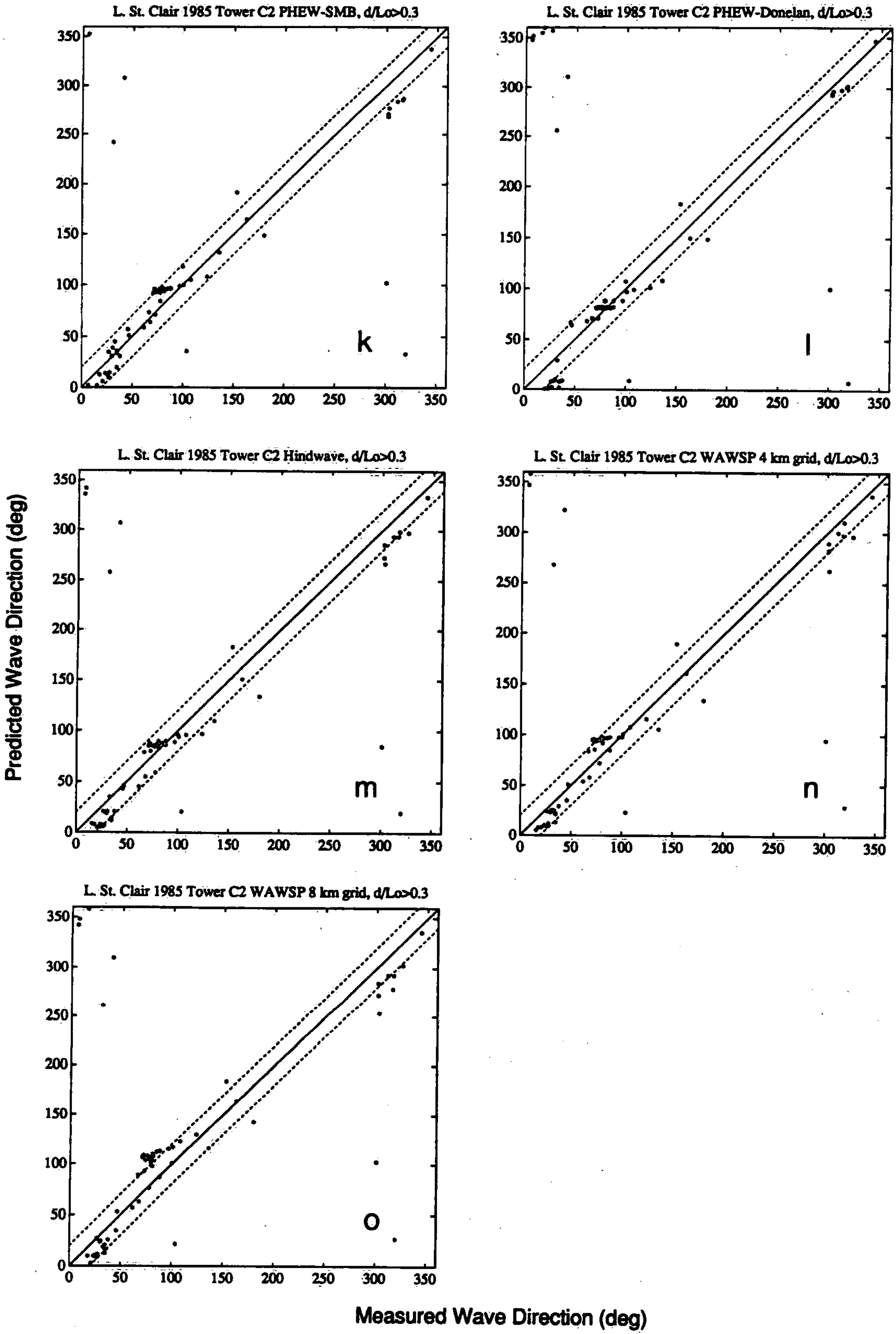

Figure 9. Continued

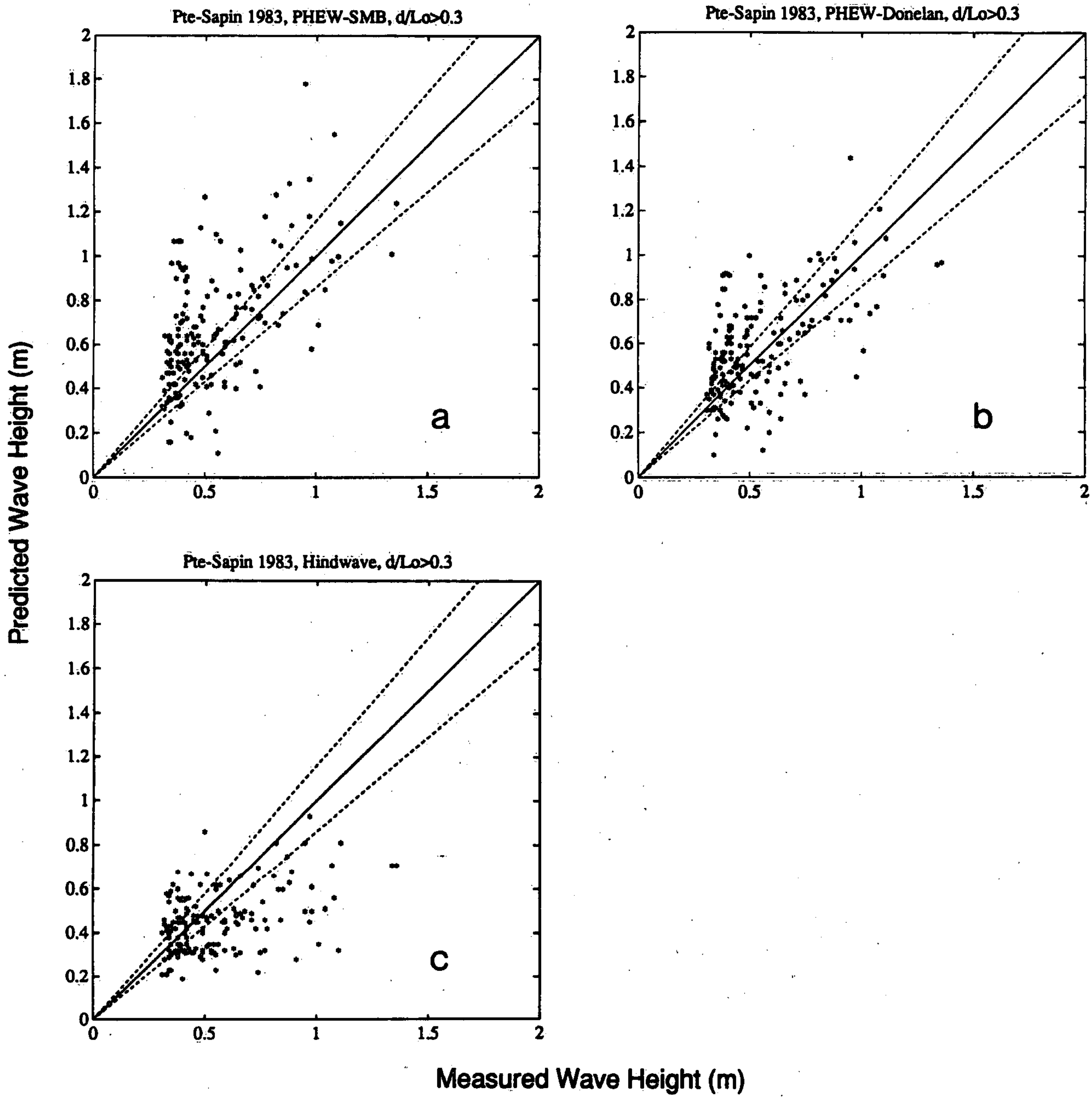

Figure 10. Comparison of predicted and measured wave parameters off Pte-Sapin.

