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AN ANALYSIS SYSTEM FOR FIELDS OF SIGNIFICANT WAVE HEIGHT. (U)

JAN 79 B R MENDENHALL, M J CUMING, M M HOL

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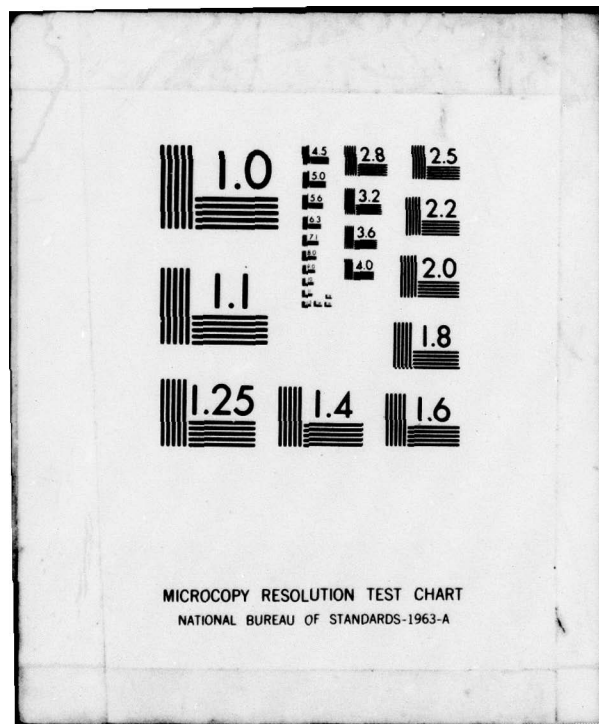
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by
Bruce R. /Mendenhall,
Michael J. /Cuming
Manfred M. /Holl

Meteorology International Incorporated
2600 Garden Road, Suite 145
Monterey, California 93940

Prepared for
The Commanding Officer
Fleet Numerical Weather Central
Monterey, California 93940

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1. SUMMARY AND INTRODUCTION

There are three fundamentally different sources of information which can contribute to an analysis of ocean wave parameter distributions in space and time. These three sources are:

- a. In-situ observations of wave parameters made from platforms located on or near the ocean surface. Such observations include those made by ships and instrumented buoys.
- b. Wave-parameter information derived from the output of remote-sensing satellite systems.
- c. Wave-parameter information generated by ocean wave numerical models.

In April 1978, under Service Order No. 7R-06 of Contract Number N00228-78-D-4316, Meteorology International Incorporated (MII) was tasked with producing design specifications of an analysis system for synoptic fields of significant wave height¹ to be based upon the general-purpose Fields by Information Blending (FIB) analysis methodology. The new analysis system, denoted by FIBWH, was to encompass capabilities for assimilating and blending all relevant information available from the three primary sources outlined above. In particular the satellite system to be utilized was SEASAT-A and the ocean wave model to be utilized was the FNWC Spectral Ocean Wave Model (SOWM).

The design study for FIBWH was completed in July 1978 and shortly thereafter, under Service Order No. 7R-11 of the same contract, MII

¹The term "significant wave height" refers to the mean height of the one-third highest waves. The term may be applied either to sea waves, or to swell waves, or to a combination of sea and swell waves. In this Report it refers to the combined value of significant wave height unless otherwise indicated.

was tasked with developing this system, thus providing FNWC with an operational capability for producing synoptic fields of analyzed significant wave height. FIBWH was placed on the FNWC system in February 1979. This Report describes the FIBWH analysis capability established under the two Service Orders referenced above.

Section 2 discusses the data sources. SEASAT-A failed in October 1978 and no alternative remote-sensing system for wave parameters currently is available. Hence, although FIBWH has the capability of assimilating satellite-derived information, this capability must remain dormant until a suitable input becomes available. The peculiarities of satellite-derived data have, nevertheless, been described in terms of SEASAT-A for convenience. In effect it has been assumed that its replacement, whether or not of the same family, will provide data of an essentially similar nature in the context of FIBWH requirements and capabilities.

The FIBWH analysis system is described in Section 3. This description assumes familiarity with the information-processing concepts upon which FIB is based and with the associated terminology. Examples of analyses of significant wave height distributions produced by FIBWH are given in Section 4 together with verification statistics.

The FNWC Spectral Ocean Wave Model, discussed briefly under Section 2.3 with regard to its input to the FIBWH system, is a wind-driven model--it does not utilize actual observations of wave parameters except for tuning and verification purposes. The design of FIBWH includes the concept, as yet unrealized, of enhancing the SOWM spectrum based on exploitation of the improved resolution of significant wave height which is provided by each FIBWH analysis. The problem of adjusting the SOWM spectrum to conform more closely to analyzed values of significant wave height is discussed in Section 5.

2. DATA SOURCES FOR ANALYSIS

2.1 In-Situ Observations

The large majority of in-situ observations of wave parameters are made by ships as part of their normal synoptic weather report. The WMO code for ship reports includes provision for reporting the significant height and associated period for sea waves, and significant wave height, period and direction for any number of separately-distinguishable swell waves. (The direction of sea waves corresponds to that reported for the surface wind.) A relatively small number of in-situ observations originate from other sources such as appropriately-equipped buoys.

