NOGAP B.8: Final Report:

WAVE HINDCASTING FOR EXTREME WAVE ANALYSIS IN THE BEAUFORT SEA

A Study for the
Northern Oil and Gas Action Program

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ABSTRACT

This report is a study of the Beaufort Sea wave climate for the Northern Oil and Gas Action Program. Extreme waves were estimated using modeled wave data and the joint probabilities of storm and ice conditions. A shallow water wave model was developed. This was used to hindcast a set of past Beaufort storms. Scientific errors were estimated for each stage of these analyses.

PREFACE

This report has been prepared as part of:

<u>**NOGAP Project B.8 "Beaufort Sea Wave Climate"**</u>

NOGAP is an acronym for a Canadian Government sponsored program called the **Northern Oil and Gas Action Program.** This was coordinated through the **NOGAP Secretariat** within the **Department of Indian and Northern Affairs.**

The specific project B.8 was arranged by the **Ocean Science Affairs Branch** of the **Department of Fisheries and Oceans.** Production of the report was carried out within the **Marine Environment Data Service Branch**, and under the direction of **Dr. R. Wilson.**

It has been the author's task to meet an objective which was stated: "To accelerate the development of wave climate knowledge of the Beaufort Sea in order to ascertain the appropriate techniques to be used in estimating design wave parameters and develop estimates of the parameters and their reliability."

To this end, many people have addressed their efforts. These groups were:

Department of Fisheries and Oceans
- **Marine Environment Data Service Branch (MEDS)**
  - **Ocean Information and Systems Division;**
  - **Data Management and User Services Division;**
  - **Wave Climate Study**
- **Bedford Institute of Oceanography**
- **Canadian Hydrographic Service**

Environment Canada
- **Canadian Climate Centre**
  - **Climate Applications Branch;**
  - **Arctic Meteorology Section**
- **Arctic Weather Centre**
  and Scientific Services Division – Western Region
- **Ice Centre**
  - **Ice Climatology Division**

Energy, Mines and Resources
- **Canadian Oil and Gas Lands Administration (COGLA)**

Department of Supplies and Services
- **Science Branch**
  - **Science and Professional Services Directorate**

And under contract to this project:

Maclaren Plansearch Limited, Halifax

Seaconsult Marine Research Ltd., Vancouver

EXECUTIVE SUMMARY

The Northern Oil and Gas Action Program (NOGAP) was a federal program,policy aimed at ensuring government preparedness in dealing with Beaufort Sea hydrocarbon development projects. DFO recognized that marine environmental information was required for government regulation of designs of structures, islands and facilities. As a consequence, it submitted a proposal to carry out certain studies concerning the wave climate in the Beaufort Sea. This was accepted and given the project name B.8: ”Beaufort Sea Wave Climate”.

The purpose of the B.8 was to evaluate limitations of present knowledge of the wave climate and hindcast technology. This depended on the development of the necessary hindcast techniques and wave climate information. Well proven methods used in Canada’s east coast Hibernia and Scotian Shelf oil fields, were not necessarily applicable to the arctic climate because of the presence of ice, shallow water and arctic meteorology. A review of previous Beaufort studies showed results for the 100–year significant wave height, ranging from about 5 to 15 meters. The review also high: lighted the dependency of the analysis on the approach to a statistical analysis and the design of a hindcast method.

The primary reference for this DFO study was a report by D.O.Hodgins–1983 entitled ”A Review of Extreme Waves Conditions in the Beaufort Sea”. This report recommended that the approach to an extreme wave estimate from extrapolated data, was a joint probability analysis using marginal distributions specific to storm populations and ice conditions. In response, the B.8 project had to implement a modern hindcast model, coupled to a joint probability approach to handle storms and ice. Of major importance was to conduct a careful analysis of the sources of variability affecting the hindcast results.

Estimates of the accuracy for extrapolated return period wave heights, depends on three factors. The probability distribution must apply to a set of stationary and independent hindcast wave data. From this there is a determinable level of confidence for the extrapolated extreme values. Also, the statistical analysis depends on wave data, which has errors due to hindcast modeling. Statistical procedures were examined in this DFO study under the heading of: ”Joint Probability Extremes”. The wave modeling was examined in this study under the heading: ”Storm Hindcasts”.

Joint Probability Extremes

Past studies have assumed, but not demonstrated that the joint probabilities of ice and winds had been properly accounted for.

The Beaufort Sea is a narrow stretch of water. One side and the end are shallow waters over a continental shelf. The polar pack ice advances and retreats over deep water, bordering the north side with variable concentration fields of ice floes. The naturally varying

storm winds were randomly restricted by the ice conditions, producing yearly maximum waves often under very different conditions. This study examined the impact of the variable Beaufort ice and weather patterns on the extrapolated value of the 100–year wave. It showed that the joint probability of the interaction of these factors was important in determining the extreme events.

The first step of the study was to extract the position of the ice edge from the weekly ice charts for the past thirty years. These were classified by fetch length, and summarized by month. Also there are three types of storms over the Beaufort. One is a small arctic disturbance. The second is a large extratropical cyclone. The other type are gales produced by the prevailing high pressure systems. Given plenty of open water, the waves produced by these storms depend on the path the storm takes over the area, the direction of the winds and their speed. Marginal probabilities for wind direction and population were calculated from available references. The marginal probabilities of waves for fetch and winds were combined.

For a given type of storm, and for a specific ice edge location, the probability of extreme waves can be described by the FT–1 distribution. The joint probability analysis was used to identify classes based on storm and ice conditions. This was followed by an extreme analysis for each class. All classes were then recombined using the probabilities of their occurrence. This method was developed as a logical extension of a design storm approach, Next, the class probabilities were applied to the hindcast studies. Results showed 100–year waves for deep water nearly 30 percent higher than the results for a simple FT–1 analysis. This demonstrated that the method used to estimate extreme waves should include some form of joint probability analysis.

For return period waves of between 2 to 20 years, the results showed extreme waves could be produced by any type of storm during open water providing fetches of 150 kilometers or more. It also showed that for the most extreme waves, during very rare encounters of the order of 50 to 100 years, there was a very great likelihood that these would be produced only by large extratropical westerlies and under the most open water conditions.

Storm Hindcast

A more modern hindcast modeling of Beaufort storm seas, was explored in the second part of the study. The first task was to compile a list of storms to be hindcast and to acquire the data for them. The list was to include a set of the most severe wave producing storms. This was done by reviewing the available Beaufort wind, ice and wave data. Reliable coverage of ice, weather and waves was available for the years 1977 to 1985. Windfields were produced for the storms on the resulting list by meteorologists of Maclaren Plansearch Ltd. using available weather data. The results were then reviewed by the Canadian Climate Center.

At the same time, DFO activities concentrated on making necessary additions to an available version of a Resio wave model. This was a ”spectral model”, which computed two dimensional wave energy spectra. It was intended to be used for large, uniform bodies of deep water. The Bedford Institute of Technology added shallow water equations. BIO tested the model using the SWAMP and SWIM methods. The B.8 study examined the model for growth over a complicated bathymetry. Many results were unrealistic when compared to the physical characteristics described by JONSWAP and HYPAS. The study changed coefficients in the spectral equations where they conflicted with JONSWAP. Problems within the model procedure, had been caused by inaccuracies in time–step and space–grid calculations; and the evaluation of spectral parameters in shallow water. Mathematical changes were made to the analysis of wave propagation, growth, and bottom interaction. Tests showed improved results.

The selection of storms were then hindcast using the winds and weekly ice conditions. The model input was three hourly winds on a grid of 25 km squares describing the Beaufort Sea. Each storm had specific open water defined by a ”solid” ice edge (taken at the one tenth ice cover boundary). This was fixed for the complete hindcast. Water depth was overlaid on the grid. The model calculated two dimensional wave energy spectral growth at each grid point. During the course of the storm, wave growth depended on wind speed and direction, water depth and the existing energy spectra. Outputs were significant wave height, peak period and average wave direction for each grid point at every three hours.

Modeling errors were quantified by comparing time series to available records of wind and wave conditions, and this report shows these results. Many storms showed good agreement. Typical differences between wave measurements and well modeled seas were of the order of 10 percent for a storm peak wave height at any location. For these storms the growth, peak waves and decay of the measured time series were well modeled by the hindcast. Storms that were characterized by rapidly changing winds, or that caused the ice edge to move substantially, were not well modeled. The shallow water effects were not well modeled in depths less than twenty meters.

Finally, to end this study, an evaluation of the entire process was made in order to determine the usefulness and limitations of the methods and results incorporated in the study. Maclaren provided an error analysis of their wind data. It showed statistical differences between winds derived from a meteorological analysis and observed winds during each storm. Seaconsult Marine Research Ltd. Was contracted to hindcast a few of the storms, using the Maclaren winds. These storms were chosen to investigate some of the problems with the DFO hindcast model. Results were very similar. They concluded that the hindcasts were limited by wind errors. The Seaconsult study also made some progress toward a better understanding of waves in the most shallow Beaufort water. This was accomplished in an experimental hindcast of a storm for which extensive shallow water measurements had been made during a separately funded experiment.

Technical notes on Beaufort data and the complete work done for the first part of this study, are available from MEDS. Model inputs and outputs were archived on magnetic tape. A report by MacLaren on winds, and wind errors has been made available through this NOGAP project and the Canadian Climate Center. A report on the Seaconsult hindcast contract has been made available through this NOGAP project.

Extreme Wave Estimate

A simple FT–1 probability plot was done using wave data from the hindcast and measured records. A reference region was chosen as the 30 meter contour through the petroleum fields. Yearly maximum wave heights along the contour were extracted from the storm hindcasts. Where the storms had been poorly modeled, any existing wave measurements were blended with the hindcast data. As a result, the largest waves of the final list, were from a storm that had uncertainties in the ice edge movement and no measurement coverage. The return year plot for these data showed a 100–year wave of about 6 meters.

However, the analysis was limited by several circumstances. The data set represented a very short list of years. Another limitation was, that hindcast model errors could not be properly corrected using wave measurements. Also, the method did not account for the joint probability of storm waves being randomly restricted by the variable Beaufort open water area. Finally, the shallow water wave physics change as the waves increase in size, It has not been shown that data representing these combined effects can be extrapolated using a straight forward FT–1 plot.

Conclusions

This study demonstrated that modern methods were a route towards a desirably improved Beaufort Sea wave climatology. The wind data produced by MacLaren were determined from a complete analysis of all available meteorological information. The hindcast wave data provided accurate information about waves during storms which could be properly modeled. Recommendations of this study are for further improvements to the wave hindcast methodology. Final hindcast data could be enhanced by blending modeled waves with measured waves. But, emphasis must be placed on ensuring the reliability of the model. Improvements to the wave model should be made to show effects of moving ice and rapidly changing winds. Further research into very shallow water modeling has been recommended as a result of the Seaconsult study. In the end, a complete set of hindcast wave error statistics should be produced using measured waves. Finally, an extreme wave estimate must include the joint probabilities of ice and winds.

TABLE OF CONTENTS

INTRODUCTION

The Beaufort Sea is a prolific arctic ecosystem which overlies a substantial petroleum field. Petroleum exploration and production has been intensive on the continental shelf area, offshore of the Tuktoyaktuk Peninsula. Between the years 1973 and 1984 at least sixty four wells had been sunk in depths of 2 meters, to over 50 meters. Approximately twenty of these were from semi-permanent gravity structures (such as artificial islands, and berm supported caisson structures). A general wave climate and estimates of the probable extreme waves are needed to design facilities for the unique Beaufort climate.

For most of the year, the area is ice bound. For the other 50 to 100 days during the July to October season, offshore structures and construction projects are subjected to loads induced by waves. Spring breakup begins sometime during late July or early August, and in the southeast corner of the Beaufort between Banks island and the Tuktoyaktuk-Peninsula. The ice recedes to the north and west resulting in an open water area slightly larger than, Lake Superior. For a year of poor conditions, this would be its maximum retreat. During the mid-season weeks of other years, the ice breaks abruptly along the west coastlines (north of Alaska). For a fair year the ice surrounds the sea, but open water extends about 450 kilometers from the Tuktoyaktuk shelf area to the west and northeast. A good year is a maximum withdrawal of the temporary ice, to the boundary of the permanent polar pack. The geometry of the open water is then a 200-300 km wide stretch, along the west coast of Banks Island to the shelf and then west along the Alaskan Coast to the Chukchi Sea.

Common summer storms move across the open water, generating two to four meter waves. The size of these waves depend on the force of the wind and the area of water covered by the storm. Huge storm systems will only generate modest waves when ice conditions are poor. Small storms also produce modest waves for even the best ice conditions. However there is a risk that a large storm with extremely strong winds will pass over the Beaufort during a time of maximum open water. The size of these waves are estimated from the statistics of the worst of past years storms.

Waverider buoys have provided wave measurements since 1974, with up to six buoys being deployed for a given year, and in depths of 15 to 70 meters. Sea state modeling, using available wind data, has been the means to provide wave data where measurements are lacking. However, data coverage of both wind and waves, has been sparse and only reliable over about the past decade. Estimation of extreme waves are sensitive to the assumptions and techniques used in the analysis of this short data base.

The purpose of this DFO study was to examine methodologies which lead to a better assessment of the Beaufort wave environment. There have been two reviews of historical extreme wave estimates in the

Beaufort Sea. The first was done by Dr.D.O.Hodgins in 1985. A second review was done by Murray and Maes in 1986. Both studies agreed that further efforts should be made toward an improved wave climatology.

To improve long term estimates, statistical analyses should include multiple distributions separating the waves generated by different populations of storms and during various ice conditions. These would then be combined to give the joint probabilities of occurrence.

To improve wave data, the references recommended that some twenty storms be selected for hindcasting. Winds for these storms should be produced from a complete isobaric and kinematic analysis. Wave hindcasting should use energy spectra models.

Empirical evidence and statistical theory have shown that a set of stationary and independent yearly maximum wave heights have a FT-1 probability distribution. These data can then be plotted according to a formula. When plotted, extrapolation can give estimates of the risk of extreme waves.

Waves caused by different types of storms are not stationary. Stationary, means that for all of the waves of a storm population, the variability of wave heights is caused by the variability of a set of storm parameters with a single joint probability distribution. Storms of different origins have different general physical structures and so will have different joint variance of their parameters. These cases are generally divided into marginal distributions of waves of a given storm population. The data is plotted on its specific distribution. Then, the results are combined according to their respective probabilities of occurrence.

In the Beaufort Sea, the physical structure of the systems that generate storm waves change in two ways. There are storms of several different populations. There is also the presence of variable polar pack ice. The presence of this marginal ice can shorten the fetch of a passing storm. By doing this, the ice adds another parameter to the wave climate.

The objective of the DFO study in this report, was to improve the Beaufort wave climatology. This would be accomplished by hindcasting past storms using exacting wind data and wave modeling. These storms would be divided into their marginal classes of conditions. From the joint probability analysis, the wave heights could be extrapolated for a level of risk.

Problems arise with the Beaufort Sea studies. The data base covers too few years. This means that there is too little data to show very much about each of the marginal distributions. Also the wind and wave data is sparse, implying greater uncertainty in the hindcasting process. Also the available wave model needed to be developed to adequately hindcast these storms.

The first step in this study was to determine the implications of a joint probability approach to the extreme wave climate. This was accomplished by modeling waves generated by projected storm and ice conditions. This was to determine parameters of the climate, to which long term statistics were sensitive. It was also to show the errors that might occur if this joint probability approach was neglected.

The second step of the study was to produce improved storm hindcasts. Even if the data base was short, the data that is .available should be used to the best potential. These results can be applied to examine the Beaufort system, show short term statistics and form the basis for future data collection.

The hindcastinq study examined the level of sophistication of modeling needed to produce reliable hindcast wave data. It showed the results of the best wind information attainable from past weather data. It was able to show reliable results for many kinds of storms. Needs for improvement or areas for development were identified for future reference.

PART ONE

EXAMINATION OF THE CLIMATOLOGY

1. Introduction

Part One examines the statistical procedures necessary for estimating extreme waves in the Beaufort Sea. The objective was to determine a return year wave height which included the joint probabilities of storm populations and ice conditions. The method was to combine results of historical hindcasts with statistics of winds and ice conditions. The study began with a review of the Beaufort Sea problem.

Maximum storm waves may be defined as the maximum significant wave height which has occurred during a single storm at a given location. Yearly maximum waves are the highest waves during a specific year, at this location. The probability that a certain extreme wave height will be exceeded is determined from a statistical analysis of a set of these yearly maxima. The analysis is accomplished by fitting the data to a probability distribution function and extrapolating. A probability value is often referred to as a return year risk, such as the 100–year wave.

Over the past ten years several extreme wave climatologies have been produced for the Beaufort Sea. A review of these was written by Hodgins in 1983. A further assessment of the most reliable studies was reported by Murray and Maes in 1985. Reports on the East Coast of North America provide a general discussion of current state–of–the–art methodologies (Wilson and Baird – 1984, Resio 1982). These reports describe methods which obtain wave data from hindcasting of storm winds. The reasons for limitations of predicting long term climates were as follows. Relatively short data bases cause large uncertainties when extrapolated to extremes. For twenty years of data, a 100 year return period wave could be estimated to within +/– 2 meters. Multiple populations of conditions show different distributions of extremes. Differences result by assuming different probability distribution functions for the same data.

These points are interrelated causing a complication of the problems. In the Beaufort, as is often the case, short data bases extrapolated to long term events, are sensitive to the assumptions of the statistical analysis. Data bases about half the length of the maximum extrapolated return period, can be used to find a probability distribution function which best fits these data. However, short data bases have too little information about the extreme tail of the function, to give much certainty about goodness of fit.

This statistical method has constraints; the series of annual maxima must be independent and identically distributed. That is, the distribution must be a constant from storm to storm. If the storm population is not stationary (multiple storm types), the wave data must be plotted according to storm and then combined using methods of joint probabilities. For example, East Coast studies (Wilson and Baird, 1984) showed that if wave data were broken down by storm population, each set extrapolated and recombined according to the joint probabilities of each set of events, the results were different than for the original undiscriminating analysis. Possibly three storm populations have been identified in the Beaufort Sea.

A second constraint on the analysis of the Beaufort waves is the presence of shallow water. The statistics of shallow water waves can differ considerably from those derived for deep water. In unbounded deep water, the significant wave height is generated by the wind speed and duration of the storm. Therefore, the wave height probabilities are closely associated with the natural variation of the storm winds. Typical yearly maximum waves have peak periods much shorter than the most extreme waves. At some hindcast point, these shorter waves may not be affected by bottom interaction and show variation similar to the winds. However, the extrapolated extreme waves will have longer wave lengths and might be touching bottom. In this case the bottom interaction changes the physics of the extreme tail of the probability distribution, from wind only generation to wind generated and bottom restricted waves.

Another physical influence on wave growth which might not be apparent in–the typical yearly maximum wave height values, is the effect of a fetch limit on the open water boundary. For a sea the size of the Beaufort, storm waves often develop as if they were unbounded by the shores. These waves might be restricted by the size of the storm. The waves might be limited by the duration of the storm. Or the waves might reach the maximum size possible for the given wind speed of the storm. All of these conditions are typical of unbounded storm systems which, statistically, show the FT–1 return periods. However, for the conditions which produce the most extreme waves, storms are large, long and have very strong winds. These wave conditions may not reach the potential of the storm due to the up–wind or down–wind coastline. Imposing a fetch limit on the extreme value extrapolation is more involved for this case than for shallow water effects.

In the Beaufort Sea, fetches vary with the ice conditions. This ice can limit the area of water exposed to the wind field of a passing storm. The Beaufort environment has storms which are large cyclones with diameters of over a thousand kilometers. These wind fields are often much larger than the open water. To hindcast the height of waves generated by these storms, one must use the speed of the winds as they rise and subside with the storm, and the length of the fetch over which they blow. However some years have maximum waves produced when the ice is withdrawn and the storms are weak or small. So the extreme height extrapolation is complicated by the fact that the data base of yearly maxima contains waves produced during fetch restricted conditions and waves produced when the storm is effectively unbounded.

The examination of the climatology begins with a description of the extreme wave information available for the Beaufort. The joint probabilities of storms and ice were calculated to show estimates of long term waves. Wave and other data were taken from available sources. The approach of the analysis was to assume that the FT-1 distribution describes the basic stationary wave environment. Storm populations were first separated into classes. To each of these storm analyses, the physical influences of shallow water and ice edge bounds were then used to scale the heights of the data and extreme value estimates. The sequence of the study shows the most logical route to understanding the nature of the Beaufort environment system.

2. Measured Wave Data Extreme Wave Height Estimates

Waverider buoy data has been collected in the Beaufort since the mid 1970's. A demonstration of an extreme wave estimate using these data, was shown in Hodgins-1963. This DFO study repeated his work using yearly maximum wave heights, taken from data archived at MEDS for the years 1977-1983. A straight forward FT-1 plot of the data showed a 100-year wave of about 4.8 meters.

These estimates assumed that the Waveriders were in operation during the complete open water season. Ice statistics (see a following section) were compared to the periods of Waverider operation. For the complete MEDS data records from 1974-84, the buoys were in operation for:

- 85% of the time during which an extensive west fetch was open;
- 67% of the time during which an extensive north east fetch was open.

A second limitation to the analysis was that the Waveriders had been anchored at many different locations over these years. Wave data were influenced by windfield definition and shallow water effects. Very strong depth influences on wave height make it difficult to compare data from depths differing by more than a few meters. Although there may be a fairly uniform wind pattern over the Beaufort, Waverider data at the same depth and during the same storm, but at locations about 150 km apart, show wind waves of very different heights.

To improve the estimate, depth effects could be negated by scaling the measured wave spectra using contemporary shallow water wave theory. However there are too few buoys deployed each year to form a definition of a storm wave field given the spatial variation described above.

A problem expressed by Hodgins about his analysis, was that the data were taken from "arguably, two different storm populations". There is no direct way of determining the storm type from the measurements of waverider buoys.

So, the major problems of this type of analysis were to be solved by introducing windfield data. These show storm types for the joint probability analysis of wave heights and storm populations. Hindcast wave data, from these winds and ice data, then provide spatial descriptions of the storm wave fields. The Waverider data were used to support the hindcast wave model results, by providing estimates of errors. Some further use of the measurements included identification of poor wind or wave modeling procedures.

3. Historical Extreme Value Hindcast Studies

The general application of wave hindcasting provides data where measurements are lacking. Several independent studies have been carried out for the Beaufort Sea in the last decade, each producing a summary of return year wave height estimates. These were reviewed by Hodgins–1983. When data for each study was plotted using the FT–1 plotting formula, the return year waves were all about the same. These showed a deep water 100–year significant wave of about 6 meters (when each was adjusted for noted limitations in the source data). For the short data bases of 10 to 20 years, 100–year statistical confidence limits were from about 4.5 to 8 meters.

Hodgins stated in his review that the estimates did not show the joint probabilities of the storm population or effects of the variable ice edge. The straight forward plot of yearly maximum waves was not valid, in that the data did not necessarily represent identical distributions. First of all, the waves were produced by storms from different populations. Secondly, some wave heights were severely restricted by the fetch outlined by the polar pack ice, where as other data derived from conditions governed solely by the storm fetch and duration.

An attempt was made by the ISR study (Hodgins–1983), to estimate extreme waves using the joint probabilities of storms and ice conditions. The study summarized wind speed and direction and ice restricted fetch length from about 30 years of data. Wave heights were calculated for each of the conditions. The distributions were then recombined using the calculated probabilities of occurrence. The major limitation to this study was that the waves were assumed to be only fetch limited by the ice edge. The storm duration and fetch (the storm wind field) was not considered. Therefore their results were necessarily too high. The study showed the 100–year wave in deep water of about 10 meters, with inferred confidence limits of about 8 to 12 meters.

The two types of studies showed a range of extrapolated 100–year significant wave heights from a value of 6 meters to a too high value of 10 meters. The low value was derived from data that were sometimes fetch limited and are biased low. A review of these same studies by Murray and maes 1985, out–line the hindcasting errors associated with the estimates. They have suggested that a deep water 100–year wave height of 8 to 9 meters would be an appropriate estimate based on their review of past hindcast studies.

The Murray and Maes assessment largely derived from their review of a design storm study by Seaconsult. This Seaconsult approach was similar to the ISR study in that it attempted to estimate return year wave heights by modeling extrapolated wind data. The study differed by using a design storm to describe the over water wind fields. However, other storm types, wind directions or ice conditions other than the most open, were not considered.

The following section describes the results of a complete joint probability approach to the design storm analysis.

4. A Model Storm Analysis of Climatic Joint Probabilities

The Seaconsult report for MEDS on the Beaufort Sea wave climatology (Hodgins–1983), described a design storm estimation of return year waves. A prototype storm was selected as being commensurate with a population of severe extra tropical cyclones which developed intense, long duration winds over an extensive fetch. This storm was synthesized into a design storm by numerically adjusting the barometric pressures to fit return year wind speeds. Although it was never shown that it would be possible for these central lows to develop in this size of storm. The resulting wind fields were certainly possible (although the return periods of these have also not been substantiated). Referring to Beaufort Weather and Ice Office (BWIO) reports, showed examples of storms which were very similar to both frequent low wind storms and infrequent high wind storms, modeled by the design storm.

Winds were taken from extreme value studies for all data, and over the hindcast sites over the Mackenzie Delta. The BWIO reports indicate occasionally yearly maximum winds and waves, were developed by alternative storm systems. Also, the extensive westerly windfields may have been locally intensified by coastline convergence and secondary pressure systems produced near the coastal mountain range (Earle – 1979).

Open water conditions are independent of storm winds. A study was done (Markham – 1975), that showed a relationship between the seasonal open water conditions and semi– permanent Arctic pressure systems. Studies of both of these factors may indicate a correlation between some storm parameters (eg. trajectory and local air temperatures and therefore ice conditions). However there is little correlation between overall storm frequency and seasonal ice conditions.

The method used in this report, was to derive estimates of probabilities of storm size, trajectory, duration and resulting wind speeds and direction from available references. From these derived wind fields, and for all ice conditions, waves were calculated. The marginal distributions of waves were recombined according to the probabilities of the ice and storms. The errors of the modeling and probability assessments were estimated. Extrapolated extreme waves were taken from the results. The method was similar to the ISR study, but used models of wind fields as in the Seaconsult study.

Ice Statistics

Probability distributions for fetch occurrences were calculated from seventeen years of ice chart data. Ship, satellite and airborne observed ice concentration for the Beaufort Sea had been compiled onto weekly composite charts, and stored at the Ice Branch of the Atmospheric Environment Service. An overview of these charts showed that the Beaufort open water conditions could be described by the extent of two independent fetches. One fetch opened up to the west along the Alaskan coast. The other fetch extended north-east along Banks Island.

The charts showed ice conditions which were characterized by three types of conditions. For each of the two directions there were for a given week, either poor, fair or good conditions. Good conditions were the most open waters with a western fetch extending to past 1,000 km. Fair conditions had fetches of about 200 to 300 km. Poor conditions had fetches less than about 150 km. Each fetch condition, for each weekly chart was listed. Probabilities of ice conditions were calculated for each direction and for each month of occurrence. The final values showed the chance that a fetch would be of a specific class for a given direction and month of all years.

Windfields

The next step was to determine return year wind fields. The Seaconsult wind fields had been derived from meteorological surface pressure charts. Maximum return period winds were determined by extrapolatinq extremes for 10 years of summer season weather data. A single extratropical cyclone with long duration westerly winds was selected to describe the wind field. For a return year storm, winds were scaled onto the design storm isotacs. Each estimated wind speed defined the peak winds of the design storm for the same return period. All other winds within a return period storm were derived from the subsequently modified pressure field.

Extreme wind speeds were surmised from historical estimates. A study of winds for Sachs Harbour (east of the shelf area) by Berry et al – 1975 and used by Dames and Moore in a hindcast study (see Hodgins 1983), showed 1 minute, 1 hour and 6 hour return year winds. Hydrotechnology produced 1 hour winds for Tuktoyaktuk (central to the shelf) which were adjusted by 10% (see Murray and Maes – 1985). These were very close to the Berry study. Brower (see Hodgins – 1983) extrapolated 1 minute winds from Point Barrow (west of the shelf) and these compared to the Berry study. Seaconsult design storms had winds of 3 to 6 hour duration. Each of the estimates was based on a Gumbel (or similar) probability distribution function. All studies showed a close agreement (+/– 1 knot) when adjusted for duration. They also showed that: to 300 km east or west of the Mackenzie Bay area winds could be described by a single general climate.

From the reference, wind fields were determined for the ice restricted wave modeling. The figure of the simulated prototype windfield (Figure 2.22 of Hodgins – 1983) was scaled and contoured.

The contour winds were overlaid on a map of the sea, with the storm centre located at each six hourly trajectory centre location (Figure 4.3 – Hodgins – 1983). Wind profiles along the western fetch were plotted, where a time history of the prototype storm in Mackenzie Bay (Figure 2.24 Hodgins – 1983) was used for calibration and comparison. These winds, for the final section of the fetch of practically parallel winds, represents the relative intensity of over water wind velocity toward the hindcast site at each six hour interval of the storm peak.

Several points of description were noted. The wind field straight fetch stretches over 600 km. Before this the fetch was curved due to the passing of the storm and subsequent redirecting of small waves. The windfield is relatively constant over the fetch at each six hour time point, particularly in length intervals equivalent to the distance a wave front will travel in the six hour intervals (about 200 km). The storm lasts about 24 hours and peaks for six hours at mid–storm and mid–fetch. Errors in assuming that the windfield is consistent about the central low during the storm are minimal since:

– up fetch winds in the early stages of the storm are close to the storm centre which was remote from topographic features such as mountains and the coast;

– down fetch winds were calibrated, to the time history plot for a point at the end of the fetch.