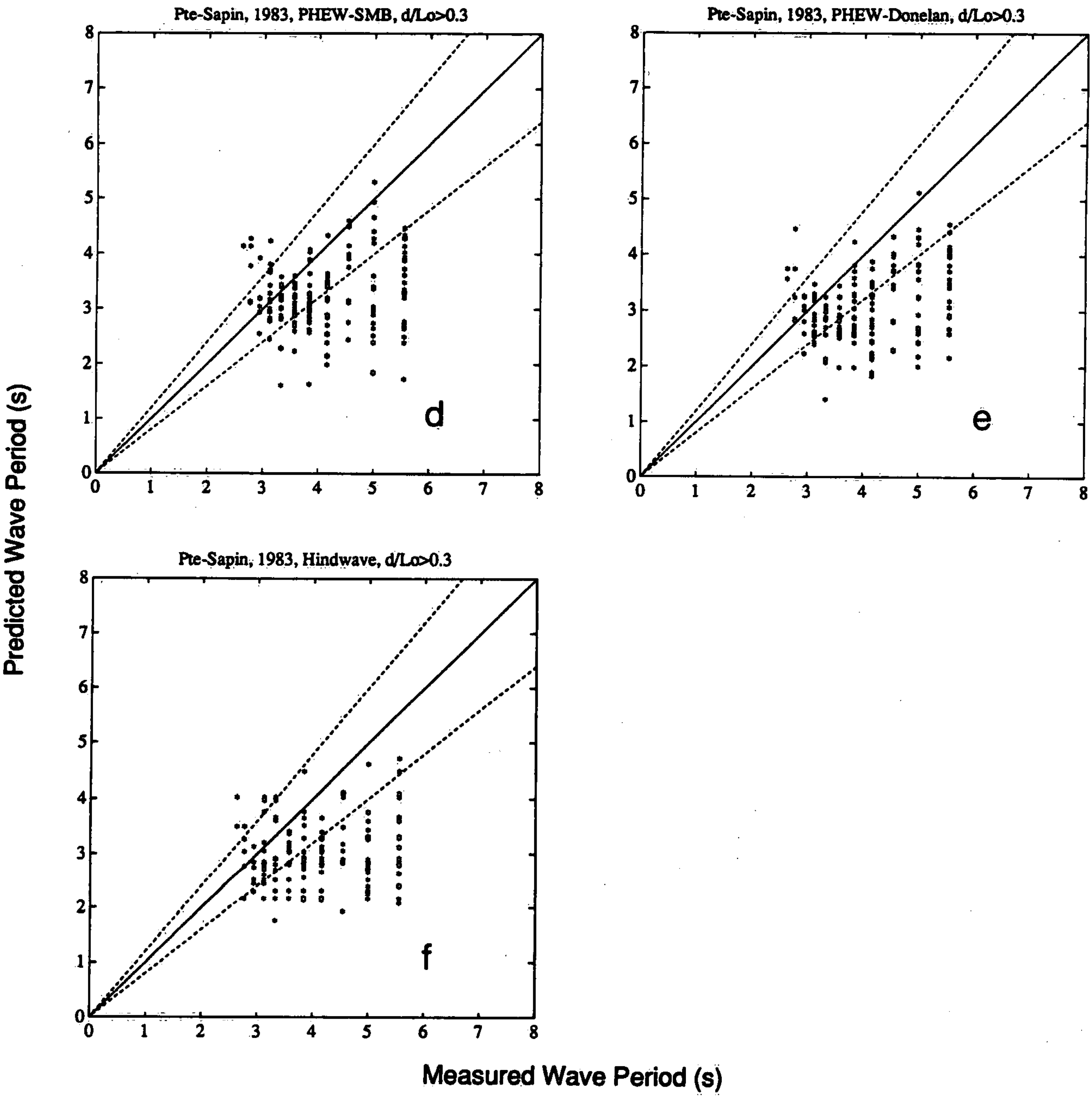

Figure 10. Continued