Ship reports generally are based on visual estimates; very few ships are equipped with wave recorders. Visual observations of ocean wave parameters from ships generally have been disparaged because it has been assumed that the "noise" level--the variance relative to an objective, locally representative value--is high.² However a significant feature of the FIB analysis methodology is that it can separate information from noise in the object scale of analysis resolution as long as the observations are mutually independent--i.e., the error-components of the reports are not correlated. Ship reports are independent--they are made by different observers on different ships. Individual observers may be biased and observations from a particular class of ship may be biased (e.g., smaller ships "see" bigger waves). However, except for some minor rounded-number preferences, it is unlikely that ship reports as a whole contain any significant bias.³

²As will be shown in Section 4, the noise level exhibited by ship reports is lower than commonly believed.

³This comment is supported by verification statistics produced during test runs of the analysis system--see Section 4.2.

The ocean wave data contributed by ships provides separate estimates of significant sea and swell wave heights. According to random phase addition the combined significant wave height may be estimated from

$$H = \left(H_{\text{sea}}^2 + H_1^2 + H_2^2 + \dots \right)^{1/2} \quad (1)$$

where H_1, H_2, \dots refer to reported swell trains.

Ships rarely report more than one swell train and in many cases do not report any. It is possible that estimates of combined wave height derived from ship reports containing both sea and swell elements are more representative than estimates derived from ship reports which omit the swell group. In the FIB methodology as applied to the analysis of significant (combined) wave height, this difference in reliability may be taken into account by allocating the two types of report (i.e., with or without a swell element) to different classes for assembly purposes, the class weight being chosen to reflect the expected (i.e., normally occurring) difference in reliability.⁴

2.2 Satellite-Derived Information

The design specifications of the analysis system for synoptic fields of significant wave height encompassed a capability for assimilating wave-parameter information derived from SEASAT-A data. Due to the early demise of this system such data is not available. Nevertheless the FIBWH system can assimilate satellite-derived wave parameter information and this capability may be activated when a suitable input becomes available.

⁴Class weights are determined from class distributions of the object parameter. Note that if the assumption made above is not true and both types of report are equally reliable, then the class weights will be the same.

In order to appreciate the unique space-and-time distributions of wave-parameter data provided by satellites, and the associated problems of realistically assimilating the inherent information into analyses, a description of the relevant features of a satellite system is given below in terms of SEASAT-A--in effect SEASAT-A has been regarded as a typical rather than a specific system. While future systems may differ in many respects it is likely that the satellite-derived data input to FIBWH will be essentially similar with regard to the space and time distribution of wave height observations.

A radar altimeter such as sensor ALT of SEASAT-A looks only at the nadir. Processing of the altimeter return-pulse yields an estimate of the combined significant wave height, H , with an expected accuracy of $\pm 0.5\text{m}$ or 10%, whichever is the larger, for values of H ranging from 0 to 20m. The diameter of the effective field of view of a pulse varies from about 2 to 12 km depending on the surface roughness, i.e., on H . The estimates of H are spaced at intervals of about 7 km along the near-polar, sub-orbital path of the satellite. This path crosses the equator at intervals of about 22.5° in longitude, corresponding to about 100 minutes in time. Estimates of H are provided for both day and night passes and, in any 24-hour period, about 36,000 such reports may be available.

The ground trace for the orbit specified for SEASAT-A is shown in Fig. 1. An example of geographic coverage for a time span of about ten hours is shown in Fig. 2.

To be of most benefit to an analysis for a particular time, observations of an environmental object parameter--in this case combined significant wave height--should satisfy three conditions:

- a. The observations should be accurate, non-biased local estimates of the object parameter in the scale of the analysis resolution;