Storm Populations

Descriptions of other types of storms were constructed for the DFO study. Return year winds, used in the design storm study by Seaconsult had been calculated from all winds over Mackenzie Bay. Extremes, irrespective of direction, were extrapolated to return years and assumed to be produced only by storms exactly like the design storms. This section examined the probability that extreme waves were produced by other storm systems and/or from other fetch directions.

Seasonal distributions of the design storm were taken from the Seaconsult report. Severe storms producing westerly winds along the Alaskan coast, were summarized in a study by Hodgins – 1983. These storms were classified by trajectory and counted by month for twelve years of meteorological charts. The study showed that each population class had distinct and different seasonal distributions. For this study, the probability that the prototype storm came from any of these classes depended on the relative proportion of the class size to the total of the three classes.

The design storm study did not ensure that the return period wind speeds, up wind of hindcast sites, were representative of all large extra tropical cyclones. A review of the BWIO seasonal storm summaries and a study by Hodgins – 1983 indicated that these storms vary in overall structure. The storms often have troughs extending south, over the Mackenzie Shelf. The curvature, gradients, extent of pressure fields, and the trajectory of the storm centre vary between storms.

A table of directional frequencies of strong winds (from Berry et al. 1975) showed directional frequencies of Beaufort winds. The storms were of several types and sizes. Therefore, an extreme wind study for this report fit winds from large extra tropical cyclones, local pressure ridges and troughs from anticyclones and cyclones, and small scale Arctic lows.

Here it was assumed that the probabilities of the design storm systems were reduced to the percentage of extreme winds from the population and direction, and that all storms had equal return period winds and differed only in size and characteristic wind directions.

Small storm windfields were modeled. The maximum effective fetches were taken as 150-250 km which resulted in a six to eight hour effective duration. Over this duration, winds were constant at their 6 hourly peak.

Storm Trajectory

The over water windfield depends on the trajectory of the storm. Trajectory was defined as the track followed by the central barometric low. A reworking of the joint probability analysis was done to include storm to storm variations in trajectory (for storms of Seaconsult's prototype storm parent population). The method was to move the contoured windfield over trajectories selected from Figure 4.5 of Hodgins – 1983, and remodel waves for fetch, wind and trajectory joint probabilities.

The effective duration depended on the relative velocities of the storm trajectory and the developing wave celerity. The trajectory speed was taken to be equal to the speeds recorded for the prototype storm over the same area of ocean (see Figure 4.3, Hodgins 1983).

Storms and Ice

Since the ice conditions had been classified by month, the storm winds were also distributed by month. The probability that the a type of storm would hit during any given ice condition was computed. This was done by combining the monthly fetch probabilities with the monthly relative storm frequencies for the storm population.

The joint probability was based on the assumption that there was no correlation between storms and ice conditions. To test this assumption yearly ice conditions were compared to yearly totals of severe storms. A general comparison of storm count to good or bad ice conditions (as discussed in Markham-1975) showed no discernible correlation.

Wave Generation

The maximum significant wave heights were calculated for each storm intensity and type, under different ice conditions. The wind field calculations were taken such that the growing waves were exposed to the maximum winds. Comparison of calculated wave heights from a

Bretschnider nomogram, CERC equations and JONSWAP equations suggest that the Seaconsult modeled waves were 20% too high. These calculations were based on the JONSWAP equations.

Observation of the results showed several aspects of the Beaufort wave systems. For the most restrictive ice conditions, the wave heights were most sensitive to the path of the storm. More importantly, there were equally large waves produced during either infrequent open water with frequent storm winds, and frequent poor ice conditions with infrequent strong storm winds.

Errors and Assessment

Errors in the fetch-storm probabilities were encountered in the statistical summaries of the ice charts and storm records. In the review of Seaconsult’s return year winds, the season of winds was not defined. The joint probability analysis assumed this season to be July 1 to October 31, as was the season for storm class summary. If this season is taken for the earliest ice breakup to the latest freeze over (August 1 to October 15) with the same return period winds computation of storm-fetch probabilities results in an increase of 5% for the 100 year significant wave height (Hs).

For the original probabilities, an error in the length of the ice restricted fetch (ie. the 450 km fetch) of +/-50 km results in a 3% variation in return year significant wave height.

If a shorter fetch is included by assuming that 25% of the storms will hit a fetch of 200 km and the longer fetch probabilities remain unchanged: the return year Hs increases by 1%.

If the duration of the peak winds increases from an effective duration of six hours to eight hours: the return year Hs increases by 2%.

The last three errors are windfield and wave modeling errors. The effect of these inaccuracies is small, since the proportion of the joint probability calculation derived from short fetches is also relatively small. In summary, the analytical errors were +/-5% with an additional possibility of 6% increase in Hs for ambiguities in the defined length of season.

The analysis of trajectory types were repeated for the various return period storms and the joint probabilities computed using the percentages of trajectories. The above assumptions and their respective errors showed a maximum expected increase in the 100 year wave estimates of 0.6 meters or 5%.

5. Results and Conclusions

The results of this model storm analysis depended heavily on the description of return year wind fields. Examination of the return year wind speeds from each of the historical Beaufort studies, suggested that the most reliable results were in agreement. Measured winds from locations across the Mackenzie shelf area showed differences of less than 1 m/s. The design storm derived by Seaconsult was a good representation of large Beaufort extra tropical cyclones. BWIO reports gave descriptions of smaller storms. These storms could be modeled by short fetch, constant winds. Statistics for the dominant storm parameters were taken from references. The occurrence of storms was independent of ice conditions. Ice boundaries were summarized from 30 years of weekly ice charts.

Deep Water Waves

The probability (or return period) of exceeding a given significant wave height was obtained by summing the marginal distributions of waves generated under different ice conditions and storm types. The results showed a 100 year significant wave of 8.0 meters with a peak period of 11 seconds. The estimate was insensitive to the variations in the ratio of small storms to large storms. Errors of modeling the return period wind fields resulted in a 7.5 to 9.0 meter range for the calculated 100-year wave height. The statistical confidence interval resulting from the 12 years of winds and extrapolated to about 20 years, was a further +/- 1.0 meter. So the range of values for the 100-year wave was between 6.5 to 10.0 meters. This is reasonable for extrapolations of the short data base to beyond four times a reasonable period of twice the data base length.

The BWIO report for 1984 shows yearly maximum reported waves for nine years. A comparison of wind direction and ice statistics for each year showed that at least half of these waves were produced over severely restrictive fetch conditions and from several directions. This suggests only that yearly maximum storm seas have a possibly of being generated by any type of storm.

The joint probability analysis showed that there would be an 88% chance that the 100 year wave would be produced by a large extra tropical storm. Also, that there was a 65% chance that the large storm would develop this wave over a maximum fetch to the west. Together these conditions would need only 10 to 15 year winds of about 47 Knots. For 50 to 100 year return periods, there was a 90% chance that the waves would be produced by large extratropical cyclones blowing over fetches exceeding 450 km. It was concluded that waves produced during times of open fetch by the population of large extratropical cyclones have a unique distribution, and that this differs from the probability distribution for the same storm population over shorter fetches.

In summary it was concluded that large scale extra tropical cyclones are the population which produces extreme wave storms. This showed that the value of 6.0 meters from a straight forward FT-1 plot, changed to 8.0 meters. Also for return periods in the order of 10 to 20 years, all storms and under many ice conditions, generate severe waves. Given this, 10 years of data, extrapolated to the 100 year return period, would be accurate to +/- 30%. The values were not conclusive, but: extreme wave estimates were sensitive to large variations in some parameters describing the storm climate and ice conditions.

Shallow Water Waves

The major fetches of the Beaufort Sea extend over deep and shallow water. The transition onto the shelf from depths well over 75 meters to the 30-meter contour is short in terms of general wind-wave growth. The three types of sea bed interaction are refraction, bottom damping and modification of the wave-wave interaction mechanism. Refraction spreads the waves out, causing a reduction in per unit energy. The bottom absorbs energy. However, the over water winds quickly replace this loss, up to the point where white capping occurs. This returns the wave spectrum to its characteristic JONSWAP shape. The wave-wave interaction predominates the shallow water transition by changing the point where white capping energy dissipation occurs. This energy balance is governed by the interaction of waves of different wave lengths. In shallow water the longer wave lengths shorten, causing a modification of the spectral equilibrium. This mechanism is described in the references of this report (such as Perrie 1986).

Scaling the deep water waves was accomplished by assuming the JONSWAP spectrum, and modifying the equilibrium for depth. This resulted in the deep water 100-year wave of 8.0 meters and 11 seconds being reduced to 6.5 meters and 11 seconds at 30 meters depth. Combined confidence and errors, when scaled gave a range of heights of about 5.5 to 7.5 meters.

Recommendations

This report examined the sensitivity of the return year wave heights, to considerations of the joint probability of storm populations and variable ice conditions. However, the need for accurate storm by storm hindcasts, remains. Current wave models show that wave heights are very sensitive to the over water wind speed and direction. For an accurate hindcast of any particular storm, or an over all description of the Beaufort wind fields, there is a great need for high resolution wind analyses.

A second point is the need for a high resolution wave model. many storm seas are restricted by the ice edge, and these ice fields can move great distances during a storm. Also the open water area of the Beaufort can be quite complicated, exhibiting long narrow stretches and greatly varying bathymetry. Therefore, the complicated nature of the winds, ice and bathymetry necessitate the use of a responsive wave model.

The hindcasts of severe storms will lead to a description of the general storm seas of the area. Short records of good environmental data, are not capable of showing the probability distribution for a reliable long term extrapolation.

The methods of long term wave climatology suggested that separate probability distributions would be necessary for each storm population and each ice condition. Recommendations for further study include:

– hindcasting storms derived from high resolution pressure grids, and during the prevailing ice conditions, and verified by Waverider data of the day;

– windfield studies to determine return year winds by storm population, direction, and month of occurrence, for an indication of most severe conditions;

– determination of the most descriptive probability distribution function and the joint probability factors of storm and ice parameters.

PART TWO

DESIGNING THE STUDY

1. The Hindcasting Process

Hindcasting of sea states, is the computation of past events. it has been discussed in previous sections of this report that: compiling a set of past storms would provide the basis for a statistical summary of the climate. The recommended technique was to simulate these storms using meteorological data and an energy spectra wave model. This section describes the design of the system which was used for the study.

For studies using well documented windfields, good deep water wave models could be expected to produce wave height data to within 0.6 meters, or perhaps 10% of what might be measured. It has not been demonstrated, but certainly indicated that wave models for areas of complicated shoreline and finite depths, could be as accurate. This accuracy has depended on good modeling of the overwater windfield.

Wind inputs to wave hindcasts are in the form of time point "maps". The geography of an area would be first defined at nodes of a grid system. For a selected hour, wind information is determined at each grid point. Wave modeling would then follow from a consecutive series of wind maps.

The Marine Environment Data Service had a software system for the prediction of wind-waves, originally written by D.T. Resio. In his description of the hindcast process he wrote:

> " There are four basic steps in the calculation of waves from past meteorological data. First, pressure data must be assimilated into a pressure field that depicts all important synaptic weather features. Gradients of pressure in time and space, along with certain thermal characteristics of the planetary boundary layer, are then used to construct an estimate of a quasi-geostrophic wind speed and direction at some level where it is assumed that the frictional effects of the ocean surface on the atmosphere are negligible. Next, an analysis of the vertical variation of the wind in the planetary boundary layer is used to reduce this wind to a common 19.5m level. Finally, these surface winds are input into a numerical wave model to simulate wave generation, propagation, and decay.
>
> If any one of the above steps contributes significant bias (on a geographical basis, seasonally or overall), it can introduce errors into the results that are difficult or impossible to remove. Similarly, if any step contains a large random error, certain statistics (such as duration curves, extremes, and conditional probabilities) can be seriously affected. Thus, each step must be checked independently where possible. This serves to substantiate the merit of the physics

and data processing techniques used in each step and hence tends to lend support to the worth of the final product more so than the performance of only wave comparisons, regardless of how extensive these comparisons may be. Indeed, if each step is shown to be physically valid, it can be argued that the results should be as accurate in sites where there are no wave data for verification as they are in areas where large amounts of gage data are available. Additionally, if all steps are modeled correctly, factors such as directions and angular spreading, which are not generally available for comparisons, can reasonably be assumed to be at least approximately correct. ”

It was Resio’s methodology which this project adopted as the basic hindcast system. In accordance to recommendations by Murray and maes–1986, and a selection of current publications, a kinematic analysis of the wind fields were added to the machine–only analysis in this system.

The entire wind analysis procedure was contracted out to meteorological specialists. This was done in accordance with recommendations from climatologists at the Atmospheric Environment Service (Environment Canada). The remainder of the hindcast process was done at MEDS.

It was an important part of the project, to check the validity of the wind and wave analysis procedures. The winds were the responsibility of the contractor. Their methods were state–of–the–art, and they were experienced in operational forecasting of the Beaufort Sea, itself. Validating the wave model was the responsibility of the author. Adapting the wave model to applications for the Beaufort region proved to require considerable effort.

1.1 Wave Energy Spectra Modeling

The version of the Resio wave model at hand had been developed for applications in areas of large regular ocean geometry, such as the Atlantic. The basic method used by the model was to, as for all spectral wind–wave models, input winds onto a grid of points over a series of time steps. At each grid point and time step the spectrum of wave energy was calculated and stored until the next time step wind input. The computed wave growth at these grid points was determined by physical relationships governing the wind and wave interaction based on the existing state of wave development.

The level of resolution or accuracy employed in the wind–wave growth equations, govern the physical representation of the modeling process. As for many applications of computer simulation calculation of absolute mechanical properties and dynamics has not been practical. One reason for this unfortunate circumstance, has always been the limitations of the computer hardware. A second aspect has been the physical representation of the analytical equations themselves. Many aspects of the wave growth process have only ever been described by empirical or statistical relationships. Thus, the numerical methods of spectral modeling have had to rely on parametric or descriptive improvisation of real world mechanical behaviors. These considerations have been the subject of ongoing work in this field. Therefore it became an important secondary task within the objective of the project, to validate the merit of the physical representation of the wave modeling software.

1.2 Wave Hindcasting in the Beaufort Sea

The Beaufort Sea is not a large regular body of oceanic proportions. It is an area where geographical irregularities such as bays, shallow water, and the changing pack ice coverage, play important roles in shaping storm sea states.

Effects of shallow water on developing wave spectra has been the subject of fundamental research and model developments, in recent years. At the Bedford Institute of Oceanography, W.Perrie and B.Toulany had been working on a ”Second Generation Shallow Water wave Model”. Their efforts had been to add code for the effects of sea bed wave damping and refraction and most importantly, a factor which relates the shape of the spectrum to finite depths. Also, this model was being modified in order to optimize the use of computer memory, which would prove useful in increasing the resolution of a gridded sea surface. Some performance tests had been completed, by the time this study was being designed. However, in order to ensure that the model represented the current state–of–the–art and, was usable in the Beaufort, research, programming, testing and modifying of the model at hand became important activities of this study. A review of the model developments follows in a section of this report.

The basic framework of the Resio model was, of course, to remain intact. The inputs required a general description of the shoreline and shallow water bathymetric depths and specific data of the meteorological events and ice conditions during the period of each particular storm. Also recorded wave measurements were needed for verification and testing of the hindcast. The available data sources are described in the next subsection. The following subsection specifies how these data were to be utilized in the hindcast process. Further sections of this part of the report outline the system developments and information processing, leading to the final hindcast results.

2. Data Sources

This section outlines the environmental data available for application in spectral hindcasting of the Beaufort wind seas. The lists of these wind ice and wave data are quite short. There has been much effort by groups of the Atmospheric Environment Service (AES), the marine Environment Data Service (MEDS) and the BWIO to collect, compile and assess information. References, as listed at the end of this report, were used to choose the final selection for this study.

2.1 Ice

Records of sea ice are held by the Ice Branch of AES in Ottawa. The period of coverage available is from about 1959 to present. The form of the data are:

- Hard copy 'weekly composite summaries' for all years;
- Hard copy 'current' or daily charts;
- Satellite photographs of the region at about daily intervals;
- Some digitized weekly composites for charts up to 1980.

The hard copy weekly ice charts were chosen for this study, since little information could be gained from the other forms of data. These charts represented the most complete map of the Beaufort ice for two reasons. First, the satellite photos showed little besides cloud during a storm, and during a storm few ship or airborne observations were taken. Second, the weekly charts were well prepared and most readily usable for routine handling.

2.2 Winds

The final form of wind data for input to a wind-wave hindcast, is a grid point field of wind speeds and directions at some specific altitude over the sea. Winds between these grid points can the be interpolated for increased resolution. In general these records do not exist to the level of accuracy needed of reliable wave hindcasts.

Coastal weather stations in the southeastern Beaufort region are widely separated. These records have been augmented by routine reports from oil rigs and by occasional ship observations. Whereas these stations report winds and atmospheric pressures, drifting buoys deployed further to the north report only atmospheric pressures.

It has only been since the operations of the BWIO that pressure charts have been produced to the resolution that describe many of the intense small-scale storms frequently encountered during the open water season. The representation of the spatial structure of winds can not be adequately described by measured winds without these pressure charts to describe the large-scale system. Also, the sparse reporting stations still result in a need for blending of winds where possible, in order to augment these pressure derived winds.

Good quality wind fields are currently constructed from:

- an objective analysis of the pressure data, which in the case of BWIO data, is enhanced by subjective analysis of developing storm systems and drafted onto six hourly isobaric meteorological charts;
- digitization,smoothing and iteration of MSL pressure patterns to give gradient winds;
- analysis utilizing a planetary boundary layer model to reduce gradient winds to 10 meter winds;
- a kinematic analysis to interpolate stream flow isotach maps onto the wave model grid;

– analysis by experienced meteorologists, to blend in controlled and converted values of recorded wind measurements.

Practically no data of this final form was available for the Beaufort area. Weather data for the recreation of windfields, could be obtained by contacting: Atmospheric Environment Service, Environment Canada. These data consisted of the meteorological isobaric pressure charts and rig reports. The rig reports contained information that was not available at the time the charts were drawn. Two kinds of charts were available:

	Scale	Years
Beaufort Charts	1:5 million	1976–85
Arctic Weather	1:10 million	1965–85

The area of global surface which was to be processed depended on the area of open water. However, for consistency, the maximum possible area for any case should be taken for all storms. Therefore, for each storm the boundary of multiyear pack ice was taken as the northern limit to the sea.

Data Production

A complete record of the 1975 to 1986 measured winds and isobaric meteorological pressure charts were obtained from the Arctic Weather Center (AES), Edmonton. The pressures were digitized at 1 degree latitude by 1 degree longitude intervals on a grid described by the area 120 to 160 degrees West longitude and 68 to 75 degrees North latitude. The results of each objective analysis and a separate kinematic analysis were representative of the wind field at 10 meters above the sea. The two sets of winds were combined using a reiterative procedure of blending and refining, resulting in the most reasonable description of wind speed and direction over the field of interest. All processing of each of the three analyses (objective, kinematic and blended) were done on this same grid reference and resolution. Also, an assessment and summary of scientific errors was made, which indicated the reliability and variability of resultant wind vector values for each type of analysis. References and copies of source data were listed.

The deliverables (on Magnetic tape where applicable) for each storm were summarized

- reference to source data used and copies of these data;
- digitized pressure data, all other input parameters;
- objective winds;
- kinematic winds and relevant analytical back ground;
- blended winds;
- an assessment of the scientific errors for the results of the study.

2.3 Wave Data

There are two types of wave data available. The first is records of subjective observations taken by ships of opportunity and oil rigs. The second type is instrumental measurements by Datawell Waverider Buoys. The latter of these has been generally, the only objective source of wave information.

There has been no formal assessment of subjective wave observations in the Beaufort Sea. However, it has been evident that many of the most extreme reported wave heights have not compared well to waverider data.

The earliest record of waverider data was made in 1970. A complete list of the spatial and temporal coverage of all waverider data can be obtained from MEDS.

3. Setting the Goal and Methods

This section outlines the specific criteria or 'design specifications' which were decided upon in order to carry out the Beaufort Sea hindcast study.

3.1 The Input Requirements

Inputs to the actual wave model program, were described in the Resio system outline. Essentially there were two specific input files. One file Was to contain the grid pattern of the sea geography (and for the shallow water model: bathymetry), and several 'control' parameters specific to a particular storm model run (the CFILE). It was necessary to determine the optimal grid size and the accuracy of the ice edge information pertinent to the model analysis. The second was a file of wind vectors, comprised of a time sequenced set three hourly maps, of grid point wind speeds and directions (the NFILE).

In usual applications of the Resio system, this geographic grid of the CFILE, had only needed to be created once for any area of interest. The Beaufort open water area was different for each storm, due to the variable ice edge. In order to speed up this part of the process, an automated preprocessing system was to be devised to digitize and overlay incidental ice coverage on to a general bathymetric back ground. When for each storm the NFILE and CFILE was created, the wave model was to be run.

3.3 Output Specifications

Typical outputs of the Resio system were a set of two files.
one file contained a set of one dimensional spectra at locations set in the CFILE. The second file contained a similar file of two dimensional spectra. The output for each model run were to be on two files. One file contained the model program, CFILE and NFILE inputs and both of the one and two dimensional spectra of a selection of points over the area of interest. The second file contained a complete record of significant wave height, peak period and spectral direction at every grid point and for each three hourly interval.

3.4 Error Analysis

In the first instance, modeled seas were verified by comparison to measured wave data. To this end, some measure of errors in the data recovery and processing were assessed. These error sources were the following:

– Accumulated wind velocity (which describes the reliability of contemporary methods of windfield derivation for the case of the Beaufort Sea)

– Wave modeling for deep and shallow water (as being independent of the wind velocity errors, and therefore indicative of the theoretical wave growth processes)

STORM WIND SELECTION

1. Objective

The objective of this was to assess and select suitable storms for hindcasting severe sea states. These were to produce time series of storm conditions characteristic of the Beaufort Sea.

Results were to contain some measure of reliability and degree of application or relevance.

Secondly, the storms were to give some ascertainable indication of severe wave conditions which could be expected in a general climatology of the area. This perhaps vague statement of what usually pertains to some specific statistical appraisal, reflected the ”first guess” approach of this study. This second objective was then, to select storms which seem to be the most severe on record. Since wave data usable in selecting these storms may have been questionable, or at least be site specific, some storms would be selected by general assessment of ice and wind data. So the list of 10 storms produced by this report may not be the 10 most severe storms. However the recorded history of well documented weather in the Beaufort Sea was also about ten years long. Any exacting long term estimates of return period events, or specific probabilities of encounter would then be limited not only by the short base of 10 storms, but also by the short history of source data.

Objectives were generally to select storms to be hindcast in the most rigorous analysis Available. The results would then be used:

- to determine the achievable quality of information produced;
- as a record of well defined sea states;
- and for a good overview of extreme conditions experienced since the beginning of heightened offshore activities of Beaufort Sea petroleum interests.

2. Storm Selection

Selection criteria were a set of general guide lines that ideally would describe storm data most useful to the extreme event study. These were as in the following list.

- Available isobaric meteorological pressure charts, and measured winds from weather stations, weather buoys and oil rigs.
- Recorded or estimated (as from an assessment of visual reports and weather conditions) waves of 3.0 meters or more in deep water near the Mackenzie shelf/delta area.
- Good Waverider coverage in deep and shallow water.
- Good ice conditions, which result in fetches of 200 km or more, for the given wind direction of the storm.

– Judgment of the representation of the storm for typical extreme event conditions.

Twenty storms were selected. Several events had good Waverider coverage. All storms were well described by atmospheric pressures and measured wind velocities. Large extratropical anti–cyclones, and small scale arctic disturbances were represented. The period of coverage required to describe a storm was taken to include a wave model warm up of between 24 and 48 hours of data before the advent of extreme conditions.

The list of storms originated from two sources. Besides a list of storms specifically wanted for wave hindcasting by this study, a list of storms exhibiting severe wind conditions, without specific reference to the wave climate, was requested by the Atmospheric Environment Service. This list was then sent to the contractor for analysis. Although, many of the storms on the composite list, had produced severe wave conditions, not all storms were to be used in the wave modeling study. The storms which were to be wave modeled were described in the paragraphs, below. The storm reference numbers were taken from the contractor report.

STORM 1 25 Aug. to 28 Aug. 1977

Storm Pattern: small scale intense disturbance, winds WNW 25 to 40 knots for 6+ hrs. Fairly open ice conditions; fetches of 200 to 250 km. Poor comparison of pressure derived winds and measured winds. Small storm that shows spatial variability of wave fields due to winds and shallow water. Excellent coverage by waverider data. Waves of about Average Annual Maximum, at about WNW of 3.0 to 3.5 meters.

Waverider Coverage:

Stn. No.	Name	Depth (m)	Maximum wave Hs(m)	Tp(sec)
190	Gulf–1	33	2.0	8
191	Gulf–2	42	3.1	8
192	Canmar–1	34	1.5	8
193	Canmar–2	64	2.2	8
194	Isserk	14	2.0	8

STORM 2 23 Sept. to 26 Sept. 1977

Storm Pattern: Large scale LOW, SE changing to westerlies. Wide open ice conditions with extensive fetches. Good agreement between measured winds and pressures. Waves SE changing to West up to 2.5 meters.

Waverider Coverage:

Stn. No.	Name	Depth (m)	Maximum Wave Hs(m)	Tp(sec)
190	Gulf–1	33	2.1	6
191	Gulf–2	42	2.53	7

192	Canmar-1	34	2.0	7
193	Canmar-2	64	2.5	6

STORM 5 28 Sept. to 2 Oct. 1978

Storm Pattern: West north west winds of 25 knots, Open ice conditions with extensive fetches.

Waverider Coverage:

Stn. No.	Name	Depth (M)	Maximum Wave Hs(m)	Tp(sec)
192	Ukalerk	31	2.06	9
193	Kopanoar	57	2.36	9

STORM 7 22 Aug. to 24 Aug. 1979

Storm Pattern: Westerly winds of 25 Knots. Fair ice conditions with west fetch of 200 km.

Waverider Coverage:

Stn. No.	Name	Depth (m)	Maximum Wave Hs(m)	Tp(sec)
198	Issungnak	24	1.08	5
200	Nerlerk	46	2.37	8
201	Tarsuit	30	1.74	6

STORM 8 29 Sept. to 6 OCt. 1979

Storm Pattern: Easterly winds up to 30 knots. Fair ice conditions with fetch of 200 to 300 km.

Waverider Coverage:

Stn. No.	Name	Depth (m)	Maximum Wave Hs(m)	Tp(sec)
198	Issungnak	24	2.42	7

STORM 10/11 28 Aug. to 2 Sept. 1980

Storm Pattern: WNW winds up to 30 knots; 6 hour winds near 22 knots. Open ice conditions with an extensive fetch. Year of 1980 maximum storm waves, and average annual max. Some deep water wave data. Waves WNW of 3.5 meters.

Waverider Coverage:

Stn. No.	Name	Depth (m)	Maximum Hs(m)	Wave Tp(sec)
200	Nerlerk	50	2.95	8
202	Explorer IV	60	3.27	8

STORM 13 16 Aug. to 18 Aug. 1981

Storm Pattern: WNW winds of 36 to 42 knots, 6 hour winds below 26 to 30 knots. Poor ice conditions with small open sea fetches of 50 to 150 km. Maximum seas reported for 1981. Waves WNW of 3.0 to 3.5 meters.

Waverider Coverage:

Stn. No.	Name	Depth (m)	Maximum Hs(m)	Wave Tp(sec)
201	Issungnak	27	3.12	7.5

STORM 14 30 Aug. to 1 Sept. 1981

Storm Pattern: North westerlies up to 25 knots. Fair ice conditions with fetch of 100 to 200 km.

Waverider Coverage:

Stn. No.	Name	Depth (m)	Maximum Hs(m)	Wave Tp(sec)
196	Nerlerk	52	2.36	7

STORM 15 27 Sept. to 29 Sept. 1981

Storm pattern: North winds at 26 to 30 knots for 6 hours. Open ice conditions with fetches of 200 to 250 km. Visual reports say these are some of the highest seas. Long duration severe winds blowing over large fetch. Waves North of 3 to 4 meters (Tp= 9 sec).

Waverider Coverage:

Stn. No.	Name	Depth (m)	Maximum Hs(m)	Wave Tp(sec)
196	Nerlerk	52	2.8	8

STORM 16 26 July to 29 July 1982

Storm Pattern: Small scale disturbance, WNW winds up to 35 knots for 12 hrs. Maximum winds over 45 knots. Moderate ice conditions with fetches of 200 km. One of the most severe storms according to visual wave reports. Seas were about 5 to 10 year maximum. Small scale trough system moving over Mackenzie Bay.
Estimated waves of WNW of 3 to 5 meters.

STORM 17 20 Sept. to 22 Sept. 1982

Storm Pattern: ENE winds of 33 knots for 20 hrs, Maximum winds of 38 knots. Moderate ice conditions with a fetch to Mackenzie Bay of 300 km and a fetch to Ballie Is. of 100 km. Excellent Waverider coverage. Storm wave about Average Annual maximum. Estimated waves of ENE of 3.5 to 4 meters.

Waverider Coverage:

Stn. No.	Name	Depth (m)	Maximum Hs(m)	Wave Tp(sec)
196	Orvilruk	58	3.35	8
201	Aivark	62	3.28	8
204	Tarsuit	20	2.8	8
205	Itiyok	14	2.2	7
206	Mckinley Bay	8	0.94	6

STORM 20   16 Sept. to 19 Sept. 1985

Storm Pattern: Large scale LOW, WNW winds of 37 knots for 48 hrs. and 44 knots for 6 hrs. moderate ice conditions with fetch to Mackenzie Bay of 200 km. Ballie Island was ice bound. Seas were at about 8 to 10 year return period. Large scale well monitored storm with minimum of expected hindcast windfield errors. One of the most extreme storms since the Beaufort weather office commenced operation in 1976. Waves were estimated at WNW of 4.5 to 6 meters Hs of 3 meters for 48 hrs.

Wave Data Coverage: Submerged wave and tide pressure sensor.