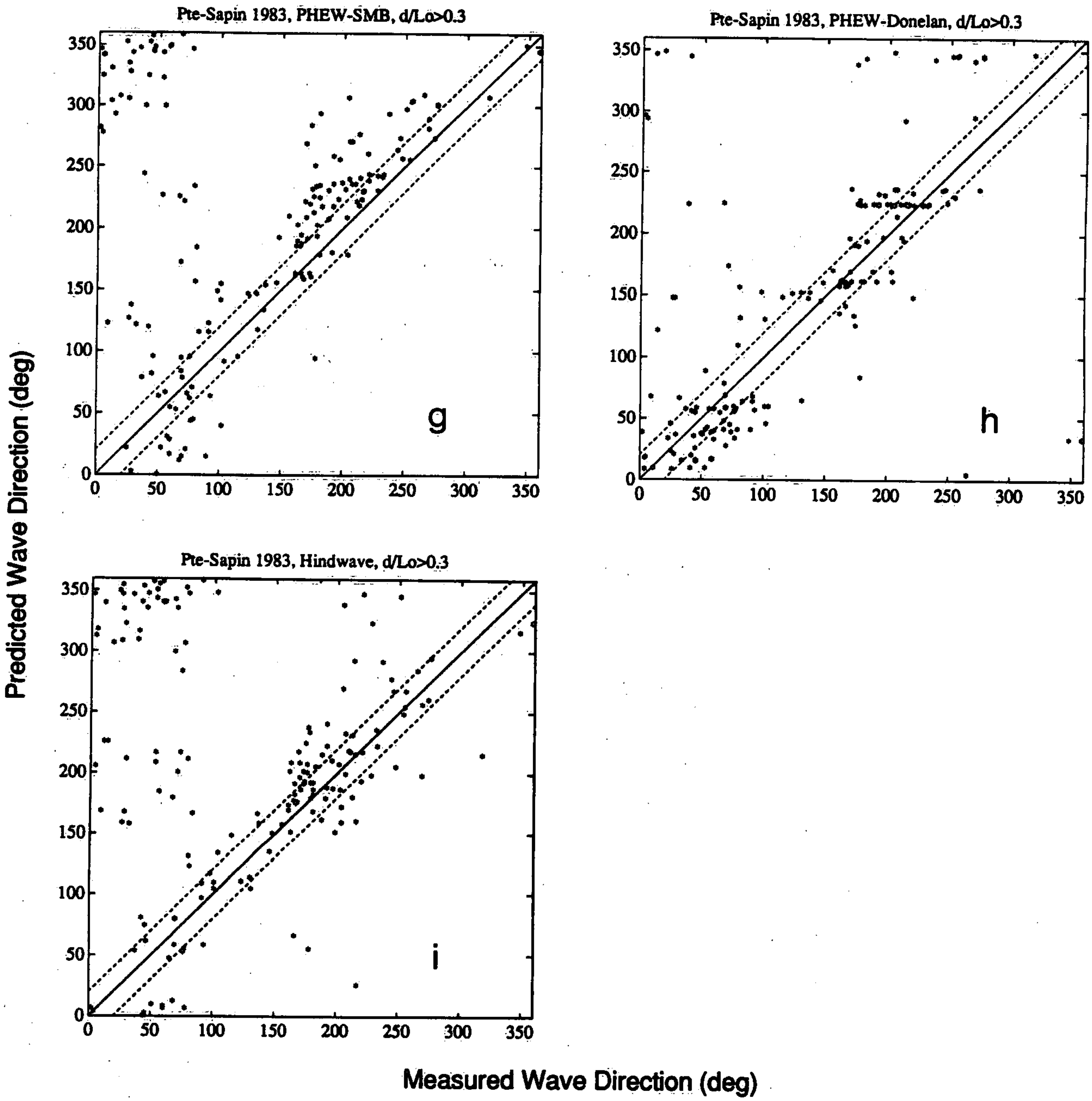

Figure 10. Continued

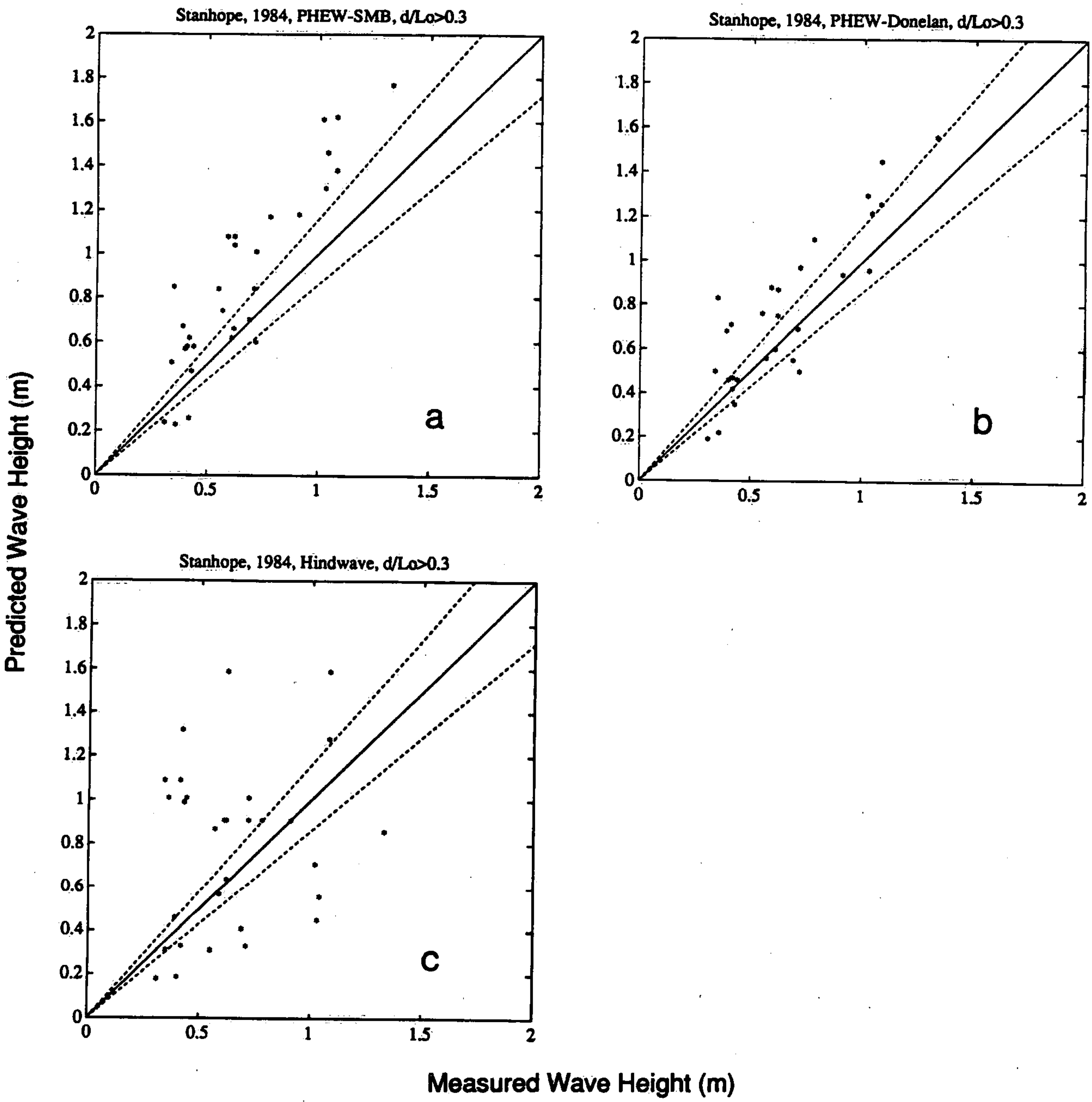

Figure 11. Comparison of predicted and measured wave parameters off Stanhope.