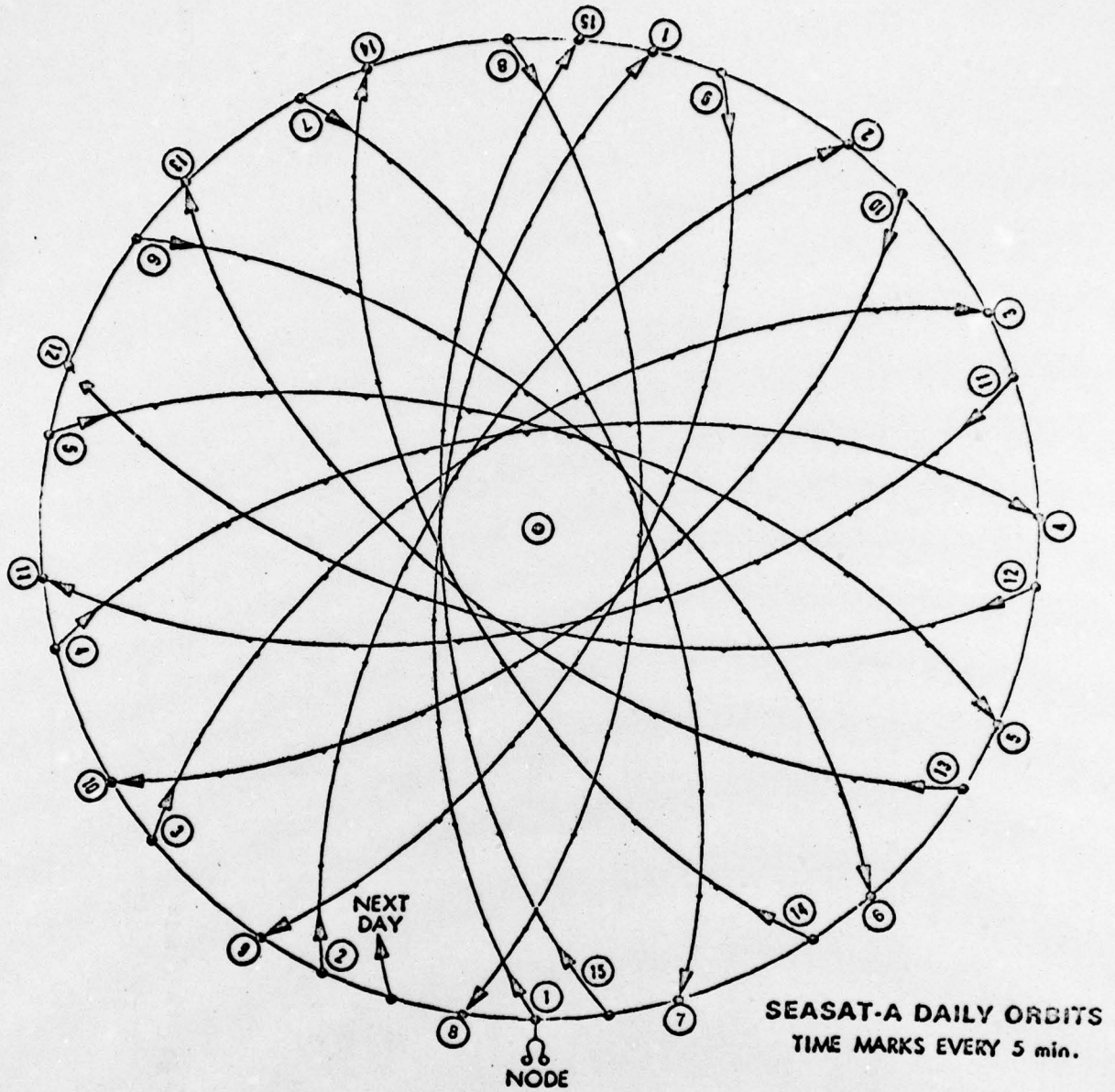


Figure 1 Ground traces for one day, Northern or Southern Hemisphere, polar stereographic projection.

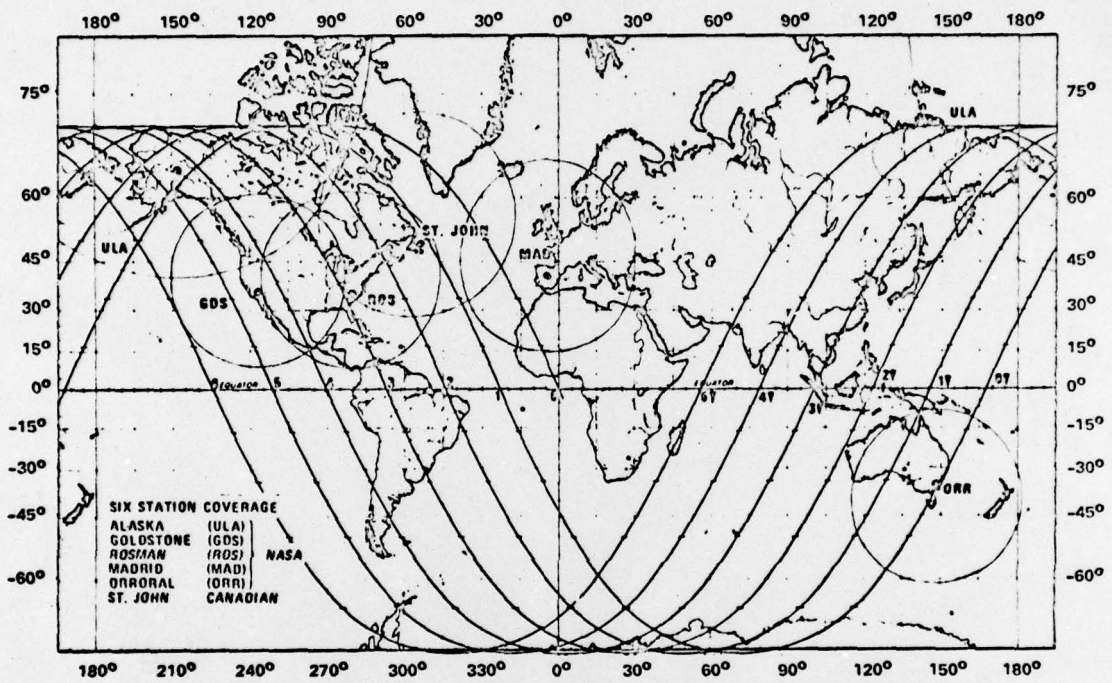


Figure 2 SEASAT-A trajectory and ground station coverage.

- b. In the context of the objective scale of the analysis resolution, there should be a sufficient number of observations which are well-distributed over the analysis area;
- c. All observations should be made simultaneously at the map time of the analysis--i.e., they should be synoptic.

