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Wave Information Workshop
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by

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ABSTRACT

Mason, C.S. 1982. Proceedings, Wave Workshop, Bedford Institute of Oceanography, October 7, 8, 9, 1980. Can. Tech. Rep. Hydrogr. Ocean Sci. 2: 128 p.

There is an increasing requirement for information about waves in the offshore regions of Canada. Several different Canadian agencies are active in the provision of wave information and there was an obvious need to plan and coordinate programs and also to determine the types of information about waves which were required. A workshop was held at BIO in 1980 to bring together the various interested scientists and engineers. This report presents the recommendations of the workshop participants and also includes some of the technical presentations. It is hoped that the report will be useful in establishing contacts and providing guidance about wave related problems and information needs.

RESUME

Mason, C.S. 1982. Proceedings, Wave Workshop, Bedford Institue of Oceanography, October 7, 8, 9, 1980. Can. Tech. Rep. Hydrogr. Ocean Sci. 2: 128 p.

On a de plus en plus besoin d'information sur les vagues dans les régions du large de la côte canadienne. Plusieurs organismes canadiens s'occupent activement de fournir cette information, et il existe un besoin évident de planifier et de coordonner les programmes et déterminer le genre d'information requis. Un groupe de travail s'est réuni à l'IOB en 1980 dans le but de permettre aux ingénieurs et scientifiques concernés de se recontrer. Le rapport qui suit contient les recommandations du groupe ainsi que quelques-uns des travaux présentés. Nous espérons que ce rapport favorisera les contacts et servira de guide quant aux problémes et les besoins en information sur les vagues.

WAVE INFORMATION WORKSHOP

BEDFORD INSTITUTE OF OCEANOGRAPHY

OCTOBER 7,8,9, 1980

CONTENTS

The Organizing Committee Gratefully
Acknowledges the Assistance of Petro Canada

OBJECTIVES

(a) To identify wave information in areas of Canadian interest (exclusive of surf zone).

(b) To review modern techniques for acquiring wave information.

(c) Recommendations, including review of gaps in data, information and services, co-ordination of programs, priority requirements, cost effectiveness, and so forth.

REPORT OF THE DISCUSSIONS OF WORKING GROUP A1-

Chairman: P. LeBlond, Department of Oceanography, University of British Columbia.

Terms of Reference

Wave Climate

This group will address observation programs and methods leading to the specifications of wave climate. Topics of concern include:

1. The relative merits and limitations of various methods (hindcasting, direct measurement, visual observations, remote sensing) leading to the definition of "design wave conditions".
2. Recognition of the role of swell and episodic waves in wave climate definition.
3. Strategies for the incorporation of satellite data in wave information systems.
4. Particular problems of data acquisition and instrumentation.

List of Participants

Vincent J. Cardone	Ocean Weather Inc.., White Plains, N.Y.
Donald T. Resio	U.S. Army Corps of Engineers, Vicksburg, MS
Douglas J. Evans	Evans-Hamilton Inc., Bethesda, MD
Simon G.P. Skey	Plansearch Inc., Dartmouth, N.S.
Ole G. Houmb	Norway Inst. of Technology, Norway
Ron Goodman	ESSO Resources Canada, Calgary
Bill Baird	Hydrotechnology LTD., Ottawa
Gabriel Godin	Fisheries & Oceans, Ottawa
Joseph Buckley	Petro-Canada, Calgary
Fred Dobson	Bedford Institute of Oceanography
Ian Wilkes	Hermes Electronics - Dartmouth, N.S.
Jim Gower	I.O.S. Pat Bay

Chris Glodowski	Public Works Canada, Ottawa
Denis Lefaivre	Bedford Institute of Oceanography
Stuart D. Smith	Bedford Institute of Oceanography
Garry J. Purcell	Nordco, Ltd., St. John's, Nfld.
David W. Pluth	Petro-Canada, Calgary
Walter Spring	Mobil R&D Corp
Mark Donelan	Canada Centre for Inland Waters
Paul H. LeBlond	University of British Columbia, Dept. of Oceanography

The discussion group met for a total of about five hours. Attendance varied between 15 and 25. The list attached shows who attended the first session; most of the people listed therein were active and faithful participants in all sittings of the discussion group.

Discussion group A1 tried to limit its deliberations to its terms of reference as defined above. The recommendations and conclusions presented below are not placed in order of priority, as they pertain to a wide variety of problems which cannot be directly ranked in order of importance.

CONCLUSIONS AND RECOMMENDATIONS

1. Visual Observations

Because of the great degree of scatter in the comparisons of visual waveheight estimates and measured values of waveheights (cf. accompanying figure from Jardine, T.P., 1979. Coastal Engng., 3, 33-38, which was referred to in the discussion), it was concluded that visual wave observations were not to be relied upon as a cornerstone of wave climatology. It was recognized that they should not be ignored at the beginning of a programme, when no other information is available. The main virtue in long time series of visual observations, such as those presented by H. Neu, was thought to lie in their showing evidence of interannual variability. Severe reservations were expressed however as to their usefulness in this regard, in view of the existence of longer and more reliable wind records from which wave conditions can be hindcast.

2. REMOTE SENSING

2A. Satellite Observations

It is recognized that satellite observation systems will provide the only practical means of achieving rapid global coverage for waves as well as for many other geophysical variables. It should be kept in mind however that satellites will not provide all required information and that local, ground-level, measurements will continue to be necessary for two reasons: (i) - to provide information when the satellite is not overhead; (ii) - as to ensure continuing calibration of the satellite remote-sensing system.

In order to be in a position to fully utilize satellite information when it becomes available we RECOMMEND that

A: Canadian participation in the planning of the NOSS satellite system be strongly encouraged. In retrospect (Oct. 1981), we can only express our regret at the indefinite pastponement of the NOSS program.

B: The wave data already available from the SEASAT and GEOS program be exploited as practice runs for the data flood to arise from the NOSS system.

It was also suggested that the SEASAT data could be utilized as ground truth to verify global wave hindcast models.

Discussion group A1 also expressed its support for the CANADA-USA Imaging Radar Satellite program. Although this system is primarily designed for ice observation, and in spite of reservations expressed concerning the ability of its Synthetic Aperture Radar to resolve wave lengths in some generation areas, some hope was expressed that some information on wave lengths and directions could be obtained from this satellite.

2B. Radar Systems

Ground-wave radar systems were held to be promising and should be kept under consideration for coastal and platform surveillance of ice movements and surface currents as well as of wave conditions.

Over-the-horizon radar was not deemed to be of immediate or short term interest.

2C. Airborne Observations

Airborne remote sensing of waves, using proven technology (Synthetic Aperture Radar, Scatterometer), would be useful particularly for model verification and could be carried out on a routine basis on ice reconnaissance missions.

The necessity of knowing the position of the ice-water boundary in formulating wave hindcast or forecast models was also discussed. It was concluded that the airborne ice reconnaissance now conducted by AES is sufficient for that purpose and should be continued at the same level of effort.

3. DIRECT MEASUREMENTS

In view of the need for scientific as well as operational information on waves, Discussion Group A1 recommends that direct measurement programs include two levels of wave measuring stations.

1. Bench mark stations, - at which long term series of detailed measurements of waves and associated variables should be carried out, in the spirit of the long term wave climate stations now operated by MEDS under the Canadian Wave Climate Program, but with some extension in coverage. These stations would provide information on interannual variability and on detailed features of the wave records which may not be worth recording at operational stations.

It is RECOMMENDED that at least two such stations be established, one on each coast, and that these stations be located in deeper water and farther offshore than the present long-term MEDS stations in order to provide a representative picture of open-ocean waves under open-ocean wind conditions.

Variables to be recorded at bench mark stations would be as follows, with appropriate specifications:

(a) Sea-surface displacement - Measurement duration to be at least equal to 200 periods of the longer period expected; continuous measurements to be made above a threshold level.

(b) Wind speed and direction - 20-minute measurement of wind speed and direction deemed necessary for obtaining a stable estimate for use in model verification. If the instantaneous time series cannot be transmitted, the mean wind speed and direction and their variance over 20 minutes should be recorded.

(c) Barometric pressure - To an accuracy which will satisfy AES and hindcast modellers.

(d) Wave directional information - There is a strongly expressed need on the part of users for directional wave spectra, and efforts should be directed towards developing and procuring instruments which will be adequate for measuring wave direction. Exact specifications as to required accuracy were not discussed as they were thought to be somewhat premature.

(e) Air temperature: to 0.1°C for estimates of stability.

(f) Sea temperature both to 0.1°C, for estimates of stability.

Benchmark stations would report every three hours, as is now the practice for MEDS data buoys.

2. Operational stations - would be installed for shorter time-scales in areas of special interest, by industry or government, and would distinguish themselves from the benchmark stations by their shorter life and by their less comprehensive

sampling capability. Variables measured at the operational stations would be subject to sampling requirements listed above, and would be obtained, as feasible and locally desirable, in the priority ranking corresponding to the above list.

4. DATA ARCHIVING

Proper data archiving and accessibility thereto was considered of extreme importance.

It was RECOMMENDED that all data from a wave measuring station (benchmark or operational), i.e. oceanographic and meteorological information, be available from the same source and be stored together.

It was RECOMMENDED most strongly that data records for any wave measuring station include as part of the record itself specifications as to instruments used, sampling methods, instrument calibrations, geographical position and detailed location of instruments with respect to other structures (as on rigs or ships).

It was RECOMMENDED that, in view of our lack of understanding of all that may be important in a data record, original time series of the data be stored as much as possible in addition to commonly used data products such as histograms, significant wave heights and spectra. Our successors will then have at hand information to test and verify theories as yet undeveloped.

Finally, it was RECOMMENDED that a listing of all available oceanographic and meteorological information of relevance to wave climate information be made available to all interested parties and that this listing be periodically brought up to date.

5. SPECIAL TOPICS

A. Spatial Variability

Spatial variability associated with refraction and with current interactions was recognized to be an important feature of local wave climate specifications. In view of the influence of these effects on the height and directionality of waves, it is RECOMMENDED that special attention be paid to the possibility of small scale (tens of kilometres...) variability of the wave climate in regions where current interactions or refraction is to be expected. Spatial coverage of the wave sampling should be made on a smaller scale in such areas. Theoretical understanding of expected effects should be refined and applied to specific areas of interest.

B. Hindcast Models

The hindcast model is recognized as an extremely useful tool in the study of wave climatology. From the point of view of a discussion group on data requirements, it appears that the availability of accurate and sufficiently dense wind data is the most crucial requirement of a useful hindcast model. Accordingly, the following three basic components were identified in the development of a hindcast model: 1 - accurate measurement or calculation of winds to be used as input to the model - the verification of the winds obtained at this step constitutes an essential part of the hindcast process; 2 - a model which will predict wave conditions given the wind; 3 - verification of the model by local wave measurements. Any hindcast model which does not satisfy these properties is not to be considered adequate. Careful attention should also be given to model verification in rapidly changing wind conditions.

C. Storm Surges

Although long period variations in sea-level associated with the passage of storms are not strictly understood as "waves" in the context of this workshop, their importance is recognized in terms of possible overtopping of low structures such as artificial islands. Instruments required to monitor and to verify hindcast storm surge models are simply sea-level gauges with a resolution of a few centimetres over an averaging period of less than five minutes. Such instruments are to be deployed on a spatial scale intermediate between that of the storm which generates the surge and that of the bathymetry of the oceanic basin where they travel. Experiments with vertical pendula as sensors and predictors of North Sea surges have been very primising (Kümpel and Zochau, 1979), and the technique might prove useful in Canadian waters.

Reference

Kümpel, H.-J. and J. Zschau, 1979. Das Vertikal - pendel in der Slurmflutrochersage. Wasser and Boden, 31, (10), October 1979.

CONCLUSIONS AND RECOMMENDATIONS

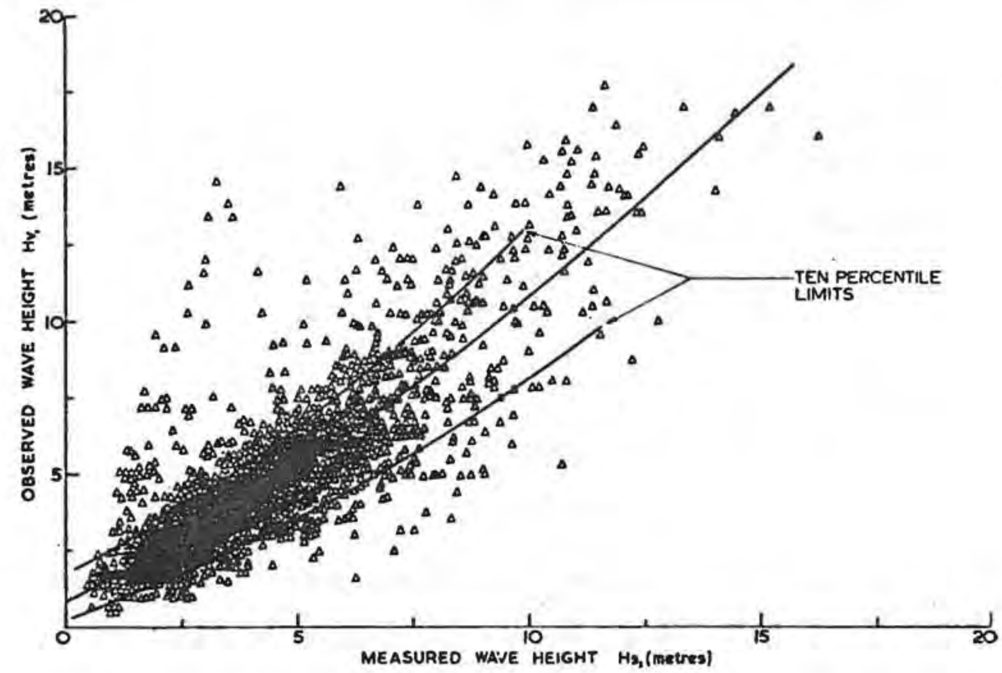

Fig. 1. Scatter diagram of correlated observed and measured wave heights with weighted quadratic curve of best fit superimposed.

Fig. 1. Scatter diagram of observed and measured wave heights (from Jardine, 1979).

REPORT OF THE DISCUSSIONS OF WORKING GROUP A2

Chairman: V.R. Swail, Dept. of Environment
Atmospheric Environment Service

Terms of Reference

Analysis of Wave Climate Information for Design

This group will address analysis methods for definition of "design wave conditions" given wave climate information. Topics of concern include:

1. Appropriateness of current statistical methods of extreme value analysis and return period prediction.
2. Questions of data quality, format and archiving procedures.
3. Incorporation of episodic waves in design conditions; means of recognizing and identifying these waves.
4. Swell-wind wave interactions.
5. Wave groupiness.

List of Participants

D. Bellows	AES, Department of Environment
M. Birkinshaw	BP Trading
D.M. Chartrand	Marine Directorate, Public Works Canada
A.R. Fallon	Chevron Oil Field Research Company
E.R. Funke	National Research Council
H. Gerlach	Petro-Can Limited
A. Lachapelle	AES, Department of Environment
J. Nasr	MEDS, Fisheries and Oceans

Participants cont'd

S.D. Smith	Fisheries and Oceans
V.R. Swail	AES, Dept. of Environment
B. Thompson	Petro-Canada Limited

The discussion group consisted of those listed most of whom attended all group sessions. A few others attended some sessions. The group met for about seven hours and had some lively, informative discussions. Within the first 20 minutes the group decided that the topics listed were too restrictive and the field of discussion was expanded. Working Group A1 also expanded its terms of reference so there is some overlap.

1. Statistical Methods/Data Sources

The design information required includes wave height, period, direction and spectral information, including directional spectra. Extremes of wave heights, eg. the 100-year wave, and peak period are important parameters for design. The Gumbel distribution has been found to fit the annual extremes series. Fatigue due to repeated occurrences of lesser wave heights is equally important so exceedance diagrams are also necessary. Also, due to different response characteristics of vessels and structures, information on the joint occurrence of wave height and period (scattergrams) was identified as very important.

Hindcast data were considered to be the most appropriate for design. At least 20 years of data should be hindcast and this should be combined with at least one year of buoy data at the site. However, hindcast data are preferable to one year of buoy data alone. Since wind data is the most critical factor in wave hindcasting, attempts should be made to improve the historical wind data base over the water.

Buoy data are considered to be very good but the problem has been that there is not enough of it in either a temporal or spatial sense. Most of the buoys have been located in shallow water and records have been for only a few months. What is needed is information in deep water with a long period of record. There should also be at least measuring directional spectra located in deep water.

Satellite was seen as a major advance in provision of both high quality wind and wave data which will be useful both as data in itself and as a check on model output. However, this will not replace conventional data, merely supplement it. The biggest advantage of satellite data was in frequent global coverage. It was recommended that agencies in Canada should actively participate in NOSS. Radar systems were seen as unproven and a wait-and-see attitude was adopted.

Visual data were considered to be of too low quality to use for frequency analyses or return periods. It was felt that where nothing else was available they were useful as a first indication but no one would design on them. They might also be used in analysis of long term trends although even for this they were considered inadequate. The METOC charts were considered a better data set since the fair weather bias is apparently removed. Further evaluation of this data set should be done. The METOC charts would be improved if additional waverider data were available in real time in deep water for input to the analyses. However, even the METOC charts are not considered adequate as a data base for design. Of the existing techniques the AES grid point climatology was deemed most likely to provide reasonable design criteria. But these should be used only as a first guess, to be modified with better information. Visual data in any form should not be considered a basis for a wave climatology.

2. Data Quality, Format, Archiving

High quality data are essential to produce good design values. The single largest problem with wave hindcasts, for example, is inadequate quality wind data. Instruments must be properly sited in a representative location and observers must have an adequate level of expertise. It is better to put an anemometer at 250 feet than to put it at 10 m in a poor location for example. The archiving of data is critical also. An archive must tell what the data is, where it was collected, the type of instrument, sampling period and frequency. You can not put too many flags on the data - everything which is non-standard should be flagged. The flags should be on a computer tape and not in books in the basement. Ready access to the data is also important. Industry needs 1-2 points of contact from whom they can get a good, complete, quality controlled data set. If this means that data sets must be stored in two locations then it should be done. At the very least there should be only a couple of places where the data is stored (instead of a multitude) and an up-to-date catalogue should be readily available.

It was also specifically recommended that the sampling period for buoy measurements be standardized and that longer record lengths be obtained. Also it was recommended that actual spectra be saved, and not just the parameters derived from it, since in the future some derived parameters not now being abstracted may be considered important.

3. Groupiness

There is groupiness in all sea states. Groupiness can be high with low sea states - this is not a problem. The problems may arise with high waves and high groupiness. Forces due to groupiness may be increased by factor 4. There is experimental evidence that groupiness affects moored vessels and breakwaters. However, some industry will have to be convinced that it is a problem; there is insufficient evidence that present offshore structures have been affected. Groupiness should always be evaluated to determine if the effects will be marked. We may need only to look at the severe sea states to cut down the workload. Work should be done on parameterizing the output so the user is not faced with thousands of graphs. It was recommended that the topic have a better airing to see whether the idea is widely acceptable.

4. Episodic Waves, Wave-Current Interaction

The main topic of this discussion was "what is an episodic wave?". They may merely be the high end of the natural variability of waves, i.e. the Gaussian distribution. If this is the case the episodic wave may be a million year wave which is more design than is demanded by regulatory agencies.

There was some speculation that some episodic waves might be the result of wave-current interaction, i.e. refraction of a wave field by a current causing a pattern of enhanced and diminshed wave heights. It may not be possible to design for this but industry should be aware of the possibility in areas where currents are significant. Deep water breaking was discussed but was not considered a problem. Large waves in the North Sea have not been seen to break and no one designs for large breaking waves.

5. Communication/Consultation

The lack of communication among the various groups in Canada was very obvious. Also, Canadian industry seems to be isolated from international industry. There are international forums at the technical level for industry to discuss developments. This is where groupiness should be brought up. It was recommended that Canadian industry seek representation in these groups. It was also recommended that there be more industry-government consultation and dialogue. This meeting was identified as an excellent example. Thirdly, it was recommended that there be much more coordination and consultation between Canadian government agencies especially regarding data acquisition and archiving.

REPORT OF THE DISCUSSIONS OF WORKING GROUP B

Chairman: J.R. Wilson, Ocean and Aquatic Sciences
Department of Fisheries and Oceans

Co-Chairman: P.E. Vandall, Jr., Energy Conservation
Department of Energy, Mines and Resources

Terms of Reference

Engineering Requirements for the Design of Ships and Offshore Structures

i.e. - Static and dynamic analysis
(directional?) spectral analysis

- Fatigue analysis
- Wave breaking impulsive forces in deep water
- Current and wave interaction
- Wave direction

This discussion group will address the technical problems in calculating forces and the practical requirements for the design of ships and offshore structures.

What are the important forces operating on structures due to wind-generated waves and how does one evaluate the forces from a wave record?

- For use of the wave spectrum, how important is the actual spectral shape? How significant is the difference between some of the "standard" spectra, such as Jonswap or Pierson-Moskowitz? How important to design is the effect of currents or refraction on the spectrum? Are spectral width and various spectral moments of use in design?
- What are the requirements for directional spectra and how might they be satisfied? Is hindcast direction information sufficient? Can satellite measurements of direction meet any design requirements?
- Is deep water wave breaking important in the design of structures and, if so, what measurements and analyses need to be done to identify and evaluate the necessary design parameters.
- What individual wave characteristics or statistics are useful to design (e.g. slopes, grouping, etc.)?
- How do you incorporate episodic waves into design statistics?
- How might interactive wave trains be characterized for the purpose of design?

How important is the interaction between waves and currents, i.e.:

- What kind of distorted waves might be expected because of an opposing current?
- Can a breaker be created because of an opposing current?
- How should the wave orbital velocity and a current transverse to the wave direction be combined?
- Should the characteristics of a design wave be modified because of an opposing current?

The report of the Working Group should review the requirements for collecting, analyzing and distributing wave data to be used for engineering design.

List of Participants

Harold Alexander	Technical College, N.S.
Bruce Dunwoody	Dome Petroleum
Ahmed Ewida	Petro-Canada
Doug Murphy	Swan Wooster Eng. Co. Ltd.
Des O'Neil	AES - Bedford, N.S.
Joe Ploeg	NRC (Hydraulics Lab)
B. Read	Aquitaine Company of Canada
Wilson Russell	NORDCO Limited
Bob Smyth	EMR
R.A. Stacy	Mobil Oil
Howard Westergard	Aquitaine Company of Canada
Paul Vandall (Co-Chairman)	Resource Management Branch Energy, Mines and Resources
J.R. Wilson (Chairman)	MEDS, Fisheries and Oceans

A question was also raised at the beginning of the meeting concerning the effect of pack ice on waves. The Group did not find itself equipped to discuss this item, although it was recognized as an important problem, particularly in Canadian waters. It was felt that if Canadians did not address the effect of pack ice on waves, nobody else would.

The phenomena of episodic waves and interacting wave trains was also generally beyond the present knowledge of the Group.

The nine recommendations and supporting comments of the Group are presented below.

RECOMMENDATIONS AND COMMENTS

1. Spectral Characteristics of Wave Data

Recommendation: Analysis of existing one-dimensional measured spectra and of directional hindcast spectra should be performed to develop spectral climatologies for Canadian waters.

At present, there exists two spectral hindcasts for the North Atlantic Ocean and a significant body of measured one-dimensional data which can be used for the above purpose.

The Group noted a deficiency in the measured wave data set in that the bulk of the data is in shallower water. There is a requirement for measured data in more exposed locations and in deeper water.

It is also noted that there will be a requirement for real-time spectral data at offshore facilities for mooring and loading tankers. The data will be used for real-time computation of mooring forces for operations.

There will probably also be a requirement for real-time spectral data at ports receiving large ships.

In both of these cases, directional data will have to be incorporated from numerical forecasts or by other means.

2. Wave Directional Measurements

Recommendation: The development of instrumentation to routinely measure wave directional spectra should be encouraged at every opportunity.

At present, there are no instruments available capable of measuring wave directional spectra on a routine basis. There is, however, a very real requirement for this information, both for design and operational purposes. It would also be useful to have the capability in the instrumentation to measure wave slopes.

3. MEDS Wave Data Analysis

Recommendation: The MEDS standard wave analysis should be upgraded to include wave-by-wave analyses to produce statistics of various heights, periods, and slopes and to determine the occurrence of wave grouping.

It is recognized that while breaking waves have effects on the integrity, stability and safety of marine structures, not enough is known on the subject at this time to incorporate the phenomenon into the design of structures and ships. As a beginning, it would be useful to upgrade the present MEDS wave analysis procedures to include wave-by-wave analyses for heights, periods, and slopes to produce statistics from which might be inferred the frequency of occurrence of wave breaking in deep water. See also Recommendation 4 below.

Also, it was considered that wave grouping is an important parameter to design and that there is a requirement to identify the possible occurrence of wave grouping through routine computation of a grouping factor. This factor can, for the time being, be defined as in NRC Report LTR-HY-66, until such time as an internationally agreed upon factor becomes available.

4. Wave Breaking

Recommendation: An effort should be made to assemble a list of offshore structures around the world which are known to have been hit by breaking waves and to determine the effects and problems which have occurred as a result.

The scope of the problems associated with wave breaking in deep water seems not to be known. The compilation of the above list would be a starting point for evaluating the magnitude of the problem. See also Recommendation 3 above for other comments on wave breaking.

5. Interaction of Waves and Currents

Recommendation: The problem of wave-current interactions should be tackled from theoretical, modeling and observational points of view.

It was noted that while the problem of wave-current interaction is important to design, present knowledge of the processes is inadequate for proper treatment of the phenomenon. It was also noted that it would be useful to have more current profiles in areas where wave-current interactions are expected.

6. Integration of Environmental Data Sets

Recommendation: The oceanographic and meteorological data managers in government should, at an early date, organize their data handling procedures so that integrated data sets of oceanic and atmospheric parameters containing all available parameters can be easily and efficiently created.

It is a requirement for design of offshore structures and for research work into wave phenomena that unified data sets of known quality containing all available environmental parameters can be easily and efficiently made available. Thus, the atmospheric and oceanographic data managers must archive data in a fashion and develop retrieval capabilities to permit integration of the outputs from their data bases into a unified data set. This does not mean that all data must be archived in one location.

7. Calibration of Instruments

Recommendation: Calibration of instruments recording environmental parameters in the offshore regions must be regularly checked.

This is a requirement to construct data sets of "known" quality.

8. Long-Term Wave Statistics

Recommendation: The data from the MEDS wave stations at Osborne Head, N.S.; Torbay, Nfld.; Tofino, B.C.; and Station PAPA should be analyzed to present the data in the form of long-term statistics.

These data were collected to examine long-term wave statistics on each coast. The data have not as yet been used for this purpose, and useful presentations need to be developed.

9. Statistical Uncertainity in Wave Spectra

Recommendation: MEDS should show on the wave spectrum plots the statistical reliability of the spectral estimates as error bars.

The statistical reliability of spectral estimates is a function of the bandwidth of the analysis and of the length of a wave record. This reliability in a single spectral estimate is generally much lower than is appreciated by most users of wave data. The reliability, therefore, should be indicated on the spectral diagram.

J.R. Wilson

REPORT OF WORKING GROUP C

Chairman: R.L. Jones, DMETOC, Department of National Department of National Defence

Co-Chairman: A. Saulesleja, Department of Environment Atmospheric Environment Service

Terms of Reference

Marine Operational Requirements

A. Definition of Users

1. Examples of users/potential users of operational wave information are the offshore oil and gas industry; marine transportation; recreational small craft; the fishing industry; DND; and search and rescue. Is this list essentially complete or are there other users whose interests should be considered?

B. Wave Data Requirements

2. What are the day-to-day and specialized needs of each of these users in terms of:

(a) real time wave observations (e.g. from ships, buoys, satellites) and wave analyses (what form of data, what communications system?)?

(b) wave forecasts (what form, what parameters, what inputs and how often)?

(c) wave climate/climatology (atlases, climate forecasts, digital data, parameters)?

C. Wave Data Products and Recommendations of Working Group

3. If we are to satisfy the user's needs, as defined above, what means will be required to:

(a) upgrade existing systems and products, and

(b) create new systems and products if required?

4. An estimate of cost in terms of resources and/or facilities will be attempted.

A. INTRODUCTION AND REVIEW OF PRESENT PROCEDURES

It was agreed in early discussion that the quality of wave hindcasts/forecasts could be much improved with availability of better wind data. Winds remotely sensed from satellite and over-the-horizon radar were suggested as ways of improving the initial analysis, but realistically, it was agreed that the deployment of many simple (sea surface temperature and pressure only) drifting buoys could give substantial improvement to analyzed and forecast wind fields. Also it was noted that only about 25 to 30 percent of ships at sea send weather reports ashore, therefore a simple automated reporting system was deemed appropriate.

The accuracy of visual wave height observations and consequently the METOC Centre analyses were suspect, or at least subject to some uncertainity. However, it was also pointed out that, because of errors in the analysis of surface pressures and procedures for obtaining surface winds, wave analysis methods depending on wind fields would suffer the same sort of inaccuracy.