Stn. No.	Name	Depth (m)	Maximum Hs(m)	Wave Tp(sec)
	Adgo	2.7	1.78	10

As a note, the storm number 18 showed the potential of the late summer storms and the effects of a sea ice field. There has not been any attempt to model this storm, for this report. The assessment was as follows:

Storm Pattern: Large scale LOW, WNW winds of 50+ knots for 6 hrs. and 41 knots for 46 hrs. Large scale near perfect anti–cyclone with Low to the North of the Beaufort area. Pack ice had retreated to the permanent limit, but on the 19th October, ice cover over the drill area was primarily gray ice or nilas. The storm physically broke up much of the ice over the area. Wave at maximum reported Hs were partially damped by the broken gray ice. This storm produced 25 to 50 year ”open season” WINDS and reported 4 meter waves. If the storm could be considered as occurring independent of the general decline in temperatures at that time: then if it had hit just 10 days earlier, ice free seas would have risen to 10 meters! Good example of large extra–tropical low.

THE MODEL GRID

A background grid of shoreline, bathymetry and ’permanent pack ice’ was created using the Resio system. For each particular storm hindcast, a current ice field was overlaid to create an open water area.

1. The SOG Grid

The wave model utilizes a orthogonal grid of sea and land points. This grid layout had to be setup at the beginning of the hindcast process. The Resio hindcast system of programs, provided the initial conversion of the standard latitude and longitude grid (LLG) to a spherical orthogonal grid (SOG). The object of this step was to generate a grid pattern of roughly square elements. The method was to let the user of the conversion programs select an area to be gridded, and some reference start point in LLG coordinates. The program then transposed the LLG poles and equator, such that the SOG ’equator’ passed through the reference point. The SOG layout of latitudes, and longitudes, were then computed for the grid points. Finally, the actual LLG locations were listed in the output file. Subsequent Resio programs calculate LLG to SOG direction conversion constants, so that data referenced in LLG locations and direction could be converted to the wave model grid network.

For a relatively narrow geographical band of the earth, the resulting SOG grid (like the LLG grid near Earth’s equator), would be roughly square. Although the original Resio wave model did allow for rectangular distortions ’north and south’ of the SOG ’equator’, it was not necessary to implement this facility in the wave model for the Beaufort.

The first task in setting up the grid layout was to set the reference point so that the resulting ’equator’ passed down the open water area of the Beaufort, thereby conserving the square grid layout as much as possible. The results of this showed as little as 2 or 3 kilometer cumulative error at any point over the open water. Secondly, a grid size of about 25 kilometers was chosen. This general size had been recommended (Hodgins–83) to best describe the Beaufort, in terms of the accuracy of the wave modeling process. Finally, the area, contributing to the waves over the area of interest. Although the open water, at times, stretches out over the Chukchi Sea and east of the Beaufort into the waters of Canada’s arctic islands, the boundaries of the grid did not extend past the west coast of Alaska. This limit was necessary in order to conserve computer resources (space and cost). Also, any winds and waves beyond this limit had little or no influence on storm waves in the Eastern Beaufort area. The four corners of the grid in LLG coordinates were:

– (78.2,164.9); (68.5,162.7); (72.9,112.6); (65.3,128.8) ..LAT,LON

Once the Geometric grid had been constructed, the point values were preserved for use in transposing wind data and for the final construction of the geographical grid of land, sea and ice.

2. The Geographical Background Grid

The wave model input grid network has no knowledge of the original LLG coordinates. it was simply a layout of coded points referenced by their order. Prior to a wave model run, geographical data had to be transposed, automatically or by hand, to this input network. The method used here, was to create a background file of shoreline, bathymetry and permanent pack ice, once. This was done by locating an LLG output point on a contemporary hydrographic chart, and coding the appropriate point on the model grid. The next section explains how specific ice conditions for a particular storm were overlaid, prior to the hindcast modeling.

3. Modeling the Ice Edge

Defining the ice field has always been a problem to wave modelers. There has not been any application to modeled wave physics, of the little that is known about seas in fractured ice fields. The usual approach to the problem has been to define some limit of open water, at some concentration of sea ice, and to assume the open water area is ice free (or effectively so).

Rational to support this supposition, describe severe sea states (modeled or real), as being somewhat insensitive to the limits of the ice edge. This may be explained by an examination of a typical graph of wave growth over fetch. Notice that wave growth would be slow over the region of fully developed waves. The degree of damping or growth retardation at the beginning of the fetch, due to the ice would be rapidly compensated by the steep wave size growth past the ice edge. Thus since most of the wave growth occurs at the beginning of the fetch, a 5 or 10% error in the fetch length results in a very small error in developed sea states far down the fetch.

The storm ice conditions were taken to be described by the 1/10 to 3/10 ice edge, taken from an interpolation of the weekly summaries before and after each storm. Only one ice field was setup for each storm, which ignored usually obscure changes in the ice edge during the passage of a storm. The Atmospheric Environment Service, weekly summary ice charts were overlaid onto the geographical background grid using a program written for this project: ”STRMICE”. The output of the program distinguishes ice
from open water from land.

It was important to distinguish the shoreline (depth=0) from the ice edge, which was adjacent to water of any depth. This was accomplished by coding the final ice field grid, and taking this into account in the wave model. The necessity was seen during the refraction and damping calculations, both of which use the depths of grid points surrounding each open water point. An ice grid point was not considered as open water, but did have a depth value of the ocean below.

WAVE MODEL

1. Examination and Modification of the BIO–Resio Model

The existing BIO–Resio model was discussed with R.Keeley, B.Toulany, and W.Perrie at the Bedford Institute of oceanography. Will Perrie had the following comments about the model:

– On a graph of E* vs X*, the "JONSWAP Envelope" was considered as the realistic form of wave energy growth.

– The existing BIO–Resio curve demonstrated very high growth and very high peak energy, which implied a poorly tuned drag coefficient (which is used to determine the value of the wind stress, U*). However in the discussion of the day, Will suggested that the tuning they had done was arbitrary.

– There could be an improvement in the model's behavior under rapidly changing winds.

Also this study had encountered problems in the Resio model that needed some modifications:

– Waves propagating from shallow water into deep water were over growing. The study had proposed a modification to the computation of the growth factor which compensated for this but which does not affect results elsewhere in the model. A suggestion was to put an artificial cap on the growth permitted. Here, the cap value would still need to be at the low end of published values of the growth parameter.

– Over growth of waves for winds blowing directly off the ice. This is not the same problem as the first although it might appear to have similarities.

The study suggested that a solution to part of these problems may be accomplished by modification of two procedures within the model code, without changing the processes in the model. For the determination of the saturation curve, the variable coefficient "ALPHA" (Phillip's constant), used by Resio, could be redefined. (ALPHA) is a function of total spectral energy, EA, and the incumbent wind shear stress, U*. Besides the mentioned tuning of the drag coefficient, Will suggested that a re–evaluation of a constant within the formula might be a reasonable approach.

2. The NOGAP Developments to the BIO–Resio Model Coding Considerations

BIO–RESIO model outputs a set of wave information at selected grid locations. The code revisions governing input and outputs described in the above section on system design, were carried out. To this end the coding of the program was rewritten to be more readable, and that outputs be less dispersed.

BIO–RESIO input winds and output wave directions were in reference to the model grid directional bins (SOG). It remains as a suggestion, and not included at the time of this report, that the array of grid point directional conversion values created in a Resio preprocessor program, be incorporated into the wave model to give wave directions in the universal axis (LLG).

2.1 Deep Water Wave Growth

The basis for rationalization stems from a relationship stated by Resio. The relationship is that: for a spectrum in equilibrium there is a balance of source terms in the mid range of the spectrum. The BIO-RESIO model also uses a development proposed by Kitaigorodskii, Krasitskii and Zaslavskii (KKZ) (Perrie 1986), for shallow water. Also, in reference to the basic source term relationship:

$$\frac{d\,E(f)}{d\,t} = B\{U,f,D\}.E(f)$$

where B is a function of wind,frequency and depth

the wind and wave-wave source terms decrease in value as the energy in the mid range decreases.

The model scales the source terms of steady state growth (assumed by the BIO-RESIO model) to the energy of the propagating spectrum to compute growth and equilibrium saturation based on the basic B.E relationship (above).

[ALPHA]

It has not been apparent why the Resio shape function for the spectrum approaching a fully developed state, was different than the JONSWAP function, Comparison of the Resio (Energy, Wind stress) definition of (ALPHA] to the JONSWAP (Energy, Peak period) and (wind speed, Peak period) definitions, showed poor concurrence. This perhaps explained some over growth demonstrated by the BIO-RESIO model.

- Resio: [ALPHA] = K * [EA g**2 / Us**4]

This equation for (ALPHA] could be scaled to match the JONSWAP values by changing " K " from the BIO-RESIO value of 0.05 to the value in an earlier Resio model of 0.044 . The value effects both the energy of a given spectrum and its rate of growth (in terms of change in total energy and peak frequency over time and fetch).

The author suggests that the lower [ALPHA] growth shows better results for duration limited and fetch limited growth if the time dependent changes in [ALPHA] and Fp are incorporated into the calculation of the growth. The purpose of the change was to calculate the spectral growth directly from the established relationships rather than from a method of approximation and tuning of the factors.

BIO-RESIO determines the growth source for the peak frequency (Fp) and [ALPHA] at the beginning of the time step. Growth at each frequency-energy bin is then calculated for the time step assuming that the parameters Fp and [ALPHA] do not change. The propagation mechanism was handled by linearly interpolating the two parameters to a point half way between the grid point (where the waves were propagating) and the location of the peak frequency waves at the beginning of the time step. This was done only in one direction, by reverse ray tracing along the direction of the combined or average spectral direction to result in a single set of parameters.

For fetch limited waves, where wave energy and Fp do not change at specific grid points over time, the method works well. The actual values of the wave height and Fp do, however depend on the evaluation of the governing constants in [ALPHA] and other physical equations. The reason for this was that the method represents a good approximation of wave growth over time and space, since these are mutually constrained variables in the equation. Here, the time dependent change in Fp, and [ALPHA] during the time step growth, are predicted by the spatial interpolation before the time step execution. Mathematical and hence numerical integration of the energy source terms, were thus, well approximated using relationships evaluated for the two parameters at the midpoint of the time step and of course the midpoint of the propagation distance.

For seas governed by the duration of winds, rather than their proximity to upwind shorelines, the above method became ambiguous, since adjacent grid points well out to sea, during duration limited wave growth, have similar values of wave height and peak period. Then, using the Resio method the wave growth over the next step in time needs the values of [ALPHA] and Fp at the half way point of the up coming time step. This could not be determined from the spatial interpolation, which was so applicable to steady state fetch limited wave fields. Presumably this problem was compensated for by tuning the growth terms (or adjusting the [ALPHA] constant so that duration growth for a predetermined time step length and possibly grid size, followed the JONSWAP form. However as discovered by this study and also in the reference report by F.Penicka (1987), and Perrie and Toulany (1986), this final form of the Resio model demonstrated a few idiosyncrasies, such as predictably poor fetch limited growth.

A method was developed in this project which would by and large resolve many of the problems of the Resio model. The method was to first, change the half way point interpolation trace back of Fp and [ALPHA], to a full trace back. This new point was simply Resio’s original point at which the dominant peak period waves will be at the beginning of the time step, thereby propagating to their grid point during the up coming time step. Secondly, a parametric equation used by Resio in another application within the code, was used to predict the Fp development half way through the up coming time step. To this, a JONSWAP relationship of Fp to [ALPHA] was used to determine the half way point [ALPHA]. These half way parameters, were then used in the growth equations, providing the intended approximation of time/space sea state development. Using this method, the integrity of the intended JONSWAP parameter values and subsequent wave growth rates, under both fetch and duration limited conditions, was maintained without the need for arbitrary tuning of the model.

Growth Shape Function and Further Defining [ALPHA]

There is nothing in the many models that computes the decrease in input energy as the spectrum reaches final fully developed state. In these models, the growth rate is uninhibited until it is artificially capped when the peak waves are traveling the wind speed. The problem was the observed continuation of growth to the forward face. Scaling the saturation shape function to the source terms for spectral growth, a growth curve (over fetch and time) may be seen to be more compatible with the SMB equations and perhaps JONSWAP.

Peak Frequency Search

By scanning the one dimensional spectrum for the energy bin with the highest frequency (with some restrictions eg,Fp has to be greater than wind specific frequency as per the Resio model) a non physical double peak effect is negated. JONSWAP equations, and then the methods of numerical analysis within the model were developed and improved.

However, there had been no effort to examine the model response to rapidly changing wind directions. This was a problem characteristic of many spectral models. Primarily it wasn’t known how serious this effect might be on severe storms in the Beaufort. Secondly, very little explicit information about how this should be modeled in the BIO–Resio code, was available. The problem, if it was serious, could only be solved by a restructuring of the energy source terms, and possibly the two dimensional wave spectrum itself. As was seen, in the Penicka report and the SWAMP report on all other available models, and Perrie and Toulany, the Resio model exhibits some unnatural spectra in a changing wind field, or near shorelines. most often these effects are not important, or at least justifiable. However in the Beaufort where the sea surface is small, and often storm winds fields are curved tightly, compared to the time and space needed for the spectral formation to react, the analysis might be misleading. However, the effects demonstrated by the model would be conservative, by over predicting the wave heights.

3. Wave Model Outputs and Data Archival at MEDS

The set of processing programs, wind and wave data were available at MEDS. The programs were a set of the original Resio processing system, with reformatting, plotting and wave model additions introduced by this study. The original contractor winds were stored on a 9 Track tape. This file contains gridded pressures, objective winds, kinematic winds and blended winds.

The wave model outputs for the set of hindcast storms were stored on magnetic tape. For each storm there was a file containing:

- The model listing;
- The ice/land grid;

– The three hourly wind inputs;
– 1D and 2D energy spectra for a set of twenty selected grid point locations and at every three hours.

Also for each storm, there exists a file of Three hourly significant wave height, peak period and wave direction. The direction shown was in reference to the Resio defined grid direction, which has not been converted to global vectors.

THE WAVE HINDCAST RESULTS

1. Verification by Comparison to Waverider Data

Thirteen storms, from the original AES–MEDS list of twenty, were chosen for hindcasting. These represented a set of extreme sea–state storms over a seven year data base. most of these storms had waverider coverage, to compare the hindcast results. Time series of significant wave height and peak period, were prepared for this report. Waverider data and hindcast data, taken from a similar location (latitude, longitude and depth), were plotted and presented at the end of the report.

These plots were examined storm by storm, in order to assess the validity of the hindcast model and the errors in the windfield. it was noted that there were measurement errors within the waverider data. These errors might have been up to 15% (Muir and El–Shaarawi, 1985) or for a typical 3.0 meter value: + or – 0.45 meters.

The errors and their interpretation were discussed in a following section.

2. Wave Fields and Time Series

An initial view of the time/space development of wave heights and periods during a hindcast storm, was made over the area of interest (east of the Mackenzie Bay) at a constant depth of 30 meters.

Typical results showed up to a two meter variation of maximum storm wave height, along this contour. Mainly this was due to low wave heights in the sheltered waters of the Mackenzie Bay. However, in more open waters there were still variations of over one meter, due to variations in storm wind profiles and in some cases, difference in fetch due to ice conditions and fetch restrictions.

In order to show some comparisons of yearly maximum wave heights, the yearly maximum hindcast wave on any point of this 30 meter contour, were chosen and listed below. At this point it was seen that there were two storms with particularly unrealistic results (by comparison to their waverider records). These storms were left out of the estimate.

Year	Yearly Maximum Significant Wave Height (meters)
1977	3.2
1978	3.2*
1979	2.9*
1980	4.2
1981	4.3
1982	3.7
1985	4.6

(asterisk denotes an estimate based on Waveryder data)

These results were applied to a 100 year return, extreme value analysis. From seven years of data, it was unlikely that little might be said about the 100 year wave without the appreciation of statistical and measurement, confidence intervals. Also it has not been shown to which probability distribution these data might be applied. It has been shown that Beaufort Sea wave data show similar extreme estimates for both the FT–1 and Weibull distributions (Hodgins 1985). It must also be noted that other distributions such as the FT–2, show markedly different return year estimates for similar hindcast data. This was demonstrated by Hodgins (1985) and Murray and Maes (1986). Hodgins plotted each of the results of several historical hindcast studies using the same FT–1 distribution. These results were essentially similar (to with less than one meter at the 100 year point). Murray and Maes plotted these same studies using the distribution of the original study. These results showed differences of over five meters at the 100 year point. This comparison was made by this report only for those studies which were taken as valid (see Hodgins 1985).

However, if it could be assumed here, that the FT–1 distribution was a valid representation of the climate, then some results were as follows. Using the hindcast results of this study, and the methods outlined by Muir and El–Shaarawi (1985) the plot of the yearly maximum wave heights showed a 100 year wave of 5.7 meters. The confidence intervals were determined by the method of Maximum Likelihood (from Challenor 1979), and were for the 100 year wave estimate at a low of 4 meters and a high of 8 meters. It must be reiterated that these results were tentative. Discussion of the effects of the hindcast errors on this result were presented in the following section.

3. Errors in the Modeling

The results of the FT–1 extreme value estimate were very sensitive to two aspects of the study at hand. Primarily, the data base was too short to extrapolate much beyond the twenty year return period or the 0.05 probability. Also, the plot was sensitive to the value of the most extreme values, the minimum values and the assumption of the spatial similarity (30 meter contour maximums). Since the extrapolation was well beyond the data, the slope of the fitted line was as important as the magnitude of the values. Over estimates of the most extreme data, along with good or low estimates of the lower values not only would give high extrapolated estimates, but also high confidence limits. At the other end of the interpretation, mainly constant values of data result in little difference between the 10 year wave and the 100 year wave, and particularly narrow confidence limits.

If it could be assumed that the spatial variability of the storm maximums was not a governing factor, then the extreme estimates would be the most prominent source of error for this short data base. To assess this error the difference between an available waverider measurement and the hindcast storm wave, each at their respective maxima, were 'scaled' from time series comparisons. These waverider data were (like the kinematic winds onto the objective winds) then blended, to produce estimates of the hindcast wave fields. Typical results were show below:

Storm date	Hindcast Maximum at 30 meter depth	Blended Maximum at 30 meter depth
30.08.81	4.3	3.1
16.08.81	3.5	3.5
20.09.82	3.7	3.3
28.08.80	4.2	3.3
26.08.77	3.2	3.2
27.09.81	5.2	2.5

This last storm was not included in the estimates of the previous section since it portrayed obvious problems in possibly the wave modeling process or the windfield analysis. Maclaren Plansearch showed similar results using their own wave model. This storm and storm 2 showed extreme hyper growth from rather similar windfields. Both winds were of tightly curved wind isotacs and the storm 2 had 180 degree change of direction over the duration of the storm. This gave evidence that the wave model lacked the facility to model storms for rapidly changing wind directions over both time and space. However, this problem might anticipated, whereby the smaller storms of this nature would not need to be included in an extreme estimate due to the resulting small wave heights.

A second problem with the wave modeling process became evident. Examination of the storm 13 showed a 40% over estimate of the wave heights. Here the ice data charts showed a substantial change in the limits of the upwind ice edge from days before to days after the storm. There was no way to tell how the ice edge changed during the event of the storm since satellite and airborne observations were restricted due to cloud and storm conditions. The hindcast of this study might have over estimated the fetch conditions of the storm peak. An estimate of the waves for these most restrictive ice conditions, using available nomograms, show a wave more like the waverider measurement.

The most extreme wave estimates of the hindcast study seemed to be prone to the two types of errors mentioned above. The 1985 storm (20), had no waverider coverage. It also was produced the highest hindcast value of the study. In order to determine some assessment of the hindcast errors, the ice charts and windfields were reviewed. The storm produced steady winds, and this was probably modeled well by the hindcast. However, the ice edge moved a great distance during the week of the storm. At the beginning of the week (for which the hindcast modeled), the ice edge might have been pushed west by the prevailing easterlies of the Beaufort area. Presumably during the storm of westerlies, the ice edge moved east, and would result in some fetch restriction of the waves. Again, the satellite picture was obscured by the storm clouds. If this was the case, there might have been lower waves during the actual storm than hindcast. Since the storm was long in duration, and the wave reached maximum in the early part of the storm, the effects could not be anticipated. However the extreme value estimate was very sensitive to this value since it was significantly higher than the highest of the blended results (3.5 meters). It must remain a recommendation of this study that many of the aspects of wave growth from within the low density ice edge, and the movement of this edge during a storm, must be explored before this storm can be hindcast.

4. Some Tentative Results

If the blending of hindcast results were taken to represent better estimates of the Beaufort wave climate, then some estimate of the 100 Year wave could be reassessed. Assuming that the 1985 storm was restricted by the advancing ice fields, to the same type of magnitude other similar storms were (ie. 40% lower than hindcast). Then the seven year range of storm waves might be about 2.9 to 3.5 meters. This would produce a 100 year wave of approximately 4.3 meters for the 30 meter depth contour. Although it was not calculated for this report, the high confidence band would be less than the two meters of the previous analysis, giving the 100 year wave to be no larger than perhaps 6 meters. These last guesses, showed the still high variability in extreme value estimates, given the uncertainty of the hindcast method and the short data base.

CONCLUSION

Beaufort Sea wave hindcasting needs both, an accurate model of the sea state, and a reasonable approach to resolve long term climatologies.

The hindcast model used accurate descriptions of pack ice boundaries, storm winds and sea bed bathymetry. The author's study necessitated intensive improvements to a spectral wave model. The most important of these were to match the JONSWAP wave growth for both fetch and duration limited conditions. And to properly implement shallow water effects. Hindcasts of actual storms demonstrated that the model accurately calculated both significant wave height and peak period.

Recommendations of this study are for further improvements to the wave hindcast methodology. Final hindcast data could be enhanced by blending modeled waves with measured waves. But, emphasis must be placed on ensuring the reliability of the model. Improvements to the wave model should be made to show effects of moving ice and rapidly changing winds. Further research into very shallow water modeling has been recommended as a result of the Seaconsult study. In the end, a complete set of hindcast wave error statistics should be produced using measured waves.

Sea states hindcast using the methods of this study can produce a description of the Beaufort climate. However, the short history of wind and ice records, and the unique interelationship between storm winds and ice coverage, renders usual extreme wave statistical analyses to be limited. Although there are successful probability analyses techniques used throughout the world, the probability distribution functions have not been proven for seas that change their shape with year to year variations in pack ice coverage and withdrawal.

This study demonstrated that modern methods were a route towards a desirably improved Beaufort Sea wave climatology. The wind data produced by Maclaren were determined from a complete analysis of all available meteorological information. The hindcast wave data provided accurate information about waves during storms which could be properly modeled. In order to determine extreme wave estimates, this report recommends a rational approach to evaluating the interelationship of storm winds, ice coverage and the waves these produce. One such approach is to hindcast each actual storm for all of the probable ice conditions. The ice can be considered to be largely independent of storm force. And the wave produced can then be assigned probabilities based on the joint probability of these winds and the ice boundary.

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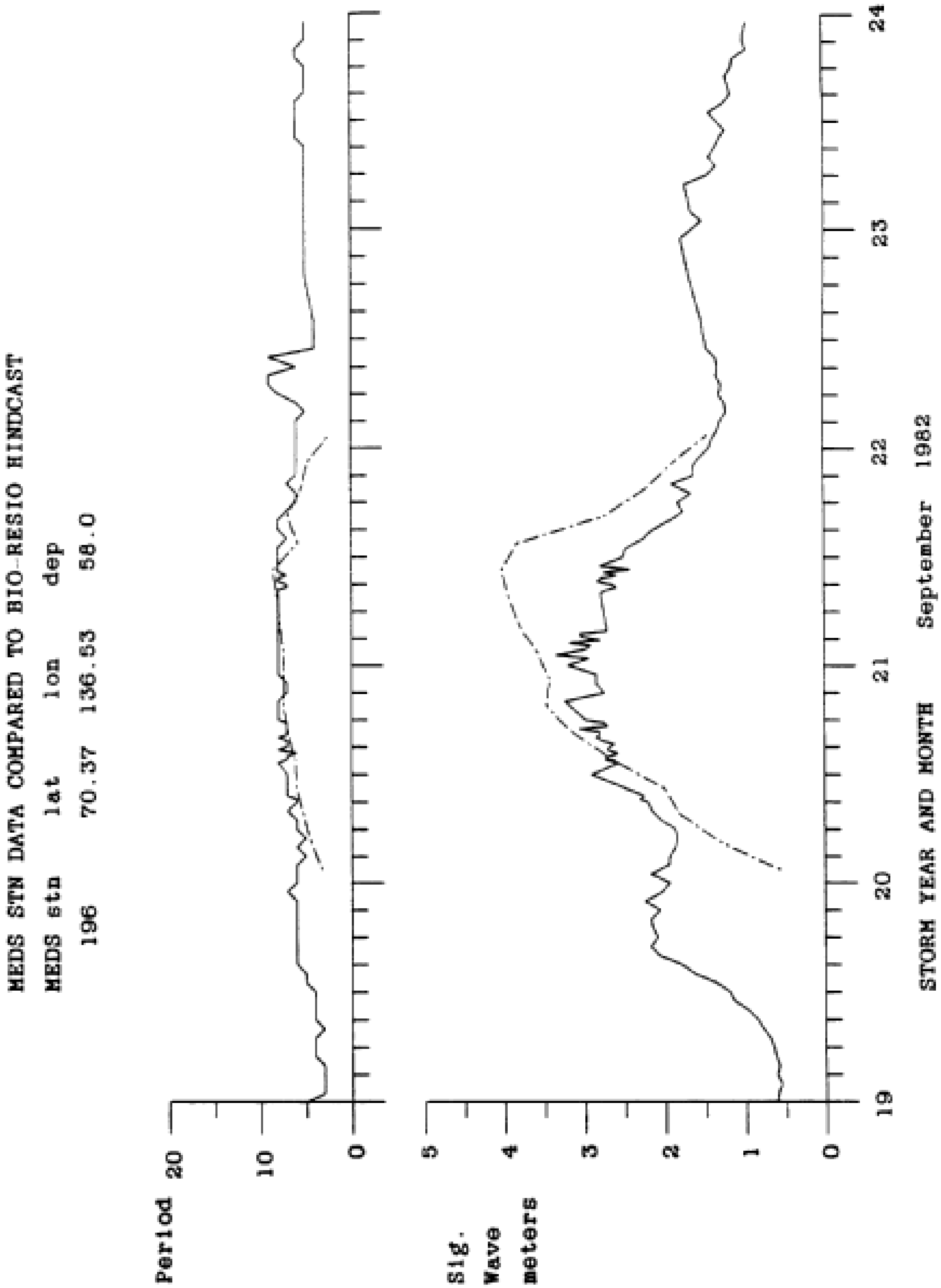
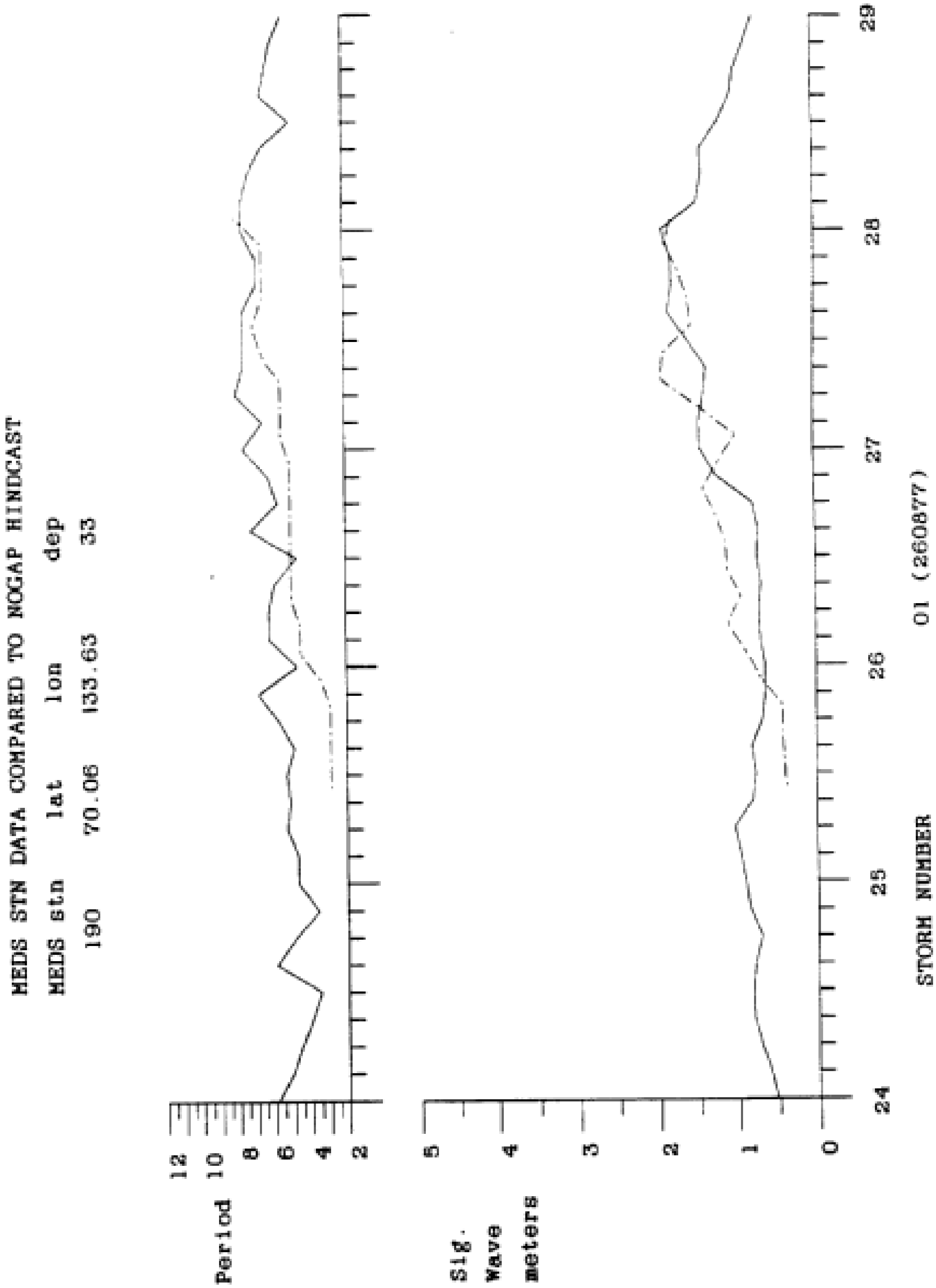
FIGURES