It can be seen that estimates of significant wave height provided by satellite data do not satisfy conditions b. and c. and probably do not satisfy condition a. If analyses are carried out at 3-hourly intervals (map time) about two "thin lines" of reports will be available as input with the time difference between the first and last reports being about the same as the analysis interval. The two arcs of reports are separated by about 2500 kms at the equator, converging to zero in the vicinity of the pole. Corresponding points on the two arcs are separated in time by about 100 minutes (see Fig. 3). If analyses are conducted at 6-hourly intervals about four arcs of reports will be available. Although there is a more than sufficient density of reports along an arc no data is available outside the area for which estimates are representative of local wave height conditions.

The percentage area of a hemisphere "sampled" by a satellite for a synoptic analysis is given by

$$S \approx \frac{50 nw}{R} \quad (2)$$

where n is the number of passes contributing data to the analysis, w is the "effective width" of a pass and R is the radius of the earth. (This equation ignores any overlap such as occurs in polar regions for SEASAT-A.)

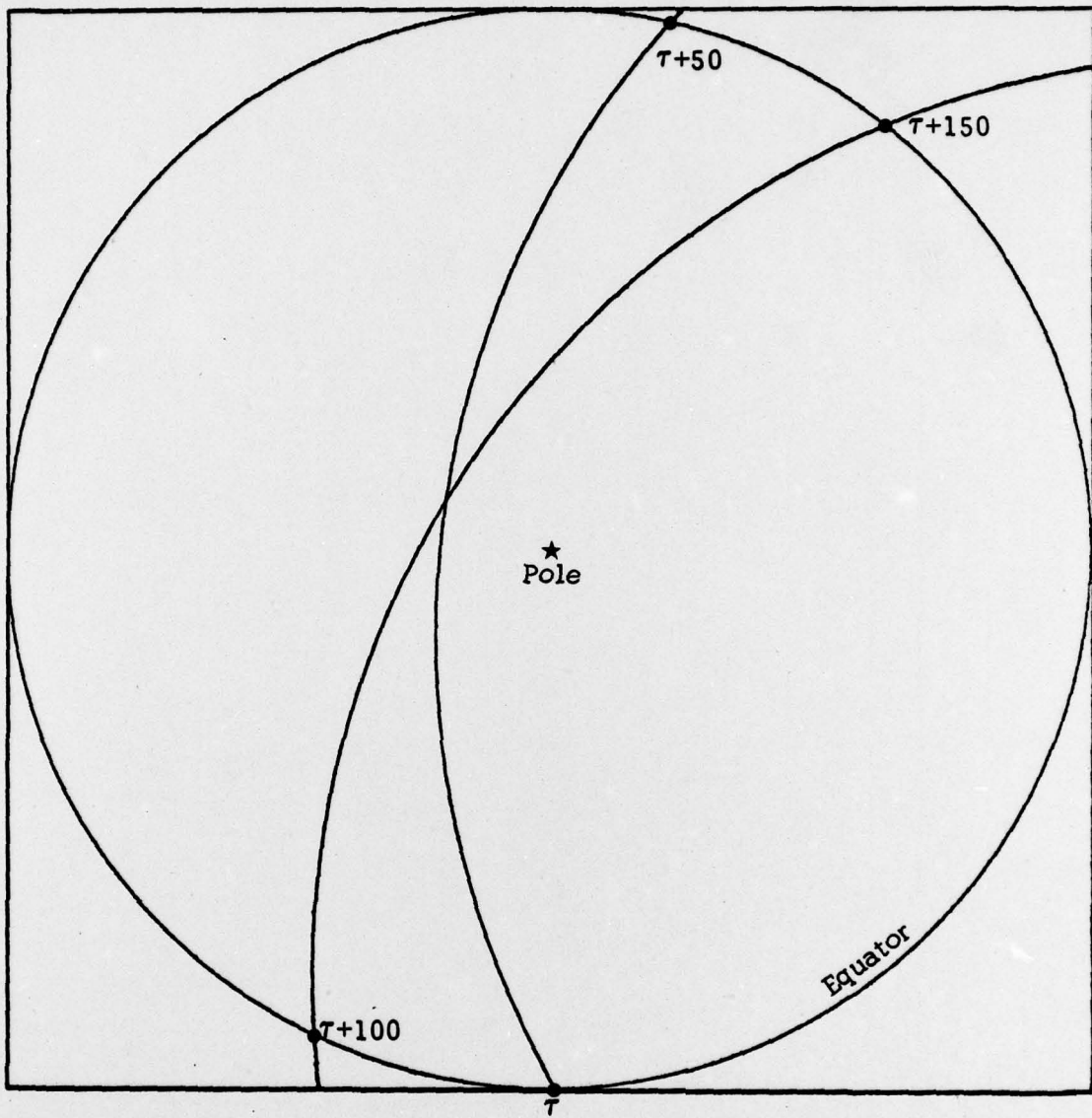


Figure 3 The two lines of H data available as input to a typical synoptic analysis if analyses are conducted at 3-hourly intervals (map time). Note that the data are not synoptic--they cover a period of about 2 1/2-3 hours with a gap of about 50 minutes between two reporting time-spans.