The winds, as presently reported and measured by ships, were not considered to be a useful unput to a wave model or initial analysis. There is simply too much variance in the speed and direction of the 0-3 minute average winds being reported at sea. It was agreed that a consistent 20 minute average wind is needed.

B. DEFINITION OF USERS

Four main categories of users of operational wave data were identified, namely the oil and gas industry; marine transportation; recreation and fishing; and DND and Search & Rescue. Many other users were also identified, such as the Coast Guard, inshore fisheries, Environmental Protection Service and some research goups, but the consensus was that each of these users could be adequately considered within one or more of the above groups.

C. WAVE DATA REQUIREMENTS/NEEDS OF THE USERS

The most acute and wide-ranging needs for wave information were those of the oil industry. For their normal operations or possible emergencies wave height, period and direction were all required. The response of some structures was such that a site specific forecast and wave directional energy spectra would be useful for routine operations. Because of the continuing nature of this industry's activities, the high cost of interruption and its sensitivity to sea state, a third day or further outlook on storms or potential storms was also needed.

Marine transportation utilizes wave information which is not site specific for ship routing. Depending on the operation, ship routing can become quite complex and may require the incorporation of an individual ship's roll, pitch and heave response into routing considerations. Forecast fields of wave heights, periods and directions and in addition, a digital climatological archive would be useful to ship routing.

The needs of recreational small craft and the inshore fishermen were site specific and could not normally be addressed through an organized forecast system. However, forecasts giving the combined effects of wind, tides, waves and currents would be useful for a few critical specific locations such as the Strait of Belle Isle and the Bay of Fundy. The Barr forecast for the mouth of the Columbia River is an example of what is needed. Anomalously high steep waves often result from the interaction between waves, tides and currents. Small boat operators or near-shore operations would find useful a simple chart listing where and under what conditions such an anomalous wave conditions could occur. The offshore fisherman would likely find forecasts of significant wave height useful for his operations.

Military needs were directed primarily towards anti-submarine warfare and ship-borne helicopter operations. These activities must proceed in spite of waves and weather but forecasts of significant wave heights are necessary in planning naval operations and exercises. Forecasts of directions and periods of wave components have not been available for Canadian military operations but have been found useful elsewhere.

As recorded in the above paragraphs, there is considerable overlap between the needs of various users. Table 1 is a consolidated review of those needs. From the table it can be seen that there are essentially two categories of needs: Point specific detail of directional energy spectra and summarized information (charts). At the present time some of the latter are being met by the existing meteorological and oceanographic services. However these continuing needs are surpassed by the relatively specific wave characteristics which can only be obtained from more sophisticated approaches to wave analysis and forecasting.

One need identified, but not included in Table 1, was a requirement for "Atlases". Atlases are here defined as any format, not necessarily printed, which permits interpretation of raw or processed information by users. In this regard the following needs were put forth:

1. coordinated, quality controlled meteorological/oceanographic digital archives with real-time update and access capability; and

2. revised pilot charts and/or manuals to indicate:

   (a) areas of intense refraction as functions of wave direction versus local wind conditions; and

   (b) effects of tides/currents on waves.

D. CONCLUDING DISCUSSIONS

After considerable discussion of the needs of various users, it was agreed that a computer model capable of generating a wave field description including height or energy, direction and wave length for each component was needed. In addition, there was an expressed need to extend the warning of potential storms to 72 hours or beyond. As well there was an industry comment that METOC forecasts to 48 hours were better than purely objective methods such as the USN's Spectral Ocean Wave Model (SOWM) because there was knowledgeable manual input to METOC forecasts which compensated for deficiences in model wind fields.

A model such as the SOWM could easily be run on a large main frame computer every 12 hour forecast cycle and could easily be implemented. There would, however, be a need to "tune" this model, and to continue an ongoing evaluation of its output. A requirement to interactively correct or edit forecast windfield inputs to such a model was suggested. Methods for displaying the forecast fields for the communications system, and procedures for making spectral forecast data available to users are problems which need to be investigated. For example, to describe the forecast directional energy spectrum for grid points separated by 100 kms over the North Atlantic would require the transmission of about two million numbers every forecast cycle. More practically, one could envisage the transmission of charts summarizing wave heights, peak periods and directions but having a computer data base with the output fields accessible on demand to individual users.

E. RECOMMENDATIONS IN ORDER OF PRIORITY

1. A deep water wave model, capable of providing directional energy spectra must be acquired and modified to fit the Canadian situation. It must have high resolution capabilities and should have the potential to expand into shallow water configuration. It should also have the ability to allow man-machine interaction on an operational basis in the evolution of various products.

2. An on-going development and verification routine must be established in order to ensure that products are improving in accordance with state-of-the-art forecast and data acquisition techniques.

3. An improved low level wind and surface pressure field analysis and forecast capability must be developed as primary operational input into the model identified in 1. above. A necessary prerequisite to this improvement is better, more accurate wind measurements from marine areas, either directly or by better specification of the surface pressure field through the deployment of simple drifting buoys and instrumentation of ships with automated reporting systems.

4. One government agency should be responsible for coordinated quality control and digitally archiving of all relevant meteorological and oceanographic data with real-time update and real-time access capability.

5. Open ocean qualitative storm advisory procedures must be developed for periods beyond 48 hours.

6. Attempts must be made to quantify for general use, information on wave refraction and interaction with tides, currents and bottom topography.

F. ESTIMATE OF RESOURCES

The group identified the need for access to a large main-frame computer similar to CMC's (Canadian Meteorological Centre) CYBER system. An oceanographic model as recommended above, accessing wind data, would require an estimated 20 to 30 minutes run time every 12 hours forecast cycle. The group also considered that interactive access to the raw or processed data by users was essential. In addition, better wind and wave analyses would require drifting buoys capable of measuring surface pressures and water temperatures at a cost of $3K each and an automated system for reporting surface pressures from ships, costing under $1K. The number of buoys/systems needed were not estimated.

A report comparing Seasat altimeter measurements with the Halifax METOC centre wave analyses is attached.

Robert J. Jones
Chairman
Working Group "C"

TABLE 1 - WORKING GROUP "C"

OPERATIONAL WAVE DATA REQUIREMENTS

USERS	Oil/Gas Industry	Marine Transportation	Recreational/ Fishing	DND/Search & Rescue
SPECTRAL DETAIL				
Individual Periods	X	X (1)		X (2)
Individual Energy	X	X (1)		
Individual Direction	X	X (1)		X (2)
INTEGRATED INFORMATION				
Significant Heights	X	X	X	X
Periods/Directions	X	X		X (2)
Total Energies	X			
DERIVED INFORMATION				
OTSR Products		X		X
Site Specific Forecasts	X			
Longer/Better Forecasts	X			
Shallow Water Detail			X	XX

(1) as related to Optimum Track Ship Routing (OTSR) products
(2) West coast only.

WAVE INFORMATION WORKSHOP - DARTMOUTH NOVA SCOTIA - 7, 8, 9 OCTOBER 1980

1. During the discussions on satellite measurement of sea state by radar altimeter such as on "SEASAT", I mentioned an invetigation carried out during the Canadian Surveillance Satellite (SURSAT) program to verify SEASAT-A's altimeter. Dedicated ground truth had been intended but, due to SEASAT's demise, the study really only checked SEASAT-A measurements against METOC Centre Halifax wave analysis charts.

2. One copy of the final report of this investigation is enclosed as requested by addressees. Although it is intended for eventual publication in the SURSAT Final Report, I have no objections to its inclusion in the Wave Information Workshop proceedings.

R.L. Jones
Chairman
Working Group "C"

3281-13 (D Met Oc 3-4)

4 January, 1980

FINAL REPORT OF D MET OC SURSAT EXPERIMENT

WEATHER AND OCEANS GROUP

TITLE

1. Original title submitted was: "Remote Sensing of Sea Surface Temperature (SST) and Sea State by Satellite and Aircraft for Military Operational Applications".

INVESTIGATORS

2. Principal Investigator: Mr. R.L. Jones, D Met Oc
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(processed and plotted SEASAT data)

Mr.J.B. Merrick
Officer in Charge CF METOC Centre
FMO Halifax, N.S.
B3K 2X0 Phone: (902) 426-4513

(truth data from METOC Centre's Charts)

OBJECTIVES

4. The objectives stated in the original experiment proposal to the SURSAT Project Office were:

a. Examination of the capabilities of airborne remote sensors in SEASAT-A and in supporting aircraft in the SURSAT project to provide:

(1) reliable sea surface temperature (SST) and sea state read-outs for tactical usage;

(2) an improved data base for military oceanographic forecasting derived from SST and sea state analyses at CF METOC Centres in Halifax and Esquimalt; and

b. Assessment of sea surface conditions and their impact on other DND SURSAT experiments to be undertaken by DREO and CRC.

5. In fact only a partial experiment has been completed due primarily to SEASAT-A's demise, and to the fact that Scanning Multichannel Microwave Radiometer (SMMR) data had been judged inferior and has not, in any case, been made available to the experimenters in sufficient time to meet this Report's deadline. Therefore only SEASAT radar altimeter data has been examined to assess its possible usage as a data source for METOC Centres, and as a tactical data source.

SITE

6. Data were examined from the western North Atlantic west of longitude 30°W between latitude 35°N and 60°N. Altimeter data from the West Coast were not processed in time to conduct a comparison with METOC Centre Esquimalt wave analyses.

REMOTELY SENSED DATA USED AND ITS ADEQUACY

7. SEASAT-A altimeter data from 15 September to 09 October 1978 inclusive were used. The data were extracted and produced by Dr. wilson of DFO/OAS, selecting only those orbits which overflew the area of interet and which occurred within one hour of 1200 GMT, one of the times of wave height reports from ships and buoys.

8. The data were plotted at one degree of latitude intervals along the selected orbits and comprised significant wave heights sensed by SEASAT-A. Appendix "A" is a sample of the data plotted by OAS on a Mercator projection. These charts proved to be very adequate and convenient in the conduct of the experiment.

GROUND TRUTH DATA

9. Unfortunately SEASAT-A failed before dedicated ground truth collectors could be placed. It was therefore decided to examine METOC Centre's analyses for ships whose observations coincided in time and place with a SEASAT overpass. Some 41 ships were located within 60 miles of the 31 orbits used. In effect these ships were considered as "ground truth of opportunity" when this criteria and the criteria stated in para 7, above, were met, hence these data were examined as a separate set. Appendix "B" is a sample METOC Centre Significant Wave Data Chart showing orbit tracks plotted with examples of ship reports as ground truth.

METHODS USED FOR IMAGE ANALYSIS AND INTERPRETATION OF DATA

10. Dr. J.R. Wilson of DFO developed the method used to image the SEASAT data used. Jet Propulsion Laboratory (JPL) tapes were scanned to print out, in the format of Appendix "A", values of significant wave height. These significant wave heights were obtained from the JPL algorithm developed for the SEASAT altimeter.

11. The tracks of the 31 orbits used were then plotted on the corresponding METOC Centre Significant Wave Height Analysis. Two sets of data were tabulated and compared with SEASAT:

a. significant wave heights along the 31 orbits at 5° intervals of latitude, i.e. 35, 40, 45, 50, 55 and 60°N whenever possible (110 comparisons); and

b. significant wave heights reported from the ships selected as "ground truth of opportunity" (41 comparisons).

12. The 110 comparisons from para 11 a. above, were briefly examined statistically with the following results:

a. Arithmetic mean wave height = 3.2 metres;

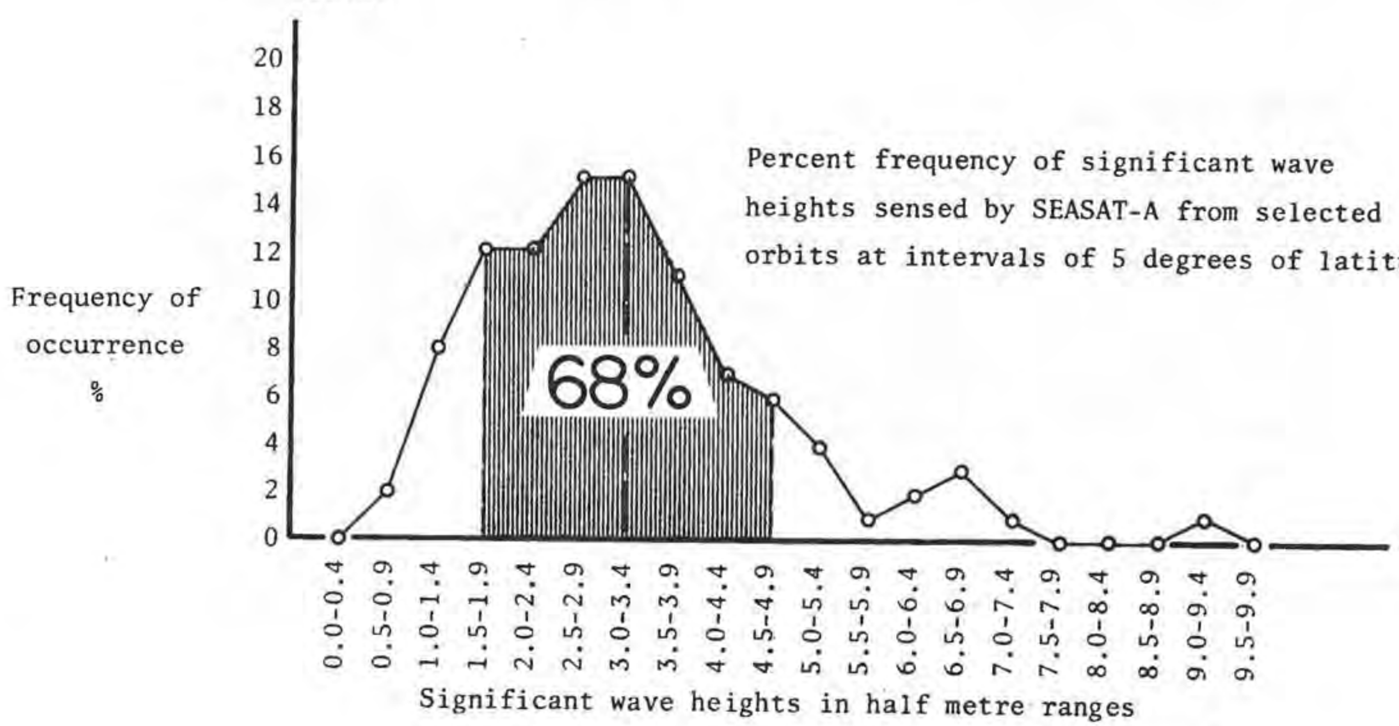
b. Median = $\frac{\text{max} - \text{min}}{2} = \frac{9.4 - 0.7}{2}$ = 4.4 metres;

c. Mode (the value which has the highest number of occurrences) = 2.9 metres

d. Mean Deviation = 1.1 metres

e. Standard Deviation = 1.5 metres

f. A graph of the frequency of occurrence of the observations was drawn:



13. From this graph it can be seen that the data assumes a moderately skewed distribution but tends towards a normal distribution as the mode and arithmetic mean are almost equal and the calculated mean deviation is nearly 80% of the standard deviation (SD). This places about 68% of the observations within one SD of the arithmetic mean. In order to investigate whether there were any biases in SEASAT's sensing ability for different wave heights, it was convenient to divide the data into three broad classes by wave height, namely: lowest heights, lower than one SD from the mean; highest heights, higher than one SD from the mean; and the middle range of heights within one SD of the mean.

RESULTS

14. It was decided to divide the data from the 41 ships in the same manner as the 110 arbitrary data points for ease of comparison although no statistical analysis was done on the ship reports. the tables following summarize the comparisons of mean significant wave heights taken from:

a. the 110 data points on the METOC analyses; and

b. the 41 ship reports considered as "ground truth of opportunity".

TABLE A

HEIGHT CLASSES	BELOW 1.8m	1.8-4.5m	ABOVE 4.5m	ALL HEIGHTS
SEASAT-A sig. wave height (metres)	1.3	3.0	5.5	3.2
METOC Analysis sig. wave height (metres)	2.0	3.1	5.2	3.3

TABLE B

HEIGHT CLASSES	BELOW 1.8m	1.8-4.5m	ABOVE 4.5m	ALL HEIGHTS
SEASAT-A sig. wave heights (metres)	1.3	2.9	6.2	3.2
Nearby ship reports (metres)	1.6	2.8	6.7	3.3

All abstractable cases have been included in these computations and no cases have been rejected.

EVALUATION OF BENEFITS IF SEASAT-TYPE REMOTE SENSED DATA WERE AVAILABLE ON A TIMELY BASIS TO METOC CENTRES

15. METOC Centres' wave analyses average from about 20 to over 50 ship reports per synoptic hour (0000, 0600, 1200, 1800 GMT). Assuming at least one SEASAT-type orbit would be available within one hour of each map time, and further assuming that each orbit provides about 10 usable reports (based on one usable report every 3 degrees over an average orbit traversing about 30 degrees of latitude), it can be seen that one satellite reporting in real time could provide 1/2 to 1/5 of the total data base. The usefulness of this data would be somewhat reduced by the "straight line" effect of the reports but this might be counteracted by the all-weather capability whenever the ssatellite senses stormy areas that ships usually avoid. During wartime when radio transmissions from ships would be curtailed, the satellite data if still available would increase sharply in value. Finally SEASAT type data from northern areas, say north of 60°N where there is a paucity of ship reports, would be of real immediate value.

16. The benefits that would be achieved if this kind of data were made available to METOC Centres, in real time, are therefore quite significant. It is obvious that data from more than one satellite would provide even greater benefits. As well, if frequent data from hours other than near synoptic times were available in real time, good use could be made of these reports for tactical and forecast verification purposes.

CONCLUSIONS

17. The following conclusions regarding the SEASAT-A altimeter are drawn:

a. Based on the comparisons and calculations made, it is evident that an altimeter of the type flown in SEASAT-A can accurately measure significant wave heights directly under orbit path. The errors noted were of both signs (+ and -) and are more likely due to shipboard observer error in wave height estimation and/or METOC analysis error than to SEASAT-A.

b. A bias toward low SEASAT-A altimeter readings is suspected in the 0-1.7 metre range but this could not be absolutely confirmed due to lack of dedicated ground truth.

c. Other biases, if they exist, were not detected in this limited experiment.

18. It is further concluded that SEASAT type data can provide an improved data base for significant wave analyses. Improved wave forecasts (up to 36 hours) would therefore result due to the following factors:

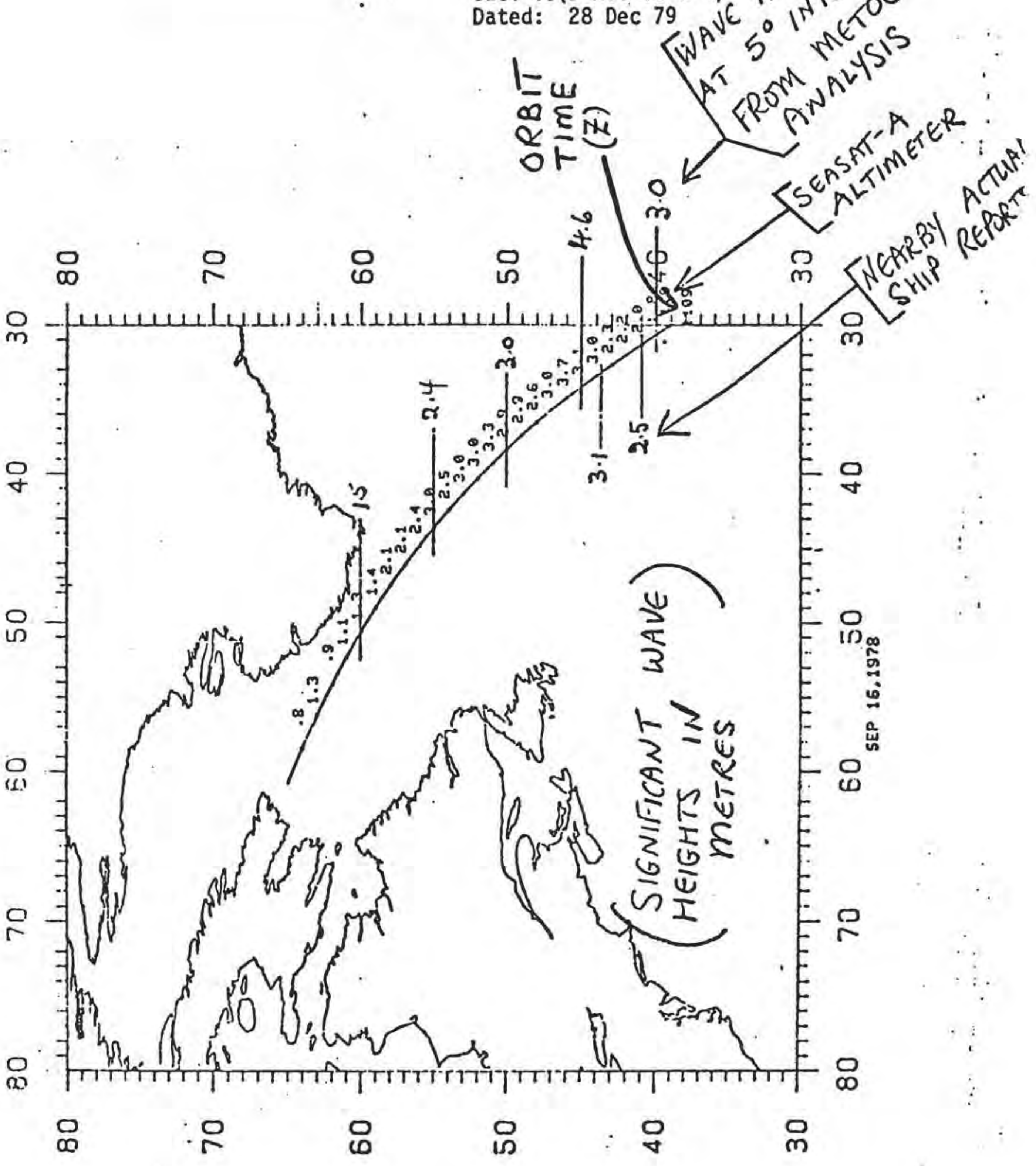
a. the starging point analyses would be better; and

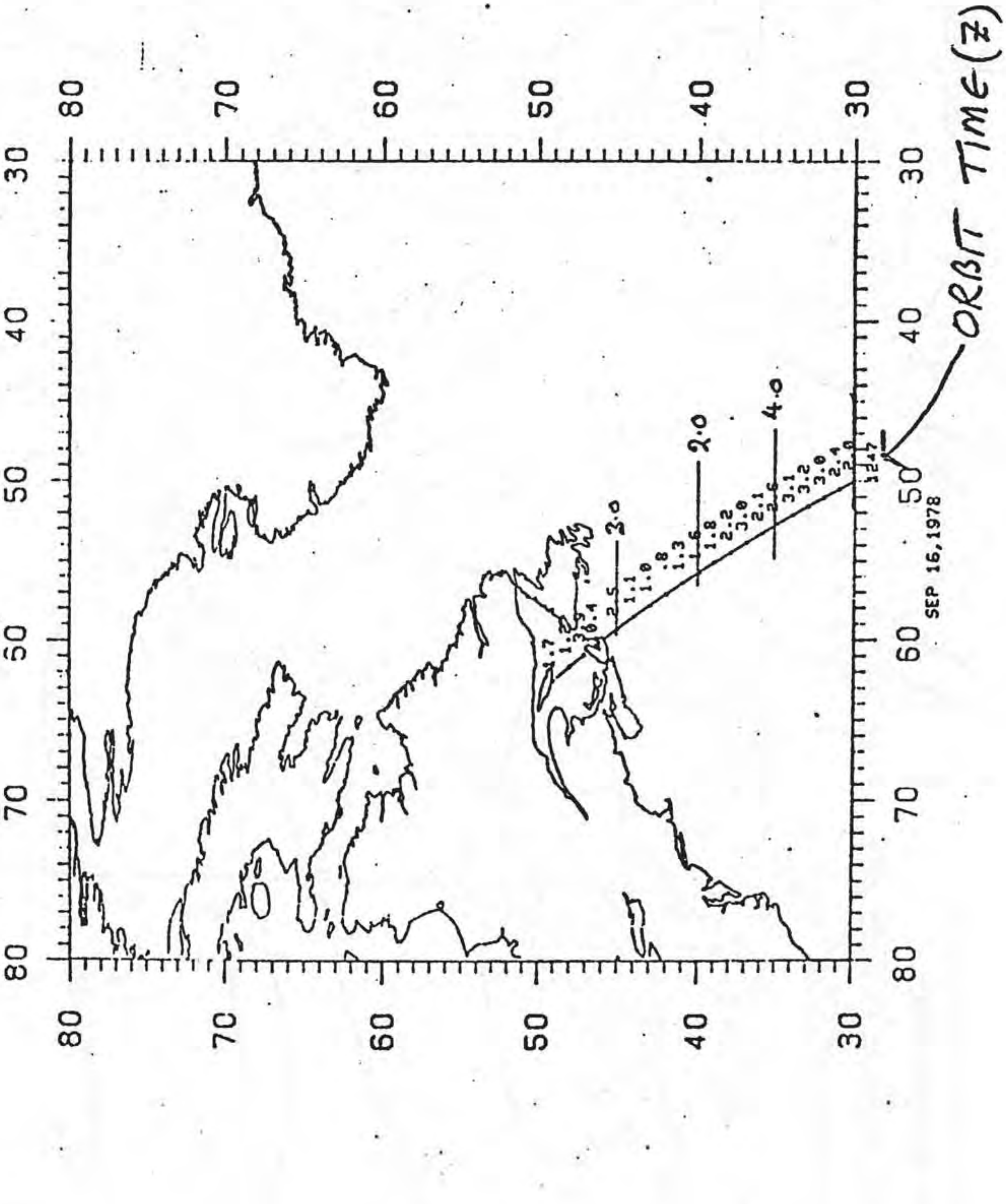
b. better verification of wave forecasts, particularly in high sea state situations, would be possible.

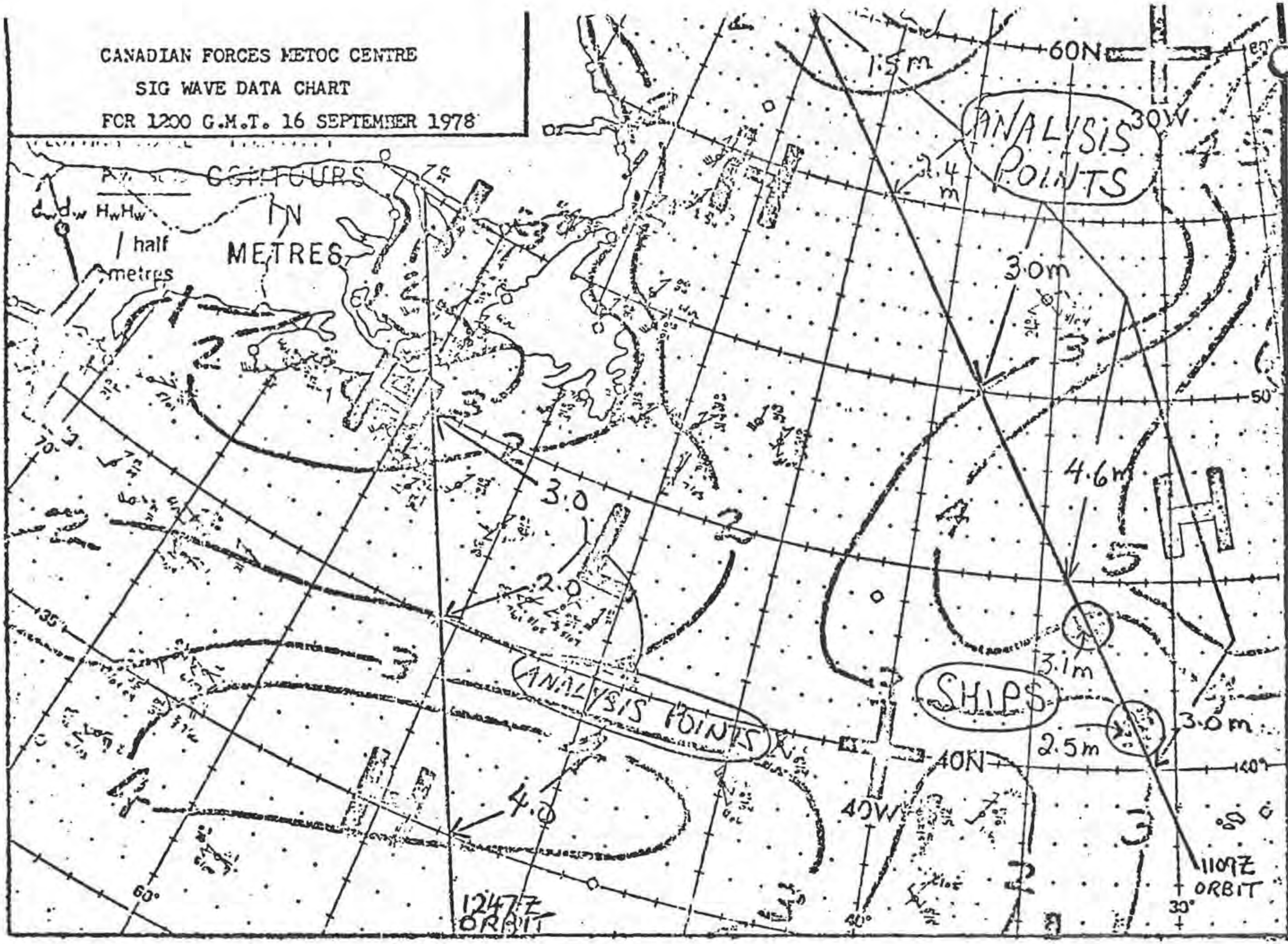
APPENDICES

19. Mr. Jones may be contacted regarding charted data as shown in the samples at Appendices A and B, as well as calculations made during the experiment.