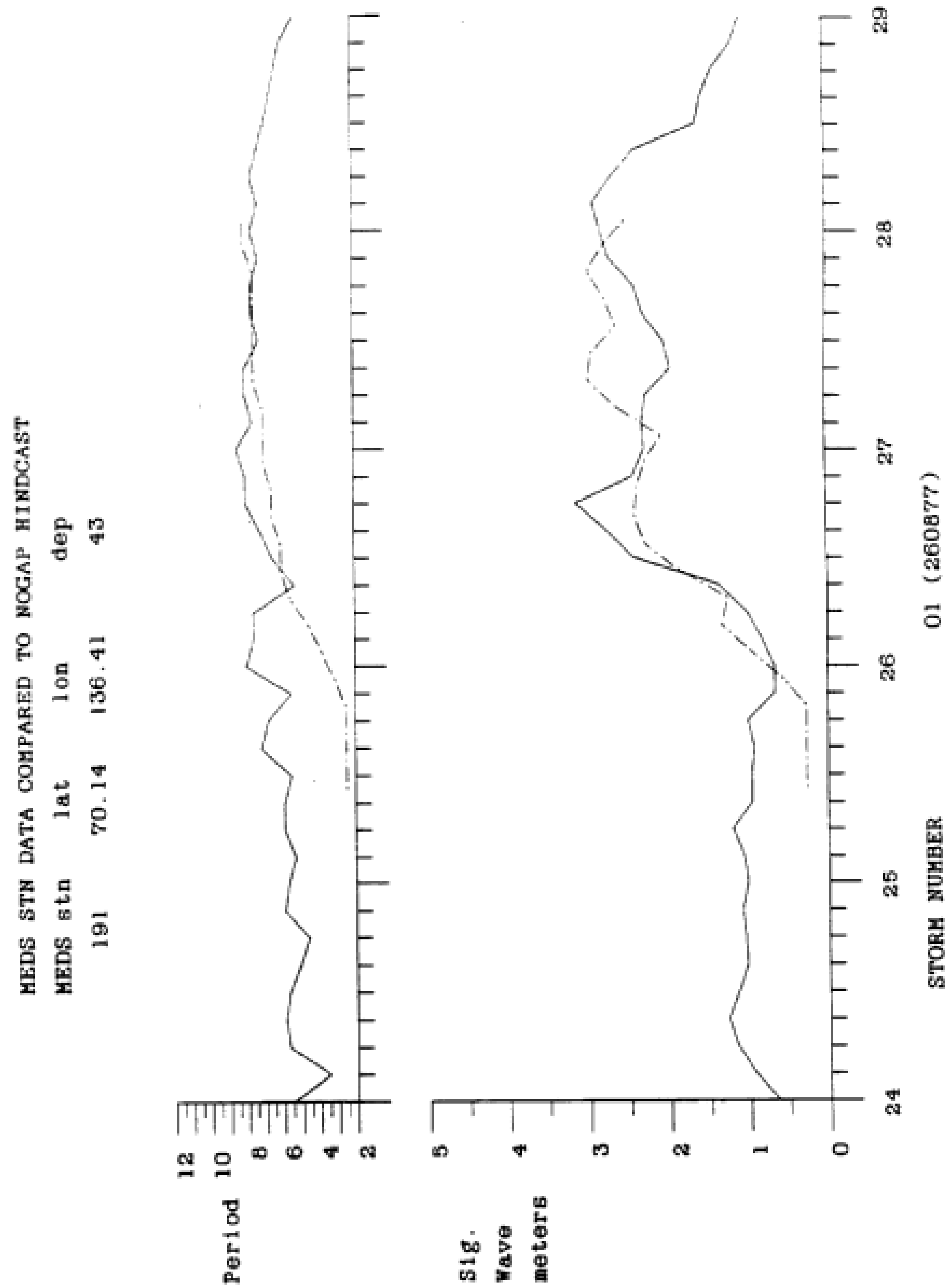
TIME SERIES PLOTS

Time series plots show hindcast and measured data, for selected storms. A description of the labels is as follows:

Title	- refers to the data sources. - MEDS STN DATA are shown as solid lines, and are records taken from archives at the Marine Environment Data Service. - The hindcast title refers to the model used by this project, and is shown as dot-dash lines.
"MEDS stn"	- The MEDS station number as per archive identification.
"lat, lon, dep"	- The latitude, longitude and depth (meters) of the station referred to by the MEDS station identification.
Vertical axis	- Top plot is of peak period in seconds. This was defined as the wave period with the maximum spectral energy. - Lower plot is of Significant Wave Height in meters. This was defined as a function of the the sum of all of the spectral wave energy.
Horizontal axis	- Storm date or number and date (day,month, year) - both axis for "Period" and "Sig. Wave", show day of month, with gradations of 3 hours.

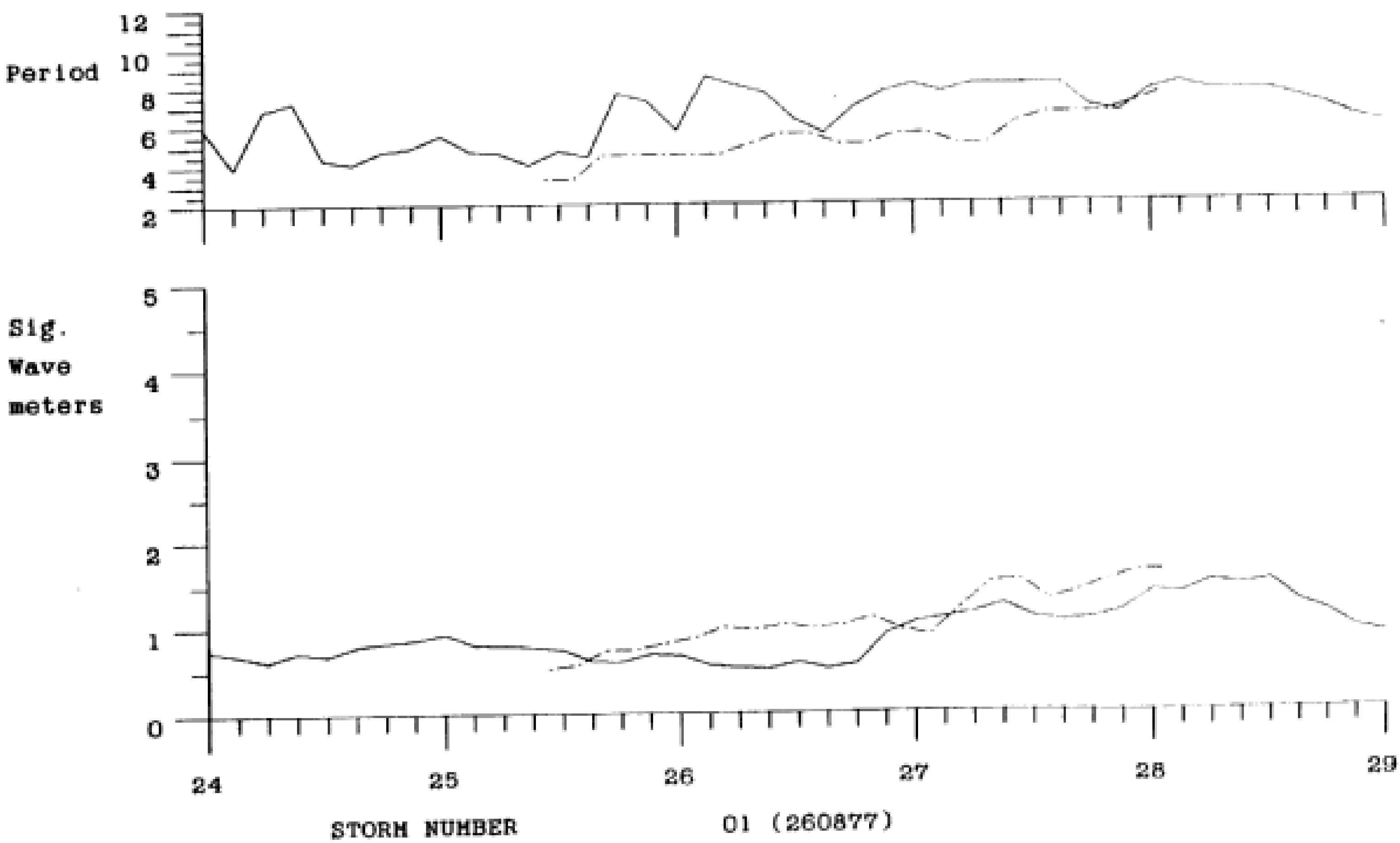

MEDS STN DATA COMPARED TO BIO-RESIO HINDCAST
MEDS stn lat lon dep
196 70.37 136.53 58.0
Period
20
10
0
Sig.
Wave
meters
5
4
3
2
1
0
19
20
21
22
23
24
STORM YEAR AND MONTH September 1982


MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
190 70.06 133.63 33
Period
12 10 8 6 4 2
Sig. Wave meters
5 4 3 2 1 0
24 25 26 27 28 29
STORM NUMBER
01 (260877)

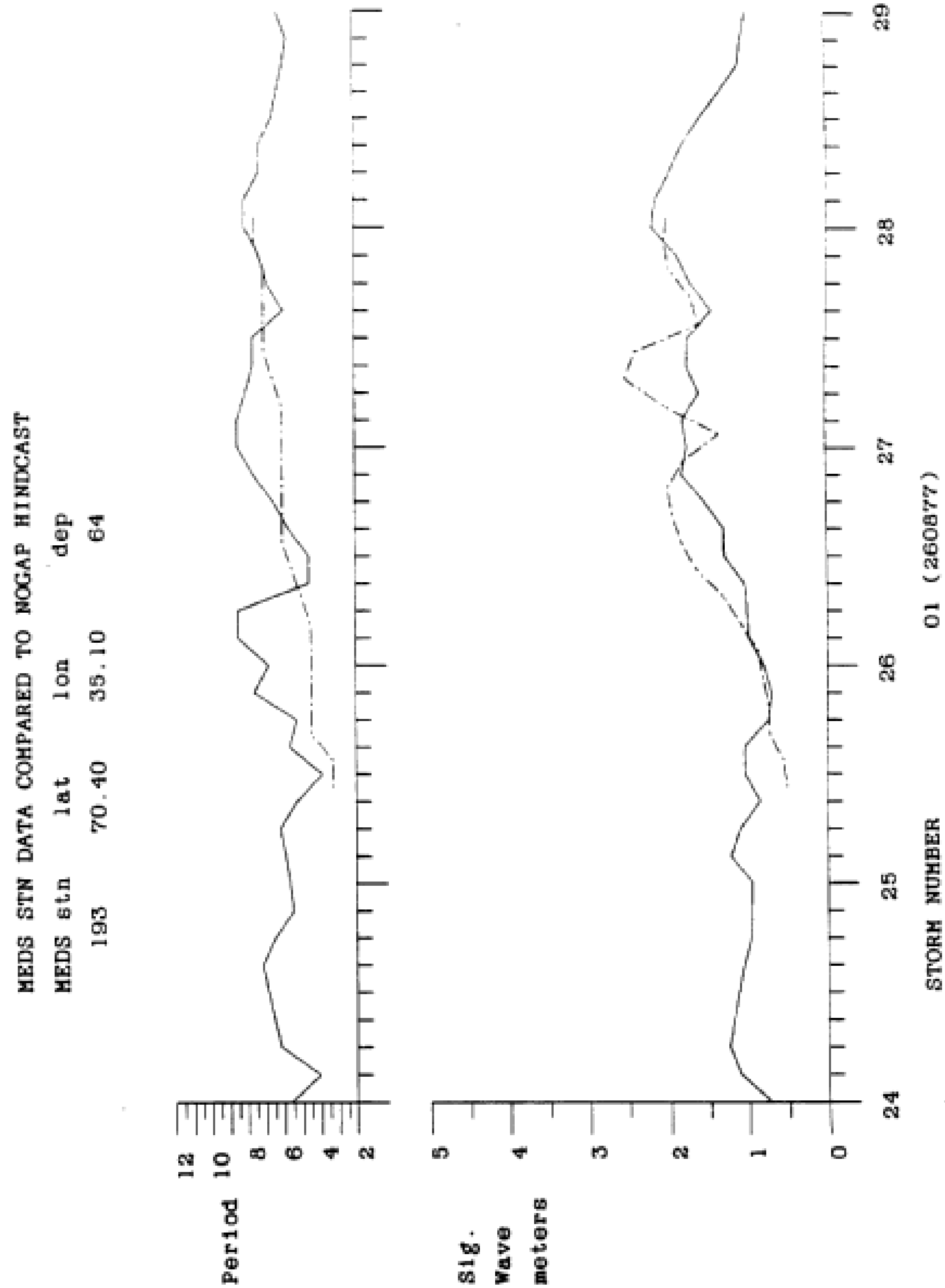

MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
191 70.14 136.41 43
Period
12
10
8
6
4
2
Sig. Wave meters
5
4
3
2
1
0
24
25
26
27
28
29
STORM NUMBER
01 (260877)

MEDS STN DATA COMPARED TO NOGAP HINDCAST

MEDS stn	lat	lon	dep
192	70.19	32.75	34



DFO 7


MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
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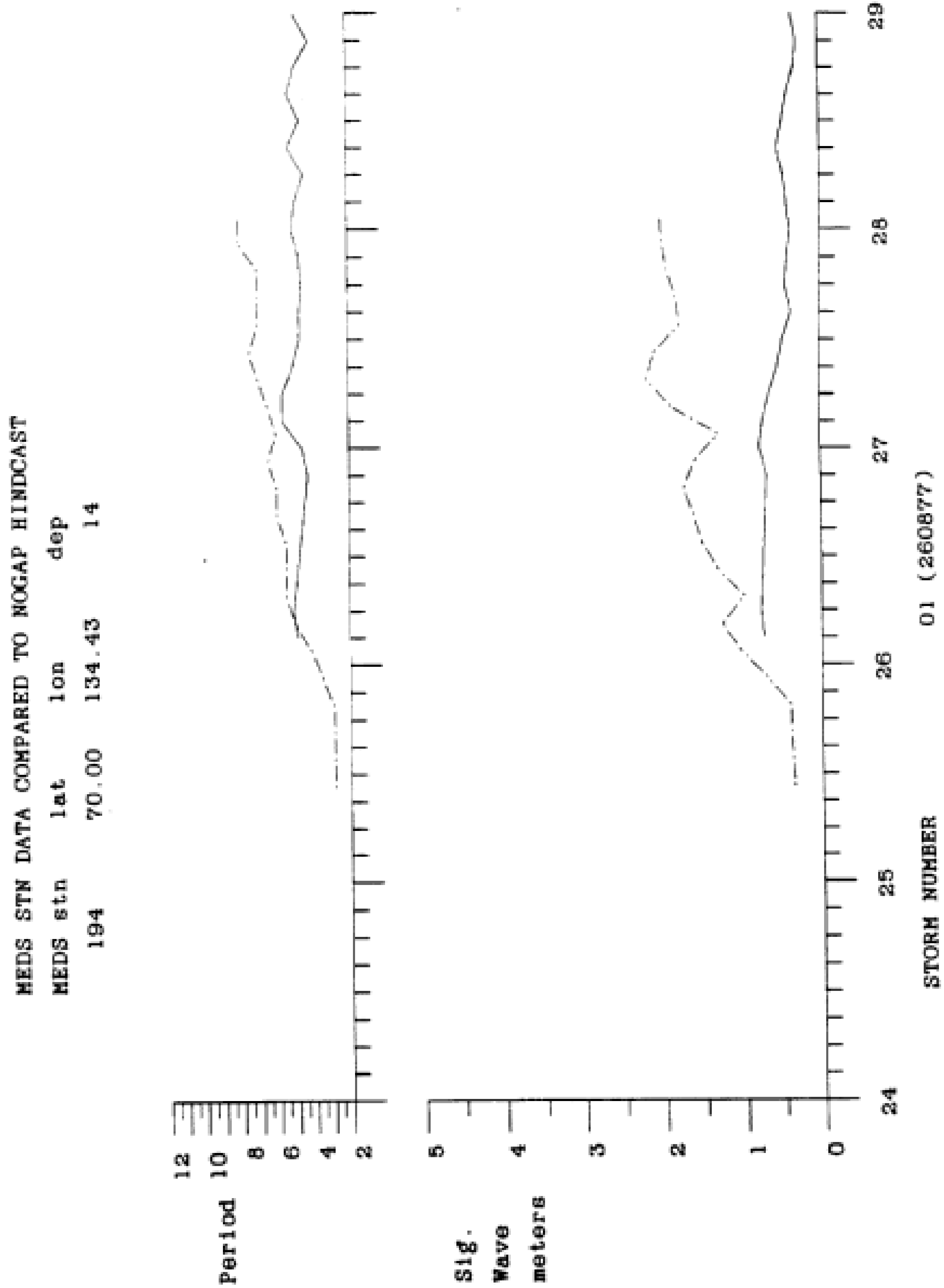
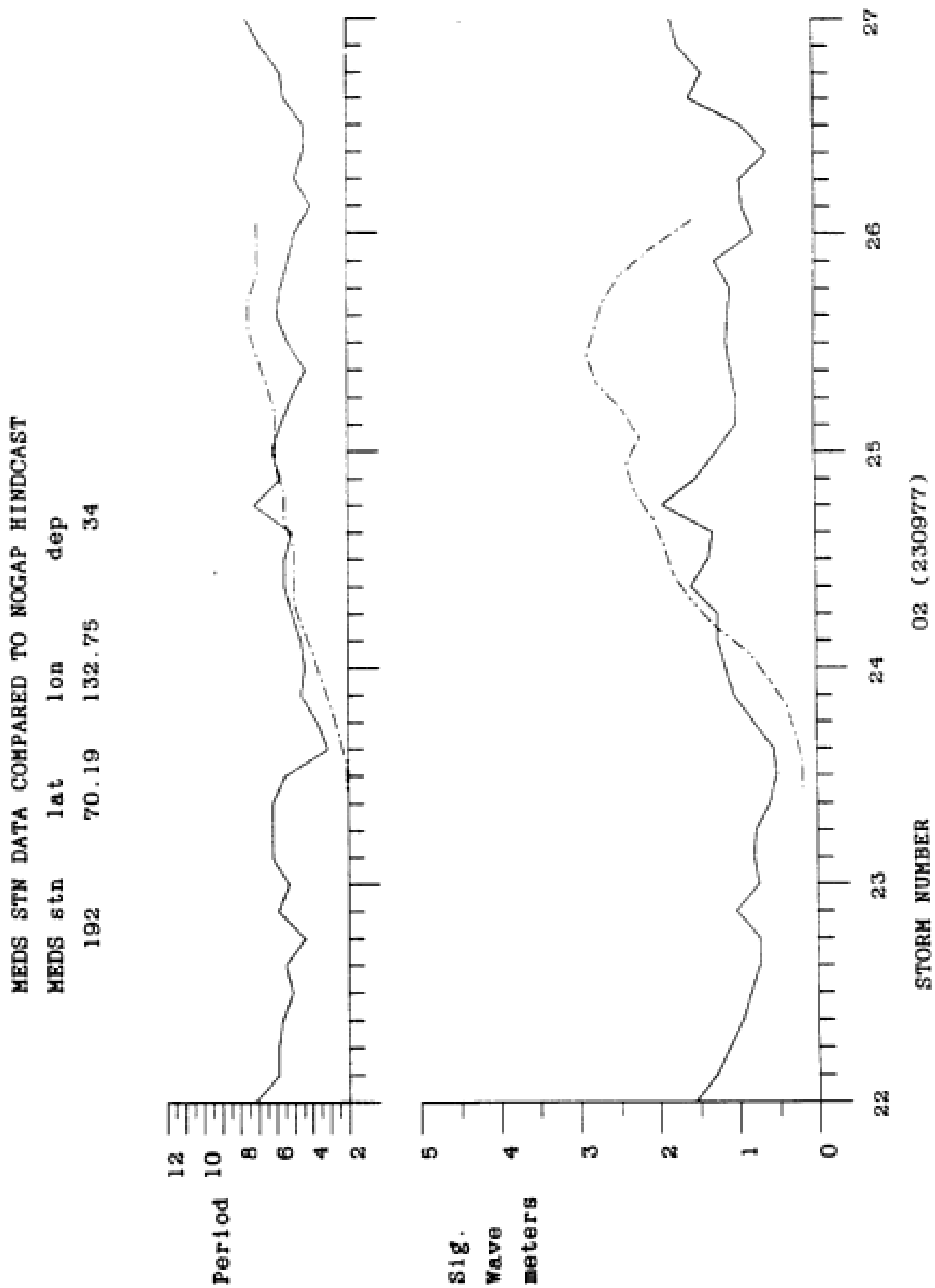
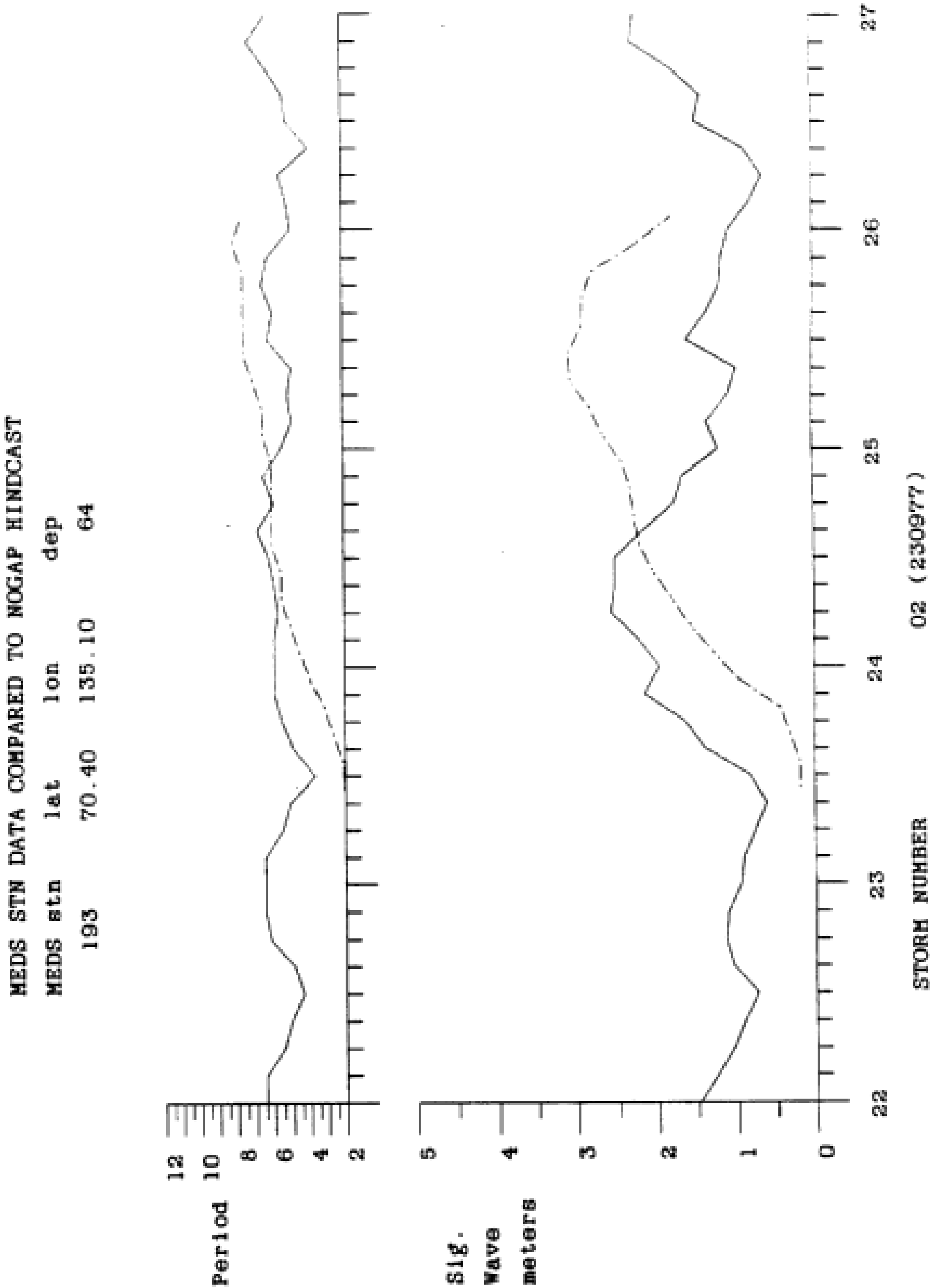
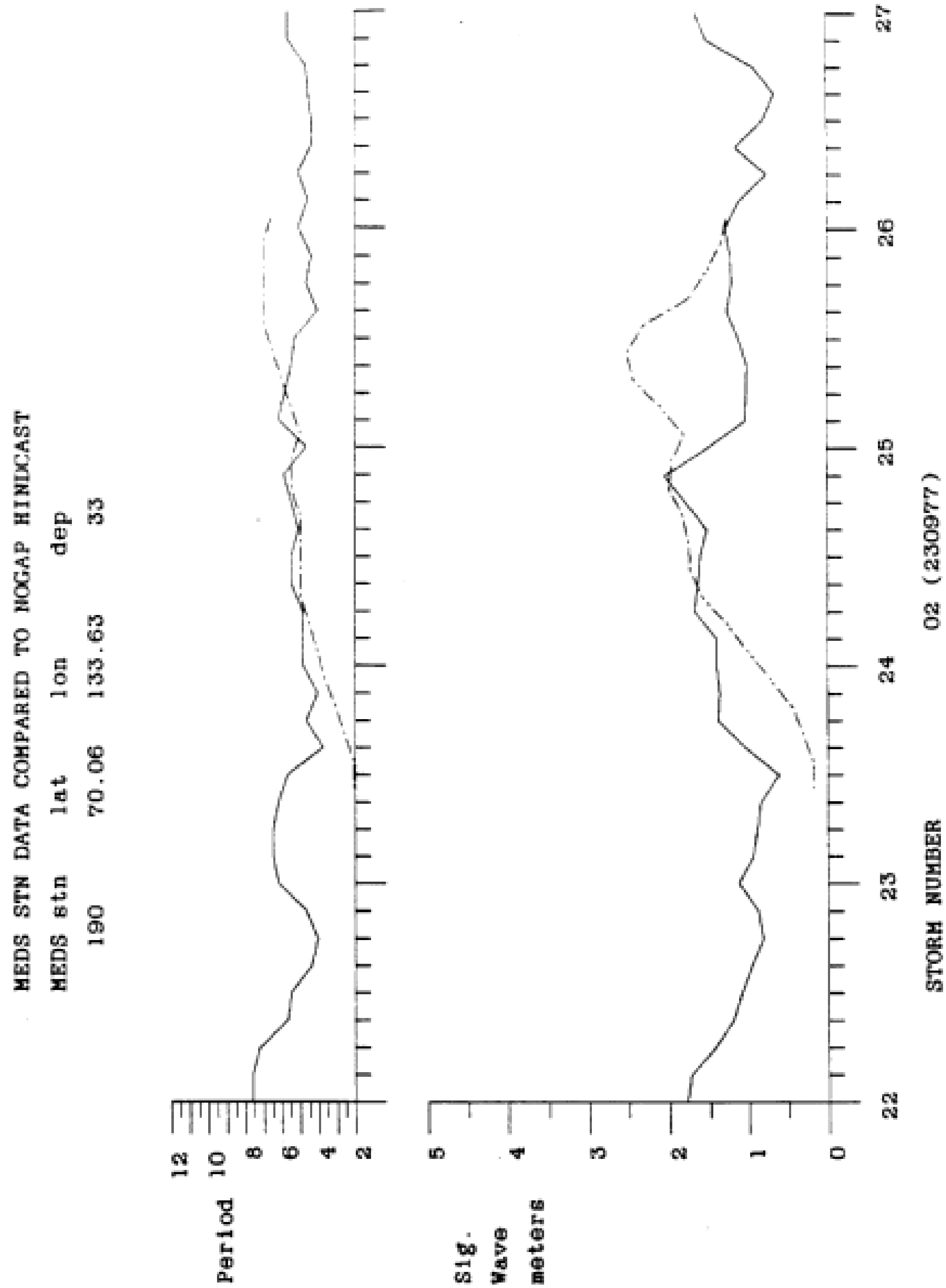
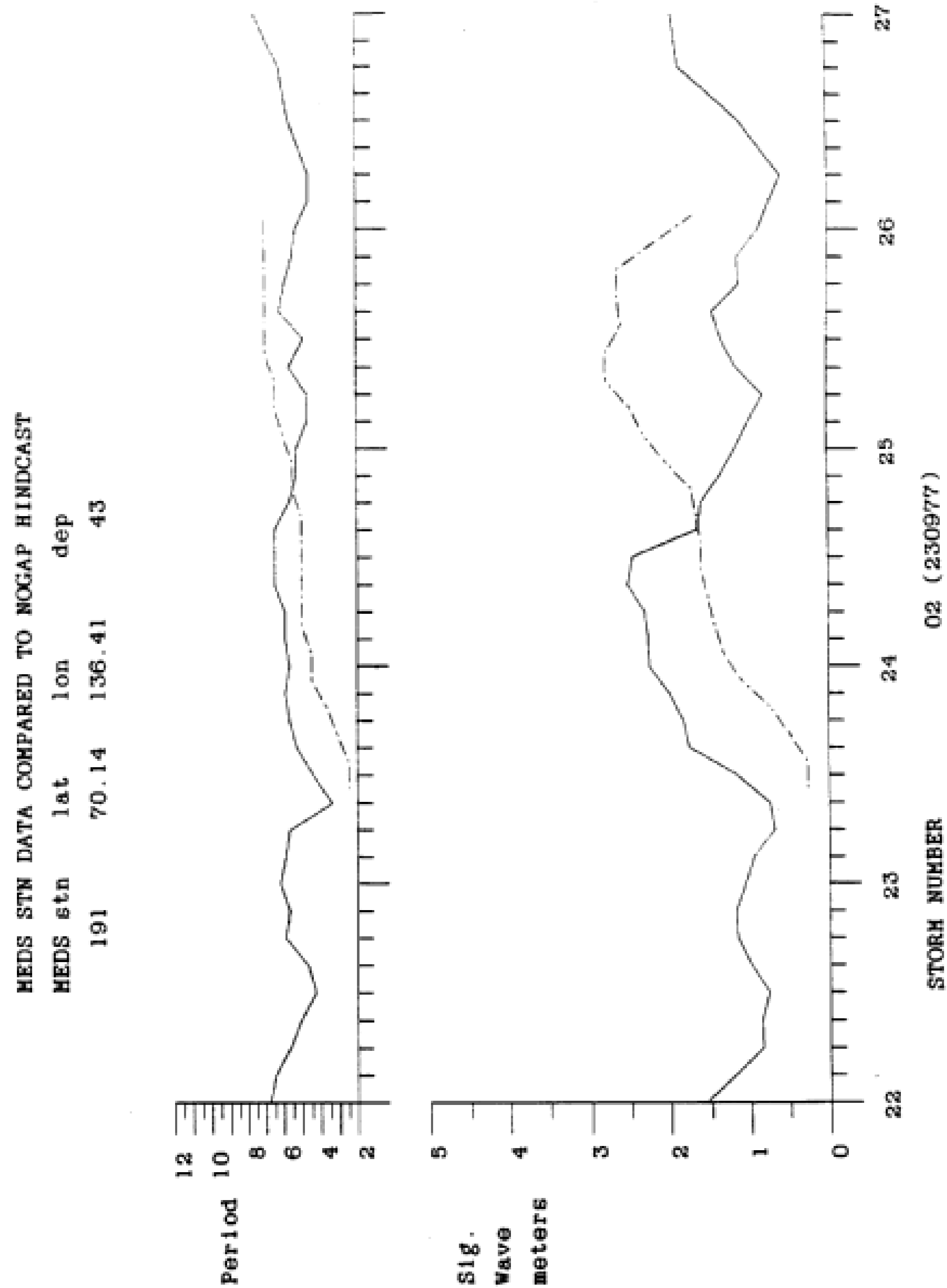
Period
12 10 8 6 4 2
Sig. Wave meters
5 4 3 2 1 0
24 25 26 27 28 29
STORM NUMBER
01 (260877)