S is about 0.01% per pass per km effective width. Thus for 3-hourly analyses ($n = 2$, $w = 10$ say) the satellite will directly observe data for about 0.2% of the area covered by a hemispheric analysis. However if it is assumed that the reports are representative of conditions within 125 kms to either side of a pass (i.e., about the same as the mean grid spacing on a 63x63 polar stereographic projection) then data is available for about 4% of the area for each 3-hourly analysis. This represents a potentially valuable data contribution to the FIBWH analysis capability which can be realized when satellite-derived wave height information becomes available.

Increasing the interval between analyses allows data from a greater number of passes to be included. However the drawback is that the synoptic relevance of ocean-wave observations decays with time. Roughly speaking the information content of the observations has a half-life of 12 hours or less depending on the size and speed of movement of the atmospheric disturbance causing the ocean waves. To minimize the effect of using data whose information content has little relevance, the time span covered by the data should be centered on the analysis map time. Thus, for example, 3-hourly analyses should use data obtained within ± 1.5 hours of map time, and 6-hourly analyses should use data obtained within ± 3 hours of map time.

The quality of satellite-derived wave data is unknown both with regard to inherent variance and calibration bias. The FIB methodology is designed to handle "noisy" data. However since usually only one wave-parameter observing instrument is used by a given satellite, the data, in general, may contain a bias error which is not normally found in more conventional data (see Section 2.1). This calibration bias can be circumvented by a FIB concept known as Alternating Parallel Analysis (APA) which, however, is not yet utilized by any analysis system.

2.3 Information Provided by an Ocean Wave Model

The wave model used to provide an input to FIBWH is the FNWC Spectral Ocean Wave Model (SOWM). SOWM is a wind-driven model for the integration of the evolution of ocean waves in space and time. Analyzed and predicted sea-level pressure fields at 6-hourly intervals are diagnosed for the friction wind velocity used to drive wave developments. The evolution of the wave spectrum is advanced in three-hour time steps, the mean of two successive six-hourly diagnosed wind fields being used as the intermediate three-hourly wind field. The operational northern hemisphere SOWM is integrated in terms of an icosahedral-gnomonic grid which effectively is terminated at the equator. The wave energy spectrum at each grid point is represented by a 15-frequency by 12-direction matrix. Output from SOWM includes H , the significant combined wave height, on a standard-mesh northern hemisphere polar stereographic grid. A global version of SOWM which uses a Lat/Lon grid is under evaluation.

The current schedule for running SOWM is shown in Fig. 4. At about 16Z (run time) for example, the 09Z waves (map time) are updated to 12Z using the mean of the winds diagnosed from the 06 and 12Z analyses. The 12Z waves are then carried along the time axis to 15Z using winds diagnosed from the 12Z analysis. Forecast waves are then computed using winds diagnosed from the output of the FNWC PE model. Shortly after 21Z (run time) the wave fields are carried along the time axis to 18Z using 15Z winds, and then from 18Z to 21Z using 18Z winds. Note that the forecast mode is run on a 12-hour cycle in tandem with the PE forecast model. The analysis mode is split into two six-hour advances every 12 hours, one just preceding the forecast mode and the other being run at a convenient time for update purposes only.