APPENDIX A to
3281-13(D Met Oc 3-4)
Dated: 28 Dec 79




ORBIT TIME (Z)
SEP 16, 1978
2.0
4.0
3.0



APPENDIX B to
3281-13 (D Met Oc 3-4)
Dated: 28 December, 197

WAVE INFORMATION REQUIREMENTS AS VIEWED BY AN OFFSHORE OIL AND GAS OPERATOR

H.O. Gerlach and A.A. Ewida

A number of questions exist with regard to design criteria to be adopted for future oil and gas production facilities offshore Eastern Canada. Many of the criteria will be dictated by the environmental conditions existing at e.g. the Grand Banks or the Labrador Shelf.

This paper highlights some of the difficulties which have arisen or are anticipated in the determination of only two of the design parameters; the design wave height and design wave spectrum. The key questions can be summarized thus: WHAT ARE THE EFFECTS OF DIFFERENT DATA ACQUISITION METHODS AND OF DATA RELIABILITY ON DESIGN WAVE PARAMETERS?

Four data acquisition methods have been identified:

1. Visual observations

2. Hindcasts

3. Indirect measurements

4. Direct measurements

The following observations can be made about the relative merits and the techniques used in each of them:

1. Visual observations, such as those made by passing ships appear to give nothing more than a general picture of the meteorological and sea state conditions. This picture has usually a 'good weather bias.' The observations should not be used to define design criteria.

2. Wave hindcasting; the techniques, their applicability and the results need to be carefully scrutinized. Questions have arisen about the adequacy of hindcast models (which is the best), about the adequacy of the input to the selected model (how can synoptic charts be improved; what is the best way to develop wind fields, from synoptic charts or from weather station observations), about the area to be modelled so that sea as well as swell can be accounted for, about the time period to be covered before and after a storm peak, about the inclusion of the storm history both in space and time, about the adequacy of the results (can spectra we developed as well as maximum storm intensity?) and finally about the necessity of calibration of the hindcast model and the techniques to be used for this purpose.

3. Indirect wave measurements; have techniques been developed or perfected so that this method can be used with confidence? The great hopes for Seasat I data have not materialized.

4. Direct measurements; a large number of instruments exists for this purpose. What are the relative merits and the accuracies of these devices? Can their performance be affected by deployment conditions or mooring arrangements? Can they be used year round, even when ice covers the area?

A general question exists about the relative accuracy of data obtained with any of the four methods above. Significant differences have been identified in the results of some methods. Are these reasonable and acceptable or should we be able to do better? Further, is it possible or allowable to combine short term data acquired from one method with those from another system?

This leads to the questions about data reliability. Advice is required on definition of reliability and on how to evaluate a given data set for its reliability. This is particularily important for the early data measured off Labrador. Questions of concern are: What is the optimum number of years with data for a reliable characterization of long term wave conditions in a given area? What are acceptable methods for extrapolating short term data to long term series? Is it possible or acceptable to extrapolate the wave climate from one area to another? What do we need to know to do this?

Once reliable data are at hand, further questions exist about the processing and use of this data for final design parameter determination. Such questions relate to the applicability of statistical methods or techniques to be used. For example, what are the expected differences in results from Tucker and spectral analyses for this same set of data, and why are there any differences? As far as the analysis effort is concerned one asks the question if it is actually necessary to develop new spectra for new areas, or is it not possible to use existing spectra such as the Pierson-Moskowitz or Jonswap spectra? (Widely different fatigue lives have been identified using different power spectra.) Also, the importance of the requirement of directional spectra needs to be defined; this could have serious implications for the data gathering efforts (different types of equipment may be required).

Even after design wave criteria have been defined on a stand-alone basis there then appear questions about the effects of wave interaction with other phenomena such as currents, or the effects of deep water breaking waves or internal waves.

Some of the problems and their engineering implications have been discussed. Engineering solutions can be achieved by joint efforts between the Canadian offshore petroleum operators and scientific institutions. In any of these efforts, the industry must play a lead role in solving these problems.

WAVE CLIMATE OF THE NORTH ATLANTIC AND THE PROBLEMS OF DETERMINING DESIGN AND OPERATING CONDITIONS FOR THIS AREA

Ole Gunnar Houmb

WAVE DATA AND INSTRUMENTATION

The paper describes visual and hindcast wave data along with results from the analysis of such data with main emphasis on the North Sea. Some well known hindcast projects for the northern hemisphere are also briefly described.

Instruments for offshore wave recordings are discussed, including buoys, platform mounted wave staffs and radars. Furthermore the use of radar altimeter data from SEASAT-A is mentioned.

SHORT TERM WAVE STATISTICS

Short term wave statistics deals with the statistical properties of single wave records of length from approximately 20 min to one hour. Included are distributions of wave height, wave height and period and wave steepness. The calculation of the variance density spectrum and its shape is discussed based on approximately 25000 empirical spectra from the North Sea. Some attention is given to various methods of calculation of the wave spectrum leading to a recommendation for the use of one superior method.

Although results from wave directionality are extremely scarce in the North Sea, the necessity for such information is stressed. The main reason for this is a probable overdesign when directionality is not included.

Phase relationships among waves including wave groupiness is of importance regarding design and operation of marine structures. The problem is discussed and some results are presented.

Wave groupiness as observed in instrumental data represents a deviation from the hypothesis of random phase that is important for engineering applications. Deviations from the Gaussian hypothesis on the sea surface elevation are also frequently observed, and some results are presented.

LONG TERM WAVE STATISTICS

Long term wave statistics deals with the analysis of wave data collected over several years. Most models for such analyses deal with some wave height parameter, but the long term distribution of wave height and period is also discussed. Comparative results based on the use of various models are discussed. The main source of data for this type of analyses is the Norwegian Hindcast Project.

Finally a model on the duration of sea state is presented along with some results pertaining to the Norwegian Sea.

WAVE HINDCAST MODELS

D.T. Resio

A discussion of the basic physics of wave generation is used to isolate particular problem areas in our understanding of the wave generation process. Wind input, wave-wave interactions and wave breaking are examined in terms of available theoretical models along with the roles of these terms in maintaining and modifying a wave spectrum. In particular the effects of variations in wind direction and speed, the approach to fully developed conditions, the use of wind velocity versus friction velocity for wind input, and characteristic spectral shapes anticipated in deep-water are reviewed.

After a certain set of source terms are adopted, some aspects of model numerics are examined. The treatment of wave propagation through various schemes is viewed in terms of numerical dispersion, computer run time, ease of application and treatment of angular spreading. Assumptions in source term approximations are also treated in order to determine what effects they might have under varying conditions.

Using a model following along the lines of the physics and numerics discussed here, 20 years of hindcasts were made. Comparisons of hindcast waves and winds have been made to measured spectra and ships observations. Errors are examined in terms of whether its probable source is due to the hindcast model or the wind input, and it is concluded that most errors are probably due in large part ot incorrect specification of the wind field.

SUGGESTED PROCEDURES FOR IMPROVING OPERATIONAL WAVE FORECASTS

Willard J. Pierson

The City College of New York

Improved operational wave forecasts require the following:

(1) Adequate meteorological data to specify the wind fields in the areas of interest including a description of the variation of wind with height and the variation of the boundary layer effects for air approaching or leaving land and moving around and over islands.

(2) Routinely available wave data of different kinds, including aircraft altimeter data and imaging radar data for refraction studies, from which either directional spectra or frequency spectra can be estimated for each time step of the wave forecasting models being used.

(3) High quality high temporal and spatial resolution specifications and forecasts of the wind fields for the areas of interest based on the data from (1) and appropriate forecasting models.

(4) Several computer models (to be tested in parallel) with adequate spatial and temporal resolution capable of describing the wave spectrum with adequate frequency and angular resolution and capable of treating wave generation, wave dissipation, and wave propagation on a sphere in both deep and shallow water.

(5) Standardized procedures for verifying both wave height and spectral hindcasts and forecasts on an operational basis that take into account sampling variability effects and that will serve as a continuous critigue of forecast and hindcast accuracy and of the <u>reason</u> for <u>poor</u> wave forecasts and <u>good</u> wave forecasts and <u>poor</u> wave hindcasts and <u>good</u> wave hindcasts.

(6) A review of wave generation and dissipation theories incuding (a) a recheck of the validity of the "overshoot" concept and the various spectral models (b) the development of ways to treat dissipation due to wave breaking and (c) dissipation effects in shallow water.

The six requirements listed above are given in an order of priority. Wave properties and wave spectra are extremely sensitive to the winds to such an extent that inadequately defined winds can completely mask differences between various wave specifications and forecasting models. As the simplest of possible examples, for a fully developed sea a 10% error in the wind speed results in a 21% error in wave height, a 46% error in the area under the spectrum and a spectral peak that is 61% too high. As simple a step as averaging the winds for 10 or 20 minutes instead of 2 minutes could improve the situation markedly.

More and better wave data are the key to improved wave forecasts. To forecast what will happen requires better knowledge of what has happened. Unless voluminous data for extreme wave conditions are collected for waves with significant heights in the 5, 10 and 15 meter height ranges the conditions for which they occur will not be well understood. Modern wave measurement techniques can define the effects of complicated coastal boundaries and refraction effects.

Good wind field forecasts are a prerequisite for good wave forecasts. Studies of the forecast accuracy of wind fields over the oceans show that there is much to be desired in this area. Most meteorological forecasting models do not move low centers correctly over the oceans and tend to forecast winds that are much too weak with increasing forecast range. There is probably a well defined tendency to miss the development of high winds in the 24 to 36 hour time frame. Basic improvements in the present primative-equation computer based numerical weather prediction schemes may be required before there will be an improvement in wave forecasts for the 24 to 36 hour time frame.

There exist a half dozen, or so, spectral wave prediction models. They need to be compared one with another for the same spatial and temporal resolution and the same spectral resolution for the best available observed wind fields using a large enough sample to obtain definitive results. They should all be verified against the same set of observed wave conditions.

Objective techniques for evaluating wave forecasts are grossly under developed. It is not possible to forecast sampling variability effects. Ways to treat these effects objectively in interpreting how good height forecasts are and in evaluating how well spectra verify need to be developed and applied routinely. If "favorite" model pre-conditions are applied in the spectral analysis procedures, care must be taken to test appropriate "null" hypotheses.

Finally, a review of the literature on waves over the past decade, or so, shows many contradictory theories and internal inconsistencies. It may be possible to make some definitive measurements in nature and in wind water tunnels that will help to chose between these contradictory theories and to decide on the important physical parameters that dominate the spectral wave forecasting problem. The effects of turbulence and of wave breaking seem to be a dominant area requiring improved theoretical analysis and improved modeling for wave forecasting.

As background to his presentation at the workshop, Professor Pierson suggests the reader refer to his recent report on the spectral ocean wave model. Because of the length of the report (222 pages) and at Professor Pierson's suggestion, the list of references is appended.

THE SPECTRAL OCEAN WAVE MODEL (SOWM); A NORTHERN HEMISPHERE COMPUTER MODEL FOR SPECIFYING AND FORECASTING OCEAN WAVE SPECTRA

by

Willard J. Pierson

CUNY Institute of Marine and Atmospheric Sciences
The City College of the City University of New York

FINAL REPORT

Prepared for David Taylor Naval Ship Research and Development Command
Contract N00167-80-M-4781.

NOVEMBER 1980

ABSTRACT

The Spectral Ocean Wave Model (SOWM) in use at the Fleet Numerical Oceanography Center since 1974 has been used to produce a twenty year ocean wave spectral climatology for the Northern Hemisphere oceans. The data sources and concepts used to develop the computer model are described. The equations and computer program structure for the model are given. The accuracy of the model is evaluated by means of the analysis of studies that used spacecraft radar altimeter measurements of significant wave height and by means of the comparison of predicted and estimated frequency spectra and significant wave heights. Sampling variability effects are described and incorporated into the interpretation of the accuracy of the model specifications. Rapid spatial and temporal variations of actual waves are documented that are not reproduced by the model, and possible errors in the specification of swell are suggested. With care in interpretation, the SOWM wave climatology should prove to be more accurate than those based on conventional ship reports.

AN ASSESSMENT OF THE SOWM WAVE CLIMATOLOGY

The SOWM wave climatology differs from all previous open ocean compilations of wave data that have been used to understand the wave environment. These previous compilations were based on wave heights and periods as reported by transient ships by means of the World Meteorological Organization's code[90].

These ship reports have become increasingly questioned. A few years ago the code was changed, and, prior to that time, waves with heights of 5 meters and 10 meters were over reported compared to their actual frequency of occurrence because of pecularities of the code. For the same reason, waves over 10 meters were not sufficiently reported. Recent studies indicate both a bias and a large scatter when ship reports are compared to wave measurements made by a national data buoy[9].

A single period, of any value, is hardly a valid description of a wave system. There are many different kinds of "periods" that can be computed from a frequency spectrum such as the "periods" associated with a spectral peak and at least two different "periods" that can be computed from the spectrum. Although various ways to convert ship reports of wave heights and wave periods to spectra have been proposed, none of them can possible preserve the information in an actual wave spectrum on in the spectra on in the spectra specified by the SOWM.

Ship reports of wave heights and periods also include a provision for reporting both sea and swell. The instructions in the WMO code are hardly adequate for differentiating between sea and swell, and the reports for the swell group usually show that the observers cannot properly separate sea and swell.

Also, ship reports are concentrated on the international shipping lanes so that vast areas of the oceans are rarely visited by a ship. The presently available ship report statistics for some of the ocean areas may be unreliable because of poor sample size. For the SOWM, these same ships are used to determine the meteorological fields to be used to compute the waves. These meteorological fields can, in general, be interpolated and extrapolated into areas with no data more accurately than the corresponding wave fields, and thus by its very nature, the SOWM provides a uniform coverage. There are, however, probably some areas for which the SOWM may be biased because of the lack of ship reports to define the wind field.

A comparison of SOWM height distributions with a conventional climatology shows that the SOWM calls for a higher incidence of high waves[68]. This difference appears to be both realistic and correct. The Institute of Oceanographic Sciences has published numerous compilations of wave statistics based on measurements made by the Tucker shipborne wave recorder[91]. A comparison of the SOWM statistics with these data could provide a calibration point for the SOWM climatology.

The available statistics on comparisons of the SOWM with wave data of various kinds all suggest a negligable bias for the SOWM of at most a few tenths of a meter. The RMS differences between the SOWM and wave height measurements have ranged from 1.20 meters through 1.00 meters and as low as 0.80 meters. A part of this RMS difference is the result of sampling variability and so the errors of the SOWM for middle latitudes may actually be as low as 0.7 to 0.8 meters.

The limited amount of data that have been used to verify the SOWM frequency spectra show that the SOWM tracked the variations in the estimated spectra fairly realistically. Much more needs to be done in the area of the verification of frequency spectra, especially in view of the effects of the improved wind fields and the FNOC modification, which was described at the end of the section on Propagate, on the performance of the model. Ways to verify frequency spectra have been illustrated. The data must be interpreted with great care.

Despite concern at the beginning with the accuracy of the winds that are used in the SOWM, the available data do not seem to show that rather large RMS errors in the winds (even after correction) have generated large RMS errors in the waves. From about 1976 onward, it was not necessary to correct the FNOC winds in the way that was described in the section on the verification of the winds. A possible explanation may be that the errors in the winds have oscillated above and below the correct values both in space and time and that the integrating effect of the SOWM calculations on the input winds has yielded output waves nearly in accord with reality.

Two last precautions are required before ending this analysis. They are concerned with the verification of swell and with the variability of the waves that has been observed over both small spatial distances and short time intervals. Both of these features require further scientific study and analyses, and both have been discussed in various sections of this paper. Care should be taken that the wave climatology have built in factors of protection against errors that may be introduced into it because of these effects.

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THE WAVE CLIMATE STUDY OF THE MARINE ENVIRONMENTAL DATA SERVICE

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INTRODUCTION

The Canadian Wave Climate Study was established in 1968 in response to a recognized need for wave data to be used in the design of marine facilities. Since that time, wave data has been collected at about 175 locations in marine and inland waters around Canada. This paper describes the purpose and the development of the Study.

THE CANADIAN REQUIREMENT FOR WAVE DATA

The original impetus for the Study was supplied by the Canadian Department of Public Works to obtain wave data in support of their rather large and costly marine construction. Since that time, a variety of offshore activities, such as hydrocarbon exploration and now the possibility of offshore production, have added dramatically to the urgent needs for measured wave data of high quality.

In particular, the Study took advantage of an opportunity to enter into joint programs with virtually all the offshore drilling operators. Beginning in 1972, the Study has applied wve recording equipment for the drilling units. The operators install, maintain and operate the equipment, and the Study undertakes to do the data analysis and provide a copy of the analysis to the operators. One condition of this type of co-operative program is that the data is immediately in the public domain.

It was recognized at the beginning of the Study that wave direction as well as height information was required. However, it was also recognized that routine collection and computation of directional wave spectra on the scale proposed was beyond the present state of the art. It was decided to gather non-directional wave data and, where necessary, to attempt to infer wave direction by other means, such as estimation using hindcast techniques based on wind speed and direction. The deficiences in this technique, such as intersecting wave trains, are recognized and admitted.

ORGANIZATION OF THE STUDY

1. Number of Stations Maintained

The Wave Climate Study has for the past five years operated at a level of about 20 to 30 recording stations per year. Of these, typically, three are long-term stations maintained to obtain long-term wave statistics, ten to fifteen are associated with offshore petroleum exploration, another six to eight are associated directly with planned marine construction, and the other four might be concerned with support to scientific experiments.

2. Wave Sensors

The Study employs a number of instruments for routine wave measurements. Wave staffs, pressure sensors, or accelerometer buoys are selected for a specific project, depending on the logistics of the situation. In most circumstances, the Waverider accelerometer buoy is used, provided current velocities are not excessive, interference from shipping or fishing is not expected, and there is sufficient area for the buoy to move in.

In situations where the instrumentation is to be located in an existing harbour where space is limited, a wave staff will be used. If a suitable mounting for the wave staff is not available, a pressure cell will be employed.

3. Waverider Buoy

The Waverider buoy has become the standard instrument of the Study because of its accuracy, reliability, and ease of handling. A further advantage of the Waverider is that it almost always either obviously fails or it functions correctly. In any comparison with other instrumentation which has been done by the Study, the agreement has been within 3 to 5 percent.

It is also standard practice in the Study to verify the calibration of each buoy before installation and immediately after removal from a site. This is accomplished using a device which physically carries the buoy in a 2-meter diameter circle at a number of constant frequencies determined by change gears on a transmission. The output of the buoy is recorded exactly as in the field situation, and the data is processed through the same programs as the field data. This provides a check not only of the buoy calibration but also of the data analysis hardware and software.

This procedure has resulted in the checking of buoy performance in this manner a total of 406 times in the past few years. In approximately 90% of the tests, the buoy performance was within 3% of the specified calibration. In the other 10% of the cases, a simple inspection of a wave record or spectrum would have indicated the instrument was faulty.

The Waverider has also proved easy to moor from a small boat. Mooring problems have been confined to abrasion of the wire rope portion of the mooring on the bottom and occasional failure of swivels or other components due to corrosion. The problem with abrasion on the bottom was solved by beading the cable with air compressor hose. The problem with corrosion of swivels was solved by changing manufacturers.

Another problem had to do with fouling of the buoy in warmer waters. An anti-fouling paint system has been found to solve this problem.

4. Data Analysis and Quality Control

Two early decisions made in establishing the analysis system for the Study were to record on magnetic tape for machine processing and to adopt a Fourier analysis of each 20-minute wave record as the standard analysis technique.

The Fourier analysis was chosen for three reasons. Firstly, it is considered by the Study to be the most useful analysis. Secondly, many wave sensors require a frequency-dependent response correction to the signal. lastly, a Fourier analysis using the Fast Fourier Transform technique is economical, costing about 50 cents per 20-minutes wave record.

Field recording of the data is automatic, except for the requirement to turn over a tape after four days of recording and to mount a new tape after eight days. The wave signal is recorded as an FM signal, and a pilot oscillator signal is recorded on the second channel of a standard stereo tape deck. Absence of the pilot oscillator signal is used by the analysis system to indicate equipment malfunction. The oscillator signal is also used to remove power line frequency fluctuations or mechanical tape recorder speed fluctuations from the data.

A special controller also records onto the tape the date, time and station identification for each wave record. The clocks are battery - and crystal-controlled for reliability and accuracy.

Data handling at headquarters begins with a scan of the tapes immediately they arrive to detect major equipment failure at an early data. The tapes are then digitized and the spectrum analysis is carried out. This yields characteristic wave height and peak period of the spectrum information.

Quality control of the data proceeds as soon as the spectrum computation is completed. A digital magnetic tape is produced containing the spectrum for each 20-minute record. This tape is processed on an off-line computer system, with displays each spectrum diagram for viewing on an oscilloscope display.

Instrument malfunction or radio interference is easily detectable and the offending 20-minute records are deleted from the file. If required, a surface elevation trace can be viewed on the oscilloscope in making the decision to keep or delete the record.

The final phase of quality control consists of producing the standard set of statistical summaries and looking for outlying points. Records corresponding to outlying points are reviewed a second time.

All data products are produced from the variance spectrum analysis and deal with the characteristic or significant wave height obtained from the zeroth moment of the spectrum and the peak period obtained from the frequency at which the maximum spectral density occurred. Occasionally, wave-by-wave analyses are undertaken for special purposes. An example of this could be a study of wave grouping. Wave-by-wave analyses are reviewed a second time.

All data products are produced from the variance spectrum analysis and deal with the characteristic or significant wave height obtained from the zeroth moment of the spectrum and the peak period obtained from the frequency at which the maximum spectral density occurred. Occasionally, wave-by-wave analyses are undertaken for special purposes. An example of this could be a study of wave grouping. Wave-by-wave analyses are relatively expensive, as they generally require digital band pass filtering of the signal prior to picking off the crests, troughs and zero crossing.

DATA AVAILABILITY

The data are available in a variety of forms. Standard data booklets are produced containing summaries of the data collected at each station. Also available are plotted spectra, Tucker-Draper type presentation, monthly plots of significant wave heights, and instantaneous surface elevation data. The data, derived parameters such as significant wave height, and spectral data are also available on magnetic tape. Because of volume, cost recovery may be necessary in certain cases. The methods of obtaining wave data, cost recovery principles, and the data presentations available are described in a booklet entitles "Available Wave Data Products." This booklet can be obtained free of charge from the Marine Environmental Data Service.

Other special processing of the wave sensor signals is carried out on an ad hoc basis. An example of this would be the regeneration of the water surface elevation trace from a pressure cell record. This is accomplished by Fourier transforming the record, correcting the Fourier amplitudes according to small wave theory, and resynthesizing the components to produce the surface elevation trace.

SUMMARY

The Study has operated since 1968 and has accumulated more than 1,500 months of wave climate data collected at approximately 175 different locations. Almost all of these data are now available on request.

The Study can, on as little as two weeks' notice, install a wave measuring system at a location and, at a cost of $15,000 to $18,000, expect to achieve an 80 to 90% success rate in obtaining a year of engineering-quality measured wave data.

The wave data file now consists of one set of magnetic tapes which contains digital surface elevation information and a second set of tapes containing wave spectrum information. There are in excess of 1/4 million records in each of these files.

QUESTION

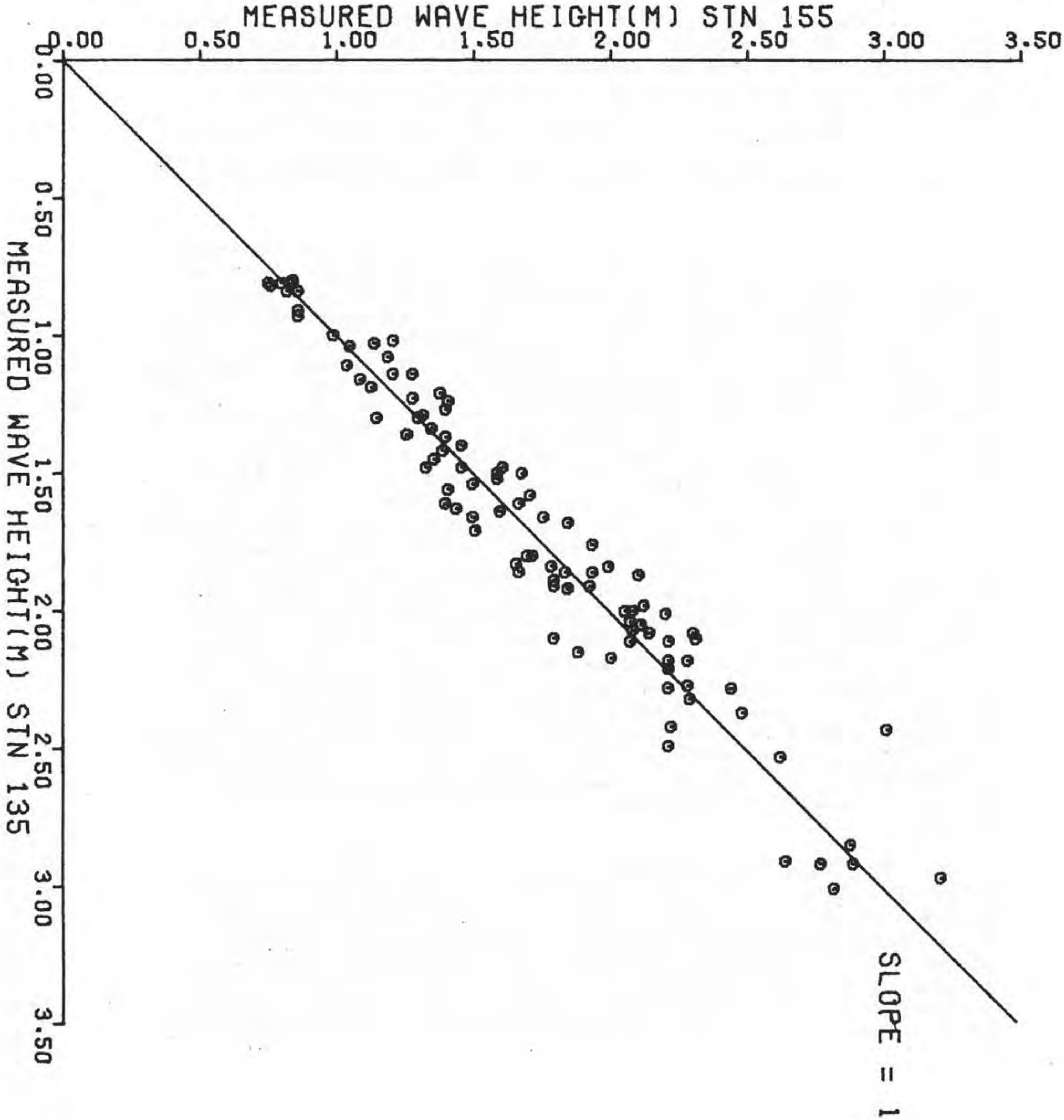
A question was raised at the Wave Information Workshop regarding the performance of the mooring recommended by the Waverider manufacturer and used by MEDS. At the time of the Workshop, an experiment had been run in the vicinity of the rig NEDRILL with a standard MEDS mooring and a mooring incorporating a sub-surface float. On the attached diagram, the standard mooring is identified as Station 135 and the sub-surface float mooring as Station 155.

Unfortunately, the recording equipment was not set up to record the two Waveriders simultaneously, but rather separated one hour in time. The results are shown in Figure 1. There were approximately 95 records taken on each recorder, with significant wave heights ranging from 0.8 to 3 meters. The best fit line (not shown) has a slope of 0.991 and an intercept of 0.025.

Clearly, there is no evidence of bias in the data obtained, and the scatter is well within the expected statistical uncertainity, not even considering that the records were separated in time. The results, however, are not conclusive in that the records were separated in time and the highest wave height encountered was 3 meters. Further work would be useful for high wave conditions.

In the meantime, MEDS is encouraging the use of sub-surface float moorings for deeper stations or the large Waveriders with their greater reserve buoyancy.

Figure 1. Comparison of Wave Heights from Two Waveriders in the Vicinity of the NEDRILL Drilling Unit.