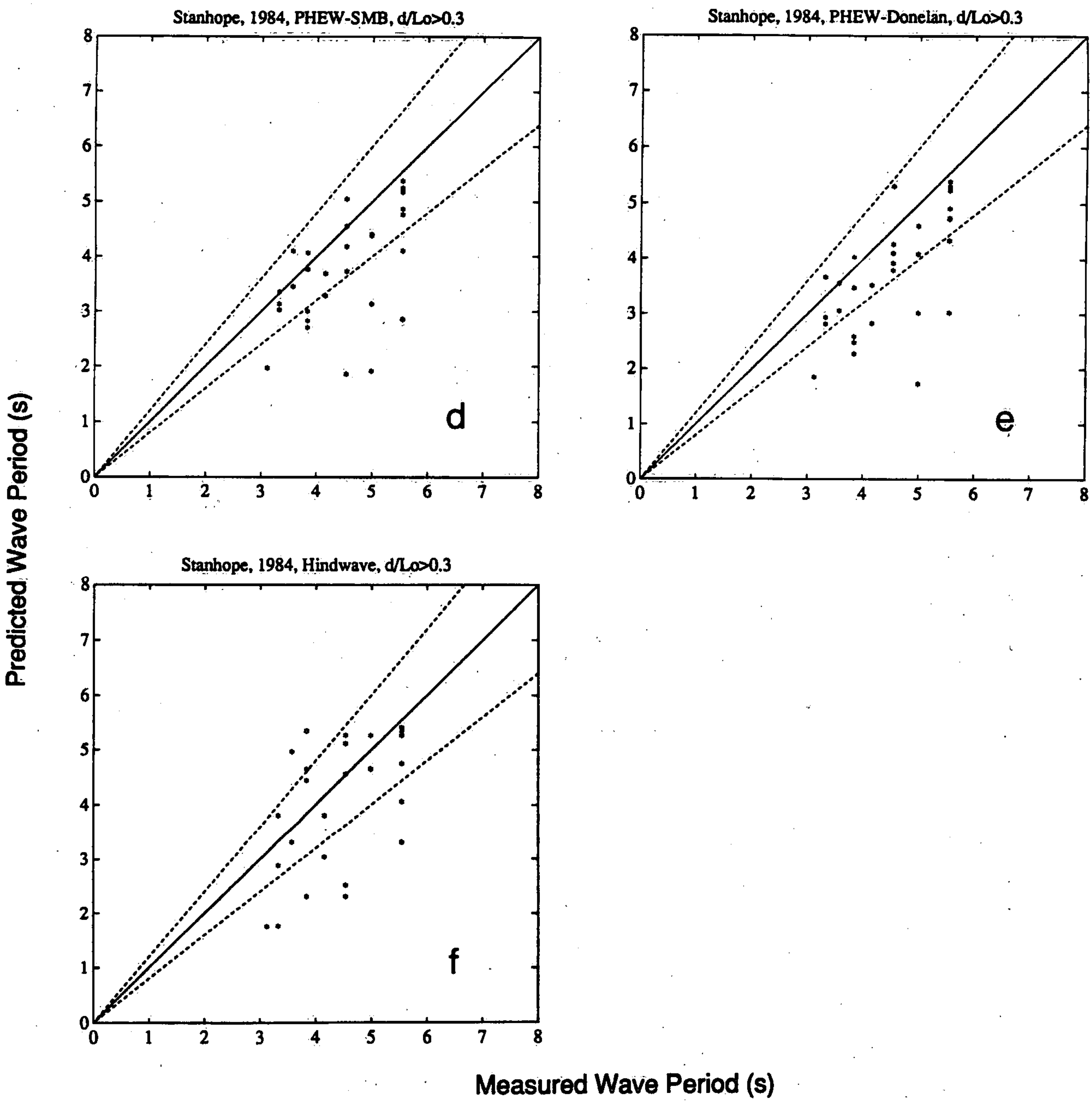

Figure 11. Continued

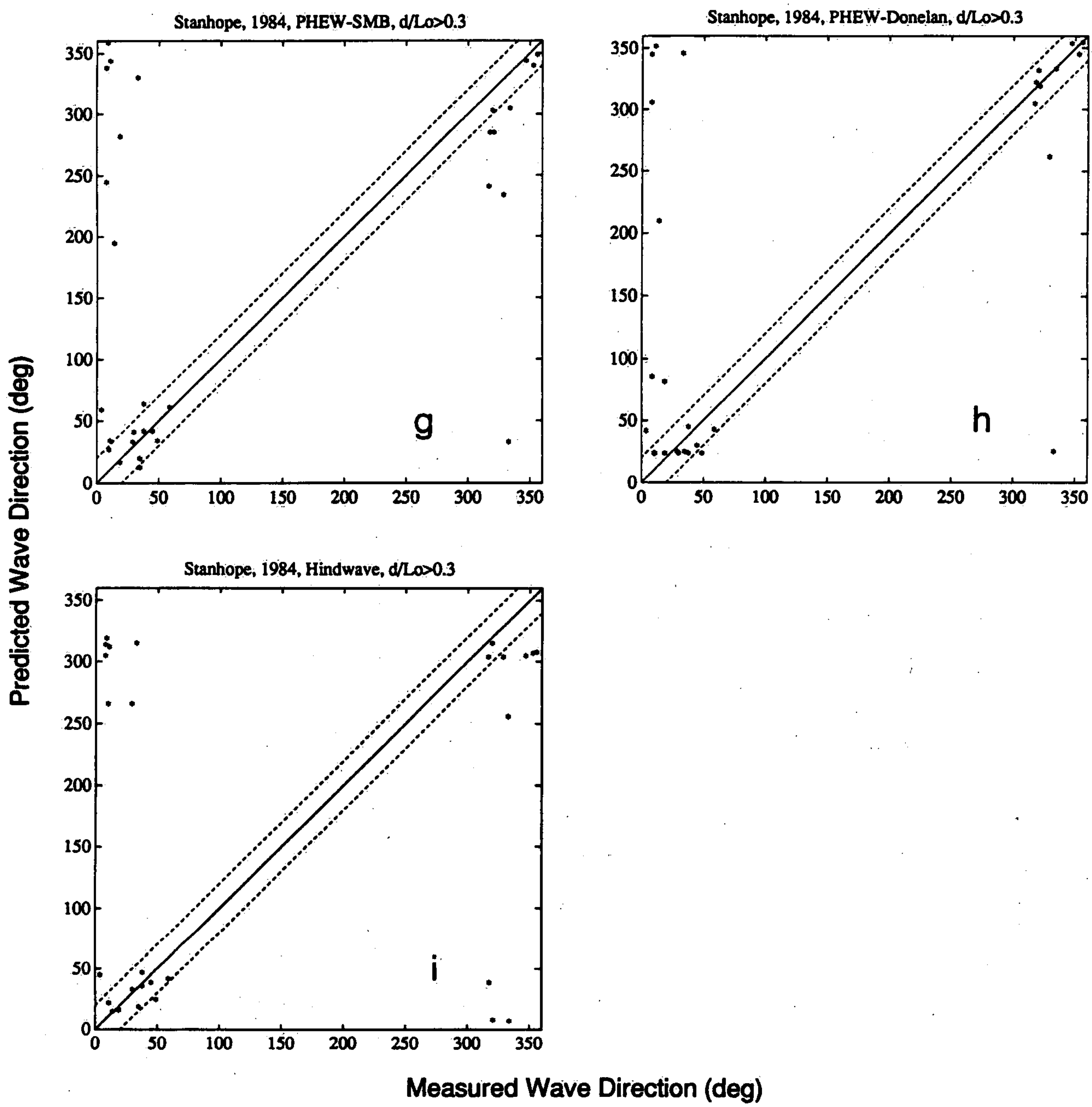

Figure 11. Continued

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