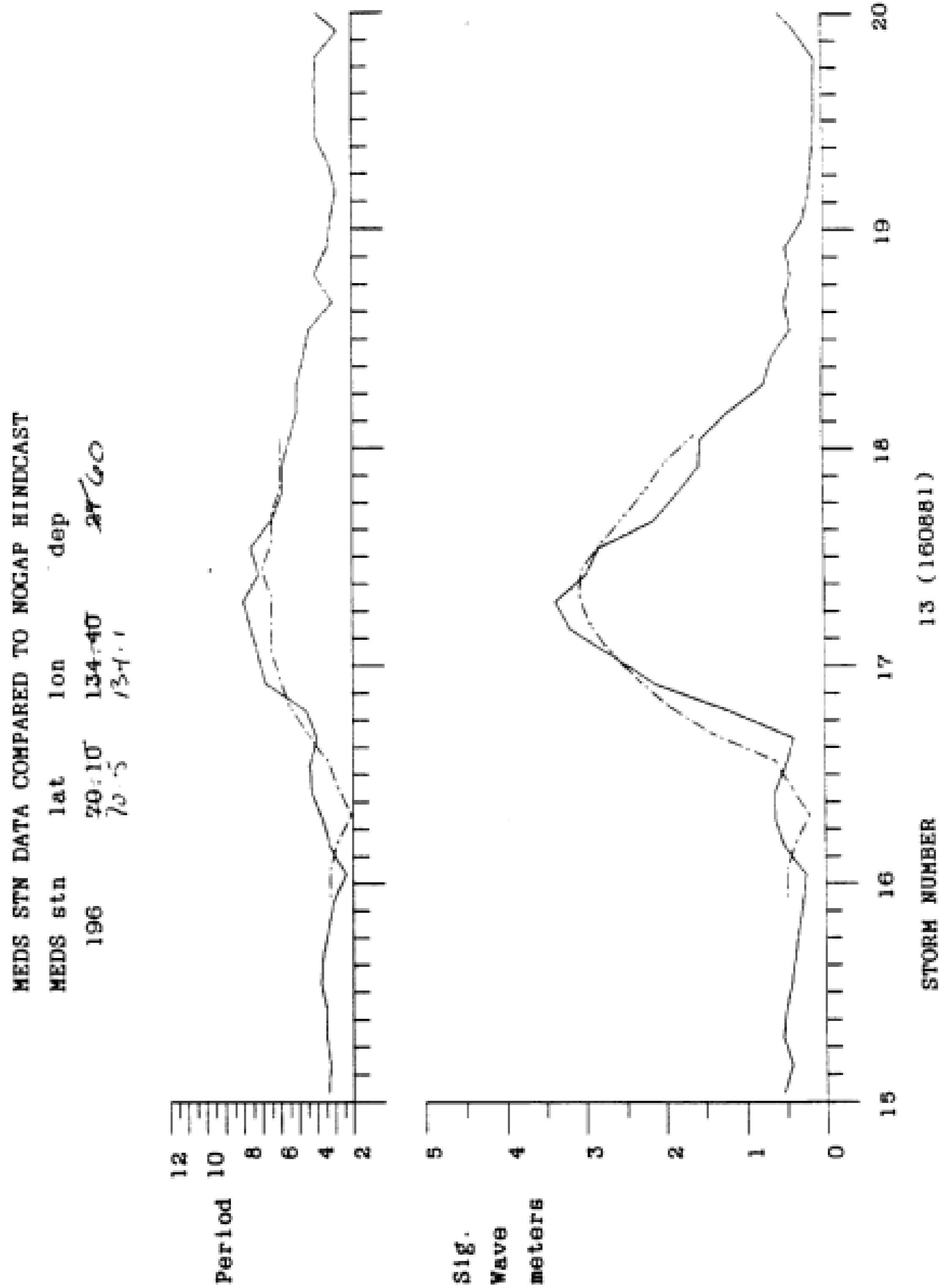

MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
194 70.00 134.43 14
Period
12
10
8
6
4
2
Sig. Wave meters
5
4
3
2
1
0
24
25
26
27
28
29
STORM NUMBER
01 (260877)

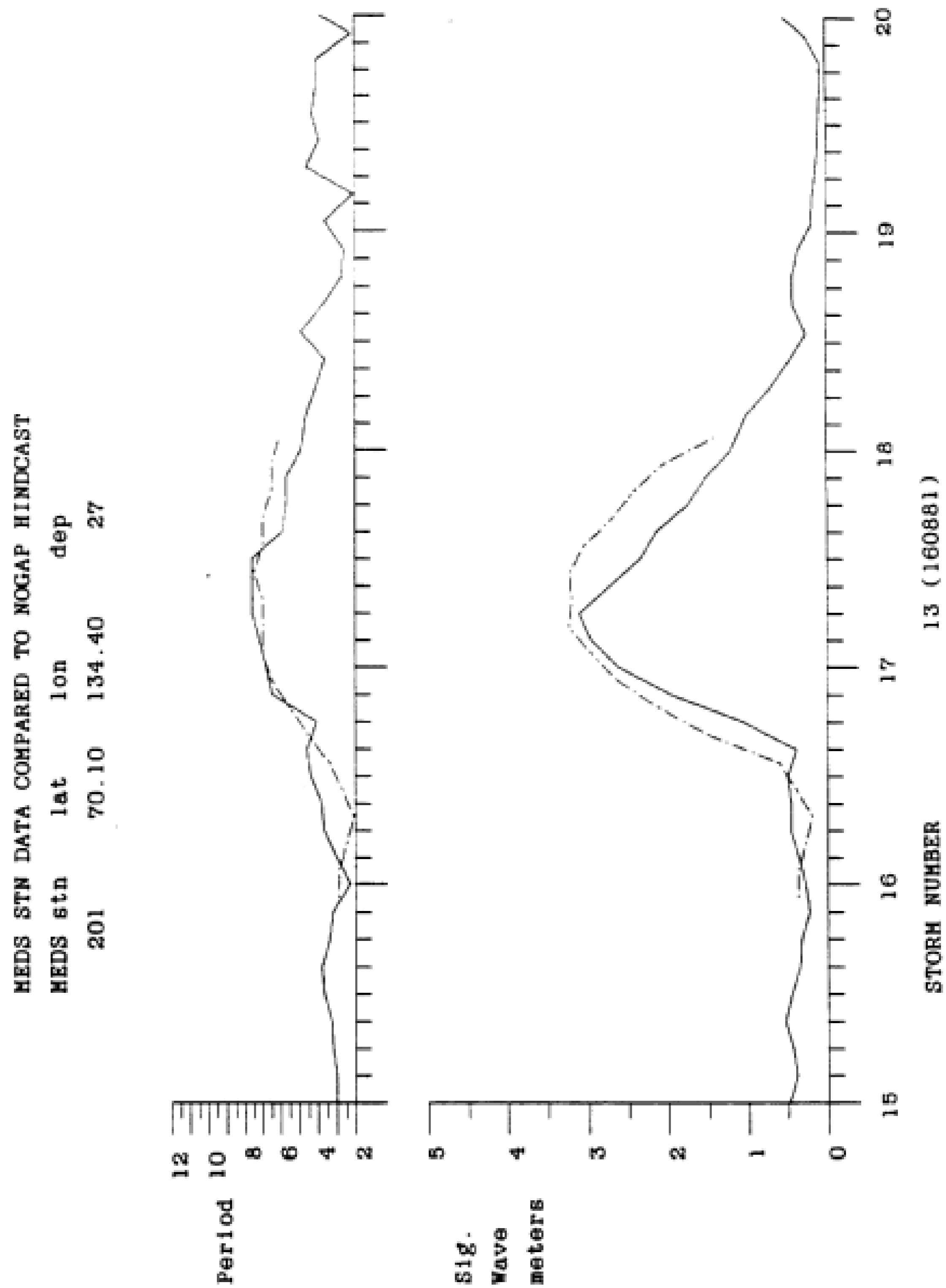

MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
192 70.19 132.75 34
Period
12 10 8 6 4 2
Sig. Wave meters
5 4 3 2 1 0
22 23 24 25 26 27
STORM NUMBER
03 (230977)

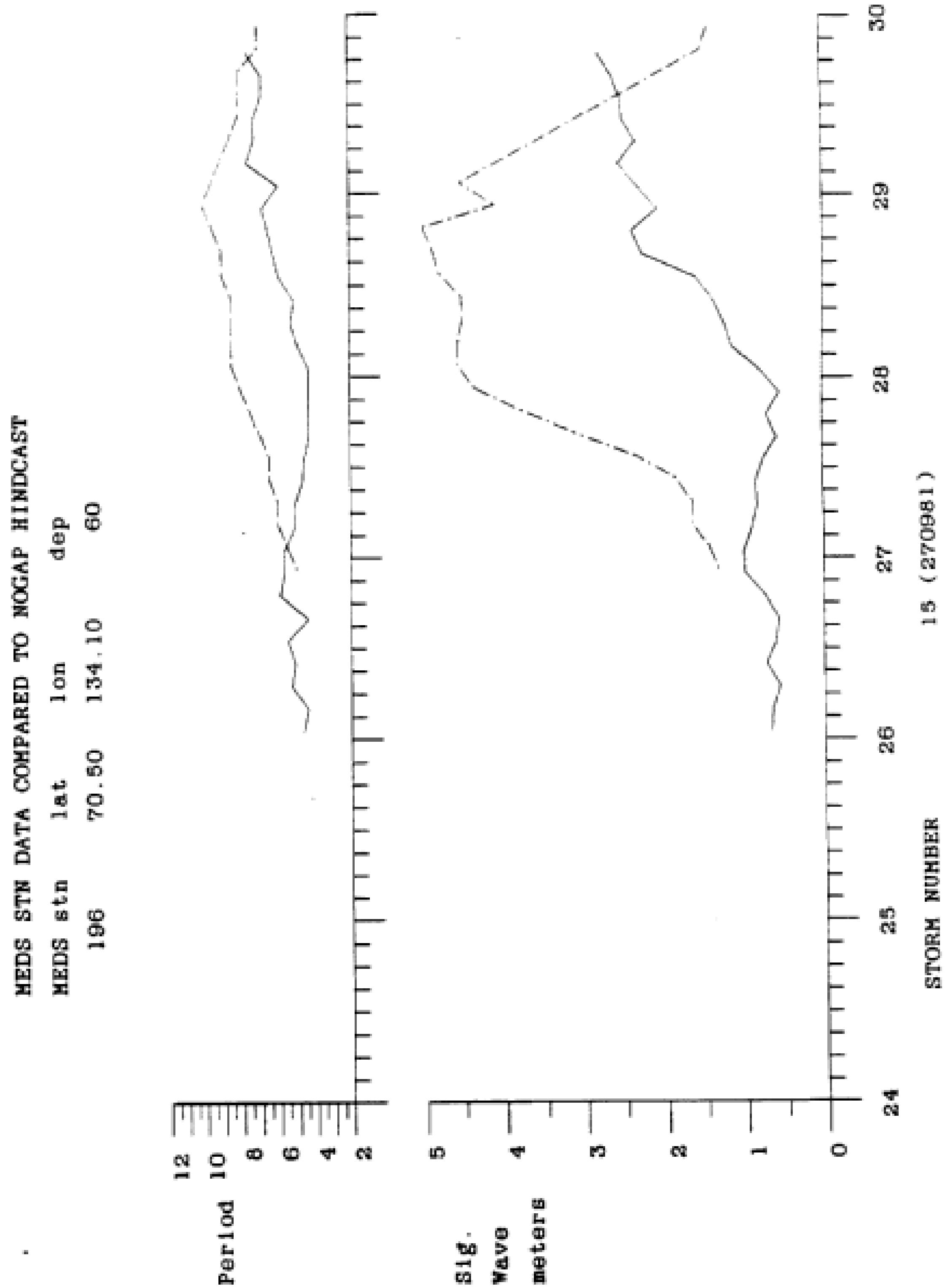

MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
193 70.40 135.10 64
Period
12
10
8
6
4
2
Sig. Wave meters
5
4
3
2
1
0
22
23
24
25
26
27
STORM NUMBER
02 (230977)

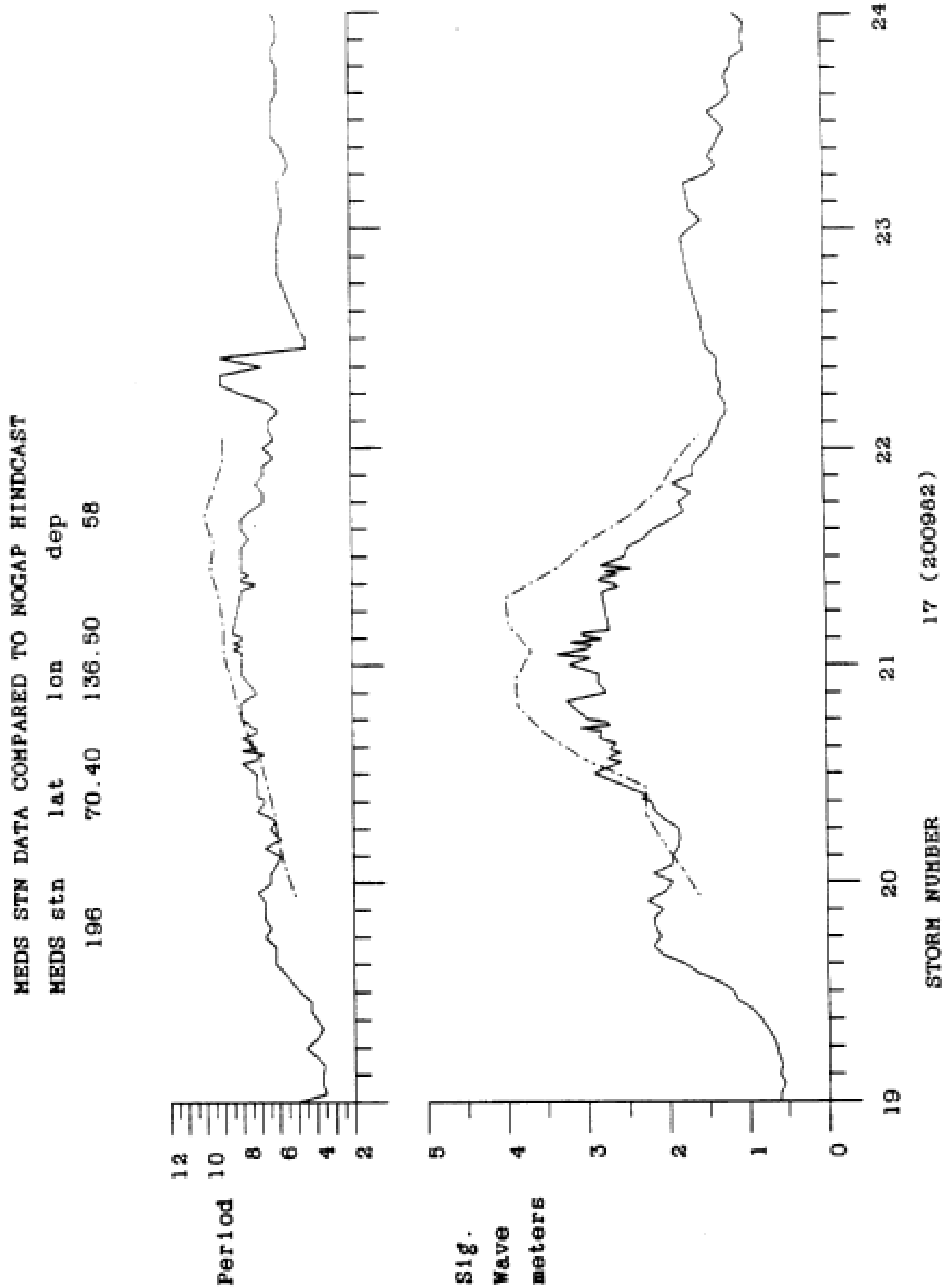

MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
190 70.06 133.63 33
Period
12
10
8
6
4
2
Sig.
Wave
meters
5
4
3
2
1
0
22
23
24
25
26
27
STORM NUMBER
02 (230977)


MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
191 70.14 136.41 43
Period
12
10
8
6
4
2
Sig.
Wave
meters
5
4
3
2
1
0
22
23
24
25
26
27
STORM NUMBER
02 (230977)

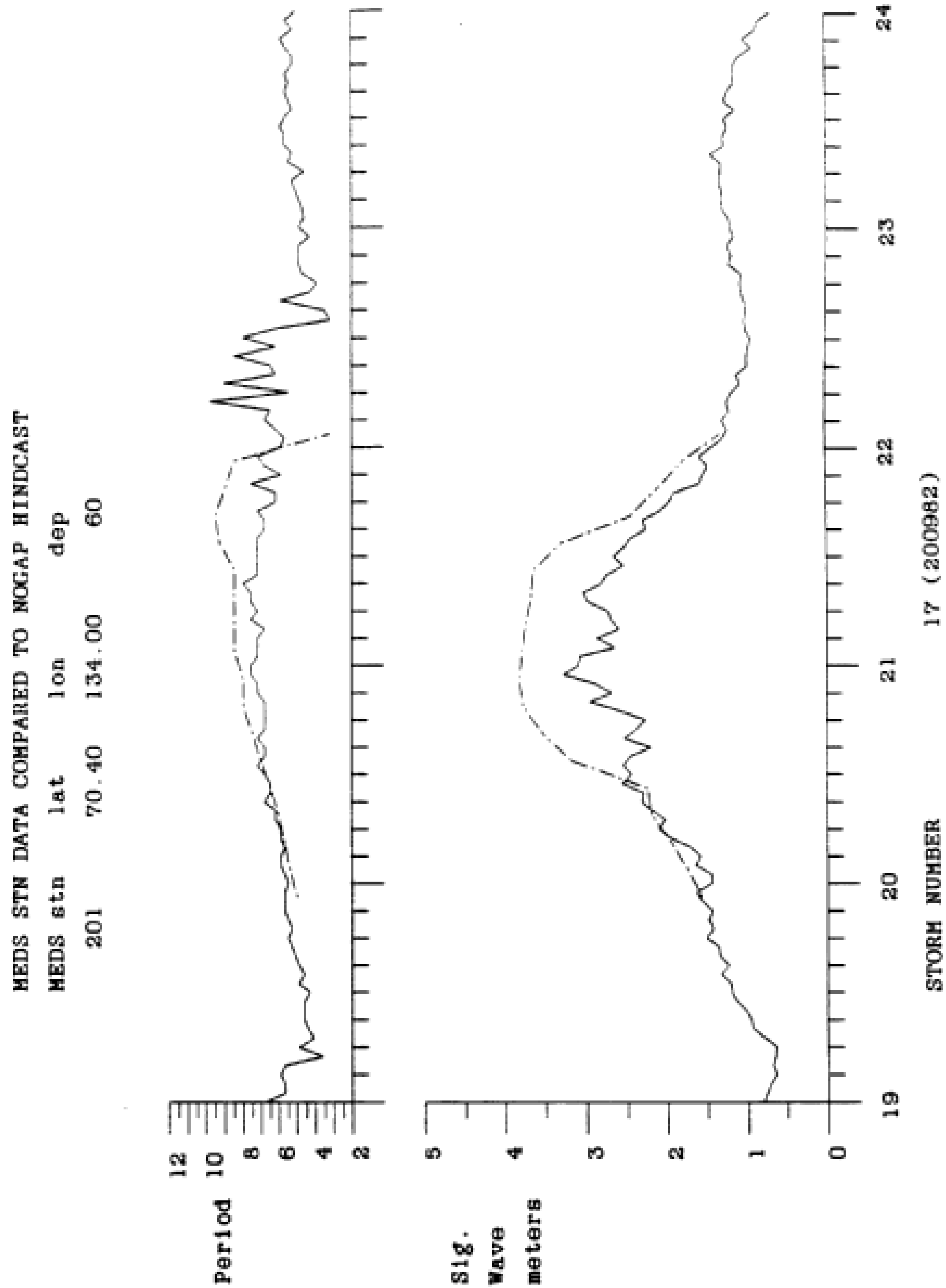

MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
196 20:10 134:40
Period
12 10 8 6 4 2
Sig. Wave meters
5 4 3 2 1 0
15 16 17 18 19 20
STORM NUMBER
13 (160881)

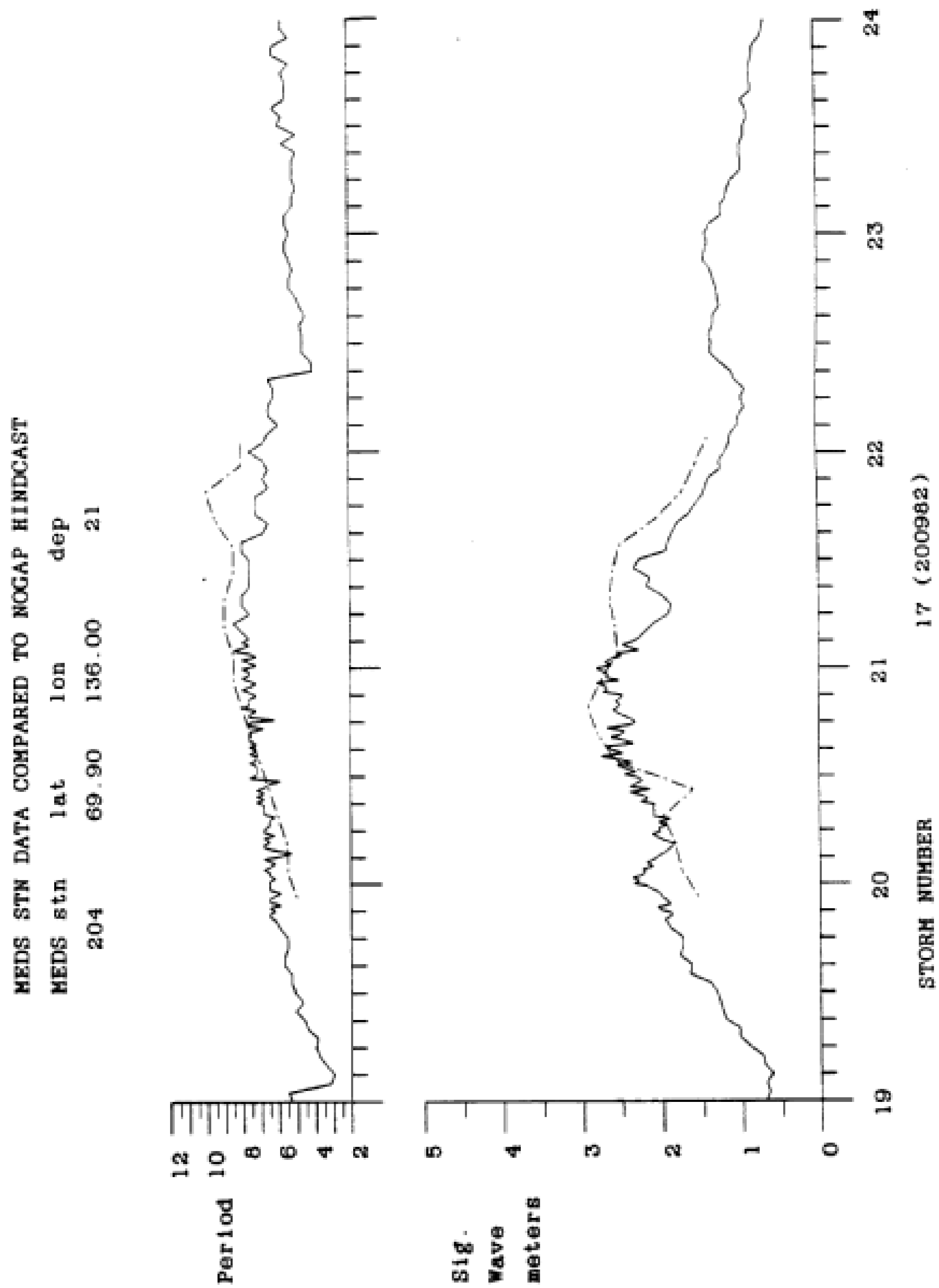

MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
201 70.10 134.40 27
Period
12 10 8 6 4 2
Sig. Wave meters
5 4 3 2 1 0
15 16 17 18 19 20
STORM NUMBER 13 (160881)

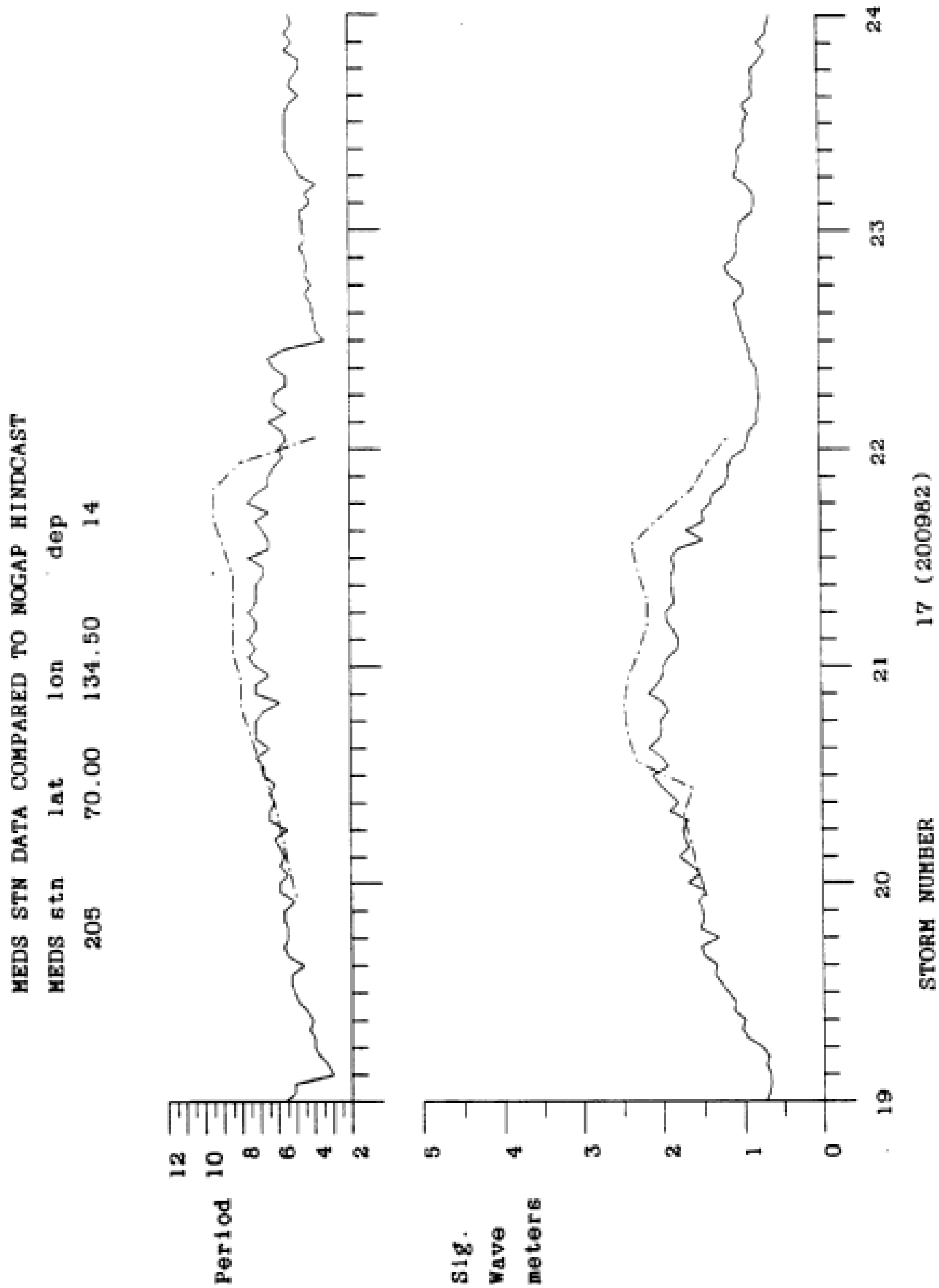

MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
196 70.50 134.10 60
Period
12 10 8 6 4 2
Sig. Wave meters
5 4 3 2 1 0
24 25 26 27 28 29 30
STORM NUMBER
15 (270981)