BIO DEEP WATER WAVE CLIMATE OF THE CANADIAN

COASTAL WATERS AND NORTH ATLANTIC

Hans J.A. Neu

In the late sixties, when oil exploration commenced on the Scotian Shelf and on the Grand Banks of Newfoundland, the need for a wave climate became apparent. In 1970, the Bedford Institute of Oceanography (BIO) initiated a wave study of the coastal waters and continental shelf of Atlantic Canada (Neu, 1971, 1972) and later expanded the study to cover the entire North Atlantic (Neu, 1976; Walker, 1976, 1977, 1978). In addition, in 1977, a new more detailed Canadian wave climate was started which also included the northern waters, the Gulf of St. Lawrence, and the Bay of Fundy.

At the outset, the term wave climate was defined as a description of the sea state with respect to time and space in which the time frame referred to month, year, and long-term values such as 10- and 100-year extremes. Information which would fulfill this requirement could derive practically only from three sources: hindcasting from wind observations; direct measurements with wave gauges; and visual observations. Hindcasting of waves would seem to be the rational method to provide the data but even today the results are still not always satisfactory. Its shortcomings lie primarily in the fact that insufficient meteorological observations are made over the open ocean particularly with respect to varying winds and moving fetches. Direct surveying with gauges appears to be the most precise method, yet gauges exposed to the hazards of the open ocean have only short operational lives. They are, therefore, too expensive and their data too sparse to develop an ocean wave climate; however, they are extremely useful for calibration purposes, spectral descriptions, and shorter term descriptions of the sea state at particular points in the ocean, such as drill platform sites and harbours. The greatest quantity of information and virtually the only consistent data which pertain to deep-water areas are those contained in ship reports. Wave and weather observations from 40 to 100 stations across the North Atlantic, consisting of weather ships, Canadian and U.S. government and navy ships, merchant ships, and oil-drilling platforms, are transmitted every 6 hours to the Meteorological and Oceanographic Centre (METOC) in Halifax where they are reviewed and plotted on wave charts. BIO started to collect these charts on 1 January 1970 and has now a continuous 10-years data bank for nearly the entire North Atlantic.

The data given in the charts are wave heights (lines of equal heights), wave period, and wave directions. The question of whether the visual observed wave height is related to the significant wave height H_{sig} - which is the mean height of the highest one-third waves in a record - has now been clearly resolved in a comprehensive comparison by Jardine in 1979 using Ocean Weather Station 'I' data. He verified previous conclusions that both values are practically equal. A similar relationship, but less firmly established, applies to the visually observed period

T_V. A comparison of period (T_p) at the peak of the power spectrum of wave records on the Scotian Shelf with visual values T indicated that T_p is between 30 and 50% greater than T. No great difficulties were encountered in determining the direction of the wave field.

Every 12 hours, representative values for height, period, and direction were determined from the wave charts for each 1° area of the Bay of Fundy and Gulf of St. Lawrence, each 2½° area of the coastal region, and each 5° area of the North Atlantic. This provided an uninterrupted time series of 730 data points per annum. From these data monthly directional scatter diagrams, monthly nondirectional and directional energy distributions, and annual exceedance diagrams were developed.

Where the general sea state of the North Atlantic is concerned, the most conclusive presentation is given by the spatial distribution of the monthly and annual largest wave heights and their periods. the smallest occurrence and the lowest monthly and annual largest waves were encountered along the coast of North America and across the ocean from Florida to North Africa. From these areas and to the east and north, respectively, the heights, periods, and occurrences grew rapidly until a high level of activity was reached in the central part of the North Atlantic. From here on the sea state increased only in the northeasterly direction. The highest wave activity occurred about 1000 km west of Ireland. The frequency of occurrence of waves was 4 to 12 times greater (depending on wave height) on the European side than on the American side of the ocean. The distribution of the periods of the highest annual waves showed similar trends for their respective heights. The annual waves had relatively short periods along the coast of North America but were nearly double in the mid-and eastern Atlantic. Generally speaking, the coastal regions of North America and of the western North Atlantic are primarily the wave-producing side of the North Atlantic while the eastern North Atlantic, in particular the northern portion, is the wave-receiving side.

A ten-year (1970-1979) time series of 12-hourly wave charts for the North Atlantic issued by the Meteorologic and Oceanographic Weather Centre, Halifax has been collected by the Bedford Institute of Oceanography (BIO). From the data, which are primarily based on ship observations, 10 years annual and monthly sea state descriptions have been developed for a location near the edge of the continental shelf of Nova Scotia. The results clearly indicate a large fluctuation in wave activity in which the height of the larger waves varied by 40%. The period of this quasi cyclic variation was about 6 years with peaks in 1972 and 1978 and lows in 1970 and mid-seventies. The energy variation involved in this long term cycle was larger than that during the regular annual cycle between winter and summer. The increase in wave activity was not only created by a few excessive storms but by a rise in wave activity during the winter generally. Samples tested in other regions of the North Atlantic show similar behavior, some with variations which were significantly higher than that on the Scotian Shelf and with additional peaks in the mid-seventies. An analysis of the entire North Atlantic based on 3 years data (1970 to 1972) shows large temporal variations in the northern North Atlantic and southern North Atlantic with a phase lag of 3 years between the two regions. Thus, long term fluctuations in wave heights are a significant feature of the north Atlantic wave climate.

Knowledge of extreme wave conditions is needed to evaluate the survival capability of marine systems and structures in the ocean. Their study is based on probability theory. Obviously, annual data banks which provide the information for these predictions are biased by year to year fluctuations which have a much greater effect on the results than the choice of theory or the precision of data. Regardless of the theory applied, the 1970 data compared with 1972 data yield 100-year values which differ in height by 40 to 50% and in energy by more than 100%. The analysis of the 10-year data on the Scotian Shelf demonstrates that, for the seventies, a data bank of at least 6 years would be required to account for this variation. The short term wave recordings from oil exploration platforms cannot satisfy this requirement but they are extremely important for the local description of storms, their spectral analysis, and for short term sea-state predictions.

THE WAVE CLIMATOLOGY PROGRAM

OF THE ATMOSPHERIC ENVIRONMENT SERVICE (AES)

V.R. Swail

1. INTRODUCTION

The Atmospheric Environment Service, in order to fulfill its mandate to provide wave information, has undertaken various projects to produce design wave information, to develop new techniques for wave hindcasting and estimation of design wave parameters, and to investigate new procedures related to technological advances such as SEASAT-A and surface-based radar.

This paper describes some of the projects undertaken to data and outlines plans for further programs. Fuller details of some of the projects are available in papers shown in the reference list.

2. THE NORTH ATLANTIC WAVE CLIMATOLOGY PROGRAM

2.1 Northwest Atlantic Wave Climatology

In 1972, the AES initiated a project to develop a wave climatology for the northwest Atlantic using the 12-hourly wave height analyses produced by the Canadian Forces Meteorological and Oceanographic Centre (METOC) in Halifax (McCulloch, 1972).

The wave height analyses are produced using the forecast wave height chart valid at that time as a first-guess field. Wave observations from ships are plotted on the chart and additional points are bogused in for data sparse areas using the analysed wind field and the Sverdrup-Munk-Bretschneider (SMB) relations. The initial field is modified subjectively incorporating the ship and hindcast data to produce an analysis (Fig. 1). Details of the analysis procedure are given by Morgan (1971). These analyses are expected to represent an improvement on the ship observations along, although a comprehensive evaluation has not been done. A recent limited comparison between the METOC charts and SEASAT-A wave height measurements (Jones, 1980) showed encouraging results.

For climatological purposes the area covered by the METOC charts is divided into squares 5° of latitude by 5° by longitude, except for coastal squares which are extended to the shoreline (Fig. 2). For each square, for each analysed wave height chart, the highest analysed value of wave height in the square and its associated period and direction are abstracted. Summaries are produced for each individual month and by collective month, eg. all Januarys. These summaries are in the form of contingency tables showing the joint occurrence of wave height and period by direction to eight points (Fig. 3). The category labelled ICE indicates that the square was more than 75% covered by ice. The ice information is taken from the routine ice cover analyses prepared by AES Ice Central in Ottawa. Almost

TABLE 1
Largest Wave Height and Period Observed in Five Years
(May 1972 - April 1977)

Grid Number	Highest Wave (Period)	Month/ Year	Highest Period (Wave)	Month/ Year
5	10(11)SE	3/74	14(6)NW	12/72
6	11(12)SE	3/74	15(9)NW	10/73
7	12(15)W	12/72	15(12)W	12/72
8	12(13)W	11/75	16(12)W	11/75
9	12(13)W	11/75	17(11)SW	10/73
10	12(12)NW	2/73	17(11)S	10/73
16	11(10)N	10/73	15(10)W	12/72
17	13(10)W	1/74	20(10)W	10/73
18	13(10)W	1/74	16(13)W	12/72
19	13(10)NW	12/72	16(12)W	11/75
20	13(10)NW	12/72	16(12)NW	11/75
24	8(8)NE	6/73	14(7)S	12/75
25	10(9)E	6/73	14(4)SE	5/75
26	10(12)W	3/74	15(8)NE	12/74
27	13(10)NW	1/74	15(9)N	4/76
28	14(12)NW	1/74	16(14)NW	2/76
29	17(14)N	12/72	16(16)NW	2/76
30	17(14)N	12/72	16(14)W	2/76
33	11(9)NE	3/73	15(3)NW	12/75
34	13(12)W	11/73	15(5)NW	12/75
35	12(14)NW	2/74	15(5)W	12/75
36	11(16)W	2/74	16(11)W	2/74
37	12(16)W	12/72	16(12)W	12/72
38	15(13)W	12/72	15(9)NW	4/76
39	18(12)NW	12/72	16(12)NW	3/76
40	18(12)W	12/72	15(12)W	1/74
42	10(11)NW	2/74	14(8)NW	4/75
43	12(10)NW	12/72	15(3)E	10/72
44	12(12)W	11/73	18(4)SE	10/73
45	12(12)NW	2/74	15(3)E	10/72
46	12(10)SW	2/74	14(9)W	2/77
47	11(14)SE	9/73	14(7)NW	12/74
48	12(12)NW	12/72	15(6)NW	2/75
49	14(12)NW	12/72	15(8)W	1/74
50	14(12)NW	12/72	15(8)W	1/74
51	9 (10)N	2/73	15(3)NE	12/75
52	10(11)IN	10/73	14(7)NW	4/75
53	10(12)N	3/73	15(8)NE	3/73
54	9(10)NW	3/73	15(15)E	10/72
55	10(12)W	1/73	15(3)E	10/72

TABLE 2
LOCATION A
WAVE HEIGHT FREQUENCY
(PERCENTAGE FREQUENCY)
1956 - 1971, 1974 - 1978

HEIGHT (Metres)	JUNE	JULY	AUG.	SEPT.	OCT.	ANNUAL
0 - 2	14200 (94.8)	14738 (94.3)	14475 (92.8)	13035 (86.2)	12681 (81.2)	69129 (89.8)
2 - 4	759 (5.1)	867 (5.6)	1066 (6.8)	1755 (11.6)	2631 (16.8)	7078 (9.2)
4 - 6	17 (0.1)	19 (0.1)	59 (0.4)	220 (1.5)	283 (1.8)	598 (0.8)
6 - 8	0	0	0	94 (0.6)	23 (0.15)	117 (0.15)
8 - 10	0	0	0	16 (0.11)	6 (0.04)	22 (0.03)
TOTAL	14976	15624	15600	15120	15624	76944
HIGHEST (M)	4.2	4.5	4.9	8.7	8.1	8.7

SIGNIFICANT WAVE
RETURN PERIODS
(Metres)

10-Year	3.6	3.6	4.2	6.0	6.0	7.2
20-Year	4.4	4.5	5.2	7.6	7.4	9.0
50-Year	5.5	5.6	6.6	9.6	9.3	11.2
100-Year	6.4	6.5	7.6	11.1	10.7	12.9
Extremes (1.8Hs)						
50-Year	9.9	10.1	11.8	17.2	16.8	20.2
100-Year	11.4	11.7	13.6	19.9	19.3	23.

nine years of data has been accumulated at this writing.

An analysis based on 1972-77 data was produced as a preliminary data summary (AES, 1977). Information presented includes the highest significant wave height and maximum period observed for each square (Table 1) and percentage frequency of occurrence of various wave height classes. An analysis which is currently being produced gives the design wave heights for various return periods for each square. Gumbel return period curves are plotted for selected squares in Fig. 4 along with comparisons of other data. The point marked BRAVO is the maximum wave height observed at OSV BRAVO in 20 years. This plotted on the 20 year return period line, although this may or may not be the 20 year return wave. Similarly the maximum from SSMO areas 3, 4, 5, 11 is plotted for comparison. The point marked HINDCAST is the maximum value hindcast in a 20 year study by Cummins and Bales (1980) using the spectral ocean wave model (SOWM).

This method is advantageous, particularly in estimating extreme values, since with the coarse time scale (12 hours)occurrences of large waves might otherwise go undetected. However, the method is not applicable for other statistics such as duration analyses and it is not representative within a few kilometers of the coast since the highest wave in the square will usually occur in the deep water portion of the square. In any event the METOC analyses are intended for deep water.

2.2 Grid Point Wave Height Climatology

In 1979 an alternative approach was developed (Swail, 1979) in order to produce a data base on which standard statistical routines could be performed to produce exceedance and duration statistics. In this method the METOC analyses are automatically digitized by tracing the wave height contours with the cursor of the digitizer which causes the X-Y coordinates of points on the contour to be written onto disk. Interpolation into a grid is done by a method of intersecting planes through the four digitized points nearest to a grid point. This is considerably better than simple averaging which results in the loss of the high and low values. The result is the creation of a time series of wave heights at 12-hour intervals for about 400 grid points over the northwest Atlantic (based on a 190.5 km grid length). The grid point locations, with an example of an interpolation and overlaid analysis, are shown in Fig. 5. Standard statistical routines can then be applied to these time series. In addition, a magnetic tape archive is created of all analyses as a by-product. This project is currently in limbo due to a lack of resources for digitizing.

2.3 Grand Banks/Scotian Shelf Climatology

Due to the lack of resources for the full grid point climatology, a subproject was undertaken in April 1980 to subjectively interpolate wave height values at nine points (A-I) on the Grand Banks (near the Hibernia location) and on the Scotian shelf for the period 1975-79 inclusive (Fig. 2). A time series of wave height values at 12-hour intervals was produced and standard statistical analyses were performed for each point. Frequency analyses, duration statistics above and below various thresholds, and Gumbel return period values were produced. The results should be published in the spring (Swail and Massek, 1981). This project may be expanded either to other grid points or in time to cover the full data set available (1972-81) or both depending on resources and priorities.

3. LANCASTER SOUND WAVE CLIMATOLOGY

In Lancaster Sound a project was undertaken to hindcast 20 years of wave heights at three points (A-C) for the months June-October, and also at OSV BRAVO for verification (Fig. 6). The wind input was synthesized from the Fleet Numerical Oceanographic Center (FNOC) 6-hourly grid point pressure data. The locations of the pressure grid points are given by the squares in Fig. 6. The geostrophic wind at 6-hour intervals was computed by using a cubic interpolation scheme on a 4x4 grid area around each point. Wind directions were backed 20 degrees to better approximate surface winds but no speed reduction was introduced and geographical influences were not considered. Hourly wind values were obtained by linear interpolation of the 6-hourly 'u' and 'v' components of the pressure gradient. The wave hindcasts were based on the Sverdrup-Munk-Bretschneider (SMB) relations. Maximum fetch values were determined for every 10 degrees of azimuth using geographical features and monthly minimum ice conditions from Fig. 6 taken from analyses produced by AES Ice Branch from their reconnaissance flights. No other fetch limitations were considered. The use of minimum ice conditions will tend to give greater fetches than actually occur and thus cause some overestimation of the wave heights but it was essential that the worst possible cast not be overlooked.

Verification was performed using the U.S. Summary of Synoptic Meteorological Observations (SSMO) tables for Lancaster Sound and OSV BRAVO, actual wind data for Resolute, and hand-drawn surface analyses. Figs. 7 and 8 give two cases of maps analysed by the AES Arctic Weather Centre in Edmonton with the FNOC grid point pressure values plotted. In the first case the situation is described very well by the FNOC data as to location of features and gradient. However, in the second case, the western low has been missed by the FNOC analysis leading to an erroneous wind field. It is expected that this type of occurrence is not an isolated case and that the wind speed statistics generated will be somewhat low. This was a contributing factor in the decision not to use a speed reduction in the geostrophic to surface wind transformation. Comparison of the wind statistics derived from the SSMO tables for OSV BRAVO and the statistics synthesized from the FNOC pressure data show a remarkable agreement in both August (Fig. 9) and October (Fig. 10) indicating that there may be a compensating effect between the non-reduction of geostrophic winds and the tendency to underestimate the gradients using the FNOC data.

Comparisons of the wave data show good agreement except for very high wave heights (Fig. 11). this is probably due to unreasonable fetch assumptions (the fetch is assumed to be 100° km unless limited by ice or land) with high wind speeds since under such conditions the fetch will generally be limited by the curvature of the isobars. Some adjustment will be made to reflect this fact.

The wave hindcast statistics are presented as frequency distributions by month of wave height within various classes plus extremes and return periods using the Gumbel distribution for each of the three points selected.

A full description of the project and the results are given by Lachapelle (1981).

4. REMOTE SENSING

AES is also working to develop techniques to use the products of new technology such as oceanic satellites for climatological studies. The Canadian Climate Centre has participated in the SURSAT Program since its inception in evaluation of the SEASAT-A sensors, particularly the radar altimeter, scatterometer, and the microwave radiometer. Comparisons have been made of the satellite radar wave height data with observations from ships of opportunity and drill ships. In addition comparisons have been made with the METOC wave height analyses. Wind speed and direction data from the scatterometer have been compared with selected land stations, ships of opportunity, drill ships, and the geostrophic winds produced from the Fleet Numerical Oceanographic Center (FNOC) grid point pressure values. A report on the comparisons should be published in the summer (Swail, 1981). Planning is already underway at AES for participation in the U.S. National Oceanic Satellite System (NOSS) Program, scheduled for launch in June 1986. Some further sensor evaluation will be done in the interim and strategies will be developed to use the data produced for climatological purposes.

Developments in remote sensing of the ocean by land-based radar have been monitored but it is felt that more development is necessary for this to be a useful system.

5. FUTURE PLANS

AES plans (resources permitting) to do climate studies for the northeast Pacific Ocean, possibly using the wave height analyses produced by the Pacific METOC Centre to produce preliminary design values. Studies are also planned for the Beaufort Sea and Hudson Bay. For these areas no such wave analyses exist so other techniques must be used. Undoubtedly some form of hindcast technique will be employed. AES is hoping to develop a spectral hindcast model to produce hindcast statistics for portions of the Atlantic and Pacific Oceans in the Canadian area of interest as well replacing the current climatologies which are essentially based on visual observations.

As indicated in section 4, AES intends to participate extensively in NOSS and to monitor progress in ground-based radar systems.

Current programs for provision of climatological wave information will continue, particularly the AES Grid Point Wave Height Climatology, at least until data from hindcast models is available to replace it.

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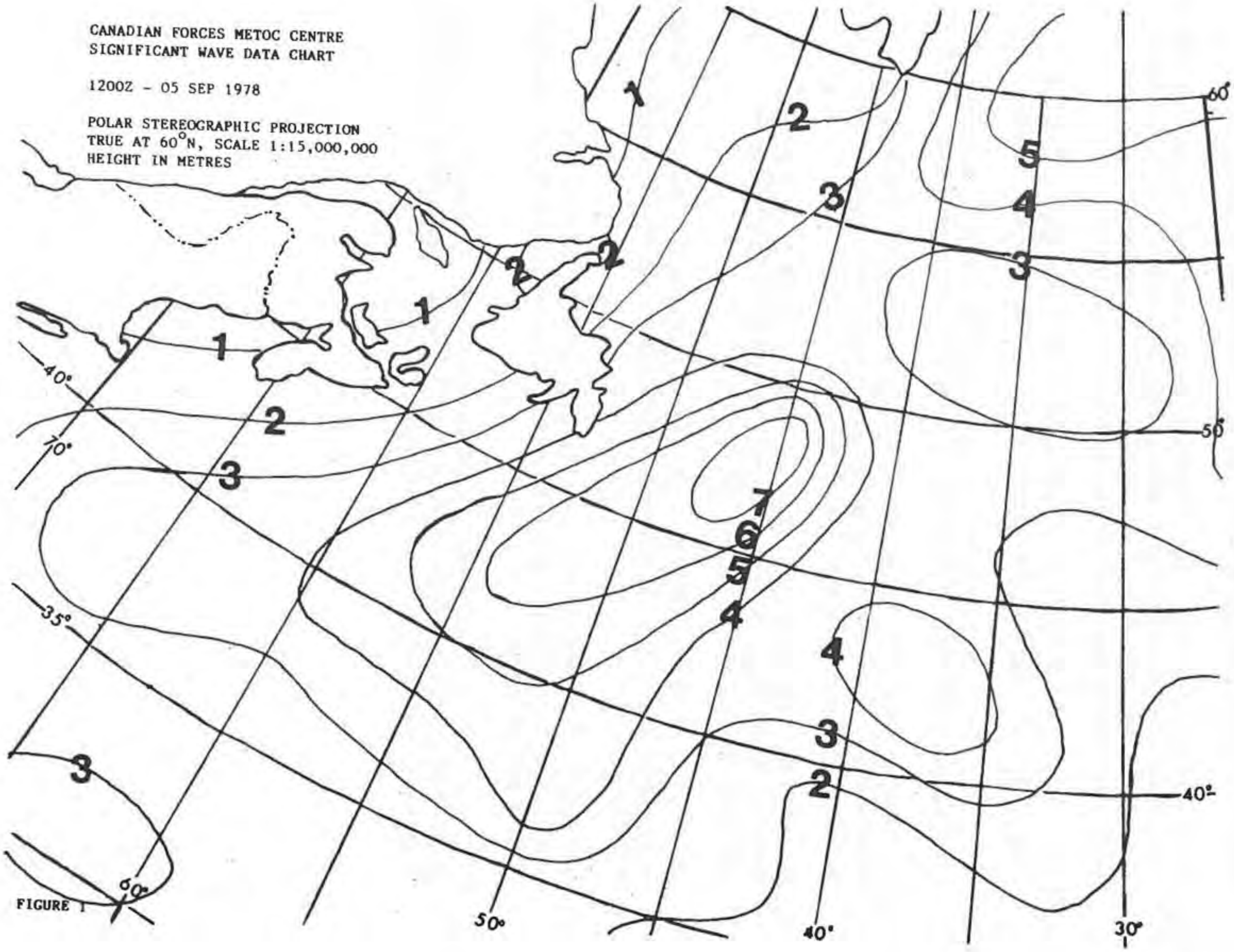

CANADIAN FORCES METOC CENTRE
SIGNIFICANT WAVE DATA CHART
1200Z - 05 SEP 1978
POLAR STEREOGRAPHIC PROJECTION
TRUE AT 60°N, SCALE 1:15,000,000
HEIGHT IN METRES
60°
50°
40°
70°
35°
60°
50°
40°
30°

FIGURE 1

SQUARE NUMBERS FOR NORTH ATLANTIC
WAVE CLIMATOLOGY
GRID POINT LOCATIONS FOR GRAND BANKS/
SCOTIAN SHELF CLIMATOLOGY

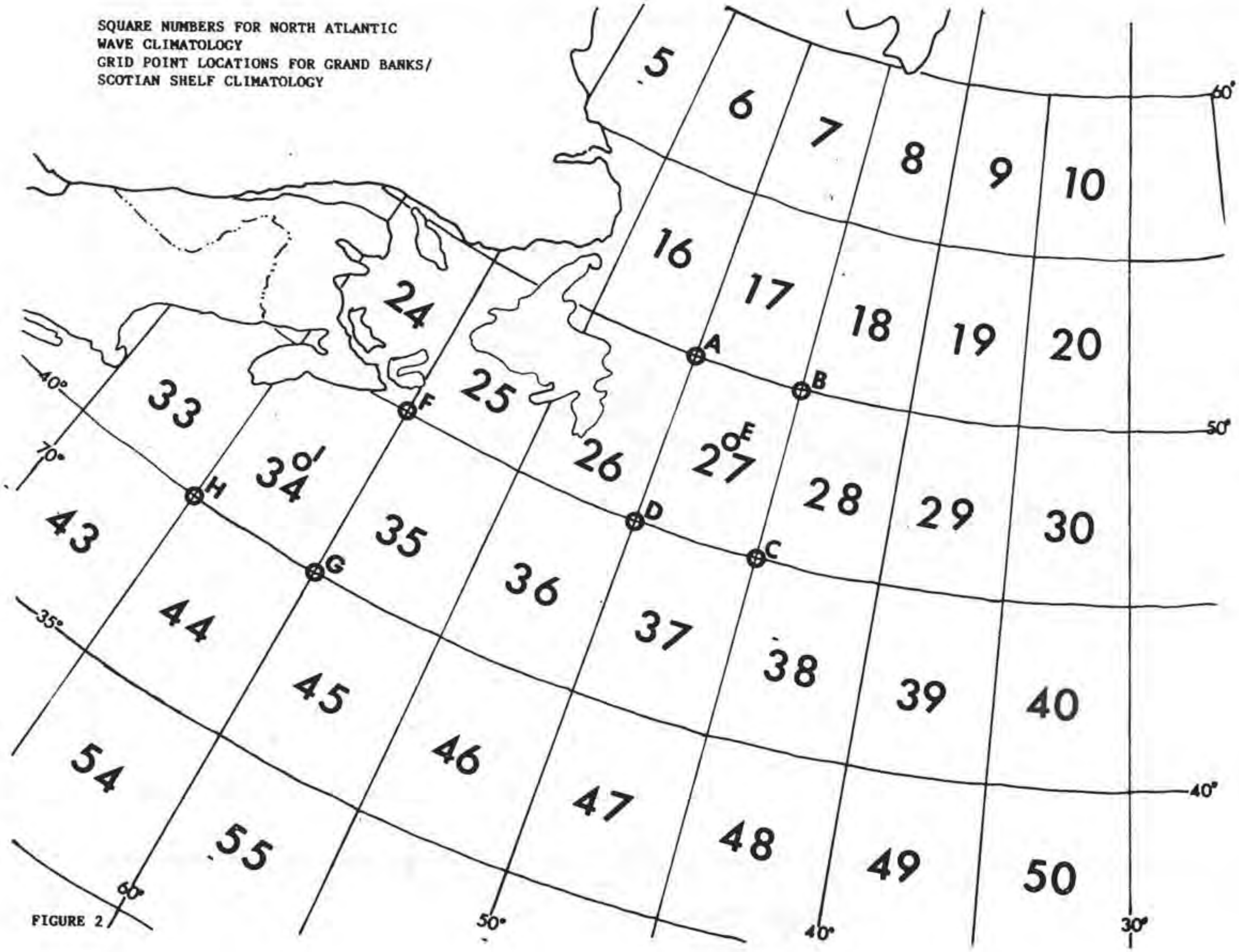


FIGURE 2

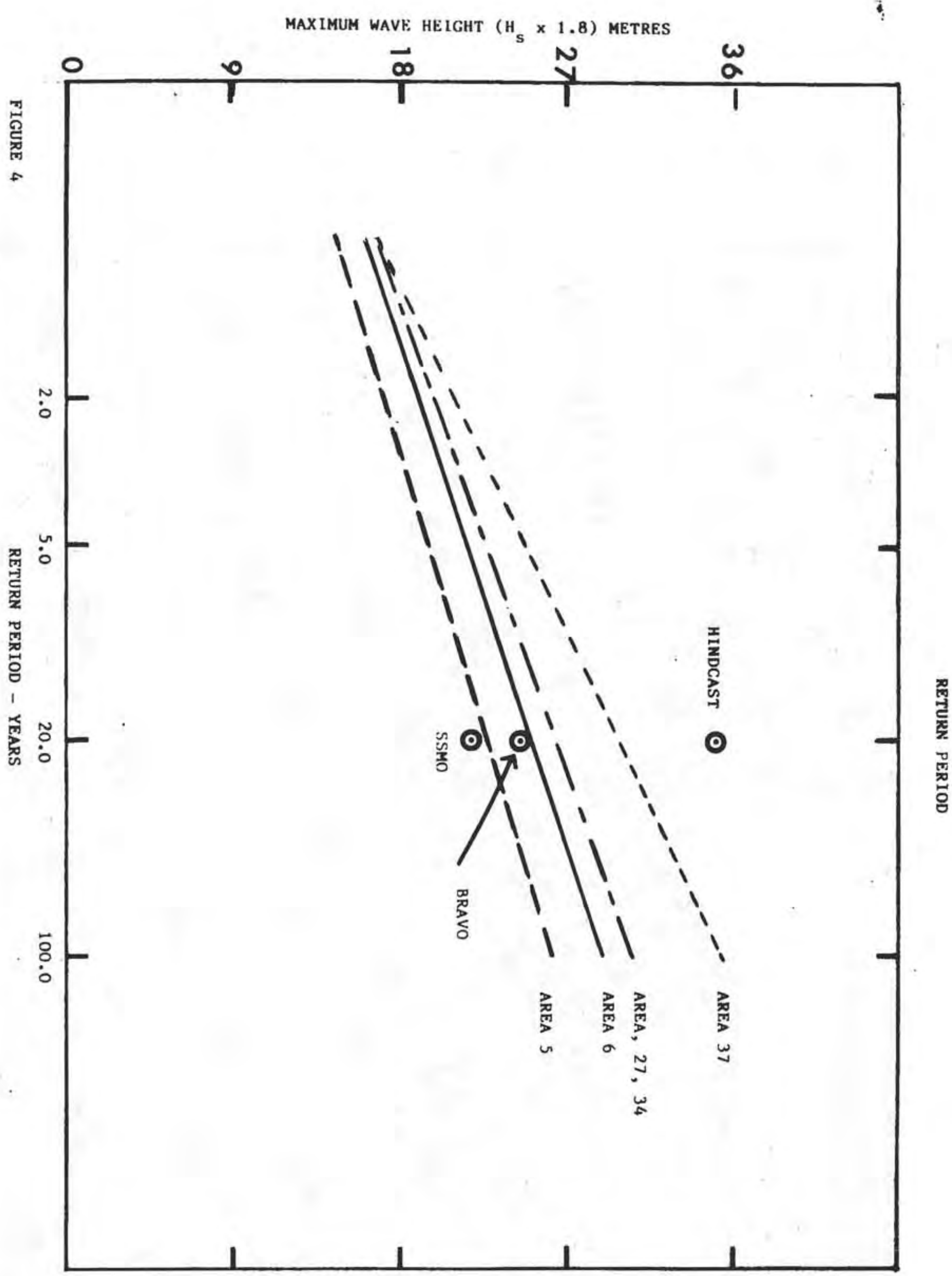

MAXIMUM WAVE HEIGHT (Hs x 1.8) METRES
0
9
18
27
36
RETURN PERIOD
2.0
5.0
20.0
100.0
RETURN PERIOD - YEARS
HINDCAST
SSMO
BRAVO
AREA 37
AREA, 27, 34
AREA 6
AREA 5