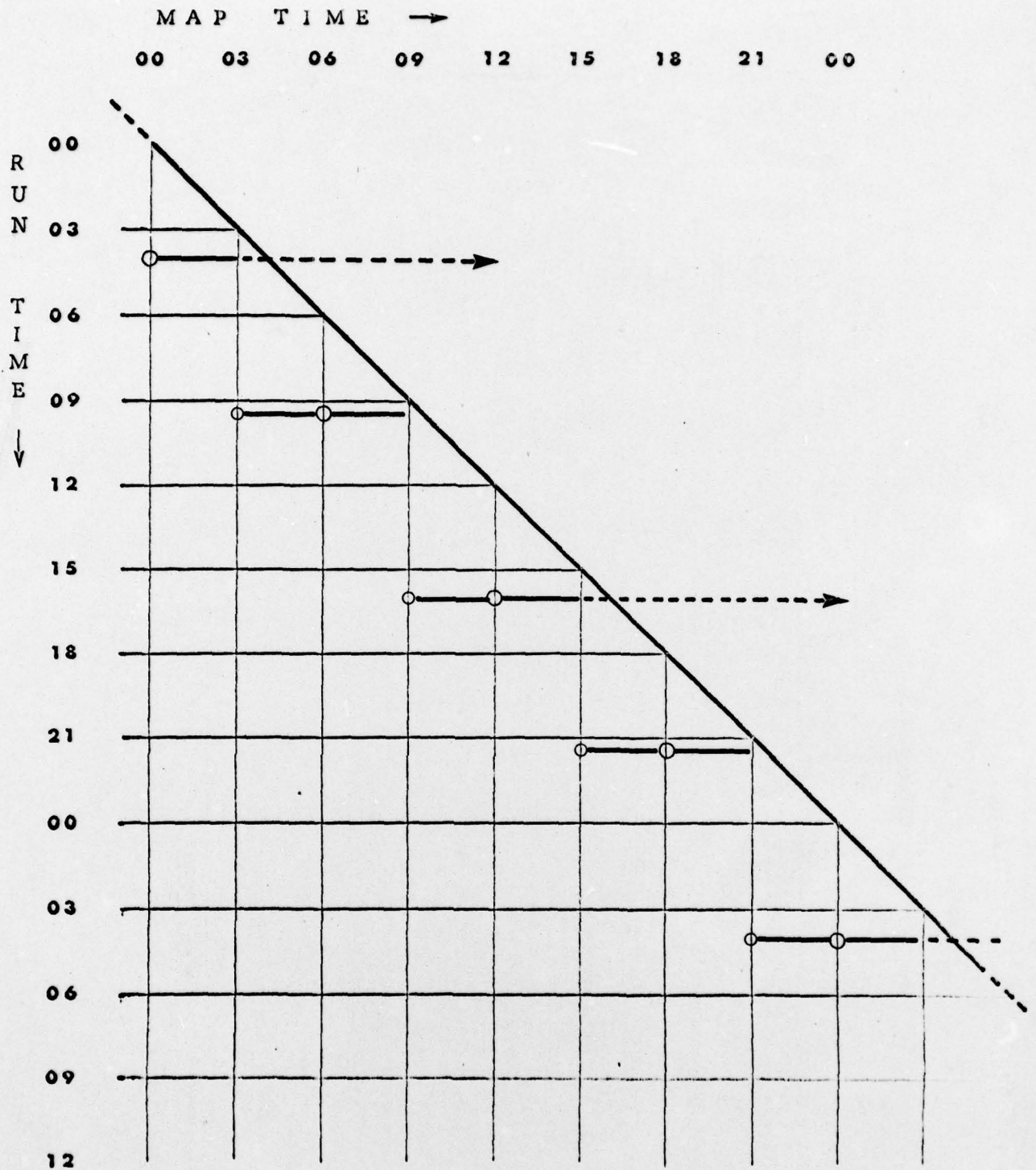


Figure 4 The schedule for running SOWM. Solid lines refer to time steps based on winds diagnosed from analyzed sea-level pressure fields. Large circles denote updates using actual analyses; small circles denote updates using mean winds diagnosed from two successive analyses. Dotted lines refer to time steps based on winds diagnosed from predicted sea-level pressure fields. See text for explanation of procedure.

3. THE FIBWH ANALYSIS SYSTEM

The analysis system for synoptic fields of significant wave height, FIBWH, is an application of the general purpose Fields by Information Blending (FIB) methodology and encompasses Blending by Weighted Spreading (FIBWS). This description of FIBWH assumes familiarity with the information-processing concepts upon which FIB is based and with the associated terminology.

FIBWH utilizes the standard FNWC 63x63 analysis grid array, north polar stereographic projection. The analysis output may be transformed to any other grid array by interpolation using subroutine INTRPS which includes provision for SCD⁵ discontinuities.

FIBWH can assimilate wave height information from the following sources:

- a. In-situ observations (see Section 2.1).
- b. Satellite-derived data when available (see Section 2.2).
- c. SOWM field values (see Section 2.3).

Figure 5 shows a block diagram for FIBWH.

The ship data are decoded and formatted for internal use. Where both sea and swell parameters have been reported the combined wave height is computed using Eq. 1. Reports are allocated to appropriate classes. Up to 16 classes are available for ship reports although, at this time, only two are used--one for observations containing only sea height, the other for observations containing both sea and swell. Appropriate class weights are assigned.

⁵Spatial Covariance Dissociation for separating non-contiguous ocean regions.