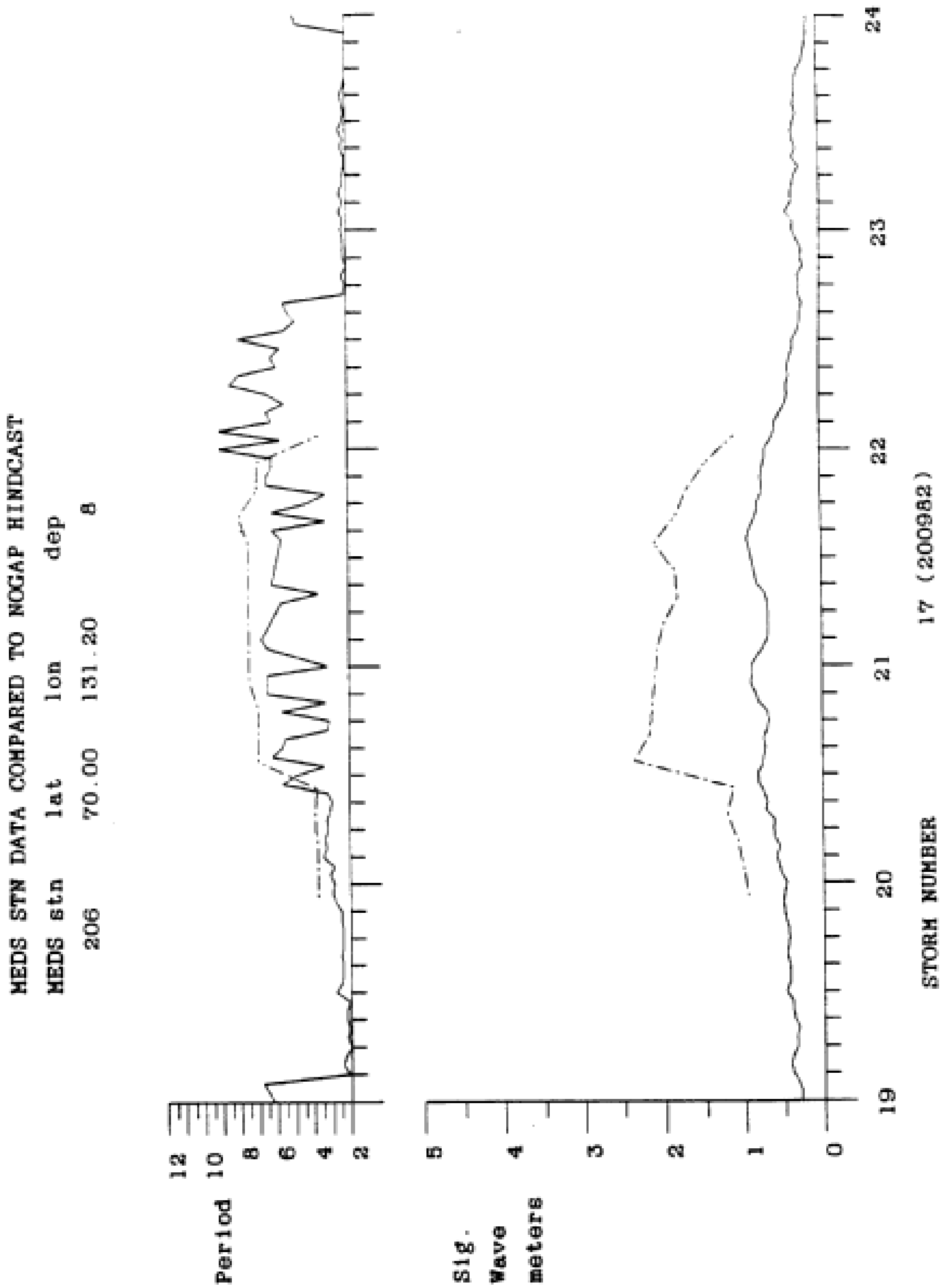

MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
196 70.40 136.50 58
Period
12 10 8 6 4 2
Sig. Wave meters
5 4 3 2 1 0
19 20 21 22 23 24
STORM NUMBER 17 (200982)

DFO 7


MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
201 70.40 134.00 60
Period
12 10 8 6 4 2
Sig.
Wave
meters
5 4 3 2 1 0
19 20 21 22 23 24
STORM NUMBER
17 (200982)


MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
204 69.90 136.00 21
Period
12 10 8 6 4 2
Sig. Wave meters
5 4 3 2 1 0
19 20 21 22 23 24
STORM NUMBER
17 (200982)


MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
205 70.00 134.50 14
Period
12
10
8
6
4
2
Sig. Wave meters
5
4
3
2
1
0
19
20
21
22
23
24
STORM NUMBER
17 (200982)


MEDS STN DATA COMPARED TO NOGAP HINDCAST
MEDS stn lat lon dep
206 70.00 131.20 8
Period
12 10 8 6 4 2
Sig. Wave meters
5 4 3 2 1 0
19 20 21 22 23 24
STORM NUMBER
17 (200982)

```
      PROGRAM NOGAP
     * (OUTPUT,TAPE1,TAPE2,TAPE3,TAPE9,TAPE11,TAPE91,
     *  TAPE92,TAPE15,INPUT)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     A spectral wave model based on the BIO-Resio model
C     (from Perrie)
C
C     Inputs:    * N-FILE : winds at three hourly "maps"
C                * C-FILE : control, ice chart
C                * H-FILE : plain language record for output tape
C
C     Outputs:   * D-FILE : tape of  header, model listing,
C                           control parameters, ice chart,
C                           wind maps, and 1-D + 2-D spectra at
C                           selected hindcast points (note the
C                           directions are wrt the model grid)
C                * W-FILE : a three hourly "field plot" of
C                           significant wave height (m),
C                           peak period (sec),
C                           wave direction (model directions)
C
C     Model notes:
C                ALPHA= 0.044*(EA*GSQ/USTA**4)**(-0.2)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C DIMENSION DIMENSION DIMENSION DIMENSION DIMENSION
C
C
C REFERENCE...................... NOTE:
C                                 GRID SIZE INDEPENDENT
C                                 16 DIRECTIONS
C                                 20+ FREQUENCIES
C                                 360 DEGREES
C                                 100 WIND SPEED INCREMENTS
C
      DIMENSION    COSR(16),      SINR(16),
     *             INGLE(16),     EPHON(16),
     *             IUA(16),       JUA(16),
     *             IUAL(16),      JUAL(16),
     *             IKEMU(16),
     *             GAMANG(361),   COSSQ(181),
     *             IAAD(361),
     *             FF11(20),      DELF(20),
     *             SINF(20),      ETMP(20),
     *                            DF2(20)
```

```
      DIMENSION     ANGL(20),        EFSUM(20),
     *              FF(21),          ZFL(21),
     *              FMX(100),        FFLIM(100),
     *              USTA(100),       USTA4(100),
     *              AFQ7(100),       FPM(100),
     *              PM(100,20),
     *              COEF(4),         SNLA(400),
     *              SHPF(20),
     *              EREFRR(16),
C
C PROPAGATION DUMMY FILE
C
     *              EMUX(2,20,20)
C
C INPUT OUTPUT CONTROL........... GRID SIZE:  I=40, J=55
C
      COMMON        ISTRING(12)
      DIMENSION     IALPHN(9),       EL1(20),
     *              TEL1(16,20,20),
     *              LOUT(20,4),      LEAP(55),
     *              FSW(55),         LOCC(40,55),
     *              LLOUT(20)
C
C SHALLOW WATER COEFFICIENTS..... NOTE:
C                                 20+ FREQUENCIES,
C                                 20  DEPTH INCREMENTS
C                                 16  DIRECTIONS
C
      DIMENSION     C(20,20),        XCR(21,20),
     *              RM33(21,20),     RM22(21,20),
     *              OMEGA(23,20),    CHI(23,20),
     *              RDAM(16),        RREF(16),
     *              BPDEP(16),
     *              CG(20,20),       PHI(21,20)
C
C SEA POINTS...................... ARRAY SIZE IS
C                                 NUMBER OF GRID SEA POINTS ONLY
C
      DIMENSION     TEL(500,16),     EL(500,20),
     *              ENA(500),        EA(500),
     *              KFA(500),        SINFKR(500),
     *              KSSA(500,16),    LSSA(500,8),
     *              LOCI(500),       LOCJ(500),
     *              LDEP(500),       IFRQ(500),
     *              WDIR(500),       WINDA(500),
     *              XPM(500),        EPMTRX(5,500),
     *              SC(500),         ESUM(500),
     *              EMX(500),        ESWL(500),
     *              FSUM(500)
```

```
      DIMENSION    VSUM(500),      USUM(500),
     *             ALPHA(500),     FOA(500),
     *             THOA(500),      EF(500),
     *                             FOOO(500),
     *             ISWO(500),      AF07(500),
     *             XFACTR(500),
     *             F02(500),       ALP2(500),
     *                             NF5(500),
     *             HSCALE(500)
C
C INTEGER INTEGER INTEGER INTEGER INTEGER INTEGER
C
      INTEGER WDIR,WINDA,AFQ7,AF07
C
C EQUIVALENCE EQUIVALENCE EQUIVALENCE EQUIVALENCE
C
      EQUIVALENCE (NPTS,NPTOT)
      EQUIVALENCE (TINC,DELT)
C
C DATA DATA DATA DATA DATA DATA DATA DATA DATA
C
      DATA SHPF/1.4,1.7,1.5,1.3,1.2,1.2,1.2,1.2,1.2,1.2,1.2,
     *          1.2,1.2,1.2,1.2,1.2,1.2,1.2,1.2,1.2/
      DATA COEF/0.005,0.05,0.12,0.60/
      DATA PI,NFREQ,NDIR,G,TWOPI/3.14159,20,16,980.,6.28319/
      DATA C1,C2,C3,GSQ/0.1525,1.47E-5,0.00371,960400./
      DATA IUA/0,0,1,1,1,1,1,0,0,0,-1,-1,-1,-1,-1,0/
      DATA JUA/-1,-1,-1,0,0,0,1,1,1,1,1,0,0,0,-1,-1/
      DATA IUAL/0,1,0,1,0,1,0,1,0,-1,0,-1,0,-1,0,-1/
      DATA JUAL/0,-1,0,-1,0,1,0,1,0,1,0,1,0,-1,0,-1/
      DATA IKEMU/1,1,2,1,1,1,2,1,1,1,2,1,1,1,2,1/
C
C FREQUENCY INCREMENTS
C
      DATA FF/0.0588,0.0625,0.0666,0.0714,0.0769,0.0833,
     *        00.0909,0.1,0.1052,0.111,0.1176,0.125,0.1333,
     *        0.142,0.153,0.166,0.181,0.2,0.222,0.25,1.0/
C
C FILES FILES FILES FILES FILES FILES FILES FILES
C
      LUIN=91
      LUOUT=92
C
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C DEFINE FREQUENCY INCREMENTS
C
      NFRQ1=NFREQ-1
      F1=0.5*(FF(2)-FF(1))
      DO 221 I=1,NFRQ1
      F2=(FF(I+1)-FF(I))*0.5
      DELF(I)=F1+F2
  221 F1=F2
      DELF(NFREQ)=2.0*F2
      DO 8888 I=1,NFRQ1
 8888 ZFL(I)=EXPOS(-(FF(I+1)/FF(I))**4)*2.718282
      DO 921 I=1,NFRQ1
  921 DF2(I)=(FF(I+1)-FF(I))/2.
C
C DEFINE NONDIMENSIONAL SHAPE FUNCTION,FORWARD FACE,LOCAL SEA
C SOURCE
C
      CON1=EXP(1.)
      FX3=1.
      DO 8849 I=1,94
 8849 SNLA(I)=FX3*CON1*EXPOS(-(0.95/(I*0.01))**4)
      DO 8850 I=95,105
 8850 SNLA(I)=1.
      DO 8860 I=106,400
 8860 SNLA(I)= -(100./I)**5
C
      IB=1
      DO 33 I=1,NFREQ
      II=NFREQ+1-I
      IE=2.482/FF(II)+0.5
      IF(IE.GT.100)IE=100
      DO 34 J=IB,IE
      AFQ7(J)=II
   34 CONTINUE
      IB=IE+1
   33 CONTINUE
C
C CONSTANTS
C
      AINC=TWOPI/NDIR
      RADC=TWOPI/360.
      RADDEG=360./TWOPI
      EPRM=5.19E-11
      ELIM=1000.
      CONEM=GSQ/TWOPI**4
      HEO   =(FF(NFREQ)+0.5*DELF(NFREQ))**(-4)*CONEM/4.0
      ECONST=GSQ/TWOPI**4
      EPINRM=2./PI
      SWCON=1.00E-5
```

```
C
      DO 651 I=1,NDIR
       INGLE(I)=(I-1)*22.5
       ANGL(I)=(I-1)*AINC
       COSR(I)=COS(ANGL(I))
       SINR(I)=SIN(ANGL(I))
  651  CONTINUE
       DO 41 I=1,90
   41  COSSQ(I)=COS((I-1)*RADC)**2
       DO 43 I=91,181
   43  COSSQ(I)=0.
       DO 42 I=1,360
       IAAD(I)=I
       IF(I.GT.180) IAAD(I)=361-I
   42  CONTINUE
       IAAD(361)=1
       DO 60 ITH=1,360
       GAMANG(ITH)=0.
       IF(ITH.GT.80.AND.ITH.LT.280) GOTO 60
       ANG=(ITH-1)*RADC
       GAMANG(ITH)=COS(ANG)**4
       GAMANG(ITH)=GAMANG(ITH)*8./(3.*PI)
   60  CONTINUE
       DO 70 I=1,NFREQ
   70  SINF(I)=TWOPI*GSQ/(TWOPI*FF(I))**5
C
C OUTPUT TAPE HEADER AND SOURCE CODE RECORD
C
       IREC=0
       ICODE=1
       IFILE=2
       CALL BUILD(IFILE,IREC,ICODE)
       IREC=0
       IFILE=3
       CALL BUILD(IFILE,IREC,ICODE)
C
C OUTPUT HEADER FOR JOB SETUP AND IDENTIFICATION
C
       ICODE=2
       WRITE(11,5040)ICODE
 5040  FORMAT(I2,8X,*JOB IDENTIFICATION*)
       READ(9,5041)(IALPHN(J),J=1,9)
 5041  FORMAT(1X,9A10)
       WRITE(11,5042)ICODE,(IALPHN(J),J=1,9)
 5042  FORMAT(I2,8X,*PROJECT*,23X,9A10)
       READ(9,5041)(IALPHN(J),J=1,9)
       WRITE(11,5043)ICODE,(IALPHN(J),J=1,9)
 5043  FORMAT(I2,8X,*RUN DATE-TIME(YYMMDDHH):      *,9A10)
       READ(9,5041)(IALPHN(J),J=1,9)
       WRITE(11,5044)ICODE,(IALPHN(J),J=1,9)
```

```
 5044 FORMAT(I2,8X,*DESCRIPTION:*,18X,9A10)
      READ(9,5041)(IALPHN(J),J=1,9)
      WRITE(11,5045)ICODE,(IALPHN(J),J=1,9)
 5045 FORMAT(I2,8X,*STORM START(YYMMDDHH):          *,9A10)
      READ(9,5041)(IALPHN(J),J=1,9)
      WRITE(11,5046)ICODE,(IALPHN(J),J=1,9)
 5046 FORMAT(I2,8X,*STORM END:*,20X,9A10)
      WRITE(11,5047)ICODE
 5047 FORMAT(I2,8X,*C A N I N  FILE:*)
      WRITE(11,5048)ICODE
 5048 FORMAT(I2,8X,7X,*I/N*,7X,*J/M*,6X,*TINC*,6X,*DINC*,6X,
     1          *MSTA*,7X,*IHR*,5X,*NMAPS*,7X,*ZM2*,6X,*DAMP*)
C
C PROBLEM PARAMETERS
C
      READ(9,5058)N,M,TINC,DINC,MSTA,IHR,NMAPS
 5058 FORMAT(1X,2I5,F10.0,F10.3,3I5)
C
C INITIALIZATION
C
      DX=DINC*100000.
      DELX=DX
      HR=IHR*3600.
      KTIMES=HR/TINC
      CDT=IHR
      CTIME=IHR
      TPRM=0.1215*TINC/G**1.33333
C
      CDAMP=0.038
      ZM2=1000.
C
C OUTPUT LOCATIONS
C
      IF(MSTA.LT.1)GOTO 4650
      DO 118 I=1,MSTA
      READ(9,101)(LOUT(I,J),J=1,4)
  118 CONTINUE
 4650 CONTINUE
  101 FORMAT(1X,2I3,1X,I4,1X,I5)
C
C
C OUTPUT A RECORD OF CANIN
C            (INCLUDE GRID POINTS: BELOW)
C
      WRITE(11,5049)ICODE,N,M,TINC,DINC,MSTA,IHR,NMAPS,ZM2,CDAMP
 5049 FORMAT(I2,8X,2I10,F10.0,F10.1,3I10,F10.0,F10.4)
      WRITE(11,5057)ICODE
 5057 FORMAT(I2,8X,*FREQUENCIES*)
      WRITE(11,5051)ICODE,(FF(J),J=1,20)
```

```
 5051 FORMAT(I2,8X,20F5.2)
      WRITE(11,5052) ICODE
 5052 FORMAT(I2,8X,*OUTPUT LOCATIONS:*)
      WRITE(11,5053)ICODE
 5053 FORMAT(I2,8X,7X,*I/N*,7X,*J/M*,2X,*LATITUDE*,1X,*LONGITUDE*,
     1      *    (LAT,LONG TO 2 DECIMAL PLACES)*)
      DO 5054 I01=1,MSTA
 5054 WRITE(11,5055)ICODE,(LOUT(I01,J),J=1,4)
 5055 FORMAT(I2,8X,4I10)
      WRITE(11,5056)ICODE
 5056 FORMAT(I2,8X,*LAND-SEA GRID WITH ICE OF THE DAY
     1       (I/N:,J/M..)*)
C
      DO 710 I=1,N
      DO 710 J=1,M
  710 LOCC(I,J)=0
      KSS=0
      JB=1
      JF=21
      IF(M.LT.21)JF=M
  635 DO 640 J02=JB,JF
  640 LEAP(J02)=J02
      PRINT 641 ,(LEAP(J02),J02=JB,JF)
  641 FORMAT(1H1,*LAND SEA GRID*/2X,*I\J*,2X,21I5)
C
C GRID SEA POINTS
C
      DO 701 I01=1,N
      READ(9,104)(LEAP(J01),J01=JB,JF)
  104 FORMAT(21I4)
      IF(EOF(9))708,709
  709 CONTINUE
      WRITE(11,5060)ICODE,(LEAP(J01),J01=JB,JF)
      PRINT 643,I01,(LEAP(J01),J01=JB,JF)
      PRINT 636
 5060 FORMAT(I2,8X,21I5)
  643 FORMAT(2X,I3,2X,21I5)
  636 FORMAT(1X,//)
  642 CONTINUE
C
      DO 701 J01=JB,JF
      IF(LEAP(J01).GT.0) GO TO 707
      LOCC(I01,J01)=IDEPCD((-1)*LEAP(J01))*(-1)
      IF(LEAP(J01).LT. -95) LOCC(I01,J01)=-20
      GO TO 701
  707 KSS=KSS+1
      LOCI(KSS)=I01
      LOCJ(KSS)=J01
      LDEP(KSS)=IDEPCD(LEAP(J01))
      LOCC(I01,J01)=KSS
  701 CONTINUE
```

```
      JB=JB+21
      JF=JF+21
      IF(JF.GT.M)JF=M
      IF(JB.LT.M)GO TO 635
  708 NPTS=KSS
      NPTS1=NPTS+1
      LDEP(NPTS1)=0
C
C  BLANK FILL TO END OF BLOCK OF 25 RECORDS
C
      WRITE(11,5061)ICODE,NPTS
 5061 FORMAT(I2,8X,*NUMBER OF SEA POINTS:*,I10)
      IREC=15+3*N+MSTA
      CALL BLANK(IREC,ICODE)
C
C SEA POINTS FOR WAVE DATA OUTPUT
C
      DO 217 ISTA=1,MSTA
      I=LOUT(ISTA,1)
      J=LOUT(ISTA,2)
      KSS=LOCC(I,J)
      IF(KSS.LT.1)KSS=NPTS1
  217 LLOUT(ISTA)=KSS
C
C SEA POINT NEIGHBOURING POINTS
C
      DO 704 KSS=1,NPTS
      I=LOCI(KSS)
      J=LOCJ(KSS)
      DO 704 IA=1,16
      IU=I+IUA(IA)
      JU=J+JUA(IA)
      KSSA(KSS,IA)=LOCC(IU,JU)
      IF(KSSA(KSS,IA).LE.0) KSSA(KSS,IA)=NPTS1
      IF(MOD(IA,2).NE.0) GOTO 704
      IU=I+IUAL(IA)
      JU=J+JUAL(IA)
      LSSA(KSS,IA/2)=LOCC(IU,JU)
      IF(LSSA(KSS,IA/2).LE.0)LSSA(KSS,IA/2)=NPTS1
  704 CONTINUE
C
C GRID SIZE DEPENDENT FUNCTINS
C
C DEFINE LIMITING VALUE OF SEA PEAK FREQUENCY AS FUNCTION
C OF WIND SPEED
C
      DX33=(DELX/100.)**(-0.33)
      DO 8855 IU=1,100
      UU=IU*0.514
      F1=16.15*UU**(-0.34)*DX33
 8858 V=G/(2.*TWOPI*F1)
```

```
      D=(DELX/100.-0.01*V*DELT)**(-0.33)
      F2=16.15*UU**(-0.34)*D
      IF(ABS(F2-F1).LT.0.001) GO TO 8857
      F1=0.5*(F1+F2)
      GO TO 8858
 8857 FFLIM(IU)=0.5*(F1+F2)
 8855 FMX(IU)=1.275/UU
C
C CONSTANTS FOR PHASE AND GROUP VELOCITY
C AND CHI  ,OMEGA
C
      DO 3026 I=1,NFREQ
      X=1.
      DO 3026 L=1,20
      OMEGA(I,L)=TWOPI*FF(I)*SQRT(DEPTH(L)*100./G)
 3024 HYP=TANH(X*OMEGA(I,L)**2)
      IF(ABS(1./X-HYP).LT..000005)GO TO 3025
      X=1./HYP
      GO TO 3024
 3025 CHI(I,L)=X
 3026 CONTINUE
      X=1.
      DO 3700 L=1,20
      OMEGA(22,L)=TWOPI*(FF(NFREQ)+0.5*DELF(NFREQ))
     *             *SQRT(DEPTH(L)*100./G)
 3701 HYP=TANH(X*OMEGA(22,L)**2)
      IF(ABS(1./X-HYP).LT..000005)GO TO 3702
      X=1./HYP
      GO TO 3701
 3702 CHI(22,L)=X
      CHI(21,L)=1.
 3700 CONTINUE
      DO 28 L=1,20
      DO 29 I=1,NFREQ
      C(I,L)=G/(TWOPI*FF(I)*CHI(I,L))
      PHI(I,L)=1.-OMEGA(I,L)**2+(CHI(I,L)
     *          *OMEGA(I,L))**2
      CG(I,L)=C(I,L)*PHI(I,L)/2.
      FF11(I)=FF(I)**11
      XCR(I,L)=TINC*CG(I,L)
      IF(XCR(I,L).LT.DELX) GO TO 2929
      XCR(I,L)=DELX
 2929 XXD=DELX-XCR(I,L)/2.
      IF(XXD.LE.0.)XXD=0.05
      XD=DELX/XXD
      RM33(I,L)=XD**0.33
      RM22(I,L)=XD**0.22
      XCR(I,L)=XCR(I,L)/DELX
   29 CONTINUE
   28 CONTINUE
```

```
      DO 3100 L=1,20
      PHI(NFREQ+1,L)=1.
      XCR(NFREQ+1,L)=0.
      RM33(NFREQ+1,L)=1.
      RM22(NFREQ+1,L)=1.
 3100 CONTINUE
C
C INITIALIZE PROPOGATION CONTROL CONSTANTS
C            (NOTE: SQUARE GRID )
C
      ICODE=1
      IREC=0
      DO 734 ITF=1,20
      DO 734   L=1,20
      DS=CG(ITF,L)*DELT
      EMUX(1,L,ITF)=DS/DX
      EMUX(2,L,ITF)=DS/(0.707*2.*DX)
      DO 734 IA=1,2
      IF(EMUX(IA,L,ITF).LE.1.0) GO TO 734
      EREM=EMUX(IA,L,ITF)
      EMUX(IA,L,ITF)=1.0
      IF(IA.NE.1) GO TO 734
      DL=DEPTH(L)
      WRITE(11,107)ICODE,FF(ITF),DL,TINC,EREM
  107 FORMAT(I2,8X,*COURANT CONDITION,EXCEEDED FOR FREQUENCY*,
     1       F10.5,5X,*DEPTH*,F10.1,5X,*TINC*,F10.2,
     2       4X,*RATIO*,F10.5)
      IREC=IREC+1
  734 CONTINUE
      ICODE=1
      CALL BLANK(IREC,ICODE)
C
C MISCELANEOUS TABLES AND CONSTANTS
C
      DO 17 IU=1,100
      VST=0.4*51.4*IU
      UST=VST
   19 Z0=C1/UST+C2*UST*UST-C3
      UST1=VST/ALOG((ZM2-Z0)/Z0)
      IF(ABS(UST1-UST).LT.0.01) GOTO 18
      UST=UST1
      GOTO 19
   18 USTA(IU)=UST1
      USTA4(IU)=UST1**4
   17 CONTINUE
      DO 721 IU=1,100
      FPM(IU)=0.13*9.81/(IU*0.514)
```

```
      DO 721 ITF=1,20
      VAR2=-1.25*(FPM(IU)/FF(ITF))**4
      VAR3=EXPOS(VAR2)
      IF(VAR3.LT.0.2865)VAR3=0.2865*FF(ITF)/FPM(IU)
      PM(IU,ITF)=VAR3
  721 CONTINUE
C
C INITIALIZATION OF ENERGY ARRAYS
C
      ENA(NPTS1)=0.
  402 DO 20 KSS=1,NPTS1
      KFA(KSS)=NFREQ+1
      NF5(KSS)=NFREQ-4
      ISWO(KSS)=NFREQ+1
      DO 8847 NPM=1,5
 8847 EPMTRX(NPM,KSS)=0.
      FOA(KSS)=0.5
      FSUM(KSS)=0.5
      ALPHA(KSS)=0.01
      THOA(KSS)=0.
      F02(KSS)=0.5
      ALP2(KSS)=0.01
      ESUM(KSS)=0.0
      NF5(KSS)=20
      EA(KSS)=1.0E-5
      DO 21 J=1,NFREQ
      EL(KSS,J)=0.
   21 CONTINUE
      DO 20 IA=1,16
      TEL(KSS,IA)=0.
   20 CONTINUE
      REWIND LUIN
      DO 210 ITF=1,20
      BUFFER OUT(LUIN,0)(TEL(1,1),TEL(500,16))
      IOERR=UNIT(LUIN)
  210 CONTINUE
      REWIND LUIN
```

```
C*************************************************************
C*************************************************************
C
C START CLCULATIONS START CALCULATIONS START CALCULATIONS
C
C LOOP STRUCTURE IS:
C
C      + READ THREE HOURLY WIND MAP
C
C           + TIME STEP SPECTRAL GROWTH
C
C                  PROPOGATION TRACE BACK
C                  SWELL SOURCE
C                + FREQUECY SPECIFIC WAVE GROWTH
C
C                     + SPACE SPECIFIC WAVE GROWTH
C
C                           + ANGLE SPECIFIC WAVE GROWTH
C
C                     + SATURATION SHAPING OF SPECTRUM
C
C                + PEAK ENERGY BIN = PEAK PERIOD
C
C           + PARAMETRIC "HIGH FREQUENCY TAIL" ENERGY
C
C      + OUTPUT SPECTRA AND FIELD OF WAVES
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      HRS=0.0
      DO 1000 NMAP=1,NMAPS
C
C INPUT A MAP OF WINDS
C
      READ(1,1146)IDP
      IF(EOF(1)) 9999,520
 1146 FORMAT(1X,I10)
  520 CONTINUE
      CALL SECOND(T1)
      JB=1
      JF=21
      IF(M.LT.21)JF=M
 5155 DO 5156 I=1,N
      READ(1,1144)(FSW(J),J=JB,JF)
      DO 5156 J=JB,JF
      KSS=LOCC(I,J)
      WINDA(KSS)=FSW(J)+0.5
 5156 IF(WINDA(KSS).LT.5)WINDA(KSS)=5
      JB=JB+21
      JF=JF+21
      IF(JF.GT.M)JF=M
```

```
      IF(JB.LT.M)GO TO 5155
      JB=1
      JF=21
      IF(M.LT.21)JF=M
 5159 DO 5158 I=1,N
      READ(1,1144)(FSW(J),J=JB,JF)
      DO 5158 J=JB,JF
      KSS=LOCC(I,J)
      WDIR(KSS)=FSW(J)+0.5
 5158 IF(WDIR(KSS).LT.0)WDIR(KSS)=WDIR(KSS)+360
      JB=JB+21
      JF=JF+21
      IF(JF.GT.M)JF=M
      IF(JB.LT.M)GO TO 5159
 1144 FORMAT(21F6.1)
 1134 CONTINUE
C
C OUTPUT WINDFIELD OVER SEA POINTS ONLY
C
C
      ICODE=2
      XHRS=HRS
      XHRF=HRS+CDT
      WRITE(11,5070)ICODE,XHRS,XHRF,IDP,ICODE
 5070 FORMAT(I2,8X,*SERIES HEADER*,5X,
     1        *WINDFIELD FROM RUN TIME:*,1X,F7.2,2X,
     2        *TO*,1X,F7.2,5X,*FROM STANDARD DATE/TIME:*,I10/
     3        I2,8X,*WIND SPEED (KNOTS),WIND DIRECTION*,
     4        * 0 DEG I SFROM RIGHT TO LEFT, 90 IS TOP TO BOTTOM*)
      JB=1
      JF=21
      IF(M.LT.21)JF=M
  637 DO 103 I=1,N
      DO 113 J=JB,JF
      KSS=LOCC(I,J)
      IF(KSS.LE.0) GO TO 114
      LEAP(J)=WINDA(KSS)
      GO TO 113
  114 LEAP(J)=0
  113 CONTINUE
      WRITE(11,5060)ICODE,(LEAP(J05),J05=JB,JF)
      DO 115 J=JB,JF
      KSS=LOCC(I,J)
      IF(KSS.GT.NPTS) GO TO 116
      LEAP(J)=WDIR(KSS)
      GO TO 115
  116 LEAP(J)=0
  115 CONTINUE
      WRITE(11,5060) ICODE,(LEAP(J05),J05=JB,JF)
  103 CONTINUE
      JB=JB+21
```

```
      JF=JF+21
      IF(JF.GT.M)JF=M
      IF(JB.LT.M)GO TO 637
      IREC=2*3*N+2
      CALL BLANK(IREC,ICODE)
C
C
C
C BEGIN TIME STEP LOOP
C
 9094 DO 1001 KTIME=1,KTIMES
      HRS=HRS+TINC/3600.0
      IPRF=0
      IF(HRS.NE.CTIME) GOTO 5050
      CTIME=CTIME+CDT
      IPRF=1
 5050 DO 40 KSS=1,NPTS
      ESUM(KSS)=0.
      USUM(KSS)=0.
      VSUM(KSS)=0.
      AF07(KSS)=NFREQ+1
      IUW=WINDA(KSS)
      UST1=USTA4(IUW)
      ALPHA(KSS)=HBARF(EA(KSS),UST1)
      IF(KFA(KSS).LT.NFREQ-2) GO TO 5013
      UST1=USTA(IUW)
      FO=FOA(KSS)
      FMBAR=FO*UST1/G
      UST1=UST1**4
      HIGH1=EPRM*FMBAR**(-3.33333)*UST1
      ALPHA(KSS)=HBARF(HIGH1,UST1)
 5013 CONTINUE
      IF(FOA(KSS).GE.FMX(IUW)) GO TO 4102
      FOA(KSS)=FMX(IUW)
      KFA(KSS)=AFQ7(IUW)
 4102 L=LDEP(KSS)
  40  CONTINUE
      DO 4450 ITF=1,20
      EFSUM(ITF)=0.
      DO 4450 KSS=1,NPTS
      EFSUM(ITF)=EFSUM(ITF)+EL(KSS,ITF)
 4450 CONTINUE
      REWIND LUIN
      REWIND LUOUT
      DO 4451 ITF=1,20
      BUFFER IN(LUIN,0)(TEL(1,1),TEL(500,16))
      IOERR=UNIT(LUIN)
      IF(EFSUM(ITF).LT.ELIM) GOTO 4454
```

```
C
C PROPOGATION
C
      DO 750 IA=1,16
      DO 751 KSS=1,NPTS
      L=LDEP(KSS)
      EMU1=EMUX(IKEMU(IA),L,ITF)
      KSSU=KSSA(KSS,IA)
      ENA(KSS)=(1.0-EMU1)*TEL(KSS,IA)
     1          +     EMU1  *TEL(KSSU,IA)
  751 CONTINUE
      DO 752 KSS=1,NPTS
      L=LDEP(KSS)
      EMU1=EMUX(2,L,ITF)
      IF(MOD(IA,2).NE.0) GO TO 752
      LSSU=LSSA(KSS,IA/2)
      ENB=(1.0-EMU1)*TEL(KSS,IA)+EMU1*TEL(LSSU,IA)
      ENA(KSS)=(ENB+ENA(KSS))/2.0
  752 CONTINUE
      DO 750 KSS=1,NPTS
      TEL(KSS,IA)=ENA(KSS)
  750 CONTINUE
 4454 BUFFER OUT(LUOUT,0)(TEL(1,1),TEL(500,16))
      IOERR=UNIT(LUOUT)
 4451 CONTINUE
      LUTMP=LUIN
      LUIN=LUOUT
      LUOUT=LUTMP
      REWIND LUIN
      REWIND LUOUT
C
C CALCULATION OF SWELL SOURCE
C
      DO 441 KSS=1,NPTS
      EMX(KSS)=0.0
      KMX=KFA(KSS)-3
      IF(KMX.GE.19) KMX=20
      IF(KMX.LT.1)  KMX=1
C
      IFRQ(KSS)=21
      DO 442 ITF=2,KMX
      IF(EL(KSS,ITF) .GT. EL(KSS,ITF-1)) GO TO 442
      IF(EL(KSS,ITF-1) .LT. EMX(KSS))    GO TO 442
      EMX(KSS)=EL(KSS,ITF-1)
      IFRQ(KSS)=ITF-1
  442 CONTINUE
C
      IF(IFRQ(KSS).GE.20) GO TO 441
      ISWO(KSS)=21
      IF (EMX(KSS) .LT. 1000.) GO TO 441
      ISWO(KSS)=IFRQ(KSS)
```

```
      IIFRQ=IFRQ(KSS)
C
      ESWL(KSS)=0.0
      X1=SWCON*TINC*FF11(IIFRQ)*(EL(KSS,IIFRQ)*AINC)**2
C
      DO 443 ITF=IIFRQ,KMX
      JFRQ=ITF+1-IIFRQ
      ETMP(ITF)=EL(KSS,ITF)*(1.0-X1*SHPF(JFRQ))
      IF(ETMP(ITF) .LT. 0.0) ETMP(ITF)=0.0
      ESWL(KSS)=ESWL(KSS)+(EL(KSS,ITF)-ETMP(ITF))*DELF(ITF)
  443 CONTINUE
C
  441 CONTINUE
C
      REWIND LUIN
      REWIND LUOUT
      DO 2449 ITF=1,20
      BUFFER IN(LUIN,0)(TEL(1,1),TEL(500,16))
      IOERR=UNIT(LUIN)
C
      DO 2448 KSS=1,NPTS
      IF(EMX(KSS) .LT. 1000.) GO TO 2448
C
      IF(IFRQ(KSS).GE.20) GO TO 2448
      KMX=KFA(KSS)-3
      IF(KMX .GE. 19) KMX=20
      IF(KMX .LT. 1)  KMX=1
C
      IIFRQ=IFRQ(KSS)
      IFRQM1=IIFRQ-1
      IFRQM4=IIFRQ-4
      IF(IFRQM4 .LT.1) IFRQM4=1
C
      K=0
      X1=SWCON*TINC*FF11(IIFRQ)*(EL(KSS,IIFRQ)*AINC)**2
C
      IF(IIFRQ.GT.KFA(KSS)-4)X1=0.0
      IF(ITF.GE.IIFRQ .AND. ITF.LE.KMX) GO TO 2444
      IF(ITF.GE.IFRQM4 .AND. ITF.LE.IFRQM1) GO TO 2445
      GO TO 2448
C
 2444 CONTINUE
      JFRQ=ITF+1-IIFRQ
      ETMP(ITF)=EL(KSS,ITF)*(1.0-X1*SHPF(JFRQ))
      IF(ETMP(ITF).LT.0.0) ETMP(ITF)=0.0
      GO TO 2446
C
 2445 K=K+1
      ETMP(ITF)=EL(KSS,ITF)+COEF(K)*ESWL(KSS)/DELF(ITF)
C
 2446 CONTINUE
```