FIGURE 4

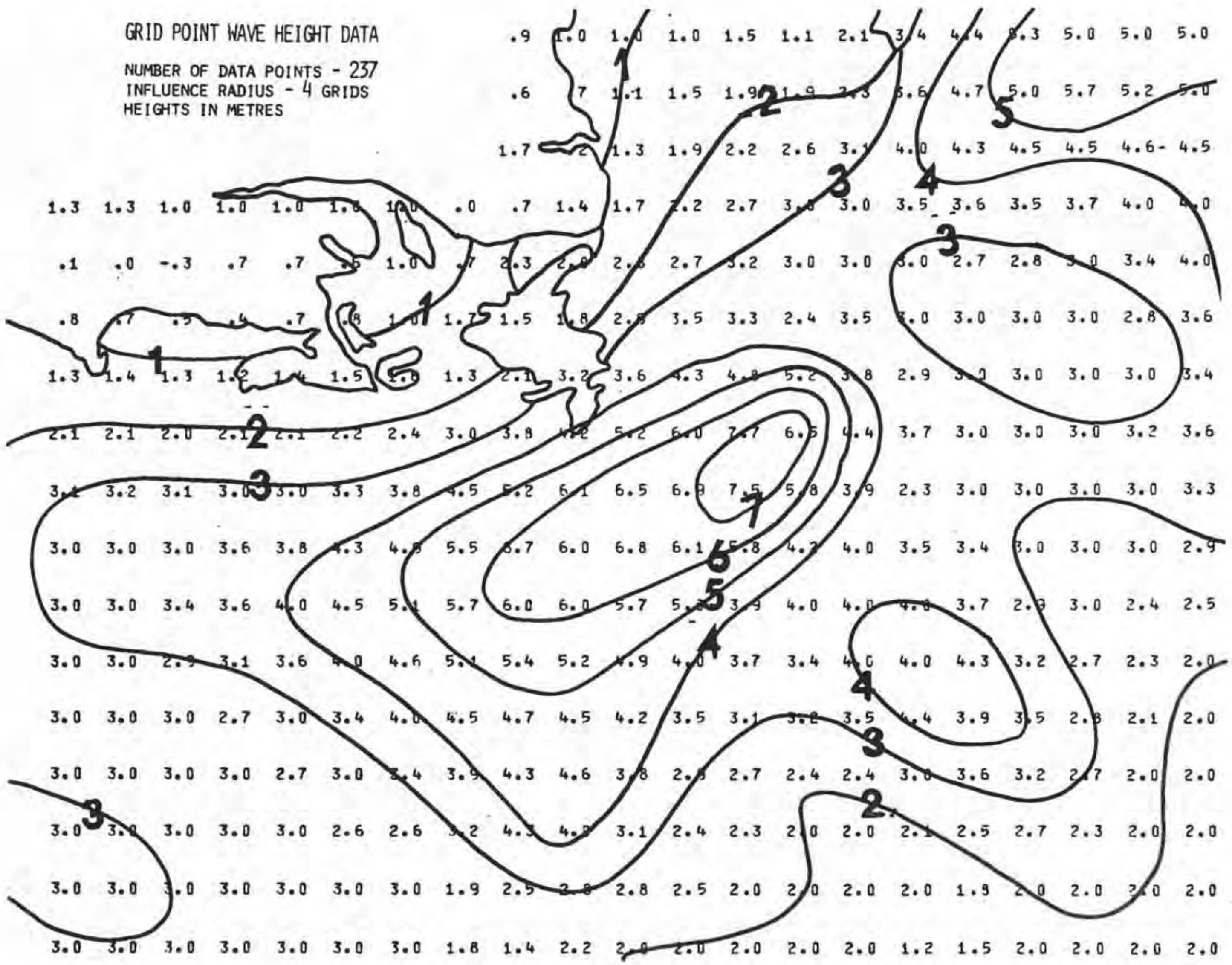

GRID POINT WAVE HEIGHT DATA
NUMBER OF DATA POINTS - 237
INFLUENCE RADIUS - 4 GRIDS
HEIGHTS IN METRES

FIGURE 5

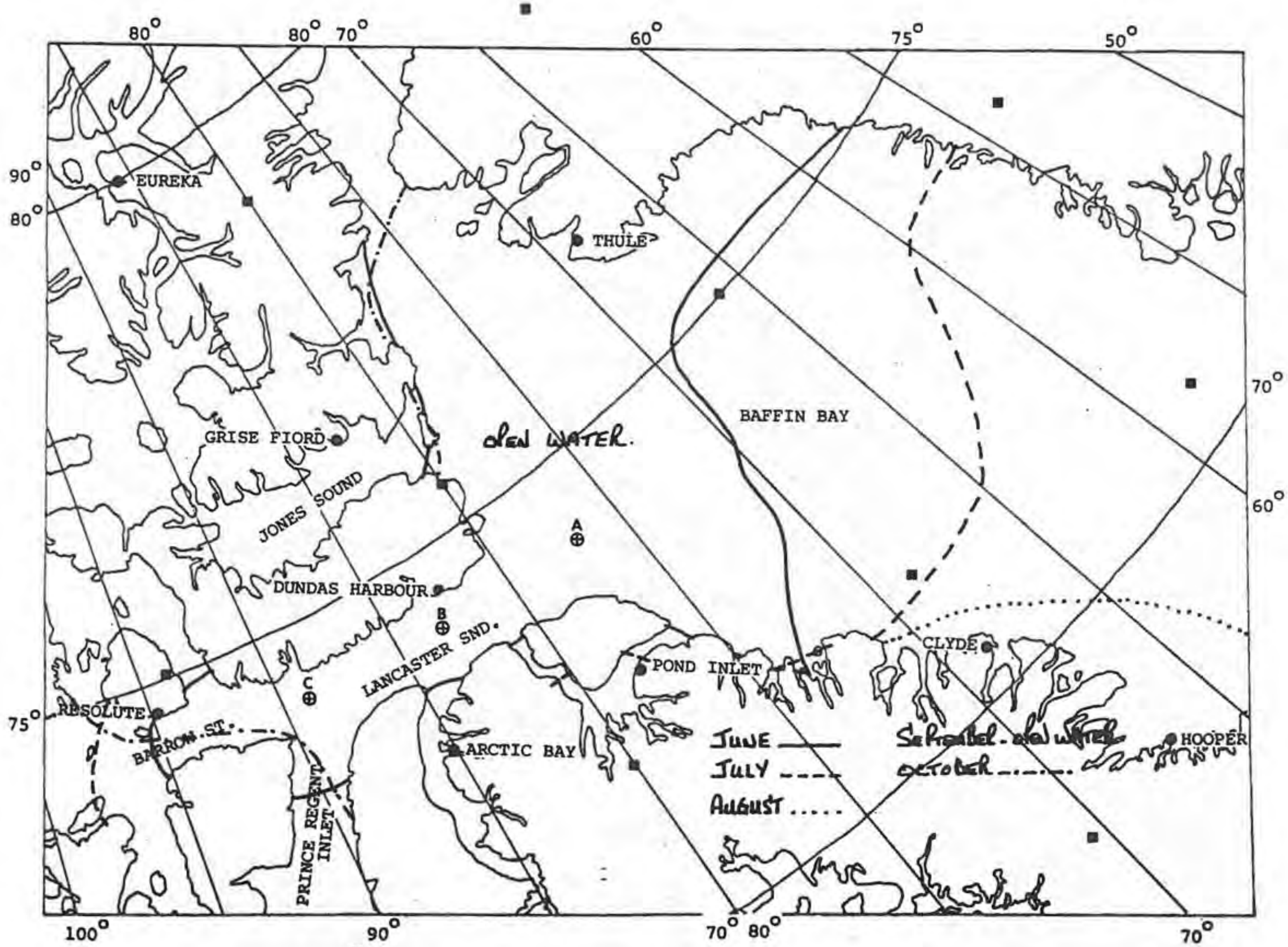


FIGURE 6 Boundary of minimum ice edge

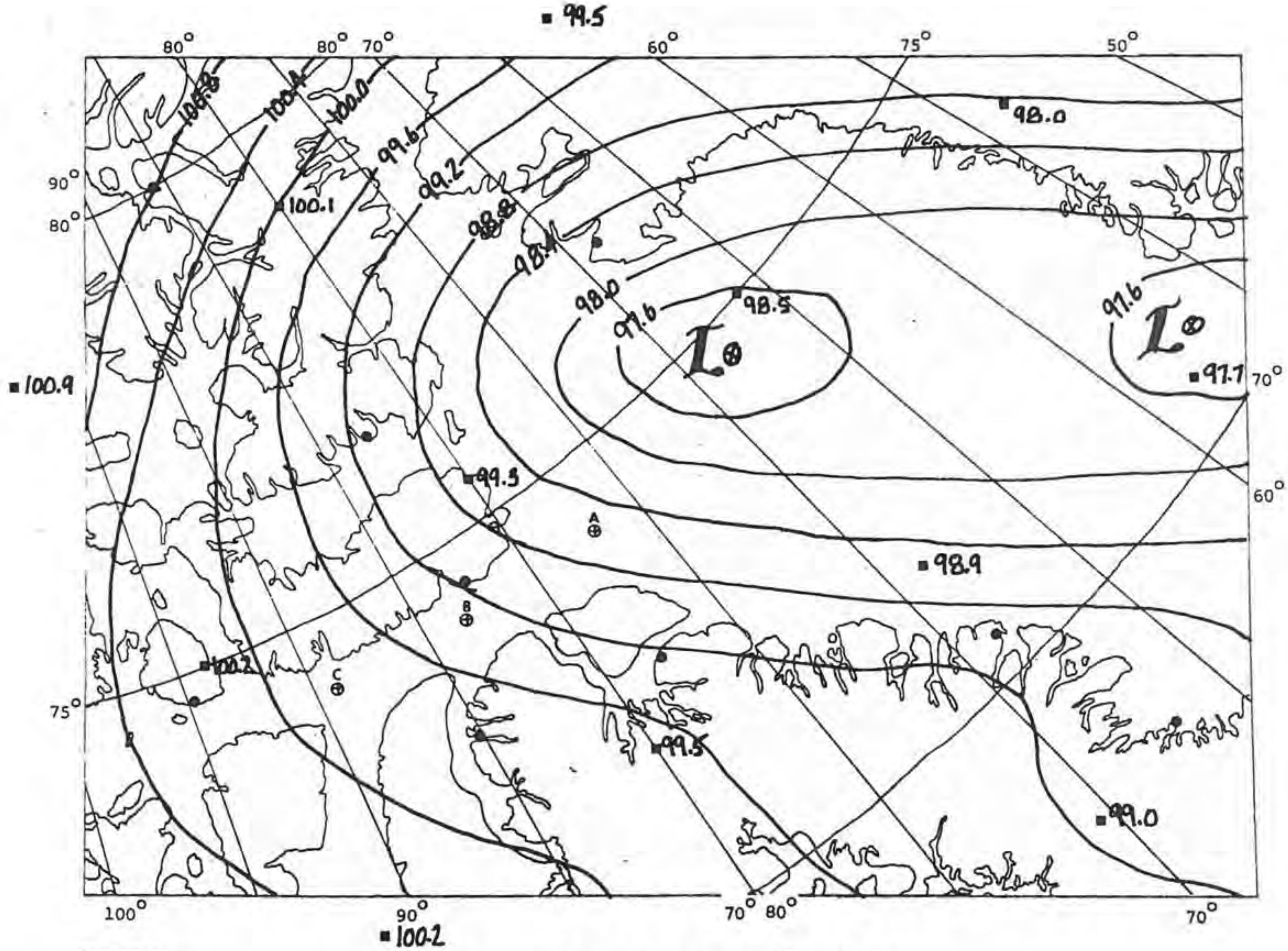


FIGURE 7

18Z 24 NOVEMBER, 1976

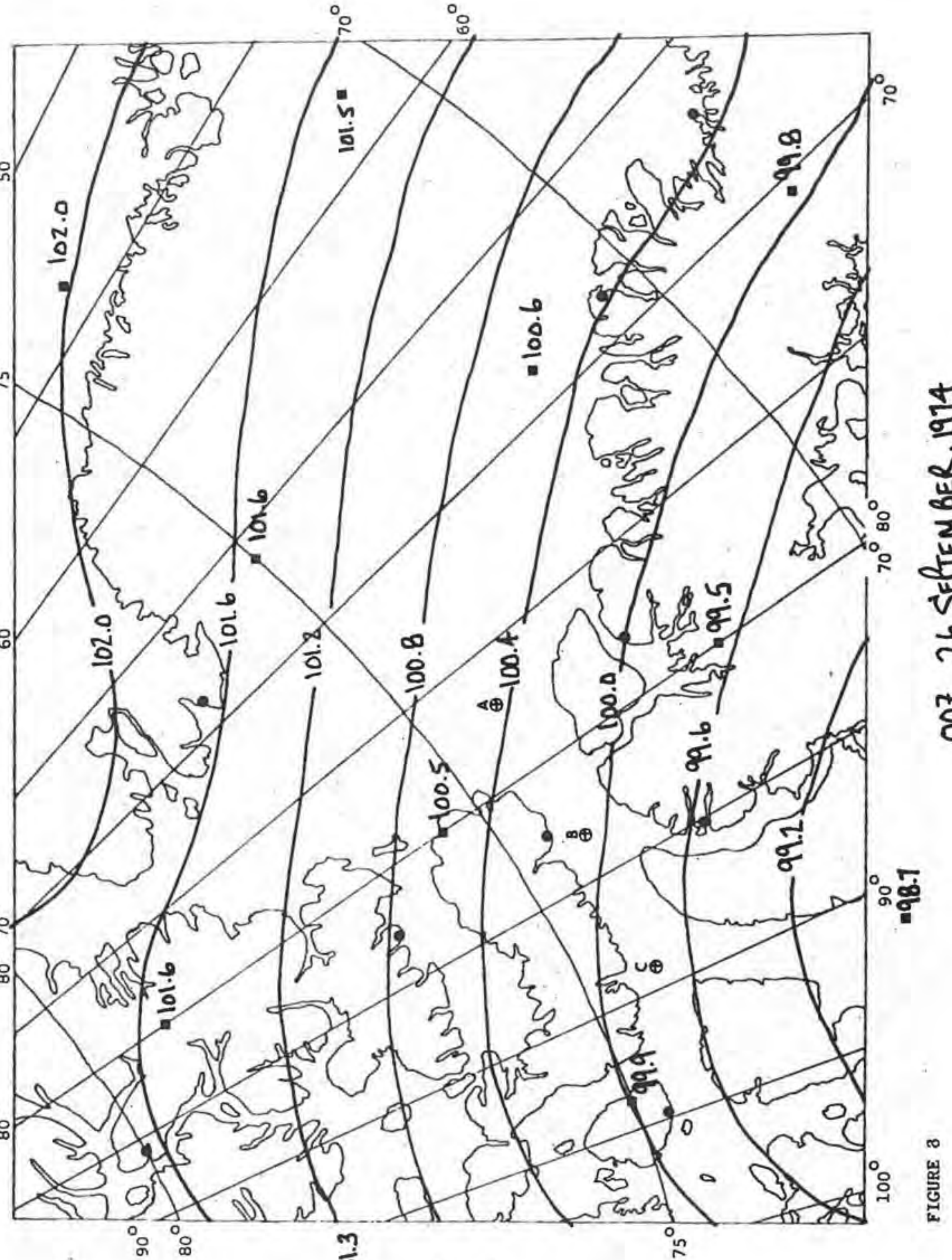
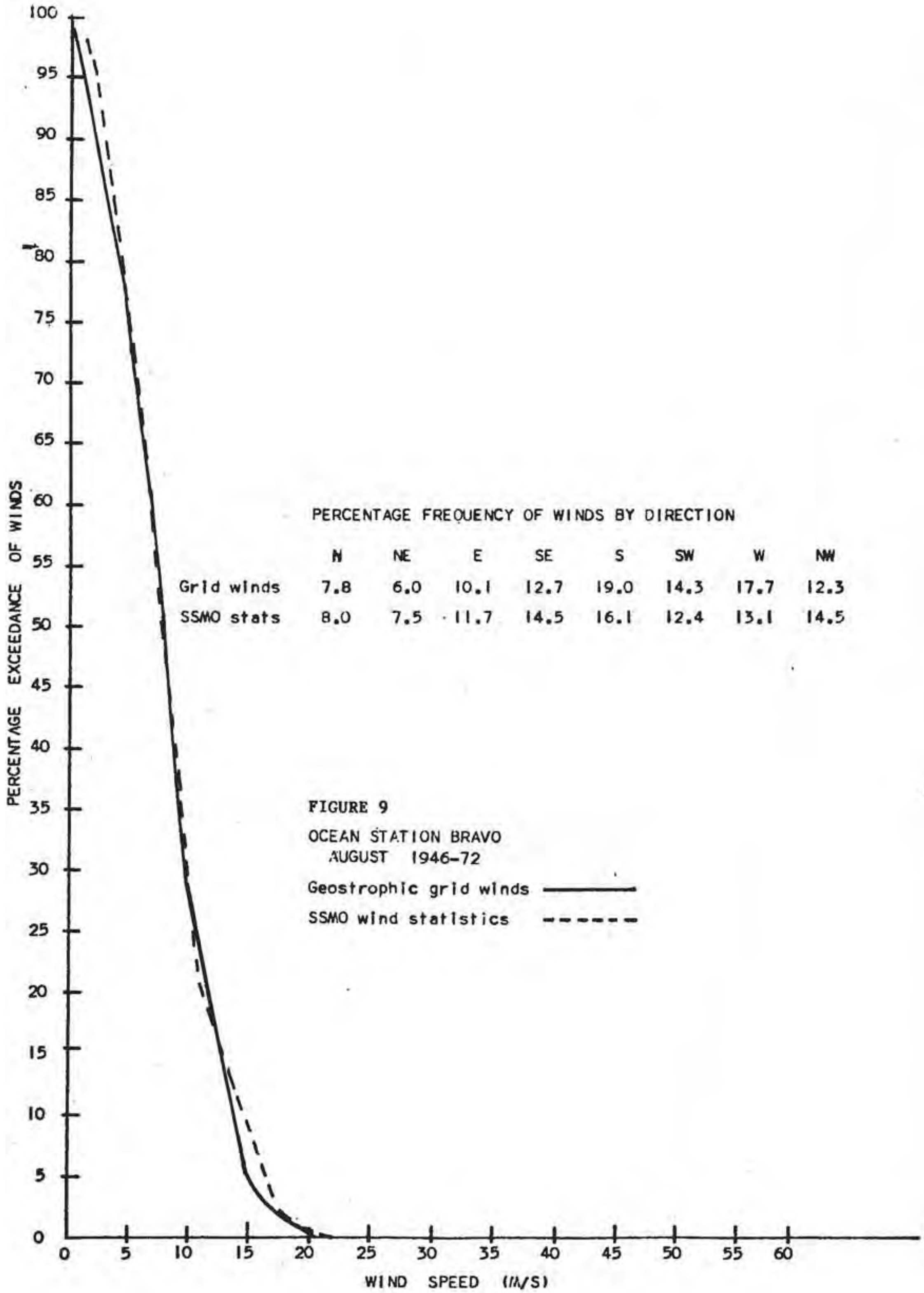

102.2
102.0
102.0
101.6
101.6
101.6
101.5
101.3
101.2
100.8
100.6
100.5
100.4
100.0
99.9
99.8
99.6
99.5
99.2
98.1
A
B
C
90°
80°
75°
80°
70°
60°
50°
75°
70°
60°
100°
90°
80°
70°
70°
00Z 26 SEPTEMBER, 1974

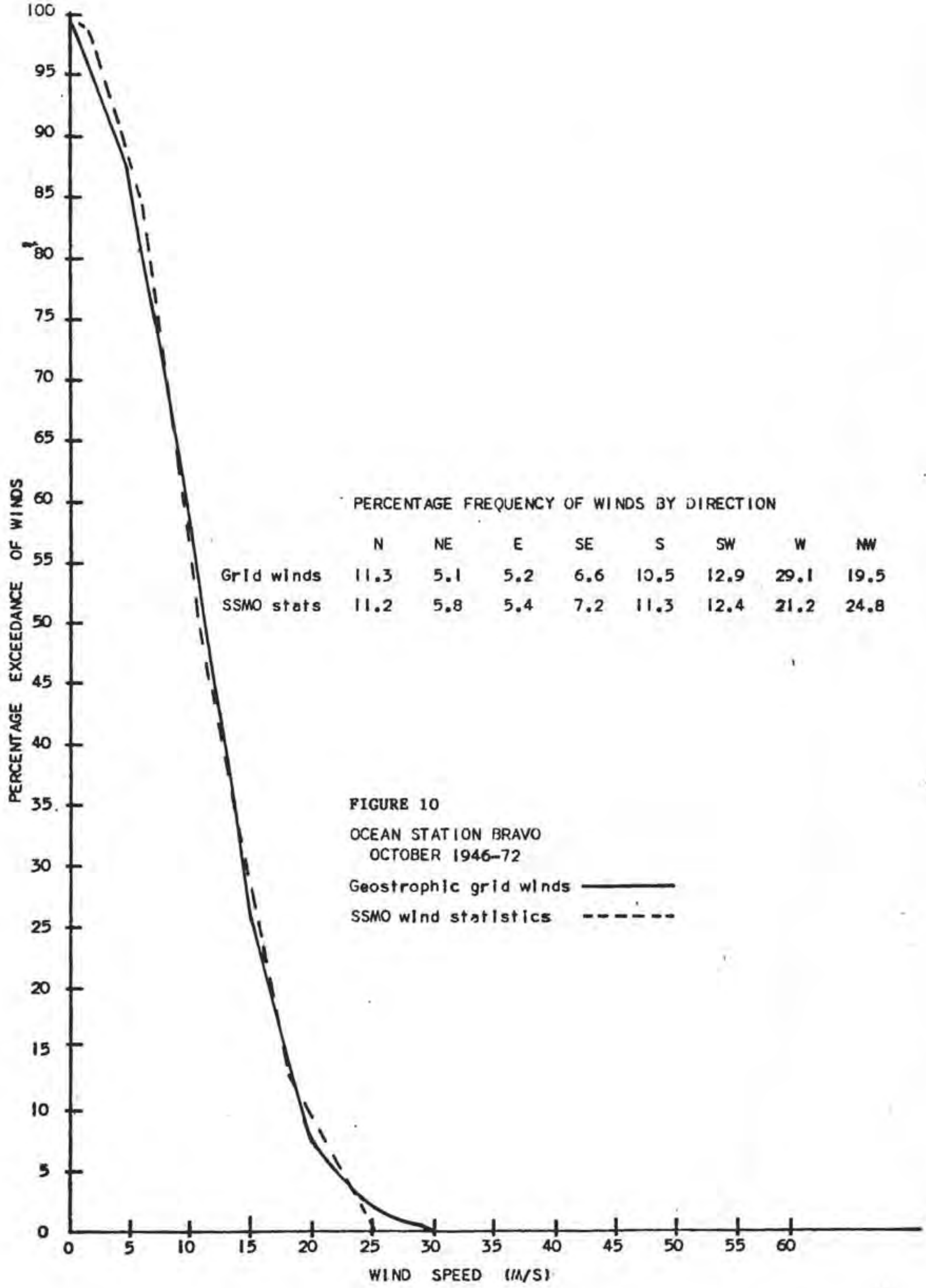
FIGURE 3



PERCENTAGE FREQUENCY OF WINDS BY DIRECTION

	N	NE	E	SE	S	SW	W	NW
Grid winds	7.8	6.0	10.1	12.7	19.0	14.3	17.7	12.3
SSMO stats	8.0	7.5	11.7	14.5	16.1	12.4	13.1	14.5

FIGURE 9
OCEAN STATION BRAVO
AUGUST 1946-72



PERCENTAGE FREQUENCY OF WINDS BY DIRECTION

	N	NE	E	SE	S	SW	W	NW
Grid winds	11.3	5.1	5.2	6.6	10.5	12.9	29.1	19.5
SSMO stats	11.2	5.8	5.4	7.2	11.3	12.4	21.2	24.8

FIGURE 10

OCEAN STATION BRAVO
OCTOBER 1946-72

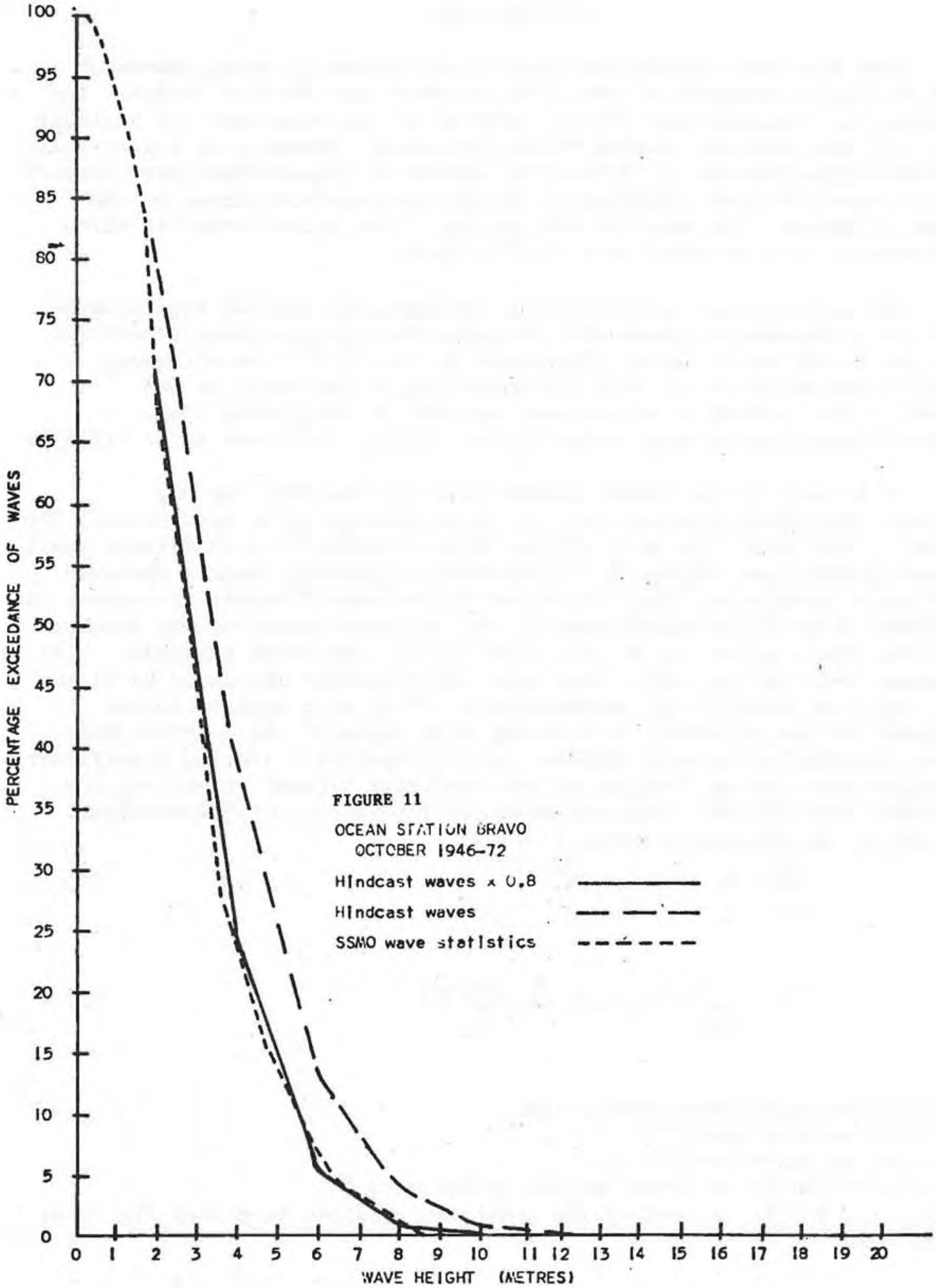


FIGURE 11
OCEAN STATION BRAVO
OCTOBER 1946-72

WAVE FORECASTING IN THE CANADIAN OFFSHORE*

S. Venkatesh

Wave forecasts in Canadian waters are presently being issued on a regular basis for portions of the North Atlantic and Pacific oceans. The Meteorology and Oceanography (METOC) centres of the Department of National Defense are the agencies issuing these forecasts. However, in recent years the extensive exploration activities in search of hydrocarbons have created a need for wave forecast information in the more northern areas of the Canadian offshore. The Beaufort Sea was the first Arctic area for which wave forecasts were provided on a routine basis.