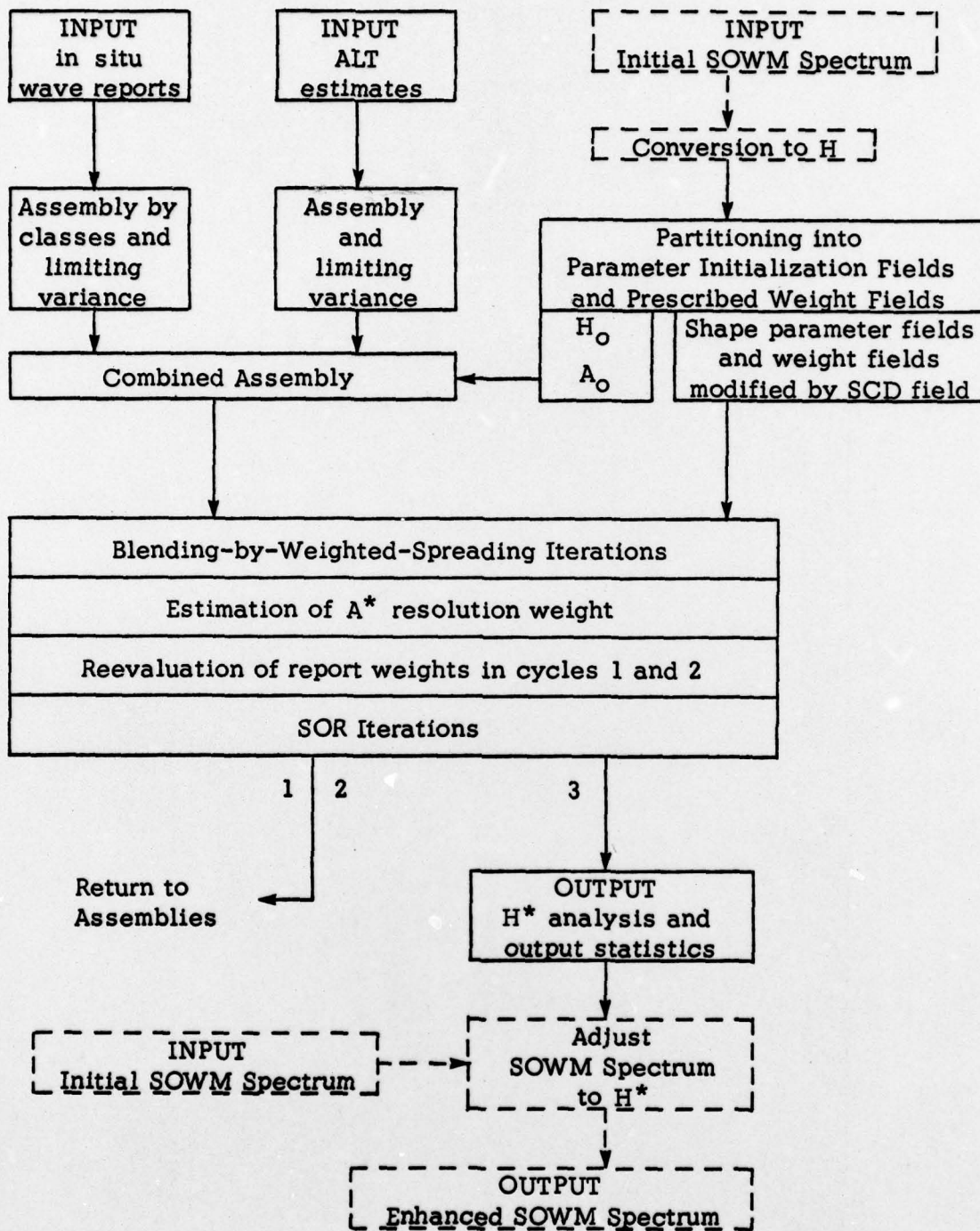


Figure 5 Block diagram for FIBWH. See text for discussion.

(If available, satellite data also would be decoded, formatted for internal use, and allocated to a report class together with an associated class weight.)

The FIBWS assembly module (ASSMBL) has been modified to provide space for two assembly fields (each containing packed values and weights) to allow a more convenient method of assembly by classes--a "staged assembly" capability. Individual reports of the same class are assembled into the first field. When all reports for this class have been assembled a limiting variance is added and the resulting fields (object parameter value and weight) are added into the second field. The first field is now initialized and used for the assembly of the next class of reports. When all reports for this class have been assembled a limiting variance is added and the resulting fields of object-parameter value and weight are combined with those previously entered into the second assembly field. (Note that the limiting variances added are a function of the report class being assembled.) The first field is again initialized and the process repeated for the next class of reports (e.g., satellite-derived data). By using this method the "sub-assemblies" of individual reports in their respective classes, as well as the full assembly of classes, can be made in any order. In addition an added limiting variance will affect only its specific class, not classes already assembled.

This process of staged assembly facilitates the withholding of all reports belonging to a particular class. The withheld reports remain in the data list and can be reevaluated along with the reports from assembled classes. In this way an objective assessment can be made of the usefulness and accuracy of a particular class (or type) of data.

Referring again to Fig. 5, the SOWM input to FIBWH consists of fields of H, the conversion from the spectrum to H being part of the output generated by SOWM. This is indicated by dashed blocks in Fig. 5. The fields of H from SOWM are partitioned into eight Parameter Initialization

Fields (PIFS)--the object-parameter PIF (H_0 and its associated weight field A_0), and seven "shape fields" consisting of four first-difference PIFS, two double-difference PIFS and the Laplacian PIF, each with an associated weight field.

The object-parameter PIF is combined with the assembled data field resulting from the staged assembly procedure described above. In effect SOWM is used to provide an estimate of the object parameter. However the prescribed weight, A_0 , is relatively low. This ensures that in regions where there is an adequate density of observed data the analysis will conform more closely to observed rather than SOWM values of H , whereas in data-sparse or data-void regions the relative significance of SOWM data increases. (This effect can be seen in the examples of FIBWH and SOWM wave height fields given in Section 4.1.)

The other seven PIFS derived from the SOWM output are used by FIBWH for information spreading. In order to preserve the shape information contained in the SOWM wave-height field, the associated spreading weights are relatively high. The weight fields of these PIFS are modified by the SCD field to control information-flow in the vicinity of land/ocean boundaries. The assembled data field and shape PIFS are provided as input to the Blending by Weighted Spreading module and a 3-cycle FIB analysis is carried out. The output from the third cycle is an analyzed field of combined significant wave height, H^* . Output statistics also are generated which enable comparisons to be made of observed values with both analyzed and SOWM field values. Examples of fields of H^* and associated output statistics are given in the following Section.

Significant wave height information resulting from observed data is not carried forward along the time axis. Time continuity between analyses is provided by way of SOWM which is driven by diagnosed winds (see Section 2.3). A potentially valuable use of FIBWH is to enhance the SOWM

spectrum, prior to its further integration, by adjusting the spectral energy distribution to conform to the energy associated with analyzed values of significant wave height. This process is indicated by dashed blocks in Fig. 5 and is discussed in Section 5.

As currently configured, FIBWH requires about 40 CP seconds per analysis on the FNWC 6500 system for a hemispheric analysis on the standard 63x63 polar stereographic grid. Core requirements are 71₈k CM and 163₈k ECS.