2.2 Shallow Water Wave Growth

[ALPHA]

In steady state (constant winds and depth) conditions the calculation of [ALPHA] does not take into consideration the reduced steady state spectral equilibrium, due to the "KKZ" factor. This results in higher values of [ALPHA] which tends to generate higher than expected rates of growth in the Fp and Hs. To solve this, each spectral energy bin was multiplied by the corresponding "KKZ" factor for the calculation of ALPHA.

Exponential Damping

BIO-RESIO uses an empirical frequency-depth-energy damping term, originally taken from JONSWAP. This was only used to damp the swell energy (which was defined as having frequencies below 0.7 times the spectral peak frequency). However, the propagating and input (wind etc.) energies can be damped at all frequencies in a exponential form. The exponential is made linear with time and space to be compatible with the model mechanism. The results demonstrate the only mechanism by which the development of the spectral peak frequency is retarded in shallow water. This behavior was seen to be compatible with the parametric SMB equations (used for the GULF hindcast study), the TEXEL experiment, and some spectral shallow water models such as GONO.

Refraction

The refraction equations were reviewed and corrected. Also the spatial resolution was refined by defining the refraction cross-slope over the directional quadrant of each propagation ray leading to the grid points. To this, the progressive refraction during the wave ray propagation over the changing depth to the grid point, was analyzed and made linear (in a similar method as would be applied to the damping mechanism)

2.3 Tests and Observations

As further testing of the model demonstrated most of the problems associated with the Beaufort application of the model disappeared. Since full time step propagation was used, rather than half step, there was less wave height persistence, as formerly noted by Penicka. The hyper growth off of shallow water into deep, and the hyper fetch growth mentioned at the beginning of this section, were also rectified. Duration restricted growth was also on target. In summary, short comings in the model performance were cleared by the reversion of the model physics to the original

```
      RR=ETMP(ITF)/(EL(KSS,ITF)+1.0)
C
      DO 2447 IA=1,16
       TEL(KSS,IA)=TEL(KSS,IA)*RR
 2447 CONTINUE
 2448 CONTINUE
C
      BUFFER OUT(LUOUT,0)(TEL(1,1),TEL(500,16))
      IOERR=UNIT(LUOUT)
 2449 CONTINUE
C
      LUTMP=LUIN
      LUIN=LUOUT
      LUOUT=LUTMP
C
C
C SOURCE INTEGRATION
C LOOP STRUCTURE IS (FREQ(SPACE(DIRECTION)))
C
      DO 56 KSS=1,NPTS
      IUW=WINDA(KSS)
      WTH=WDIR(KSS)*RADC
      L=LDEP(KSS)
      IANG=WTH/AINC + 1.5
      KFRQ=KFA(KSS)
      IF (KFRQ.LE.NFREQ) GO TO 13
      SC(KSS)=0.
      FO=FOA(KSS)
      ALP=ALPHA(KSS)
      GO TO 14
   13 CONTINUE
      EMU=XCR(KFRQ,L)
      IF(IANG.GT.NDIR) IANG=1
      IWDIR=THOA(KSS)/AINC+1.5
      IF(IWDIR.GT.16)IWDIR=1
      KSSU=KSSA(KSS,IWDIR)
      IF(KSSU.GT.NPTOT) GOTO 8343
      EMFU=EMU
      EMF=1.-EMFU
      ALP=ALPHA(KSS)*EMF+ALPHA(KSSU)*EMFU
      FOI=FOA(KSS)*EMF+FOA(KSSU)*EMFU
      FO=(FOI**(-2.333)+TPRM/2.*USTA(IUW)**1.333)**(-0.4285741)
      ALP=(FO/FOI)**0.66666 *ALP
      GOTO 8848
 8343 CONTINUE
      FOI=FOA(KSS)
      FO=(FOI**(-2.333)+TPRM/2.*USTA(IUW)**1.33)**(-0.4285741)
      ALP=(FO/FOI)**0.66666*ALPHA(KSS)
      IF(FO.GT.FFLIM(IUW)) GO TO 8848
      FO=FFLIM(IUW)*RM33(KFRQ,L)
      ALP=ALP*RM22(KFRQ,L)
```

```
 8848 SC(KSS)= 2500. * ALP**3 / FO**4
   14 CONTINUE
      FOOO(KSS)=1./FO
     F02(KSS)=(FO**(-2.333)+TPRM/2.*USTA(IUW)**1.333)**(-0.4285741)
      ALP2(KSS)=(F02(KSS)/FO)**0.66666 *ALP
   56  CONTINUE
   501 CONTINUE
      DO 4468 KSS=1,NPTS
      IU=WINDA(KSS)
      XX=FSUM(KSS)
      IF(XX.GT.F02(KSS))XX=F02(KSS)
      XX=FPM(IU)/XX
      IF(XX.GT.1.0) XX=1.0
      XPM(KSS)=XX**4
 4468 CONTINUE
C
C START FREQUENCY LOOP
C
      REWIND LUIN
      REWIND LUOUT
 3073 DO 50 ITF=1,NFREQ
      BUFFER IN(LUIN,0)(TEL(1,1),TEL(500,16))
      F=FF(ITF)
      F100=F*100.
      SINFF=SINF(ITF)/AINC
      IOERR=UNIT(LUIN)
C
C TOUCHDOWN DEPTH
C
      TDD=(9.81/(F**2*6.283))*0.5
C
C START OF SPACE LOOP
C
      DO 57 KSS=1,NPTS
      SUM=EL(KSS,ITF)
      L=LDEP(KSS)
      RDISS=(CHI(ITF,L)**2*PHI(ITF,L))
      XFACTR(KSS)=1.0
      SINFKS=SINF(ITF)/AINC*ALPHA(KSS)
      IF(FF(ITF).GE. 0.7*FOA(KSS)) GO TO 785
      IF(SUM.GE. 1.0)       GO TO 785
      GO TO 789
  785 CONTINUE
C
      KFRQ=KFA(KSS)
      L=LDEP(KSS)
      KTF=ITF-NF5(KSS)+1
      IF(KTF.LT.1 .OR. KTF.GT.5)KTF=1
      EPI=EPMTRX(KTF,KSS)
      WTH=WDIR(KSS)*RADC
```

```
      IANG=WTH/AINC+1.5
      IF(IANG.GT.NDIR)IANG=1
      THO=THOA(KSS)
      TH2=(IANG-1)*AINC
      IU2=WINDA(KSS)
      XX1=XPM(KSS)
      XX2=-1.25*(FPM(IU2)/(FF(ITF)*CHI(ITF,L)))**4
      XFACT=1.-XX1+XX1*EXPOS(XX2)
      IF(XFACT.LT.0.0)XFACT=0.00001
      XFACTR(KSS)=XFACT
      IF(FF(ITF).LT.0.95*FPM(IU2))XFACTR(KSS)=1.
C
      FOI=FOOO(KSS)
      IFR=FOI*F100
      SCIFR=SC(KSS)*SNLA(IFR)*XFACT
      SC2= -1.25*SCIFR
      IF(SC2.LT.0.0)SC2=0.0
      SUM=0.0
C
C SHALLOW WATER CALCULATIONS
C
      DO 901 IDIR=1,NDIR
      RDAM(IDIR)=1.0
      RREF(IDIR)=0.0
  901 CONTINUE
C
C DEPTH FIELD
C
      CPDEP= DEPTH(L)
      DO 923 IDIR=1,15,2
      KSSU=KSSA(KSS,IDIR)
      BPDEP(IDIR)=0.0
      IF(KSSU.LT.NPTS1)GO TO 939
      I=LOCI(KSS)+IUA(IDIR)
      J=LOCJ(KSS)+JUA(IDIR)
      LKU=LOCC(I,J)*(-1)
      BPDEP(IDIR)=DEPTH(LKU)
      GO TO 923
  939 LKU=LDEP(KSSU)
      BPDEP(IDIR)=DEPTH(LKU)
  923 CONTINUE
      DO 924 IDIR=2,16,2
      IDIRP1=IDIR+1
      IF(IDIRP1.GT.NDIR)IDIRP1=1
      IDIRM1=IDIR-1
      BPDEP(IDIR)=CPDEP*0.076
     *      +((BPDEP(IDIRP1)+BPDEP(IDIRM1))/2.0)*0.924
  924 CONTINUE
C
C START OF ANGLE LOOP
C
```

```
C
C REFRACTION AND DAMPING FACTORS
C
      DO 925 IA=1,NDIR
      DDX=DX
      TDPMIN=AMIN1(BPDEP(IA),CPDEP)
      IF(TDPMIN.GT.TDD) GO TO 925
      GO TO (931,932,932,932,933,934,934,934,935,936,936,936,
     1       937,938,938,938),IA
C
  931 XSS1=BPDEP(4)
      XSS2=BPDEP(14)
      XSS3=CPDEP
      XSS4=BPDEP(1)
      DDYY=DDX*2.
      DDXX=DDX
      GO TO 940
  932 XSS1=BPDEP(4)
      XSS2=(CPDEP+BPDEP(1))/2.0
      XSS3=(CPDEP+BPDEP(5))/2.0
      XSS4=BPDEP(2)
      IF(IA.EQ.3)DDX=DX*1.414
      DDYY=DDX
      DDXX=DDX
      GO TO 940
  933 XSS1=BPDEP(5)
      XSS2=CPDEP
      XSS3=BPDEP(8)
      XSS4=BPDEP(2)
      DDYY=DDX
      DDXX=DDX*2.
      GO TO 940
  934 XSS1=BPDEP(6)
      XSS2=(CPDEP+BPDEP(9))/2.0
      XSS3=BPDEP(8)
      XSS4=(CPDEP+BPDEP(5))/2.0
      IF(IA.EQ.7) DDX=DX*1.414
      DDYY=DDX
      DDXX=DDX
      GO TO 940
  935 XSS1=BPDEP(6)
      XSS2=BPDEP(12)
      XSS3=BPDEP(9)
      XSS4=CPDEP
      DDYY=DDX*2.
      DDXX=DDX
      GO TO 940
  936 XSS1=(CPDEP+BPDEP(9))/2.0
      XSS2=BPDEP(12)
      XSS3=BPDEP(10)
      XSS4=(CPDEP+BPDEP(13))/2.0
```

```
      IF(IA.EQ.11) DDX=DX*1.414
      DDYY=DDX
      DDXX=DDX
      GO TO 940
  937 XSS1=CPDEP
      XSS2=BPDEP(13)
      XSS3=BPDEP(10)
      XSS4=BPDEP(16)
      DDYY=DDX
      DDXX=DDX*2.
      GO TO 940
  938 XSS1=(CPDEP+BPDEP(1))/2.0
      XSS2=BPDEP(14)
      XSS3=(CPDEP+BPDEP(13))/2.0
      XSS4=BPDEP(16)
      IF(IA.EQ.15) DDX=DX*1.414
      DDYY=DDX
      DDXX=DDX
  940 CONTINUE
C
      DHDY= -(XSS1-XSS2)/DDYY
      DHDX= -(XSS3-XSS4)/DDXX
      LB=BPDEP(IA)+2.5
      LB=IDEPCD(LB)
      LC=LDEP(KSS)
C
C FACTORS AT MAXIMUM DEPTH
C
      TDPMAX=AMAX1(BPDEP(IA),CPDEP)
      L1=TDPMAX+2.5
      L1=IDEPCD(L1)
      TKWH2=2.0*CHI(ITF,L1)*OMEGA(ITF,L1)**2
      L=LDEP(KSS)
      DTDTMAX=-CG(ITF,L)*((DHDY*COSR(IA)
     1                    +DHDX*SINR(IA))
     1                    /TDPMAX          )
     1          *TKWH2/(SINH(TKWH2)+TKWH2)
      DELTT=DDX/CG(ITF,L)
      IF(TDPMAX.GT.TDD)DELTT=DELTT*(TDD-TDPMIN)/(TDPMAX-TDPMIN)
      RTOU=-CDAMP/(9.81**2)*(OMEGA(ITF,L1)**2/(DEPTH(L1)*100./G))/
     1    ((SINH((OMEGA(ITF,L1)**2)*CHI(ITF,L1)))**2)*DELTT
      RDMPMAX=EXPOS(RTOU)
C
C FACTORS AT MINIMUM DEPTH
C
      L1=TDPMIN+2.5
      L1=IDEPCD(L1)
      TKWH2= 2.0*CHI(ITF,L1)*OMEGA(ITF,L1)**2
      DTDTMIN=-CG(ITF,L)*((DHDY*COSR(IA)
     1                    +DHDX*SINR(IA))
     1                    /TDPMIN          )
```

```
     1          *TKWH2/(SINH(TKWH2)+TKWH2)
      RTOU= -CDAMP/(9.81**2)*(OMEGA(ITF,L1)**2/(DEPTH(L1)*100./G))/
     1    ((SINH((OMEGA(ITF,L1)**2)*CHI(ITF,L1)))**2)*DELTT
      RDMPMIN=EXPOS(RTOU)
C
C TOUCHDOWN AVERAGE FACTOR
C
      DTDTIA=(DTDTMAX+DTDTMIN)/2.0
      IF(TDPMAX.GT.TDD)DTDTIA=DTDTIA*(TDD-TDPMIN)/(TDPMAX-TDPMIN)
      IF(DTDTIA*TINC.GT.AINC)DTDTIA=AINC/TINC
      IF(DTDTIA.LT.0.0 .AND. DTDTIA*TINC*(-1.0).GT.AINC)
     1  DTDTIA=(-1.0)*AINC/TINC
      RREF(IA)=DTDTIA
C
      RDAMP=(RDMPMIN+RDMPMAX)/2.0
      RDAM(IA)=1.0-(TINC*CG(ITF,L)/DDX)*(1.0-RDAMP)
C
  925 CONTINUE
C
C ANGLE SOURCE TERM GROWTH
C
      DO 55 IDIR=1,NDIR
      IADIF=IABS(WDIR(KSS)-INGLE(IDIR))+1
      IA=IAAD(IADIF)
      ESP=(TEL(KSS,IDIR)+EPI*COSSQ(IA))
      ESP=ESP*RDAM(IDIR)
      THDIF=ABS(ANGL(IDIR)-THO)
      ITHDIF=RADDEG*THDIF+1.01
      ITHDIF=IAAD(ITHDIF)
      THDIF=ABS(ANGL(IDIR)-TH2)
      JTHDIF=RADDEG*THDIF+1.01
      JTHDIF=IAAD(JTHDIF)
      WNDSRC=(SC2*GAMANG(JTHDIF))
     *          /RDISS*(1.+RDAM(IDIR))/2.
      SNL=(SCIFR*GAMANG(ITHDIF))
     *          /RDISS*(1.+RDAM(IDIR))/2.
C
      EN=ESP+(SNL+WNDSRC)*TINC
      IF(EN.LT.1.0E-5) EN=1.0E-5
      EREFRR(IDIR)=EN
C
   55 CONTINUE
C
C REFRACTION
C
      DO 120 IDIR=1,NDIR
      IDIRP1=IDIR+1
      IF(IDIRP1.GT.NDIR)IDIRP1=1
      IDIRM1=IDIR-1
      IF(IDIRM1.LT.1)IDIRM1=NDIR
      EPHON(IDIR)=
```

```
     1     EREFRR(IDIR)*(1.0-ABS(RREF(IDIR)*TINC/AINC))
     1    +EREFRR(IDIRM1)*(AMAX1(0.0,RREF(IDIRM1)*TINC/AINC))
     1    -EREFRR(IDIRP1)*(AMIN1(0.0,RREF(IDIRP1)*TINC/AINC))
      SUM=SUM+EPHON(IDIR)
  120 CONTINUE
C END OF ANGLE LOOP
C
C
      I=LOCI(KSS)
      J=LOCJ(KSS)
      L=LDEP(KSS)
      IU=WINDA(KSS)
      XXPM=XPM(KSS)
      IF(FF(ITF).LT.0.95*FPM(IU)) XXPM=1.
      XXA=1.0-XXPM
      IF(KFA(KSS).LT.NFREQ-2)GO TO 870
      UST1=USTA(WINDA(KSS))
      F02X=F02(KSS)
      FMBAR=F02X*UST1/G
      UST1=UST1**4
      HIGH1=EPRM*FMBAR**(-3.3333)*UST1
      ALP=HBARF(HIGH1,UST1)
      IF(ALP.GT.ALP2(KSS))ALP=ALP2(KSS)
      GO TO 5012
  870 ALP=ALP2(KSS)
 5012 SINFKS=(SINFF/RDISS)*
     1        (ALP*XXA+PM(IU,ITF)**(1./CHI(ITF,L)**4)*XXPM*0.0081)
        IF(SUM.LT.SINFKS) GOTO 968
      ALP2(KSS)=ALP
      RNORM=SINFKS/SUM
      SUM=SINFKS
      DO 58 IDIR=1,NDIR
      EPHON(IDIR)=EPHON(IDIR)*RNORM
   58 CONTINUE
  968 IF(ITF.LT.AFQ7(IU)) GO TO 68
      CALL DOTPRD(EPHON,COSR,XSUM)
      CALL DOTPRD(EPHON,SINR,YSUM)
      USUM(KSS)=USUM(KSS)+XSUM*DELF(ITF)
      VSUM(KSS)=VSUM(KSS)+YSUM*DELF(ITF)
      IF(SUM.LT.SINFKS)GO TO 68
      EF(KSS)=SINFKS
      ESUM(KSS)=ESUM(KSS)+SINFKS*DELF(ITF)
     *          *RDISS/XFACTR(KSS)
      DO 69 IA=1,16
      TEL(KSS,IA)=EPHON(IA)
   69 CONTINUE
      GO TO 57
   68 CONTINUE
      DO 64 IA=1,16
      TEL(KSS,IA)=EPHON(IA)
   64 CONTINUE
```

```
  789 AF07(KSS)=ITF
      SINFKR(KSS)=SINFKS*AINC
      EF(KSS)=SUM
      ESUM(KSS)=ESUM(KSS)+SUM*DELF(ITF)
     *            *RDISS/XFACTR(KSS)
  57  CONTINUE
C
C END OF SPACE LOOP
C
      BUFFER OUT(LUOUT,0)(TEL(1,1),TEL(500,16))
      DO 51 KSS=1,NPTS
   51 EL(KSS,ITF)=EF(KSS)
      IOERR=UNIT(LUOUT)
   50 CONTINUE
      LUTMP=LUIN
      LUIN=LUOUT
      LUOUT=LUTMP
C
C END OF FREQUENCY LOOP
C
C
C PEAK ENERGY BIN
C
      DO 317 KSS=1,NPTS
      EMAXTM=0.0
      KF07=NFREQ
      DO 983 ITF=1,NFREQ
      EMAXIM=EL(KSS,ITF)
      IF(EMAXIM.LT.EMAXTM+1.0)GO TO 983
      EMAXTM=EMAXIM
      KF07=ITF
  983 CONTINUE
      FSUM(KSS)=FF(KF07)
      KFA(KSS)=KF07
  317 CONTINUE
C
      DO 66 KSS=1,NPTS
      KFRQ=AF07(KSS)+1
      IF(KFRQ.LT.20) GO TO 123
      IF(KFA(KSS).LT.20) GO TO 123
      IF(FOA(KSS).LT.FF(NFREQ)) FOA(KSS)=FF(NFREQ)
C
C
C PARAMETRIC HIGH FREQUENCY
C
      IU=WINDA(KSS)
      UST1=USTA(IU)
      IWDIR=THOA(KSS)/AINC+1.5
      IF(IWDIR.GT.16) IWDIR=1
      KSSU=KSSA(KSS,IWDIR)
      IF(KSSU.LE.NPTS) GOTO 7740
```

```
      IF(FOA(KSS).LT.FFLIM(IU)) FOA(KSS)=FFLIM(IU)
 7740 T=(FOA(KSS)**(-2.33333)+TPRM*(UST1)**(1.33333))**(0.4285714)
      FOA(KSS)=1./T
      FSUM(KSS)=1./T
      IF(FOA(KSS).LT.FMX(IU)) FOA(KSS)=FMX(IU)
      ITF=NFREQ
      IF(FOA(KSS).GT.FF(20))GO TO 5010
      DO 6888 ITF=12,NFREQ
      IF(FOA(KSS).LE.FF(ITF)+DELF(ITF))GO TO 6889
 6888 CONTINUE
 6889 KFA(KSS)=ITF
 5010 NF5(KSS)=ITF-3
      IF(NF5(KSS).GT.16) NF5(KSS)=16
C
C CALCULATE ENERGY INTO DISCRETE SPECTRUM FROM PARAMETRIC SOURCE
C
      FMBAR=FOA(KSS)*UST1/G
      UST1=USTA4(IU)
      HIGHE=EPRM*FMBAR**(-3.3333)*UST1
      HSCALE(KSS)=HIGHE
      EA(KSS)=HIGHE
      ALPHA(KSS)=HBARF(EA(KSS),UST1)
      EFM=FOA(KSS)**(-5) *ECONST*ALPHA(KSS)
      DO 8846 NPN=2,5
      NPM=NF5(KSS)-1+NPN
      XE=EFM*EXPOS(-(FF(NPM)/FOA(KSS))**(-4.))
      IF (FOA(KSS).LT.FF(NPM)) XE=ALPHA(KSS)*ECONST/FF(NPM)**5
      XED=XE-EL(KSS,NPM)*AINC
      IF(XED.LT.0.0)XED=0.0
 8846 EPMTRX(NPN,KSS)=XED*EPINRM
      THOA(KSS)=WDIR(KSS)*RADC
      GOTO 66
  123 IU=WINDA(KSS)
      IANG=WDIR(KSS)/22.5+1.5
      IF(IANG.GT.NDIR) IANG=1
      DO 9951 NPN=2,5
 9951 EPMTRX(NPN,KSS)=0.
      HIGHE=HEO*ALP2(KSS)
      USUM(KSS)=USUM(KSS)*AINC+HIGHE*COSR(IANG)
      VSUM(KSS)=VSUM(KSS)*AINC+HIGHE*SINR(IANG)
      USUM(KSS)=USUM(KSS)+0.000001
      X=VSUM(KSS)
      Y=USUM(KSS)
      THOA(KSS)=ATAN2(X,Y)
      IF(THOA(KSS).LT.0.) THOA(KSS)=THOA(KSS)+TWOPI
      EA(KSS)=(ESUM(KSS)*AINC) +HIGHE
      UST1=USTA4(IU)
      ALPHA(KSS)=HBARF(EA(KSS),UST1)
      HSCALE(KSS)=ALPHA(KSS)*
     *          (DEPTH(L)*100./(2.*CHI(22,L)*OMEGA(22,L)**2))**2
      L=LDEP(KSS)
```

```
      KFRQ=AF07(KSS)
      ZMIN=ZFL(KFRQ)*EL(KSS,KFRQ+1)*AINC
      Z1=EL(KSS,KFRQ)*AINC-ZMIN
      Z2=SINFKR(KSS)-ZMIN
      Z2=ABS(Z2)+0.001
      PC=Z1/Z2
      IF(PC.LT.0.0)PC=0.0
      IF(PC.GT.1.0)PC=1.0
      FOA(KSS)=FF(KFRQ+1)-2.*PC*DF2(KFRQ)
      IF(ABS(THOA(KSS)-RADC*WDIR(KSS)).GT.0.8) GO TO 66
      IF(FOA(KSS).GT.FF(KFA(KSS)+1))FOA(KSS)=FSUM(KSS)
  66  CONTINUE
C
C END OF TIME STEP LOOP
C
C
C DATA CYCLE OUTPUTS
C
      IF(MSTA.LT.1) GO TO 4651
      IF(IPRF.NE.1)GOTO 4651
      REWIND LUIN
      DO 300 ITF=1,20
      BUFFER IN (LUIN,0)(TEL(1,1),TEL(500,16))
      IOERR=UNIT(LUIN)
      DO 300 IA=1,16
      DO 300 I01=1,MSTA
      KSS=LLOUT(I01)
      TEL1(IA,ITF,I01)=TEL(KSS,IA)
 300  CONTINUE
C
C STATION CYCLE
C
      DO 301 ISTA=1,MSTA
      IF(LLOUT(ISTA).GT.NPTS)GO TO 301
      ICODE=3
      WRITE(11,302)ICODE
 302  FORMAT(I2,8X,8X,*HR*,7X,*MAP*,3X,*DATE-TIME*,2X,
     1       *STATION#*,9X,*I*,9X,*J*,2X,*LATITUDE*,1X,
     2       *LONGITUDE*,2X,*DEPTH(M)*)
      I=LOUT(ISTA,1)
      J=LOUT(ISTA,2)
      KSS=LOCC(I,J)
      IF(KSS.LE.NPTS) GOTO303
      DO 304 I01=2,50
 304  WRITE(11,305)
 305  FORMAT(*00*,8X)
      GOTO 301
 303  IDEPTH=DEPTH(LDEP(KSS))
      ICODE=4
      WRITE(11,306)ICODE,HRS,NMAP,IDP,ISTA,I,J,LOUT(ISTA,3),
     1             LOUT(ISTA,4),IDEPTH
```

```
 306 FORMAT(I2,8X,F10.2,I10,2X,7I10)
     ICODE=5
     WRITE(11,307)ICODE
 307 FORMAT(I2,8X,*A V E R A G E*,21X,* S E A*,23X,*S W E L L*)
     ICODE=6
     WRITE(11,308)ICODE
 308 FORMAT(I2,8X,3(4X,*HEIGHT*,4X,*PERIOD*,1X,*DIRECTION*))
C
C SEA AND SWELL
C
     SUM=0.0
     USS=1.0E-5
     VSS=0.0
     FSS=1.0E-5
     DO 309 ITF=1,NFREQ
     EF(ITF)=EL(KSS,ITF)*AINC
     SUM=SUM+EF(ITF)*DELF(ITF)
     FSS=FSS+EF(ITF)*DELF(ITF)*FF(ITF)
     DO 309 IA=1,16
     USS=USS+TEL1(IA,ITF,ISTA)*COSR(IA)
     VSS=VSS+TEL1(IA,ITF,ISTA)*SINR(IA)
 309 CONTINUE
     TSS=SUM/FSS
     IF(TSS.LT.1.0/FF(20)) TSS=1.3/FOA(KSS)
     TANG=ATAN2(VSS,USS)*RADDEG
     IF(TANG.LT.0.) TANG=TANG+360
     TOA=1.0/FOA(KSS)
     TSWL=1.0/FF(ISWO(KSS))
     THSEA=THOA(KSS)*RADDEG
     SUM=SUM+HSCALE(KSS)
3501 ESWL(KSS)=0.0
     I11=KFA(KSS)-1
     IF(I11.LT.1)I11=1
     DO 8701 ITF=1,I11
     XX=2.718*EXPOS(-(FOA(KSS)/FF(ITF))**4)
     IF(XX.GT.1.0) XX=1.0
     ESWL(KSS)=ESWL(KSS)+EF(ITF)*DELF(ITF)*(1.-XX)
8701 CONTINUE
     HSWL=4.01*SQRT(ESWL(KSS)+1.0E-10)
     IF(TSWL.NE.1.) GOTO 8715
     HSWL=0.
     ESWL(KSS)=0.
     THSWL=0.
     GOTO 8716
8715 XC=0.
     YC=0.
     I10=KFA(KSS)
     DO 8702 ITF=1,I10
     RR=1.-EXPOS(-(FOA(KSS)/FF(ITF))**4)*2.718282
     IF(RR.LT.0.0)RR=0.0
     DO 8702 IA=1,16
```

```
      XC=XC+TEL1(IA,ITF,ISTA)*COSR(IA)*RR
      YC=YC+TEL1(IA,ITF,ISTA)*SINR(IA)*RR
 8702 CONTINUE
      THSWL=ATAN2(YC,XC+1.0E-10)*RADDEG
      IF(THSWL.LT.0.) THSWL=THSWL+360.
 8716 ESEA=SUM-ESWL(KSS)
      HSEA=4.01*SQRT(ESEA+1.0E-10)
      HT=4.01*SQRT(SUM+1.0E-10)
      ICODE=7
      WRITE(11,310) ICODE,HT,TSS,TANG,HSEA,TOA,THSEA,
     1              HSWL,TSWL,THSWL
  310 FORMAT(I2,8X,9F10.1)
C 1-DIMENSIONAL SPECTRUM
C
      ICODE=8
      WRITE(11,321) ICODE
  321 FORMAT(I2,8X,*1 DIM. SPECTRUM...ENERGY FOR: FREQUENCIES*,
     1       * .0588 TO .091,  .1 TO .143, .154 TO .25 +HSCALE*)
      DO 311 ITF=1,NFREQ
  311 EL1(ITF)=EL(KSS,ITF)*AINC
      ICODE=9
      WRITE(11,312) ICODE,(EL1(ITF),ITF=1,7)
      ICODE=10
      WRITE(11,312) ICODE,(EL1(ITF),ITF=8,14)
      ICODE=11
      WRITE(11,312) ICODE,(EL1(ITF),ITF=15,20),HSCALE(KSS)
  312 FORMAT(I2,8X,7E13.6)
C
C 2 DIMENSIONAL SPECRUM
C
      ICODE=12
      WRITE(11,313) ICODE
  313 FORMAT(I2,8X,*2 DIM. SPECTRUM *,
     2       *... FOR DIRECTIONS 1-8/9-16(ACROSS) (DIRECTION *,
     3       *AS  RESIO CONVENTION)*)
      ICODE=13
      DO 314 ITF=1,NFREQ
      DO 316 IA=1,NDIR
      TEL1(IA,ITF,ISTA)=TEL1(IA,ITF,ISTA)*AINC
  316 IF(TEL1(IA,ITF,ISTA).LT.1.0)TEL1(IA,ITF,ISTA)=0.0
      WRITE(11,315)ICODE,FF(ITF),(TEL1(IA,ITF,ISTA),IA=1,8)
      WRITE(11,315)ICODE,FF(ITF),(TEL1(IA,ITF,ISTA),IA=9,16)
  315 FORMAT(I2,2X,F6.4,8E10.3)
  314 CONTINUE
C
C END OF SINGLE STATION
C
  301 CONTINUE
```

```
C
C PRINT THE WAVES FOR AREA OF INTEREST
C
      PRINT 628,HRS
      WRITE(15,628) HRS
  628 FORMAT(1H1,2X,*AREA WAVES AT END OF:*,F10.2,*HRS*,
     1        * - HEIGHT(CM),PEAK SEA PERIOD(SEC),DIRECTION*,
     2        *(ZERO DEREES POINTS TO RIGHT)*)
      REWIND LUIN
      DO 319 KSS=1,NPTS
      USUM(KSS)=0.0
  319 VSUM(KSS)=0.0
      REWIND LUIN
      DO 318 ITF=1,20
      BUFFER IN (LUIN,0)(TEL(1,1),TEL(500,16))
      IOERR=UNIT(LUIN)
      DO 318 KSS=1,NPTS
      DO 320 IA=1,16
  320 EPHON(IA)=TEL(KSS,IA)
      CALL DOTPRD (EPHON,COSR,XSUM)
      CALL DOTPRD (EPHON,SINR,YSUM)
      USUM(KSS)=USUM(KSS)+XSUM*DELF(ITF)
  318 VSUM(KSS)=VSUM(KSS)+YSUM*DELF(ITF)
      REWIND LUIN
C
      DO 325 KSS=1,NPTS
      IANG=WDIR(KSS)/22.5+1.5
      IF(IANG.GT.NDIR)IANG=1
      USUM(KSS)=USUM(KSS)*AINC+HSCALE(KSS)*COSR(IANG)+0.0000001
      VSUM(KSS)=VSUM(KSS)*AINC+HSCALE(KSS)*SINR(IANG)
      X=VSUM(KSS)
      Y=USUM(KSS)
  325 USUM(KSS)=ATAN2(X,Y)
C
      DO 630 J02=1,M
      LEAP(J02)=J02
  630 CONTINUE
      JB=1
      JF=21
      IF(M.LT.21)JF=M
  626 PRINT 629,(LEAP(J02),J02=JB,JF)
  629 FORMAT(2X,*I/J*,2X,21I6/)
      WRITE(15,629) (LEAP(J02),J02=JB,JF)
      DO 625 I01=1,N
      DO 622 J01=JB,JF
      JINT=JF-JB+1
      ENA(J01)=0.0
      ENA(J01+JINT)=0.0
      ENA(J01+JINT+JINT)=0.0
      KSS=LOCC(I01,J01)
      IF(KSS.LT.1) GO TO 622
```

```
      SUM1=0.0
      DO 623 ITF=1,20
  623 SUM1=SUM1+EL(KSS,ITF)*AINC*DELF(ITF)
      SUM1=SUM1+HSCALE(KSS)
      ENA(J01)=4.01*SQRT(SUM1+1.0E-10)
      ENA(J01+JINT)=1./FSUM(KSS)
      ENA(J01+JINT+JINT)=USUM(KSS)*RADDEG
  622 CONTINUE
      PRINT 624,I01,(ENA(J01),J01=JB,JF)
      WRITE(15,624) I01,(ENA(J01),J01=JB,JF)
      M1=JF+1
      M2=JF+JINT
      PRINT 624,I01,(ENA(J01),J01=M1,M2)
      WRITE(15,624) I01,(ENA(J01),J01=M1,M2)
      M1=JF+JINT+1
      M2=JF+JINT+JINT
      PRINT 624,I01,(ENA(J01),J01=M1,M2)
      WRITE(15,624) I01,(ENA(J01),J01=M1,M2)
  624 FORMAT(2X,I3,2X,21F6.1)
  625 CONTINUE
      JB=JB+21
      JF=JF+21
      IF(JF.GT.M)JF=M
      IF(JB.LT.M)GO TO 626
C
C END OF TIME STEP OUTPUTS
C
      CALL SECOND(T2)
      T1=T2-T1
      PRINT 4655, T1
 4655 FORMAT(1X,"TIME FOR ONE MAP",F12.6," SECS")
 4651 CONTINUE
 1001 CONTINUE
 1000 CONTINUE
 9999 CONTINUE
 9998 STOP
      END
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C SUBROUTINES - FUNCTIONS - SUBROUTINES - FUNCTIONS - SUBROUTINES
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C BUILD A FILE OF 25 RECORDS PER BLOCK, 120 CHAR PER REC
C
      SUBROUTINE BUILD(IFILE,IREC,ICODE)
      COMMON ISTRING(12)
      IREC=0
    1 READ(IFILE,1000) (ISTRING(J),J=1,12)
 1000 FORMAT(12A10)
      IF(EOF(IFILE)) 999,2
    2 CONTINUE
      WRITE(11,2000) ICODE,(ISTRING(J),J=1,12)
 2000 FORMAT(I2,8X,12A10)
      IREC=IREC+1
      GOTO 1
  999 CALL BLANK(IREC,ICODE)
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C FILL REST OF BLOCK WITH BLANK RECORDS
C
      SUBROUTINE BLANK (IREC,ICODE)
    5 IF(IREC .LT. 25) GO TO 6
      IREC=IREC-25
      GO TO 5
    6 IREC=IREC+1
      IF(IREC .LE. 1) RETURN
      DO 1 I=IREC,25
      WRITE(11,1000)ICODE
 1000 FORMAT(I2,8X)
    1 CONTINUE
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C PHILLIPS CONSTANT
C
      FUNCTION HBARF (E,UST4)
      EBAR=960400.*E/UST4
      HBARF=0.044*EBAR**(-0.2)
      IF (HBARF.LT.0.008) HBARF=0.008
      RETURN
      END
C
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C VECTOR DIRECTION
C
      SUBROUTINE DOTPRD(X,Y,Z)
      DIMENSION X(16),Y(16)
      Z=0.
      DO 1 I=1,16
      Z=Z+X(I)*Y(I)
    1 CONTINUE
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C DEPTH IN METERS FROM DEPTH CODE
C
      FUNCTION DEPTH(L)
      DEPTH=FLOAT(L)
      IF(L.LE.16) DEPTH=(L*5.)
      IF(L.GT.16) DEPTH=(L-16)*10.+80.0
      IF(L .EQ. 20) DEPTH=999.9
      IF(L.LT.1)DEPTH=5.0
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C DEPTH CODE FROM DEPTH IN METERS
C
      FUNCTION IDEPCD(L)
      IF(L.LT.80) J=L/5
      IF(80.LE.L.AND.L.LE.120) J=(L+5-80)/10.+16.
      IF(L.GT.120) J=20
      IDEPCD=J
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C NATURAL NUMBER EXPONENTIAL VALUES
C
      FUNCTION EXPOS (X)
      IF(X.GT.-670.0) GOTO 101
      EXPOS=0.0
      RETURN
  101 IF(X.GT.741.0)GOTO 103
      EXPOS=EXP(X)
      RETURN
  103 EXPOS=EXP(741.0)
      RETURN
      END
```

```
...........................................................................
...........................................................................
...........................................................................
.......ICE PACK.........                            .........................
........................ 999 999 999 999 999 .........................
....................                                    ...................
.................... 999 999 999 999 999 999 999 999 ...................
................                                                 .......
................ 999 999 999 999 999 999 999 999 999 999  60  55 .......
............                                                ............
............ 999 DEEP WATER  999 999 999 999 999 999  70  45 ............
........                                                             ...
........ 999 999 999 999 999 999 999 999 999 999 999  55  30  20  10 +++
                                                                    ++++
....
....  80  70  70 SHALLOW DEPTHS   50  50  50 999 999  80  30  10 +++++++
....                                                             +++++++
....  40  35  35  35  15  25  30  35  40  35  35 150 100  40  10 +++++++
....                                                             +++++++
....  20  20  20  10 +++++++++++  15  25  20 +++++++  50  35   5 +++++++
                   +++++++++++++         +++++++++          +++++++++
....
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++LAND+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
```