The wave forecast procedure for the Beaufort Sea was developed as part of an environmental prediction package that also included prediction of ice motion and water levels (Venkatesh et al, 1976). As all these parameters are dependent on wind stress acting on the water or ice surfaces, a fair amount of effort was expended in developing wind prediction models on various scales (Agnew (1977), Venkatesh et al (1976)).

It is only in the summer months that the Beaufort Sea has sufficient open water (free of ice) to allow generation of wind waves. The presence of the arctic ice pack in the vicinity makes it a relatively small (compared to the open waters of the Atlantic or Pacific oceans) enclosed body of water permitting simplifications in the wave forecast procedure. A significant simplification afforded by the enclosed nature of the Beaufort Sea is that swell waves can be neglected for all practical purposes. With this assumption the deep water wind wave relationships developed by Wilson (1955) and later modified by Bretschneider (1970) were applied in the development of the procedure to forecast wind waves in the Beaufort Sea. The wave forecast parameters that are usually specified are the significant wave height (the average) height of the one-third highest waves) and the significant wave period. They are given as functions of non-dimensional fetch and may be written as (Wilson, 1955):

$$\frac{gH}{u^2} = A_1 \tanh \left[B_1\left\{\frac{gx}{u^2}\right\}^{m_1}\right] \tag{1}$$

$$\frac{c}{u} = \frac{gT}{2\pi u} = A_2 \tanh \left[B_2\left\{\frac{gx}{u^2}\right\}^{m_2}\right] \tag{2}$$

where H is the significant wave height
u is the wind speed
x is the over-water fetch
c(T) is the phase speed (period of the wave
A_1, A_2, B_1, B_2, m_1 and m_2 are constants obtained from best fit curves to data.

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When the wind speed u is an arbitrary function of the fetch length x, which is invariably the case in the real atmosphere, wave growth may be computed in incremental space and/or time steps by differentiating eqs. (1) and (2) with respect to x treating u as constant. The wave height and period at any instant will be the net result of stresses acting on the water surface up to that time.

The hourly surface wind forecasts required to drive the wave forecast model were obtained on a 6x6 grid array with a grid spacing of 127 km (one-third of the standard CMC grid of 381 km), see figure 1. The 6x6 array was chosen to be adequate to provide wave forecasts at selected points of interest. Two such locations are also shown in figure 1. A good indication of the performance of the forecast procedure was evidenced by the Beaufort Sea storm of August 26, 1975. This was a storm with a 20 year return period and wave heights of 14 feet were reported at 1800 GMT on August 26, 1975. The forecast wave height for 2100 GMT on the same day (wave forecasts are issued at 6 hour intervals) was 13 feet with a wave period of 8 seconds.

Figure 2 gives a simplified view of the flow of data into the wave prediction model. A sample output from the prediction procedure is shown in figure 3. The station location given in grid coordinates may be readily converted to latitude/longitude position. 1976 was the first full year (summer season only) of operation of the wave prediction procedure in the Beaufort Sea. Table 1 is a contingency table giving a comparison of forecasts with observations made at four different locations in the Beaufort Sea during 1976. Three of the four locations are at Kopanoar (72° 23'N, 135° 7'W), Tingmiark (70° 11'N, 132° 57'W), Beaver MacKenzie (69° 44'N, 133° 16'W), the fourth one being at Rig 4.

In Table 1, (a) refers to forecasts obtained from the computerized wave prediction procedure which was run as part of an operational research facility, (b) refers to forecasts from the same model being run in routine operations at the Arctic Weather Centre and (c) to the wave forecasts issued by the Arctic Weather Centre using a simplified manual approach where the wind speeds are assumed constant along a given fetch line. (a) is essentially a subset of (b) and hence there is no further need to refer to it. From (b) and (c) it is seen that in both cases, a little over 60% of all cases are correctly forecast. However the forecast accuracy in (b) is better than that in (c) for the R4 category. There is also a distinct tendency for waves to be underforecast in (b) in the R2 and R3 categories.

The daily wave forecasts for North Atlantic and Pacific oceans issued by the METOC centres are also based on the significant wave relationships (eqs. (1) and (2)). There is also a subjective component to the forecasts. A wave analysis chart is prepared from reported ship observations, including "dummy ship" reports to cover large gaps in data coverage. These dummy reports are generated through an examination of the wave history in the last 12 hours. As the first step towards coming up with a forecast chart (say for 12 hours), a pre-analysis chart for current time is prepared. This is done by comparing the significant wave charts for the past three 12 hour periods and establishing the movement of the significant centres of high and low waves. Thus a first approximation of the distribution of waves for current time can be obtained. By superimposing this first approximation chart over the surface wind field prog chart valid at current time, it becomes apparent where changes in the wind field have taken place which have caused changes in the wave field. Good correlation between the pre-analysis chart and the actual data chart indicates that the procedure can also be used to produce forecasts for 12 to 24 hours or longer from current time depending on the availability of wind forecasts. Further details of the procedure are given in Morgan (1971, 1973).

If any swell waves are present, the net height of waves is given by the square root of the sum of squares of the wind generated and swell wave heights.

An independent comparison of wave heights, from four different sources was made for a drill site in the Davis Strait. The forecasts compared were those from the Fleet Numerical Oceanography Centre, a computer version of the NORDCO model, a subjectively modified version of the output from the NORDCO model and the METOC centre forecasts. It was found that the METOC centre forecasts had the best skill, especially at the higher wave heights.

The substantial amount of manual input going into the METOC centre wave forecasts will make it difficult to cope with the expected demand for specialized (in terms of various space and time scales on which forecasts will be required) sea state services. Some short (1 to 2 years) and long term (5 years) development projects have been proposed to automate and improve the forecast procedures. This involves not only changes in the wave forecast procedures themselves, e.g. use of the spectral method, but also improved wind field forecasts. Attempts are also being made to obtain improved initial wave analysis and hence forecast products. In this regard, wind and wave data from SEASAT are being evaluated for their utility in wave forecasting.

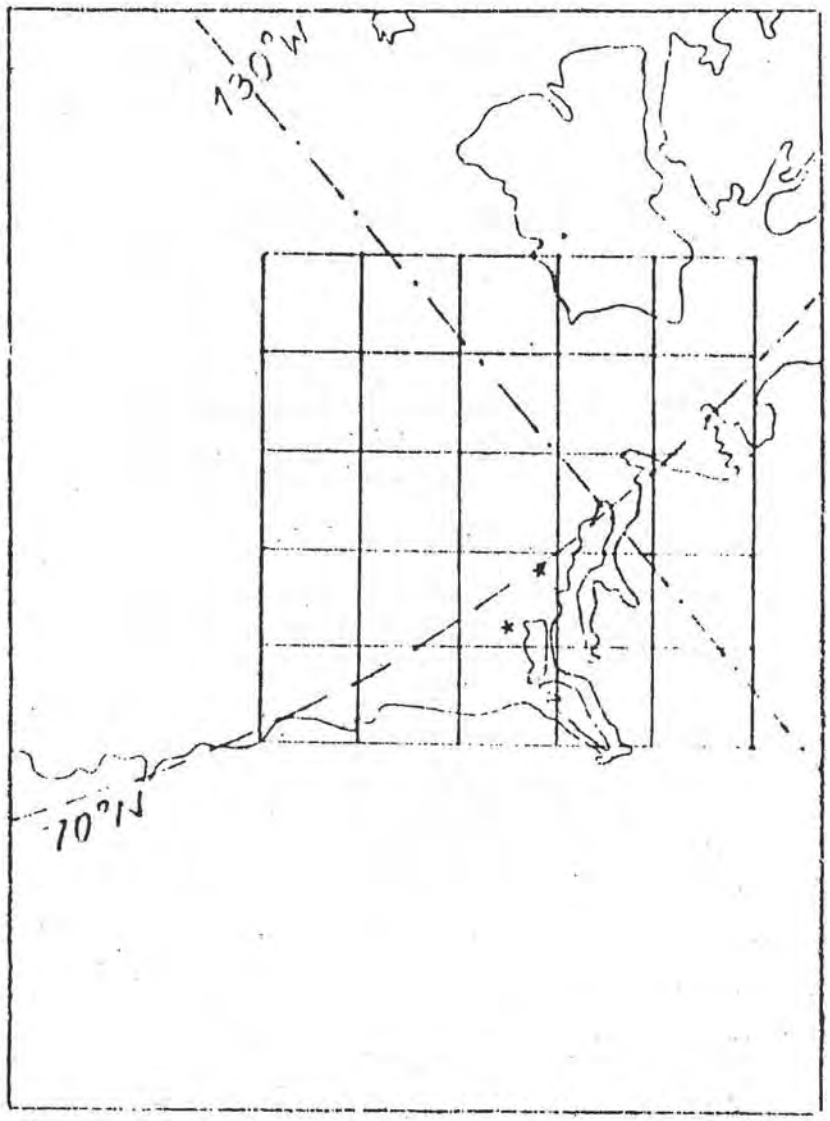

Figure 1: Figure showing location of the 6 x 6 RUM grid array in the Beaufort Sea and the two forecast points (indicated by *'s) within it.

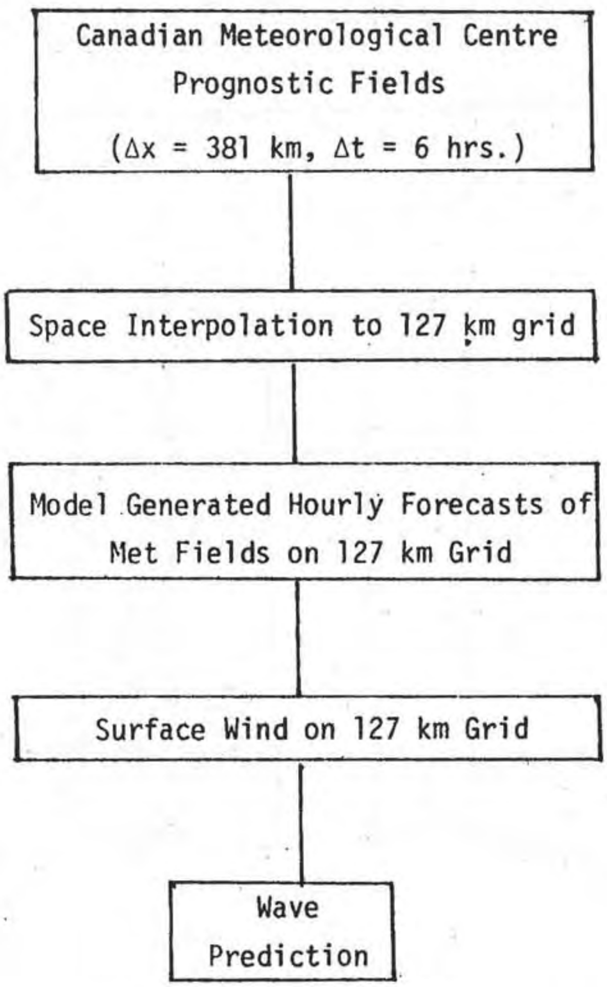

Figure 2: Flow Chart for Data Feeding into the Wave Prediction Model.

WAVE FORECASTS FROM JUN 15, 1977 1200Z DATA

SIGNIFICANT WAVES

STATION 1 LOCATED AT X - 3.84 Y - 2.96

ELEMENT	DIAGNOSIS VALID AT 12Z	6 HOUR VALID AT 18Z	12 HOUR VALID AT 0Z	18 HOUR VALID AT 6Z	24 HOUR VALID AT 12Z
SIG. HEIGHT (FEET)	4.07 FT	4.20 FT	4.26 FT	4.53 FT	3.08 FT
DIRECTION (TRUE)	337 DEG. T	7 DEG. T	67 DEG. T	67 DEG. T	67 DEG. T
PERIOD (SEC)	4.50 S	4.60 S	4.60 S	4.70 S	3.90 S

WAVE FORECASTS FROM JUN 15, 1977 1200Z DATA

SIGNIFICANT WAVES

STATION 2 LOCATED AT X - 3.23 Y - 2.73

ELEMENT	DIAGNOSIS VALID AT 12Z	6 HOUR VALID AT 18Z	12 HOUR VALID AT 0Z	18 HOUR VALID AT 6Z	24 HOUR VALID AT 12Z
SIG. HEIGHT (FEET)	5.05 FT	4.36 FT	3.90 FT	4.36 FT	0.00 FT.
DIRECTION (TRUE)	7 DEG. T	7 DEG. T	67 DEG. T	67 DEG. T	37 DEG. T
PERIOD (SEC)	5.00 S	4.70 S	4.40 S	4.70 S	0.00 S

Figure 3: Sample output from Beaufort Sea wave prediction procedure.

TABLE 1. Contingency tables of observed and forecast wave heights at 4 sites in the Beaufort Area in 4 height ranges: R1 (<2 ft.), R2 (3 to 5 ft.), R3 (6 to 8 ft.) and R4 (>8 ft.). Also included are data derived from the contingency tables. Forecast periods 0-hrs., 6-hrs., and 24-hrs., are included in the tables.

(a) MSRB - VERSION OF THE BEAUFORT CPSS *

		Forecast				
		R1	R2	R3	R4	
Observed	R1	125	16	0	0	141
	R2	27	25	5	3	60
	R3	9	9	4	6	28
	R4	0	2	1	7	10
		161	52	10	16	239

	All Ranges	R1	R2	R3	R4
Correctly forecast	67%	89%	42%	14%	70%
Under-forecast	20%	-	45%	64%	30%
Over-forecast	13%	11%	13%	22%	-
Forecasts confirmed	-	77%	48%	40%	44%
Observed frequency / Forecast frequency	-	0.87	1.15	2.80	0.63

(b) AWCB - VERSION OF THE BEAUFORT CPSS

		Forecast				
		R1	R2	R3	R4	
Observed	R1	693	103	26	1	823
	R2	260	152	56	13	481
	R3	20	53	38	9	120
	R4	0	5	7	16	28
		973	313	127	39	1452

	All Ranges	R1	R2	R3	R4
Correctly forecast	62%	84%	31%	32%	54%
Under-forecast	24%	-	54%	61%	46%
Over-forecast	14%	16%	15%	7%	-
Forecasts confirmed	-	71%	48%	30%	41%
Observed frequency / Forecast frequence	-	0.84	1.53	0.94	0.71

(c) FORECASTS ISSUED BY AWCB

		Forecast				
		R1	R2	R3	R4	
Observed	R1	550	264	31	1	846
	R2	72	317	89	1	479
	R3	7	27	60	7	101
	R4	1	4	13	9	27
		630	612	193	18	1453

	All Ranges	R1	R2	R3	R4
Correctly forecast	64%	65%	66%	59%	34%
Under-forecast	9%	-	15%	35%	66%
Over-forecast	27%	35%	19%	6%	-
Forecasts confirmed	-	87%	52%	31%	50%
Observed frequency / Forecast frequency	-	1.34	0.78	0.52	1.50

* CPSS - COMPUTERIZED PREDICTION SUPPORT SYSTEM

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WAVE PROBLEMS ASSOCIATED WITH

VESSEL DESIGN AND OPERATION

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INTRODUCTION

From earliest times, the ability of a ship to carry out its intended role at sea and in the limiting case to survive despite adverse weather conditions has been regarded as an essential requirement in ship design.

Up to the mid-nineteenth century, the design of ships as a whole, including seakeeping factors could be regarded as an art, based on observation and experience, intuition and the lessons of trial and error. Ship designs evolved relatively slowly much in keeping with the general movement in the social, political and economic order. Contrast the situation today.

Trading patterns and cargoes can change rapidly, technological advances are commonplace and fierce competition puts a premium on overall efficiency of design and operation. The result is that requirements for ship types, size, speed, performance criteria, are seldom stationary. Ships must be built correctly first time, often to meet new or considerably altered requirements.

Close to a century of ship hydrodynamics research has made much of this possible. Experience is supplemented by reliable data, intuition by science and prototype trial and error by model testing and computer simulation. In the seakeeping field, progress has been most rapid during the past twenty-five years since the first understanding of what ocean waves are really like and how ships respond to them.

We are now in the position of understanding many of the basic principles of ship response and of having some impressive theoretical techniques and experiment facilities for predicting ship behaviour in a fair range of operating conditions. Research has, however, been carried out predominantly in the Laboratory and we are somewhat short of reliable full scale data both for correlation with predicted behaviour and for giving us the bench marks or criteria of seakeeping performance required for the practical application of our design tools.

Despite these problems we can go a fair way in specifying wave information requirements important to many design situations and give informed opinions on the probable importance of additional wave parameters to vessel design and operation.

2. Seakeeping Characteristics

The seakeeping characteristics of a vessel affect its economy, habitability, operability and safety and all these factors should be addressed in the design stage.

Economy is generally associated with the speed made good in waves relative to calm water speed, or the power increase required to maintain speed. Alternatively, for a vessel required to carry out a function other than straightforward transportation, for example a fishing vessel, economy becomes synonymous with operability and can be defined in terms of the percentage of available time that the vessel can be gainfully worked.

Speed loss in waves or increase in voyage time is caused on the one hand by resistance increase and propulsive efficiency decrease, both of which yield an involuntary speed loss, and on the other hand by those characteristics which cause speed to be reduced or course to be altered voluntarily.

Voluntary (and involuntary) speed loss is, in most cases, at its worst in head seas where it results from one or more of the following phenomena - slamming on the forefoot, pounding on bow flare, shipping of green water over the bow, high vertical accelerations, propeller racing, extreme pitch angles, slamming on the bridging deck of twin hull vessels, 'springing' or two node vertical vibration and fear for structural integrity of vessel. These phenomena can be classified broadly as pertaining to operability and safety.

These characteristics affecting speed loss in head seas become less acute as a vessel veers off the predominant wave direction, but are supplemented by corkscrew motion in bow seas and largely replaced by rolling in beam seas and a combination of low frequency corkscrewing, possible heavy synchronous rolling and steering difficulties in stern quartering seas. These motions can be as uncomfortable and even more intimidating that those in head seas and can result in significant speed reductions. This is particularly important when the habitability of the vessel from the viewpoint of passengers, and safety against shifting cargo must be considered.

Ship safety is the ultimate problem to be addressed in design for seakeeping, structural failure and capsizing being the principal concern. Wave induced bending moments are generally at their worst in head seas, whereas capsizing usually results from heavy rolling in beam and stern quartering waves, loss of stability in stern quartering and following waves and broaching in heavy, often breaking, following waves.

3. Response Prediction

In order to make predictions of the seakeeping characteristics of a particular vessel design, one requires description of the ship, the wave environment and the predictor tool - either an analytical method or modelling facility and technique.

Let us take it as read that the ship description is available, and consider the current status of the response predictor - its accuracy and availability - as it affects the practical requirements of wave environment data.

In general we can state that there is a high degree of confidence in our ability to predict those ship motions which are dominated by gravity forces. These include heave and pitch and associated accelerations, etc., which, as stated above, are generally considered most important as regards speed in waves. The reason for confidence is two fold. First, the inertial and damping forces for analytical predictions may be obtained from potential theory and ship model testing is based on Froude or gravity force scaling, and second, good correlation between model, theory and a limited amount of full scale data has been established.

However, where frictional and viscous forces become more important, such as in ship rolling, our response predictor is likely to become less accurate. Froude model scaling does not necessarily result in correctly scaled roll damping and roll motion's non-linear nature is more difficult to deal with mathematically. Moreover, the limited amount of sull scale data correlates rather inconclusively with predicted response. This relative inability to predict absolute degrees of roll motion becomes worse with increase in roll severity. At present, therefore, our prediction of rolling behaviour and associated factors such as turning in waves, not to mention the ultimate safety hazard of capsizing, must be viewed in a qualitative or comparative manner.

Fortunately, roll motion lends itself to stabilization more than any other motion response and for some classes of vessel, usually naval and passenger vessels, many of the problems associated with rolling can be avoided.

The availability of ship motion predictors is, not unnaturally in a similar relative position as our ability to predict.

Most ship model experiment establishments have a facility, usually a conventional towing tank, equipped for model testing in unidirectional head waves, and computer programs, fairly well validated for head seas, are readily available. These facilities are well used by ship designers.

Model testing at oblique wave headings, however, requires a larger, in particular wider, stretch of water. These facilities, commonly called wave or seakeeping basins are not as numerous. Most basins operate using unidirectional wave systems and only a handful have provision for crossing or short-crested waves.

Wave basins are more demanding than conventional towing tanks in terms of instrumentation and labour and the frequency of carrying out experiments is generally lower.

Because of availability and cost, far fewer commercial ship seakeeping projects are carried out. Instead, these facilities tend to be used for more pressing and lucrative studies on offshore structures or for in house seakeeping research.

4. Design Requirements

The seakeeping performance requirements for a vessel are given in either qualitative or quantitative terms. That is, a vessel can be required to perform well in comparison with another vessel or to have specific maximum responses in given wave conditions. Performance in head waves is usually the predominant requirement.

Where the qualitative approach is taken, the researcher will normally choose to make the comparison for irregular long crested waves having a standard (usually the ITTC) wave spectral formulation. Experiments and calculations will be carried out for a number of significant wave heights and associated modal periods.

It is recognized that standard wave spectral formulations are highly idealized. They are, however, extremely convenient, and for similar sized vessels with similar natural frequencies of response, where one is refining a design in terms of bow and stern shape, beam/draft ratio etc., this approach is considered quite sound. In most cases, the selection of wave modal periods is, however, a problem. One can use the standard values given with the spectral formulation or select one or more periods for each wave height from a wave climate atlas. Whatever the approach, it is recognized that errors are probable but should not be too important in such a comparison.

A difficulty arises, however, when the two vessels being compared are not similar - the comparison, for example, between a conventional monohull and a SWATH (Small Waterplane Area Twin Hull vessel) intended for the same mission or service.

Here, the SWATH will probably have natural periods of motion in pitch and heave that are significantly longer than for the conventional vessel. Now let us suppose that the predominant wave period associated with a given wave height is such that the wve modal frequency of encounter coincides with the monohull's natural pitching period. The monohull will respond strongly, but the SWATH, having its natural frequency of motion considerably lower, well away from the spectral peak, will respond little. If, however, the chosen modal period is in error and should, for example, have been longer, the SWATH's motion would have been underestimated and the monohull's motion probably overestimated, very much altering the relative merits of the designs. Considerations such as this point to the need for accurate data on wave periods associated with given wave heights.

Another factor which should be considered here is the spectrum shape itself, for this too can affect the relative response of different vessels. Idealized spectral formulations have so far been produced for the North Atlantic and North Sea. They differ significantly and there is no reason to suspect other than that other different formulations will be found to pertain in other locations.

The use of a standard spectral formulation is also in question since it does not accurately represent all stages in the growth and decay of wave conditons. It may, for example, be found more accurate and convenient overall for 'typical' families of spectra to be used appropriate to specific locations and severities of the sea.

The accurate representation of wave spectral forms and associated periods, or of 'typical' families of spectra for given wave heights, as discussed above, is even more important when accurate numerical values of response must be predicted.

Additional information on the seasonal variation of wave height and predominant direction of waves is also necessary when an overall performance index is required for a particular voyage, mission or year round service. This approach has been used for some time for naval vessels and is gaining acceptance in the commercial field.

Data required for such calculations are:

(a) Description of vessel, its intended routes, missions and voyage dates;

(b) Wave data for vessel's area of operation given in terms of probabilities of occurrence of wave height, associated periods and predominent wave direction on a seasonal basis;

(c) Ship response as a function of wave height and period for all wave headings.

As mentioned above, the provision of ship responses for all wave headings in a lengthy and expensive task and not as reliable as one would wish. It is, however, an area where significant improvements are currently being made such as should eventually justify the routine commercial use of overall performance index calculations for seakeeping.

The directional spread of wave systems is a further refinement which can be introduced into the economic equation and which poses no particular problems once the oblique heading responses are known. Where such data are probably of more interest, however, is in the field of ship safety, particularly of small ships and boats. This is an area which has waited long for the required analytical and modelling tools. A few seakeeping basins can now generate short-crested waves and more are planned. Information on the directional spread of wave systems, particularly those severe enough to result in short-crested breaking waves will be required.

The final item which justifies some comment is that of wave grouping, or to be more precise, the persistence of high waves over and above what would be expected from a random process.

If, in fact, this phenomenon is prevalent in important areas of ship operation, there are a number of implications. The statistics of ship response for example could not be calculated from the response spectrum. Instead, the much lengthier deterministic process of predicting the vessel's response to encountered wave profiles must be adopted.

Just how the wide range of vessel types and sizes would be affected it is difficult to say, other than that one might suspect the long term occurrence of performance degrading phenomena to increase. The motion most strongly affected by virtue of its sharply tuned response would probably be roll.

Wave grouping could be of real significance to the ship designer, especially with regard to the safety of small vessels, and justifies close examination.

5. Wave Information Requirements

As a consequence of the explanations and arguments put forward above, it is suggested that the following wave information is required. It is listed in an order of importance based on a pragmatic view of the requirements of designers and operators and the availability of seakeeping response prediction methods.

(a) Probability of occurrence of wave periods for given wave heights;

(b) Probability of occurrence of wave height, associated periods and predominant wave direction on a seasonal basis;

(c) Spectral formulation;

(d) Possibly families of 'typical' spectra;

(e) Directional spread;

(f) Wave grouping.

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SOME ESSENTIAL PARAMETERS FOR DEFINING DESIGN SEA STATES

J. Ploeg and E.R.Funke

The design practices of coastal and offshore structures have changed considerably over the last few years. Whereas in the fifties and sixties several design manuals were written indicating a certain level of confidence, more recently the newer, revised editions of these same manuals contain various qualifying or cautionary statements, particularly those chapters which deal with the design of structures in deeper water. One of the most obvious factors is undoubtedly, that presently structures (both coastal, as well as offshore) are being designed and built in much greater depths of water than 20 years ago. At the same time the nature of the structures has changed, typically from very massive, gravity designs to slender, more flexible designs. Furthermore, the tradionally rather generous use of safety coefficients (covering all areas of uncertainty) has become somewhat less popular because only a relatively small overdesign of a structure is financially not acceptable. Of course an underdesign has always created problems. A beter understanding of the actual sea state (the basic input to the design) has on the one hand enabled the reduction of safety coefficients, but has on the other hand introduced a series of unknowns, which in turn have led to the earlier mentioned qualifiers and cautions.

The "design wave height" concept, usually referring to a significant wave height with a specified return period, was used extensively until the late sixties. Almost all model experiments used a selected design wave height for the wave height parameter to generate regular, sinusoidal wave trains, representing the natural wave conditions. Although it was well recognized that this was not an accurate simulation of the natural sea state, mechanical and electronic (and later sometimes economical) limitations prevented much progress.

Presently, this situation has changed drastically. Extremely fast, versatile computers are now available to produce control signals, which can accurately describe realistic wave conditions. At the same time, hydraulic machinery, capable of coping with large forces and nearly infinitely fast response times, can translate the control signals into mechanical motions, accurately simulating the orbital paths of water particles of an irregular wave train.

The first generation of irregular wave generators used only a one or two parameter spectrum as an input, but this did not produce any control over the actual wave train. Important wave characteristics, such as the occurrence of wave groups, or the sequential events of three or four waves in a descending or ascending order, or extreme wave steepnesses, etc., were not included in the parameters defining a design sea state. It has been shown, however, that many of these wave characteristics are very important to include in the specification of the design conditions (Johnson et al, 1978).

Not only large floating structures, but also the very tall and slender, bottom-mounted exploration platforms mayhave natural response periods of the order of 100 secs, well above the ordinary wind-generated wave periods, but uncomfortably close to possibly occurring wave group periods. Furthermore, even rubble mound structures, in concept massive gravity structures, are susceptible to more severe damage with the occurrence of wave groups in the design sea state, mainly because of the greater steepness of the wave fronts in the groups, leading to greater up-and down-rush.

The problem of defining adequate input conditions has now been moved from the laboratory to the real world, in as much that no standard method exists at this time to define these important additional parameters. For instance, the use of a spectral width parameter, as is the practice in some institutes to describe wave grouping effects, has to be questionned. Certainly in a laboratory wave flume, grouped as well as totally ungrouped wave trains, can be generated which have an identical, narrow-band spectrum. Other institutes have therefore followed the practice of using actually recorded wave trains as the input signal for model experiments. This, of course, is based on the idea that in the absence of an adequate set of defined parameters, the real sea has to include all important phenomena. This theory is, of course, severely limited by the fact that no one has the luxury of possessing an infinitely large library of recorded sea states, including all extreme conditions for all possible locations. The recorded wave trains which are available, are therefore often manipulated in frequency as well as in amplitude, to provide the desired input conditions. This manipulation of the original records certainly does not guarantee that all critical phenomena within the wave train have been preserved.

Obviously, it has become necessary to develop a complete set of parameters to define natural sea states or wave conditions. It will then be possible to determine how these additional parameters (i.e. in addition to wave heights and wave periods) vary as a function of time and location. Using standard statistical methods, extremes can be calculated for these parameters, which will form the inputs to the synthesis of a realistic sea state in a model experiment in the laboratory.

Because it can already safely be stated that full control needs to be exercised over such parameters as the amplitude spectrum, wave slopes and wave grouping, it will be inevitable to use Fourier Transform techniques in the synthesis process, rather than any other known method.

The concept of the Smoothed Instantaneous Wave Energy History spectrum (SIWEH-spectrum), as developed at NRC, is receiving some acceptance internationally. This needs to be discussed further, and perhaps modified, to serve as at least one additional parameter defining the sea state.

The SIWEH can be defined as

$$E(t) = \frac{1}{T_p} \int_{\tau=-\infty}^{\infty} \eta^2(t+\tau)\ \phi_k(\tau)\ d\tau$$

where η = water surface elevation
τ = time shift parameter
T_p = peak period of spectrum
ϕ_k = window function.

Fig. 1 illustrates how the SIWEH isolates the wave groups occurring in a wave train.

The SIWEH spectral density is defined by

$$\varepsilon(f) = \frac{2}{T_n} \left| \int_0^{T_n} \left(E(t) - \bar{E}\right) e^{-i\omega t}\, dt \right|^2$$

where T_n = length of finite wave record
$\bar{E}$ = average of $E(t)$ (= variance of wave record)

Fig. 2 shows three wave records, based on a common variance spectral density of $\eta(t)$, but with different SIWEH-spectral densities, leading to very different degrees of wave grouping.

Now, in order to define wave group activity with sufficient detail, four parameters appear to be required. First, one has to be able to define the degree of wave grouping, secondly the group repetition period needs to be defined, thirdly the average length of the groups and finally, it must be possible to provide some indication of the variation of the group repetition period.

The concept of the SIWEH and the SIWEH-spectrum offer an excellent basis for the establishment of a wave grouping factor (GF). GF has been defined as

$$GF = \sqrt{\frac{1}{\sqrt{T_n}} \int_0^{T_n} \left(E(t) - \bar{E}\right)^2 dt} \qquad \bar{E} = \frac{\sqrt{m_{0\varepsilon}}}{m_0}$$

or in words: GF is the standard deviation of the SIWEH about its mean and normalized with respect to this mean. The relative values of GF's can easily be illustrated by means of some wave trains, as produced in the laboratory and illustrated in Fig. 3, while Fig. 4 gives the variance and SIWEH-spectral densities of these three wave records.

No suitable models have been developed at this time to adequately describe the other three grouping parameters. It may therefore be necessary for the time being, to provide a graphical description of the

SIWEH-spectrum as a specification of wave grouping.

The procedures of using the SIWEH-spectrum in the synthesis of wave data has been proven to be easily implemented and are fully documented in Funke and Mansard (1979).

Time appears to be ripe to develop these ideas or proposals further and to discuss them internationally, eventually leading to a generally accepted set of parameters which define the design conditions for a sea state fully to the present state of our knowledge.

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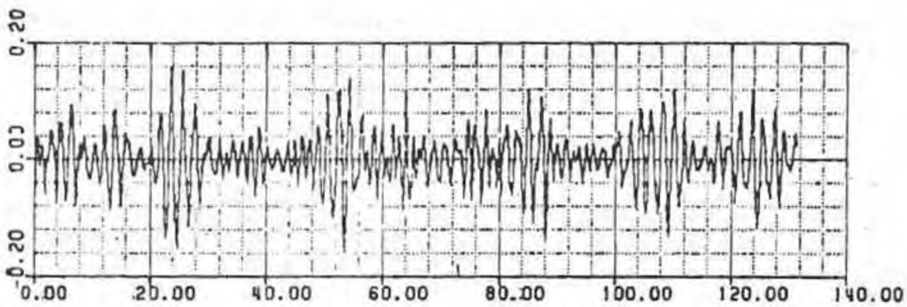
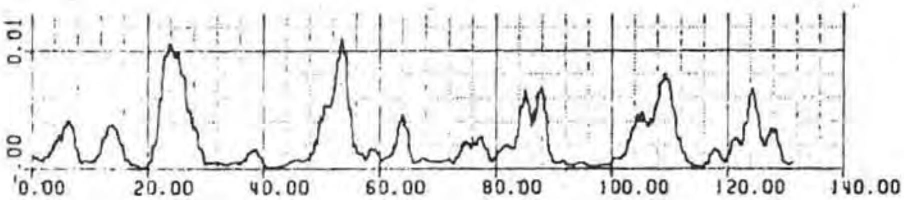
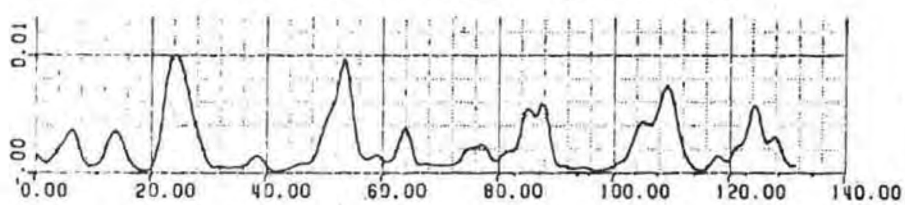


A WAVE RECORD



THE SMOOTHED INSTANTANEOUS WAVE ENERGY HISTORY
USING RECTANGULAR SMOOTHING



THE SMOOTHED INSTANTANEOUS WAVE ENERGY HISTORY
USING BARTLETT SMOOTHING

FIG. 1 EXAMPLE OF USING THE SIWEH TO ISOLATE WAVE GROUPS IN A WAVE RECORD

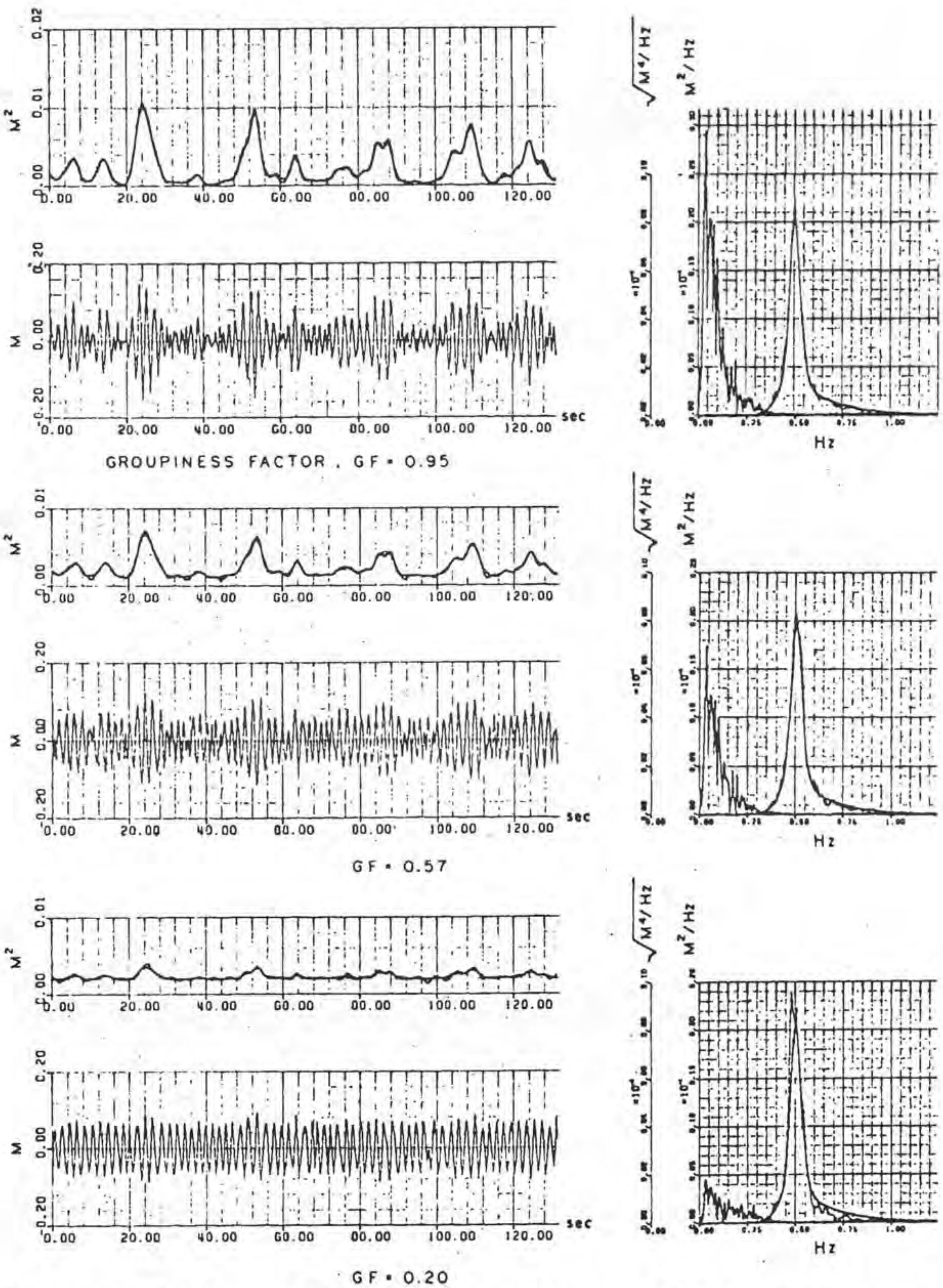
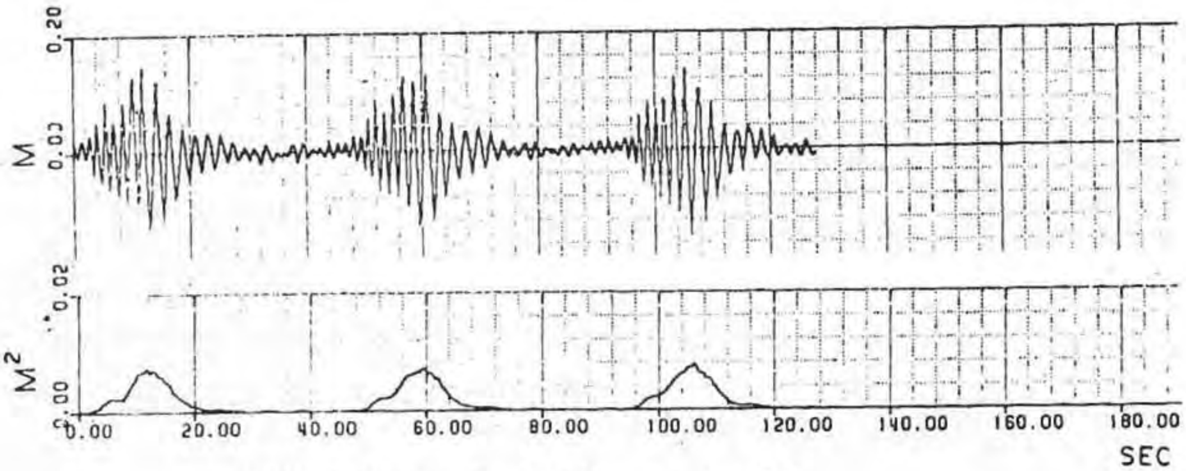
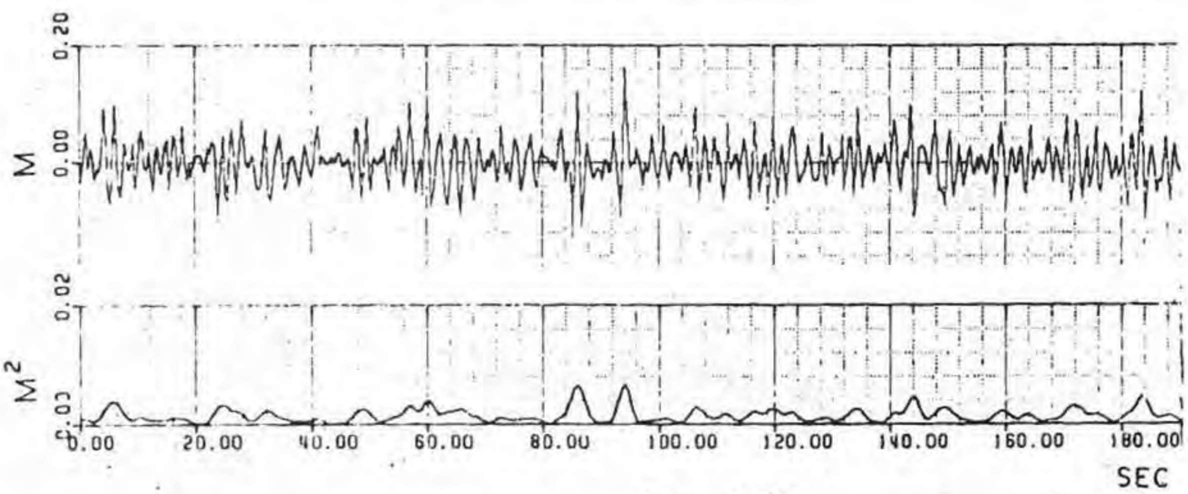


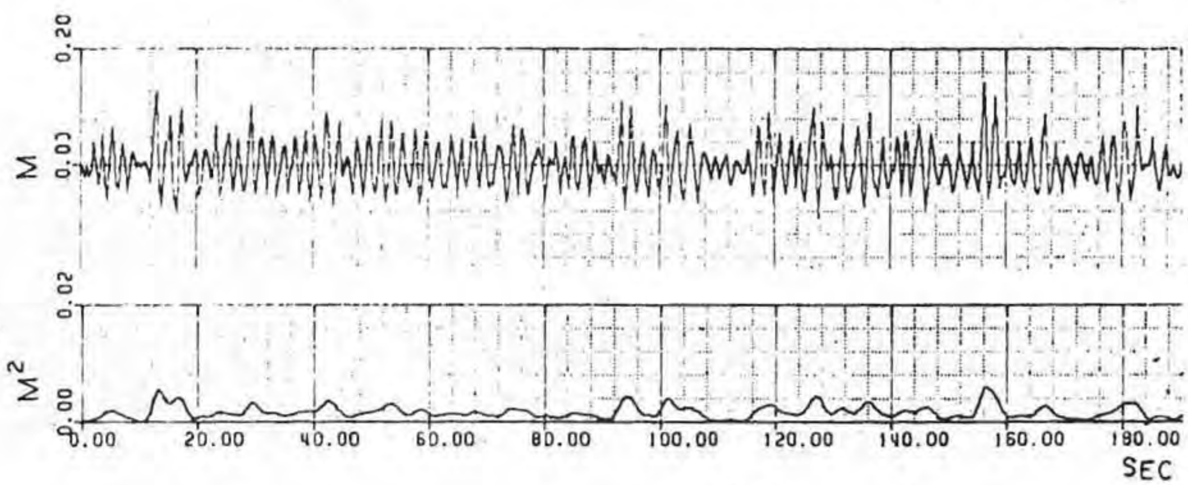
FIG. 2 THREE WAVE TRAINS WITH COMMON VARIANCE BUT DIFFERENT SIWEH SPECTRAL DENSITIES



GROUPINESS FACTOR, GF = 1.35



GF = 0.76



GF = 0.64

FIG.3 SIWEH EXAMPLES

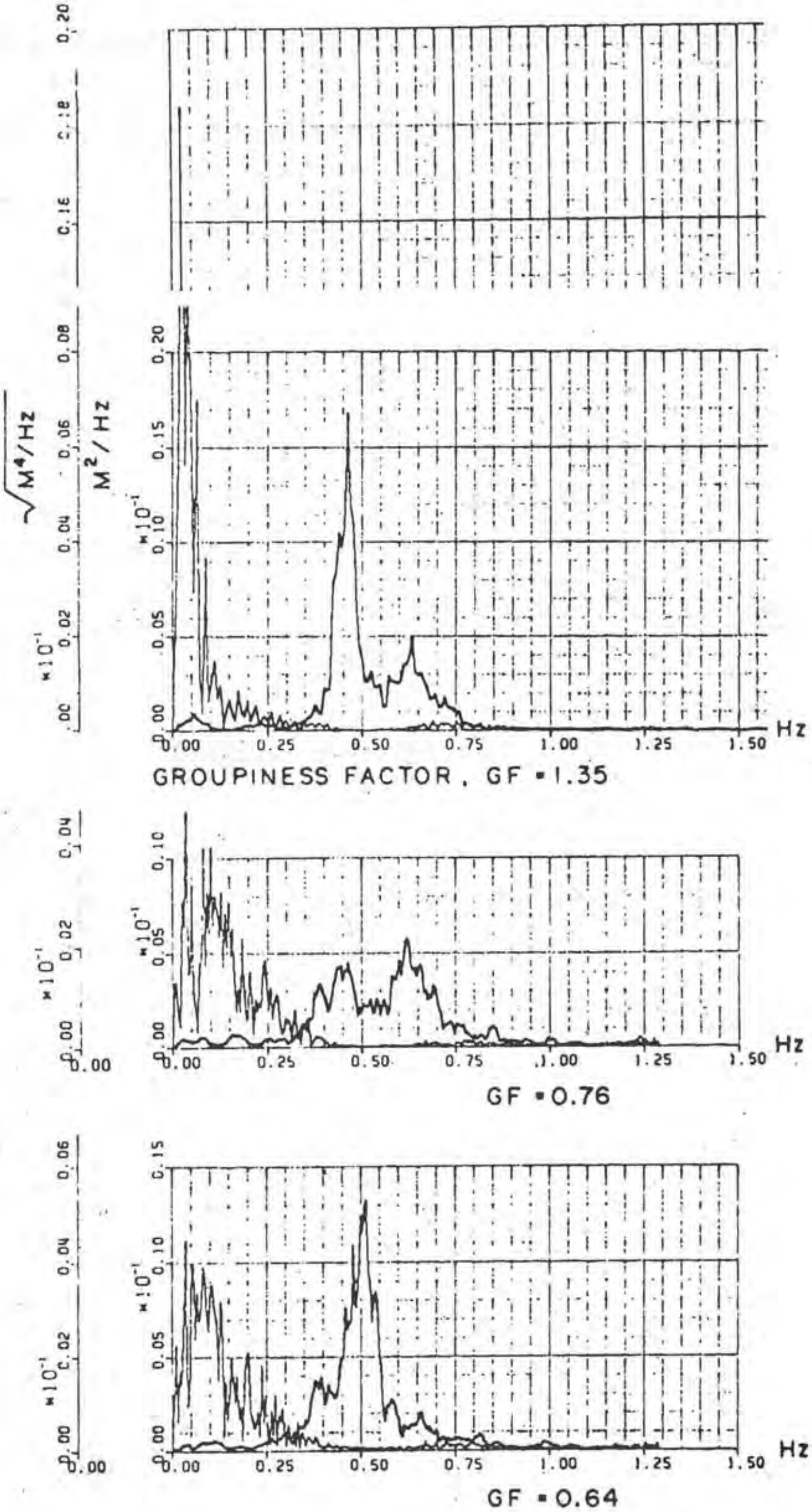


FIG. 4 SIWEH & VARIANCE SPECTRAL DENSITIES FOR DATA FROM FIG. 3

WAVE INFORMATION REQUIREMENTS FOR DESIGN OF OFFSHORE STRUCTURES

Dr. R.A. Stacy

(Mobil Oil Canada Limited)

"NOT AVAILABLE FOR PRINTING"

WAVE INFORMATION AND THE YACHTSMAN

Adam J. Kerr

In the midst of your serious scientific discussions on the measurement and prediction of waves this will come as rather light entertainment! However, if, indeed, you will find it useful to hear about some of the needs of users of this information then it is appropriate that we discuss the needs of at least one user. Of the many groups who have an interest in wave information, yachtsmen form one such group who are physically in very close contact with their environment. In discussing the topic I shall draw from my own quite limited experience as an offshore yachtsman and some of the more classic books and reports on yachting.

Although yachting has been a recreational pursuit for over two hundred years, it is only in recent years that is has gained such tremendous popularity. Associated with this popularity has been the development of all aspects of technology associated with the hobby. We have come a long way since June 27, 1898, when Captain Joshua Slocum arrived at Newport, Rhode Island, after taking three years to circle the world single handed in his 37 foot yawl SPRAY[1]. For instance, in 1977, no less than fifteen large ocean yachts, ranging in length from 41 feet to 77 feet, raced around the world spending much of that time in the Southern Ocean and taking from 119 to 144 days to complete the journey[2]. Yachts in that race, the Whitbread Round the World race, although passing through the stormiest seas of the world, pressed on day and night with no thought of heaving to and often carrying spinnakers in the strongest of winds. While it is true there were masts and other gear broken, it is significant that no hands were lost nor did any yacht founder.

Closer to home the yacht race that has probably had the greatest effect of technological improvement has been the four yearly OSTAR (Observer Singlehanded Transatlantic Race). The course of this race is from Plymouth, England to Newport, Rhode Island and is held during June and July. Upwards of a hundred yachts have participated in the race in some years, although latterly safety considerations have dictated the limiting of entries. The founders of the race had the development of vessel design and equipment as a very clear objective. Although this has in fact resulted from the competition there has also been a tendency to develop very large and expensive yachts. One particular area of yacht development that has taken place has been that of multi-hull yachts which allow a designer to overcome the theoretical speed limit imposed by a vessel's length. Contestants in this race have either chosen to take a great circle route across the Grand Banks or have taken the less rough but longer southern route, skirting north of the Azores. The fact that the race is over for most contestants by mid July cuts down the likelihood of meeting early tropical storms. The reported experience gained from this quadrennial race was of great help to me in planning a transatlantic voyage in 1977, as it no doubt has been to many other yachtsmen. Although this race was won this year by a comparatively elderly American, Phil Weld, the series has, in recent years, been dominated by French sailors, often in yachts of highly innovative design. It was perhaps justice that one of the best known of the French yachtsmen, Eric Tabarly, who was prevented from racing in the race itself this year, by an injury, raced his new 55 foot trimaran, PAUL RICHARD, back across the Atlantic in the record time of 10 days 5 hours, thus beating the 75 year old record of the large yacht ATLANTIC, by two days[3].

Unfortunately, not all yacht races have gained notoriety for the excellence of the competition but for the tragedy that has surrounded them. Such a race was the 1979 Fastnet Race[4,5]. This race, which is from the Isle of Wight, around the Fastnet Rock lighthouse off south western Ireland and back to Plymouth, England, is raced in mid August, a time at which one might expect reasonable weather. In fact it is now realized that storms of considerable violence can be expected in that location and at that time of year at an average interval of ten years. The 1979 race resulted in the loss of fifteen lives of people participating in the race and several others in yachts that were not actually racing. Since the prediction of environmental conditions has a direct bearing on the loss of lives and property it may also have been useful to know that over 300 yachts with around 2,500 crew had started in this race. Since the cost of the yachts probably ranged from $50,000 to $500,000 there is clearly a tremendous potential for both personal and financial loss.

Having set the scene in which yachts, large and small, are racing and cruising in waters all around the world, let me examine some of the actual conditions that have been experienced and particularly the effect of waves on these relatively small vessels. When I was planning my first major offshore cruise I was referred to a classical book, called Heavy Weather Sailing[6]. It was suggested that I only open one page a month or I would be so scared that I would never sail anywhere! I did not follow that advice but it must be admitted that some of the photographs were quite terrifying. On the other hand, reading the text caused the exact opposite effect, namely, that I became convinced that when properly handled the modern offshore yacht could weather practically any storm.

Apart from the occurrence of a so-called freak or rogue wave there appear to be two types of wave condition that can get even the most experienced yachtsmen in a corner. It seems doubtful to me whether there can be any particularly useful wave prediction that is separate from the prediction of the weather itself. The two particularly difficult wave conditions are the huge storm waves which exist mainly in the Southern Ocean and the extremely steep confused sea that generally results from a quick change of direction during very strong winds. This last condition can also sometimes exist when the regular wave pattern is upset by coastal tidal races or even in the Gulf Stream. Probably the classic experience of a yacht in difficulty in the Southern Ocean was that of a 45 foot yacht, TZU HANG, which somewhere to the west of Cape Horn was first capsized head over heels and then after repairing that damage was rolled sideways through 360 degrees. The couple whose yacht it was and their one crew member all lived through the ordeal and now live quietly in British Columbia. In analysing their misfortune it is apparent that the wave length in that ocean is sometimes so long that sea anchors and warps which are normally used to check a vessel's progress under storm conditions did not work as instead of their drag surface being contained in another wave they were part of the same wave in which the yacht was situated. It seems that yachts venturing into those seas must expect those conditions and it will serve little purpose to tell them how high or how long are the waves. The conditions clearly can be managed by a properly designed and equipped yacht. In the Whitbread a matter which in a lightly manned cruising yacht could be disastrous but a condition which a strong racing crew aboard a well found yacht can handle on a day to day basis.

It is the steep confused sea condition which has led to the most difficulty amongst yachtsmen, partly because these conditions are frequently prevalent in those parts of the world, particularly the North Atlantic, where yachts are numerous. Since these conditions almost always exist in tropical revolving storms the first tactic to be considered by the yachtsmen is to avoid the parts of the world at the time of the year that such storms exist. This means that yachtsmen should be careful about making passages in the north west Atlantic from August to October. The Pilot Charts of the U.S. Navy Oceanographic Office are particularly useful in this aspect of planning as previous tracks of tropical revolving storms are shown on a monthly basis. Incidentally those maps which provide statistical information on a geographical grid concerning wind velocities, gales and other environmental factors are of great assistance to the yachtsman. Predictable locations where yachtsmen can expect the steep confused seas that can cause him so much difficulty are in places where there is a strong current or where currents cause overfalls even in clam weather. It will be helpful if the hydrographer ensures that these are always mapped. It is particularly useful if the stages of tide when the current is slack are previsely shown on the charts or in other documents. Examples of current races that are known to cause hazardous conditions for small craft are the race off Portland Bill in the English Channel and off the extreme north eastern point of Scotland. Although I have no particular experience on this coast I imagine that the races off Lurcher Shoal are a place to avoid in heavy weather.

The most dangerous conditions will exist when steep confused seas result from the passage of a depression that has deepened rapidly and during its transit through the area there has been a sharp change of wind. The rapid deepening is frequently poorly predicted by the forecasters and the sharp change of wind results in a cross sea in which resonance of the wave trains will sometimes give very high peaked waves. These were exactly the conditions of the Fastnet Race, previously discussed. In the official record of this disaster it was stated that waves probably achieved a significant height* of almost 33 feet and they might have approached 46 feet. The report states further that the waves could have possessed steep or near vertical-sided profiles and that wave crests would have been travelling at 30-40 knots. Needless to say, accuracy in judging wave characteristics by eye from a vessel is difficult at the best of times, even from a large stable vessel, but from a small yacht it is particularly difficult. The Fastnet racers estimated wave heights in the order of 40-44 feet while the Meteorological Office estimated that the waves were as high

* Significant height is the average height of 33 largest waves of 99 individual waves.

as 50 feet with mean wind speeds of 50-55 knots at times, with gusts as high as 68 knots.

Unlike most of the yachts in the OSTAR the vessels in the Fastnet tended to be designed more for speed than endurance. It has been suggested that with a number of the previous events raced in light weather conditions the yachts in the 1979 race were is some cases too fragile for the task. Certainly there was considerable use of modern synthetic and not totally tested materials. In particular, the incidence of rudder failure, especially in yachts fitted with carbon fibre stocks, was particularly high. The combination of weak steering mechanisms and high steep seas proved devestating.

In concluding let me summarize by saying that in most cases the actual prediction of waves will probably not be particularly useful to the yachtsman. It will be useful if those parts of the world and the times at which hazardous waves are likely to be met could be more positively identified. Unlike, perhaps, the need for wave characteristics for designing engineering structures, wave height is not so much a consideration as is the regularity and the profiles of the waves. A high wave, be it 30 or 50 feet, presents no particular problem to the yacht provided it is sufficiently long. On the other hand precise and timely weather forecasts and, of course, the ability of the yachtsman to receive them over the entire expanse of the oceans would be of great use. Here is should be said that weather forecasts for the central parts of the oceans are not readily available. Finally the accumulation of statistical data on all aspects of environmental information should be pursued. In this way we shall gradually improve our picture of those parts of the oceans where we can expect to travel in safety and those in which we must travel at risk.