GRAPHIC REPRESENTATION OF BATHYMETRIC GRID

Grid point representation	
++++ ++++	permanent land grid points
....	storm specific ice grid points
999	open water point of "infinite" depth
50	open water point of finite depth

Note: The actual model grid is a 55 point horizontal and 40 point vertical system of grid point depths. Permanent land or pack ice points are represented by a " 0 " depth. Temporary or storm specific, pack ice is specified after the digitization program by a negative depth (which is a code to ensure real refraction along the ice edge).

```
      PROGRAM STRMICE
     1         (OUTPUT,TAPE1,TAPE2,TAPE3,TAPE4,TAPE5=OUTPUT)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C STRMICE DETERMINES THE OPEN WATER AREA OF A PREDEFINED STANDARD
C GRID
C
C THE STANDARD GRID FOR THE BEAUFORT SEA SHOWS MAXIMUM RETREAT OF
C THE SEASONAL ICE PACK. THIS PROGRAM INPUTS A SET OF LAT. LONG.
C POINTS WHICH DEFINE THE PACK ICE FOR A SELECTED DAY.
C
C  TAPE1...THE RESSIO FILE  "GDPTS"
C  TAPE2...THE BATHYMETRIC GRID AS WOULD BE INPUT TO TH WAVE MODEL
C                IF MAXIMUM WITHDRAWL OF ICE WERE BEING USED
C  TAPE3...THE JOB INPUT CONTROL PARAMETERS
C          1. A SELECTED OPEN WATER POINT LAT,LONG
C                AND THE NUMBER OF POINTS REPRESENTING THE OVERLAY
C                ICE EDGE LAT,LONG
C          2. IN A SERIES OF ADJACENT ICE EDGE POINTS
C                - A LIST OF LAT,LONG CO-ORDINATES
C  TAPE4...THE OUTPUT FILE FOR INPUT TO THE WAVE MODEL
C  TAPE5...THE HARD COPY OUTPUT
C
C
C  IBATH...THE TAPE2 INPUT
C  XICELAT,XICLON...THE OVERLAY ICE EDGE POINTS
C
C  AGRDLT,AGRDLN...THE TAPE1 INPUT
C  ICE...A CODED FOR IDENTIFYING THE GRID POINTS AS LAND, SEA,
C        ICE EDGE, OLD PACK ICE, DAILY PACK ICE
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      DIMENSION IBATH(40,55),
     *          XICELAT(100) , XICELON(100),
     *          AGRDLT(40,55), AGRDLN(40,55),
     *          ICEI(100),     ICEJ(100),
     *          ICE(40,55),    IDONE(40,55),
     *          KSSAI(4),      KSSAJ(4),
     *          KTITLE(8)
C
      DATA KSSAI/1,-1,0,0/
      DATA KSSAJ/0,0,-1,1/
C
C INITIALIZE
C
      DEGRAD=(2*3.1426)/360.
      IRNUM=1
      DO 18 I=1,40
      DO 18 J=1,55
```

```
      ICE(I,J)=1
   18 IDONE(I,J)=0
      DO 19 K=1,100
      XICELAT(K)=0.
      XICELON(K)=0.
      ICEI(K)=0
      ICEJ(K)=0
   19 CONTINUE
C
C
C READ IN "LEAP"
C
      DO 10 K=1,40
      I=41-K
   10 READ(2,1000)(IBATH(I,J),J=1,21)
      DO 11 K=1,40
      I=41-K
   11 READ(2,1000)(IBATH(I,J),J=22,42)
      DO 12 K=1,40
      I=41-K
   12 READ(2,1001)(IBATH(I,J),J=43,55)
 1000 FORMAT(21I4)
 1001 FORMAT(13I4)
C
C READ IN TAPE3, INPUT CONTROL
C
      READ(3,1006)(KTITLE(K),K=1,8)
 1006 FORMAT(8A10)
      READ(3,1002)SEALAT,SEALON,NUM
 1002 FORMAT(2F12.6,I6)
      DO 13 K=1,NUM
   13 READ(3,1003)XICELAT(K),XICELON(K)
 1003 FORMAT(2F12.6)
C
C READ IN TAPE1, "GRDPTS"
C
      DO 14 K=1,2200
      READ(1,1004)J,I,ALON,ALAT
 1004 FORMAT(2I3,2F12.6)
      AGRDLT(I,J)=ALAT
      AGRDLN(I,J)=ALON
   14 CONTINUE
C
C*********************************************************************
C
C BEGIN PROCESSING
C
C*********************************************************************
C
C LOCATE ICE EDGE ONTO NEAREST I,J GRID POINT
C
```

```
      DO 20 K=1,NUM
      XLON=XICELON(K)
      XLAT=XICELAT(K)
      XICEIJ=100.
         DO 21 I=1,40
         DO 21 J=1,55
         A=(XLON-AGRDLN(I,J))*DEGRAD
         A1=XLAT*DEGRAD
         A=(COS(A1)*ABS(A))**2
         B=(XLAT-AGRDLT(I,J))*DEGRAD
         B=(ABS(B))**2
         C=A+B
         C=SQRT(C)
         IF(C.GE.XICEIJ) GO TO 22
         XICEIJ=C
         ICEI(K)=I
         ICEJ(K)=J
   22 CONTINUE
   21 CONTINUE
      ICE(ICEI(K),ICEJ(K))=-1
   20 CONTINUE
C
C GENERATE SOLID I,J BOUNDRY BY CONECTING UP INPUT ICE EDGE PTS.
C
      NUM1=NUM-1
      DO 30 K=1,NUM1
      I1=ICEI(K)
      I2=ICEI(K+1)
      J1=ICEJ(K)
      J2=ICEJ(K+1)
      IDIF=I2-I1
      JDIF=J2-J1
      IF(I1.EQ.I2.AND.J1.EQ.J2) GO TO 30
      XLENGTH=IDIF**2+JDIF**2
      XLENGTH=SQRT(XLENGTH)
      INUM=XLENGTH*3.+0.5
         DO 31 N=1,INUM
C
C        LOCATE POINT BY SIMILAR TRIANGLES
C
         XI=0.3333*N/XLENGTH *IDIF +I1
         XJ=0.3333*N/XLENGTH *JDIF +J1
C
C        FIND NEAREST GRID POINT FROM SURROUNDING FOUR I,J'S
C
         IA=XI
         JA=XJ
         IB=XI
         JB=XJ+1.0
         IC=XI+1.0
         JC=XJ+1.0
```

```
      ID=XI+1.0
      JD=XJ
      XA=(XI-IA)**2 + (XJ-JA)**2
      XB=(XI-IB)**2 + (XJ-JB)**2
      XC=(XI-IC)**2 + (XJ-JC)**2
      XD=(XI-ID)**2 + (XJ-JD)**2
      KA=SQRT(XA)*1000.
      KB=SQRT(XB)*1000.
      KC=SQRT(XC)*1000.
      KD=SQRT(XD)*1000.
      KPT=MIN0(KA,KB,KC,KD)
      IF(KPT.EQ.KA)ICE(IA,JA)=-1
      IF(KPT.EQ.KB)ICE(IB,JB)=-1
      IF(KPT.EQ.KC)ICE(IC,JC)=-1
      IF(KPT.EQ.KD)ICE(ID,JD)=-1
   31 CONTINUE
   30 CONTINUE
C
C END OF ICE EDGE BOUNDRY
C
C
C FIND NEAREST I,J TO SEA POINT
C
      XLON=SEALON
      XLAT=SEALAT
      XICEIJ=100.
      DO 41 I=1,40
      DO 41 J=1,55
      A=(XLON-AGRDLN(I,J))*DEGRAD
      A1=XLAT*DEGRAD
      A=(COS(A1)*ABS(A))**2
      B=(XLAT-AGRDLT(I,J))*DEGRAD
      B=(ABS(B))**2
      C=A+B
      C=SQRT(C)
      IF(C.GE.XICEIJ)GO TO 42
      XICEIJ=C
      ISEAI=I
      ISEAJ=J
   42 CONTINUE
   41 CONTINUE
      ICE(ISEAI,ISEAJ)=8888
C
C FILL IN OPEN WATER BY CONECTING TO INITIAL SEA POINT
C    AND NOT CROSSING LAND OR ICE EDGE BOUNDRY
C
      JNUM=0
   50 IF(IRNUM.EQ.0) GO TO 60
      IF(JNUM.GT.100)STOP
      IRNUM=0
      DO 51 I=1,40
```

```
      DO 51 J=1,55
      IF(ICE(I,J).NE.8888) GO TO 51
      IF(IDONE(I,J).EQ.1)  GO TO 51
         DO 54 K=1,4
         IBP=I+KSSAI(K)
         JBP=J+KSSAJ(K)
         IF(IBATH(IBP,JBP).EQ.0) GO TO 54
         IF(ICE(IBP,JBP).NE.1)   GO TO 54
         ICE(IBP,JBP)=8888
   54 CONTINUE
      IRNUM=IRNUM+1
      IDONE(I,J)=1
   51 CONTINUE
      JNUM=JNUM+1
      GO TO 50
C
C END OF SEA POINT IDENTIFICATION
C
C*******************************************************************
C
C SETUP OUTPUTS
C
   60 DO 61 I=1,40
      DO 61 J=1,55
      IF(ICE(I,J).EQ.8888)GO TO 62
      IF(IBATH(I,J).EQ.0) GO TO 62
      IBATH(I,J)=IBATH(I,J)*(-1)
   62 IF(ICE(I,J).NE.1) GO TO 61
      IF(IBATH(I,J).EQ.0)ICE(I,J)=0
   61 CONTINUE
C
C WRITE RESULTS
C
C RECORD FILE "LEAP"
C
      WRITE(4,2002)(KTITLE(K),K=1,8)
 2002 FORMAT(8A10)
      DO 70 K=1,40
      I=41-K
   70 WRITE(4,2004)(IBATH(I,J),J=1,21)
      DO 71 K=1,40
      I=41-K
   71 WRITE(4,2004)(IBATH(I,J),J=22,42)
 2004 FORMAT(21I4)
      DO 72 K=1,40
      I=41-K
   72 WRITE(4,2005)(IBATH(I,J),J=43,55)
 2005 FORMAT(13I4)
C
C OUTPUT JOB DIAGNOSTICS
C
```

```
      WRITE(5,2000)
 2000 FORMAT(1H1)
      WRITE(5,2001)(KTITLE(K),K=1,8)
 2001 FORMAT(1X,8A10)
      DO 80 K=1,40
      I=41-K
   80 WRITE(5,2003)(IBATH(I,J),J=1,21)
      WRITE(5,2000)
      DO 81 K=1,40
      I=41-K
   81 WRITE(5,2003)(IBATH(I,J),J=22,42)
 2003 FORMAT(1X,21I4)
      WRITE(5,2000)
      DO 82 K=1,40
      I=41-K
   82 WRITE(5,2006)(IBATH(I,J),J=43,55)
 2006 FORMAT(1X,13I4)
      WRITE(5,2000)
C
C BOUNDRY POINT TABLE
C
      WRITE(5,4000)
 4000 FORMAT(1X,10X,4H NUM,6X,12H  ORIG. LAT.,12H  ORIG. LON.,6X,
     1       4H   I,12H  GRID  LAT.,6X,4H    J,12H  GRID  LON.)
      DO 101 K=1,NUM
  101 WRITE(5,4001)K,XICELAT(K),XICELON(K),
     1              ICEI(K),AGRDLT(ICEI(K),ICEJ(K)),
     1              ICEJ(K),AGRDLN(ICEI(K),ICEJ(K))
 4001 FORMAT(1X,10X,I4,6X,2F12.6,2(6X,I4,F12.6))
      WRITE(5,2000)
C
C LAT,LON GRID WITH ICE CODES
C      ICE CODES:   + 8888 ....SEA POINT
C                   +    0 ....LAND
C                   +   -1 ....ICE EDGE
C                   +    1 ....TEMPORARY PACK ICE FILL
C
      DO 103 K=1,40
      I=41-K
      WRITE(5,4004)(ICE(I,J),J=1,21)
 4004 FORMAT(1X,21(I5,1H+))
      WRITE(5,4002)(AGRDLT(I,J),J=1,21)
      WRITE(5,4002)(AGRDLN(I,J),J=1,21)
 4002 FORMAT(1X,21F6.1)
  103 WRITE(5,4003)
 4003 FORMAT(1X,1X)
      WRITE(5,2000)
      DO 104 K=1,40
      I=41-K
      WRITE(5,4004)(ICE(I,J),J=22,42)
      WRITE(5,4002)(AGRDLT(I,J),J=22,42)
```

```
      WRITE(5,4002)(AGRDLN(I,J),J=22,42)
  104 WRITE(5,4003)
      WRITE(5,2000)
      DO 105 K=1,40
      I=41-K
      WRITE(5,4006)(ICE(I,J),J=43,55)
 4006 FORMAT(1X,13(I5,1H+))
      WRITE(5,4005)(AGRDLT(I,J),J=43,55)
      WRITE(5,4005)(AGRDLN(I,J),J=43,55)
 4005 FORMAT(1X,13F6.1)
  105 WRITE(5,4003)
C
C TOTAL NUMBER OF OPEN WATER PPOINTS
C
      NUM3=0
      DO 106 I=1,40
      DO 106 J=1,55
  106 IF(ICE(I,J).EQ.8888)NUM3=NUM3+1
      WRITE(5,4010) NUM3
 4010 FORMAT(1X,////,1X,"NUMBER OF SEA POINTS = ",I6)
C
      STOP
      END
```