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WAVE DATA AND THE COASTAL ENGINEER

W.F. Baird, P. Eng.

This paper discusses the need for wave data, the limitations of available wave data, procedures for hindcasting wave data, and the limitations of available meteorological data as seen from the viewpoint of the coastal engineer.

The requirements of the coastal engineer for wave data are reviewed in detail and the implications of the lack of data on the design and management of coastal resources of Canada are discussed.

The limitations of available wave statistics are identified and recommendations are made to improve future wave recording programs and to undertake various analyses of the available data.

For most projects the coastal engineer must rely on wind-wave hindcast procedures to provide the required data. Generally these procedures are severly limited by the availability and quality of meteorological data. These problems are discussed and recommendations are made to improve field measurement programs and for the development of procedures for accurately defining the overwater wind.

REMOTE SENSING OF OCEAN SURFACE WAVES

J.F.R. Gower

ABSTRACT

Satellite sensors can now provide many types of ocean data with accuracy that in some cases exceeds that of surface measurements. Examples are shown of the results recently obtained using SEASAT instruments to measure wave height, length and direction, and wind velocity. Problems of timing and coverage complicate use of satellite data in standard information systems, but use of numerical models could remedy this. A brief final section describes uses of aircraft and land based remote sensing systems.

SATELLITE SYSTEMS

Ocean surface waves may be sensed remotely in a number of ways. Optical and infrared sensors could in principle image water waves from space using the same contrast effects that make waves visible from a ship or an aircraft, but for consistent and all weather, day and night operation, microwave instruments are required. The potential of such sensors was demonstrated by the U.S. 'SEASAT' satellite which operated for about three months in the summer of 1978. Details of these instruments, and some results, are summarized in a special issue of the IEEE Journal of Ocean Engineering (Volume OE-5 No. 2 April 1980). A later evaluation of the data is given in Born et al (1981). For the purposes of this workshop the instruments and their measurements may be described as follows:

(a) The SEASAT Synthetic Aperture Radar

High resolution images of microwave backscatter intensity can be formed using a side looking synthetic aperture radar from space. These images will show the reflectivity variations due to changes in surface slope and small scale roughness, and images with a spatial resolution of half and ocean wavelength or better should therefore show wave crest lines indicating wave direction and length. The SEASAT instrument operated at a frequency of 1.275 GHz and imaged a swath 100 km wide centered 20° off to the starboard side of the satellite track. Images were recorded continuously while the satellite remained in view of a ground station, giving swath lengths of up to 4000 km. A spatial resolution of 25 m was needed to meet the design goal of imaging ocean waves as short as 50 m.

Figs. 1 and 2 show examples of digitally processed SAR images taken over the Atlantic near Scotland during coverage of the JASIN experiment area. Fig. 1 shows diffraction of surface waves round the southern tip of the Shetland Islands (Sumburgh Head). The faint light marking parallel to the coast roughly overlies the 70 m depth contour. The fine structure in Fig. 2 shows surface waves in an area east of JASIN near the time of maximum waveheight ($H_{1/3} = 4$ m) recorded during JASIN. Wave frequency was .087 Hz, equivalent to a 206 m wavelength in deep water, with direction from about 220° respectively. The broader patterns are probably surface roughness variations due to internal waves, although no confirming subsurface measurements were made.

The SEASAT instrument has met its design goal of providing images, such as Figs. 1 and 2, having 25 m x 25 m resolution. Gonzales et al and Vesecky et al (1981) report good agreement ($\pm$ 15% and $\pm$ 10° with 180° ambiguity) between wavelengths and directions measured by the SEASAT SAR, and by surface instruments in the GOASEX and JASIN experimental areas in the Pacific and Atlantic oceans respectively. The minimum wavelengths measured however, were in the range 100-150 m, and the visibility of the surface waves to the radar seems to depend on the viewing angle and possibly also on environmental factors such as wind speed.

(b) The SEASAT Altimeter

The altimeter measures the total travel time for a 13.5 GHz microwave pulse, having an effective width of 3 nsec, transmitted downwards and reflected from the ocean surface directly beneath the satellite. Since this pulse is equivalent to only 0.5 metres of range difference, its shape will be strongly distorted on reflection from points at different heights on the sea surface. This pulse shape is recorded, and used to give a direct measurement of the distribution of surface height, from which the significant waveheight, $H_{1/3}$, can be computed. The distribution is measured over a circular area centred on the nadir, of radius 1.2 to 6 km depending on the waveheight. The spatial averaging reduces the effect of random fluctuations in the wavefield, to roughly the same extent as the 20 minutes of temporal averaging common in analysing waverider records. Further spatial averaging is possible as the satellite proceeds along its track.

The altimeter has met its goal of waveheight measurements to 10% or 0.5 m and the estimates of its accuracy are large limited by that of conventional buoy and ship data.

The altimeter's range measurements show sea surfacemean height variations related to major ocean current systems such as the Gulf Stream. Comparisons of the surface and the wave height measurements (Townsend et al 1981) show cases in which the waveheights appear strongly related to the current (Fig. 3), presumably due to wave/current interaction effects. Such effects are a well known, but poorly defined hazard for ocean operations.

(c) The SEASAT Scatterometer

The microwave reflectivity of the ocean surface, as measured at some wavelength and at some incidence angle greater than any larger scale wave slope, is a function of the surface roughness in this same wavelength range. The near surface wind speed induces a wind stress on the ocean which is responsible for the build up of surface roughness with a spectrum which changes with wavegrowth. This stress is difficult to measure or to relate either to wind speed, measured at some low height (10 m or 19.5 m) above the mean sea surface, or to surface roughness at some particular wavelength scale. Hence, although stress is the desired parameter for wave forecasting, the mean microwave reflecticity is usually compared to near surface measurements of wind speed, and can be input to wave forecasting models in this form.

The roughness induced by the wind is anisotropic in the sense that for oblique viewing the cross wind microwave reflectivity is less than that measured in the upwind or downwind direction. The SEASAT scattermeter measured reflectivity of elements of the sea surface in two look directions at right angles, using four beams each with incidence angles of 20 to 50°. Use of Doppler information provides a spatial resolution of 50 km over a swath 500 km wide, beginning 200 km from nadir, on each side of the spacecraft. If both measured reflectivities are equal, then the wind direction must be between the two azimuths of measurements of the anisotropy, then the wind direction is identified with only twofold (180°) ambiguity since the direction with higher reflectivity must be upwind or downwind. In the more general case, a smaller measured difference leads to a fourfold ambiguity of direction, two 180° ambiguities separated by an acute angle.

The instrument met its goal of providing wind speeds within ± 2 m/sec or 10% of surface measurements and directions within ± 20° when some external means of ambiguity removal was used. Figs. 4a and b show comparisons of scatterometer and surface measurements of wind speed and direction for JASIN. This data was particularly well calibrated, but most other comparisons will be affected by errors in the surface measurements, partly since wind speed and direction are affected by the structure of the ship or buoy from which they are measured. The scatterometer has the advantage of providing a spatially averaged measurement, so avoiding problems with random fluctuations in the wind field. Also, the surface reflectivity may be providing a better measurement of surface wind stress than of wind speed, though this has not been tested directly.

(d) The SEASAT Scanning Multichannel Microwave Radiometer (SMMR)

The SMMR was included in SEASAT primarily to give all weather measurements of sea surface temperature, but the radiometer can also assess the correction that needs to be made to these, for the effect of wind induced surface roughness. The accuracy of the resulting wind speed is comparable to that from the scatterometer, but no direction is available, and radio frequency interference can seriously affect the result. The data can be used to fill in the gap along the satellite track in the scatterometer measurements.

RECOMMENDATIONS FOR THE USE OF SATELLITE DATA

Some technical improvements are possible with the above instruments, but their basis properties will not be greatly improved on in the next decade and immediate plans for use of satellite data can be based on them. The U.S. NOSS system, the European ERS-1 and the Japanese MOS series will all carry similar instruments in the 1984-1990 time frame, though the cost and complexity of the synthetic aperture radar have caused it to be omitted from at least the U.S. NOSS. The NOSS scatterometer will observe the sea at a third azimuth direction to reduce the amniguity problem. The radiometer will have a larger antenna for higher spatial resolution, and the altimeter will have a more sophisticated range tracking system.

It is now clear that these systems can provide homogenous and accurate world wide data on winds and waves, from a satellite in near polar orbit. In all the above comparisons of satellite with surface data the errors in surface measurements formed an important and often limiting factor. Visual observations of waves are well known to be very inaccurate, but the errors in wave data recorded even by research vessels can be appreciable, see for example Stewart (1980).

The timing and spacing of the satellite measurements are, however, not compatible with many current uses. The data is concentrated near the satellite track and is gathered continuously in time with no concession to 0, 6, 12, and 18 G.M.T. reporting periods. A satellite in a low polar orbit will complete about 14 revolutions each day in a plane nearly fixed in space, while the earth rotates once inside this orbit. The ssatellite's track over the earth will therefore form an overlapping pattern with a spacing, between northbound crossings of the equator, of about 2800 km. Overlap increases towards the poles. Figure 5 shows the pattern of coverage after about 11 hours, when the combination of northbound and southbound tracks have provided a coarse coverage over most of the earth. Satellite sensors such as the scatterometer or microwave radiometer can cover a swath about 1400 km wide. Altimeter data is only available directly along the track and SAR data covers a narrow (100 km) swath to one side. Two satellites in interlocking orbits would be needed to provide close to full wind data coverage in 12 hours. The fully operational NOSS (National Ocean Satellite System) is eventually planned to consist of three satellites.

To make best use of satellite data, an analysis system must be able to accept the above pattern and timing. A large scale numerical model, of the kind repeatedly discussed and recommended by all groups at this workshop would be ideal. At each time step of the model the appropriate segment of satellite data on wind speed and direction could be inserted, with the model potentially providing the means of direction ambiguity removal. The measured waveheights would be used similarly. Radar images, if available, could be used for wave direction and period. The model would also provide the means for spatial interpolation between areas close to the satellite tracks.

If the model is to be used for forecasting, then satellite data must be available with a very small delay. For NOSS the goal is to keep this delay below three hours. For hindcasting applications, in compiling a wave climate, the delay is not critical.

While the satellite can provide remotely sensed data to the model in this way, the collection of data by satellites from ships, or drifting or moored buoys can be equally useful. Drifting buoys in FGGE greatly improved wind data in the southern oceans by providing a grid of pressure measurements, and extension of the instrumentation to give sea and air temperatures (or temperature difference) or even a direct measurement of wind and wave height, is possible. Some measurement of wave direction may also be feasible.

For forecast applications the buoy data must also be quickly available, but this can be achieved using existing data distribution systems.

AIRBORNE AND LANDBASED SENSOR SYSTEMS

Similar sensors to those described above have also been flown in aircraft. To a large extent this work has been carried out for development of satellite systems rather than to study the ocean itself. The value of the remote sensing data is best realized with the large scale, repetitive coverage provided by a satellite, while the relatively stable environment in space allows the data processing algorithms to be progressively "tuned" for improved accuracy.

Airborne systems can, however, be applied to give more versatile and intensive coverage of smaller scale operations, and will have a definite role to play in understanding local or general physical phenomena that affect the properties of waves.

Landbased systems can provide continuous coverage of local coastal areas. Standard X- and S-band radars of the type used in vessel traffic management systems can display wave length, velocity and direction out to a range of about 30 kms under moderate wave conditions. Coherent H.F. radar systems such as the NOAA CODAR, (Barrick and Lipa 1979 (a) and (b), SRI International (1980)) can map wave height and direction over a similar range. Over the horizon (OTH) radars have the potential of mapping wind direction and possibly wave height in the distance range 1500 to 3000 km (Maresca and George (1980), SRI International (1980)). Such systems are being developed and evaluated, but depend on stability in the ionosphere to achieve accurate results.

CONCLUSIONS

The satellite remote sensing data can greatly improve the accuracy of a directional wave model, and could form the sole data input to such a model if data from at least one continuously operating satellite scatterometer and altimeter were available. SEASAT data currently exists for developing such a scheme, ready for use of NOSS and other satellite data after 1986. Satellite relay of data from remote platforms can also play an important role, and the potential of shore based systems should not be ignored.

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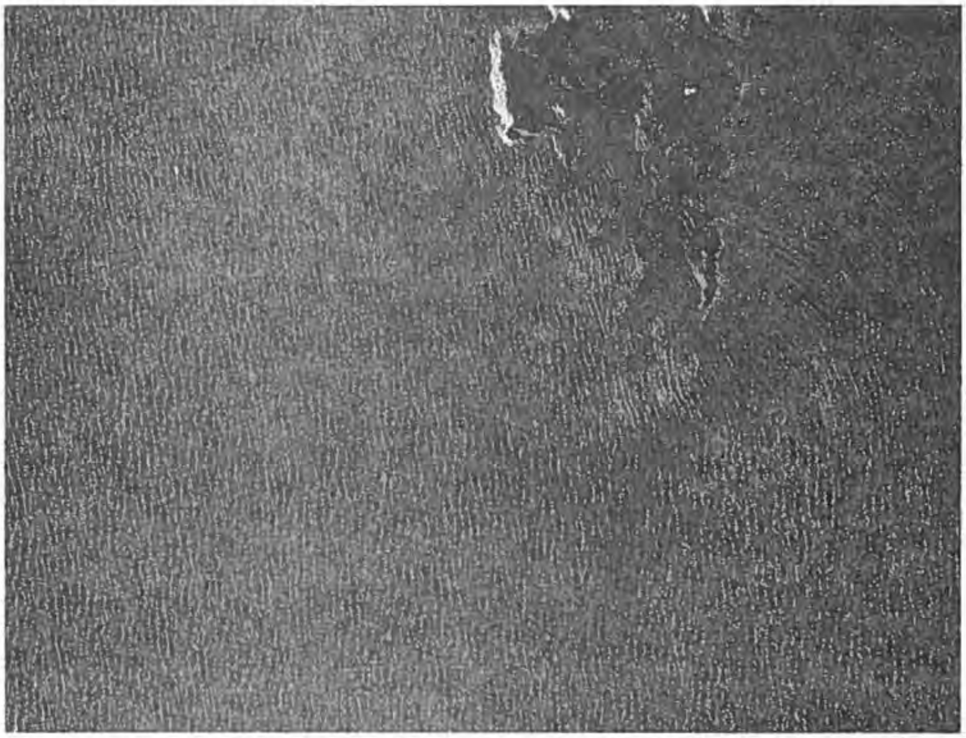

Figure 1. Digitally processed SEASAT SAR image of Sumburgh Head at tip of the Shetland Islands, North East of Scotland, on September 15, 1978. The area illustrated is about 26 km wide. Ocean waves of length 205 m are seen arriving from the West and diffracting round the head. North is up.

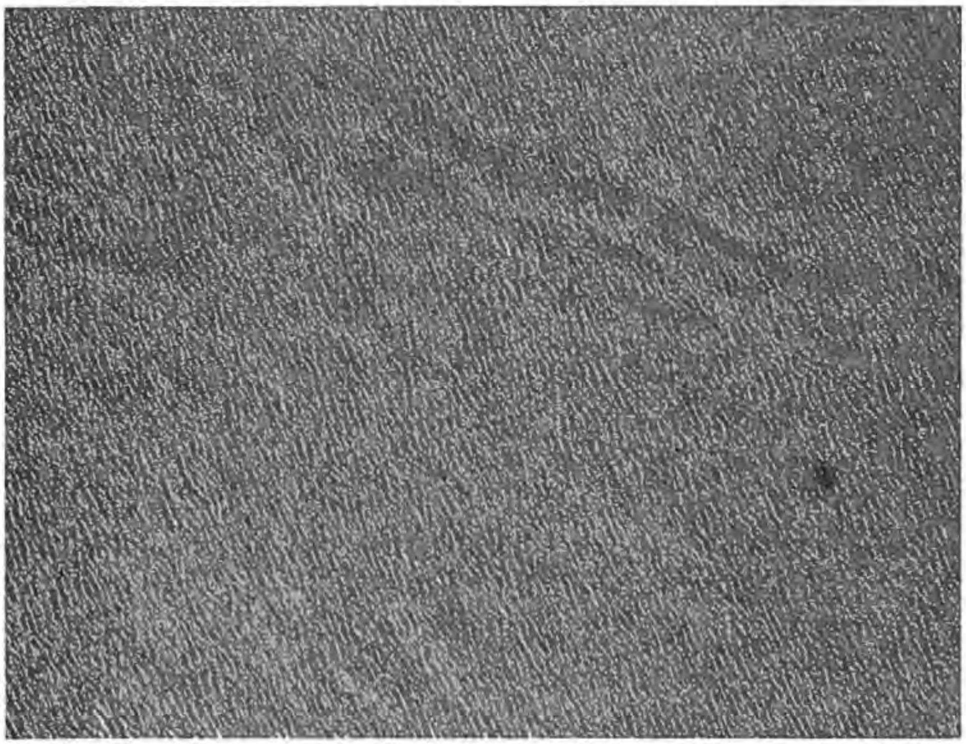

Figure 2. Digitally processed SEASAT SAR image of an ocean area North of Scotland on August 19, 1978 when waves observed in JASIN, 450 km to the West, had $H_{1/3} = 4$ m. Roughness patterns probably due to internal waves are also visible. Area illustrated is about 26 km wide. North is up. (Note: the RV Murray measured 210 m from 240° at a point 70 km north of the centre of Figure 2 within an hour of satellite overflight).

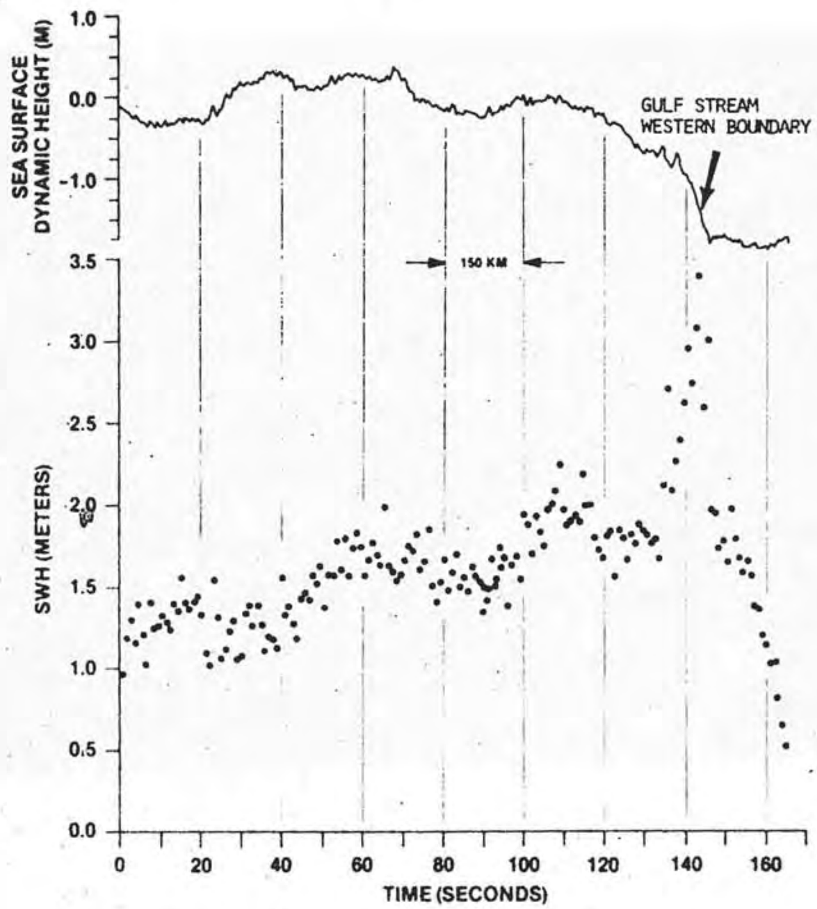

Figure 3. Sea surface dynamic heights and significant wave heights as measured by the SEASAT altimeter in a pass on September 28, 1978.

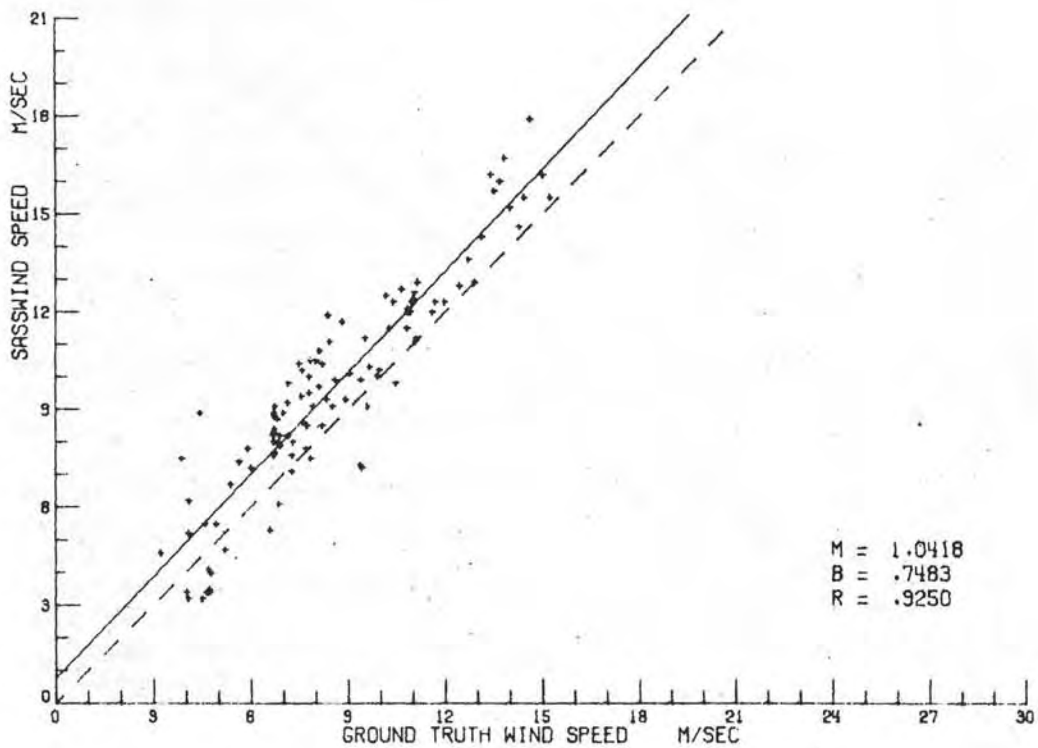

Figure 4a. Comparison of SEASAT scatterometer and ship measurements for wind speed in JASIN.

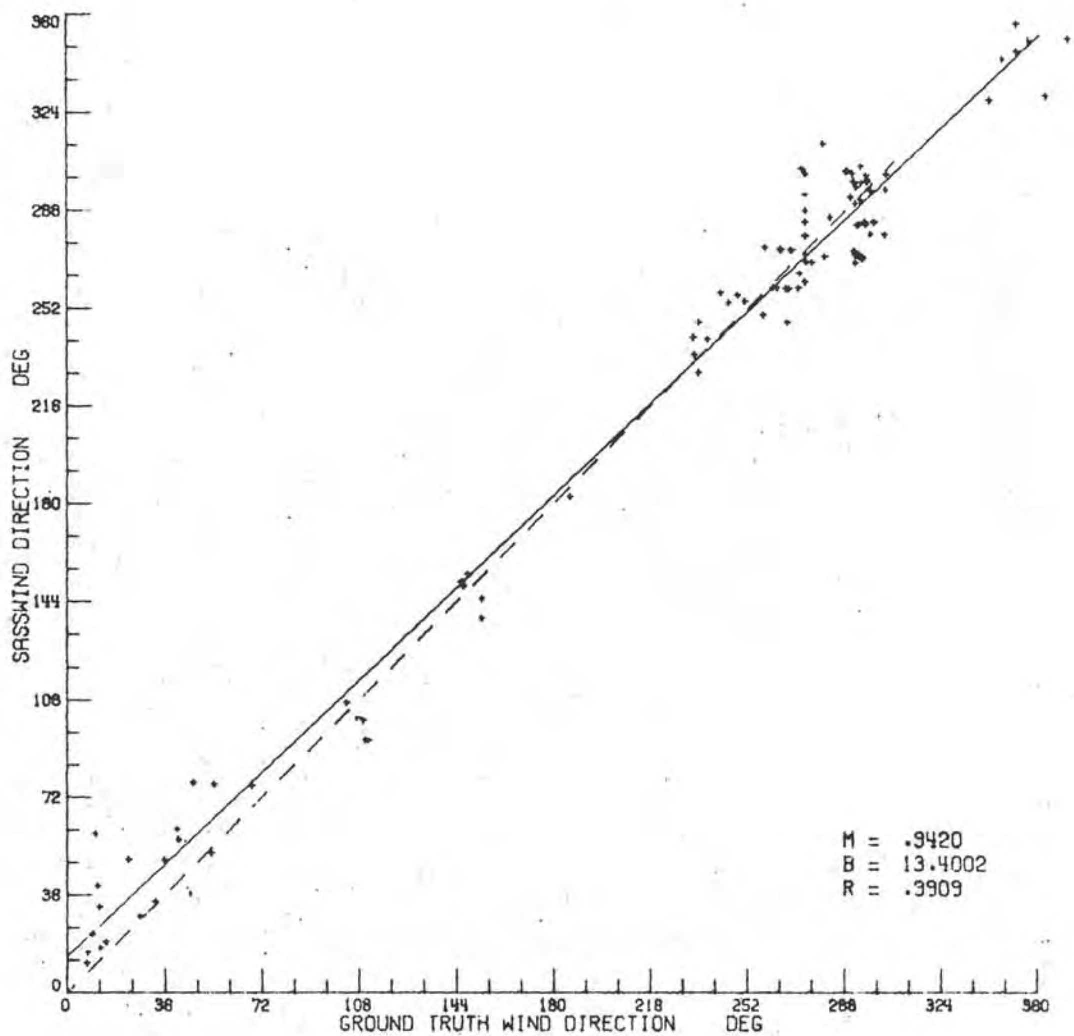

Figure 4b. Comparison of SEASAT scatterometer and ship measurements for wind direction in JASIN.

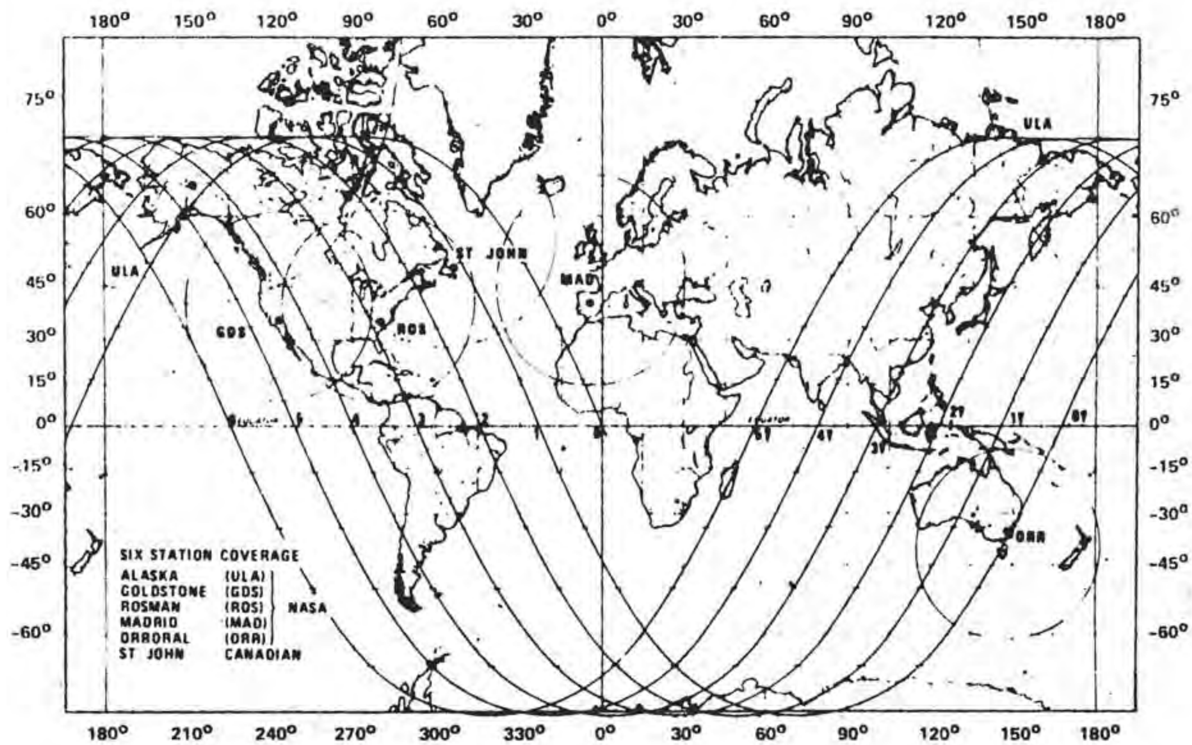

Figure 5. SEASAT ground tracks and receiving station coverage.

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