4. RESULTS AND VERIFICATION

4.1 Results

Figures 6 through 17 show a 24-hour sequence in 6-hourly intervals of analyzed fields of sea-level pressure (SLP), the corresponding fields of combined significant wave height (H) provided by SOWM, and the corresponding fields of analyzed combined significant wave height (H*) produced by FIBWH:

Fig. 6	--	SLP analysis	}	for 12Z 30 JAN 79
Fig. 7	--	H from SOWM		
Fig. 8	--	H* from FIBWH		
Fig. 9	--	SLP analysis	}	for 18Z 30 JAN 79
Fig. 10	--	H from SOWM		
Fig. 11	--	H* from FIBWH		
Fig. 12	--	SLP analysis	}	for 00Z 31 JAN 79
Fig. 13	--	H from SOWM		
Fig. 14	--	H* from FIBWH		
Fig. 15	--	SLP analysis	}	for 06Z 31 JAN 79
Fig. 16	--	H from SOWM		
Fig. 17	--	H* from FIBWH		

Note that observed data utilized in the FIBWH analysis sequence consisted of ship reports containing both sea and swell elements. Ships reporting only sea waves were not used in these particular examples and no satellite-derived data was available.

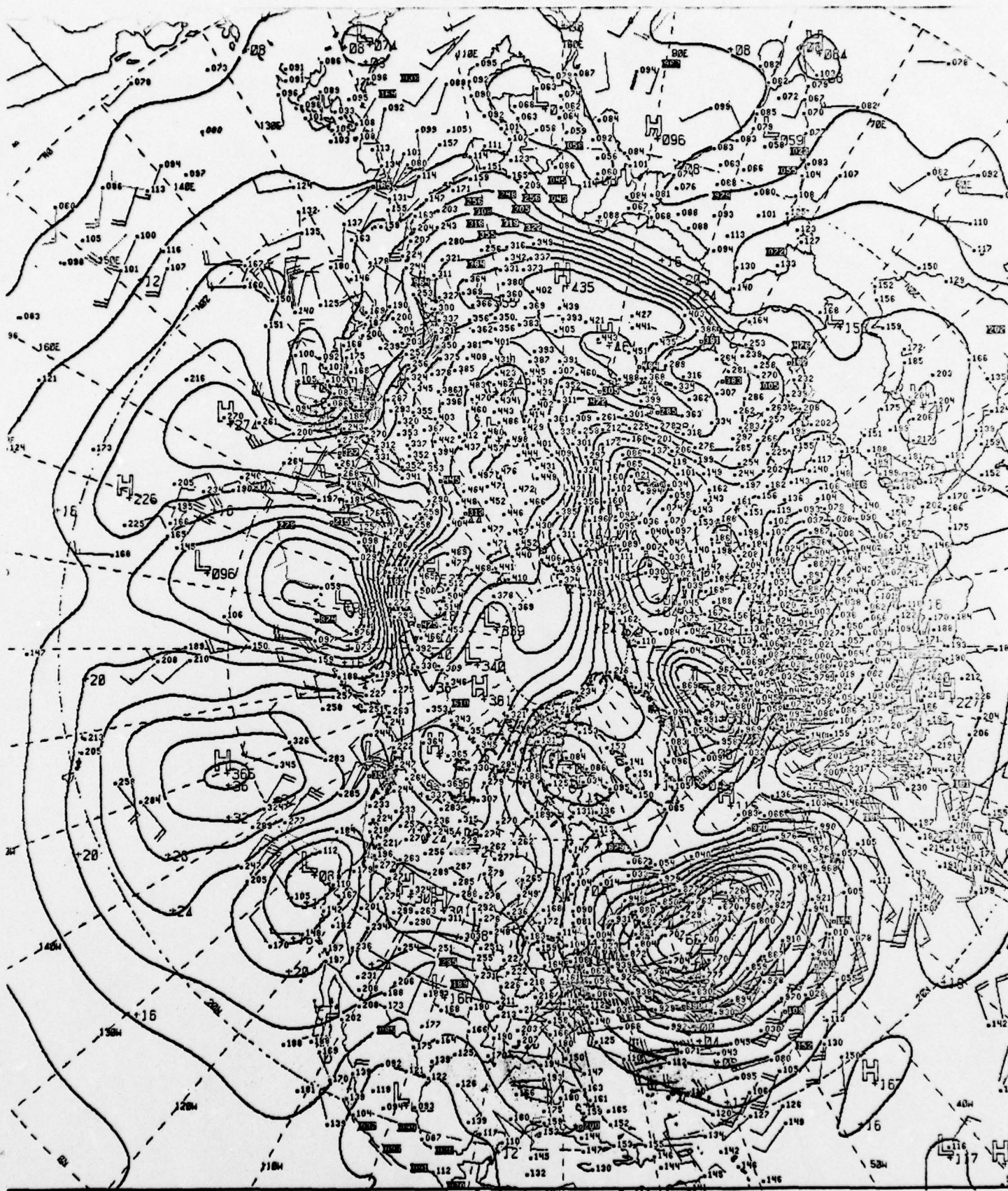


Figure 6 Sea-level pressure analysis for 12Z 30 JAN 79 No. of reports: 4172

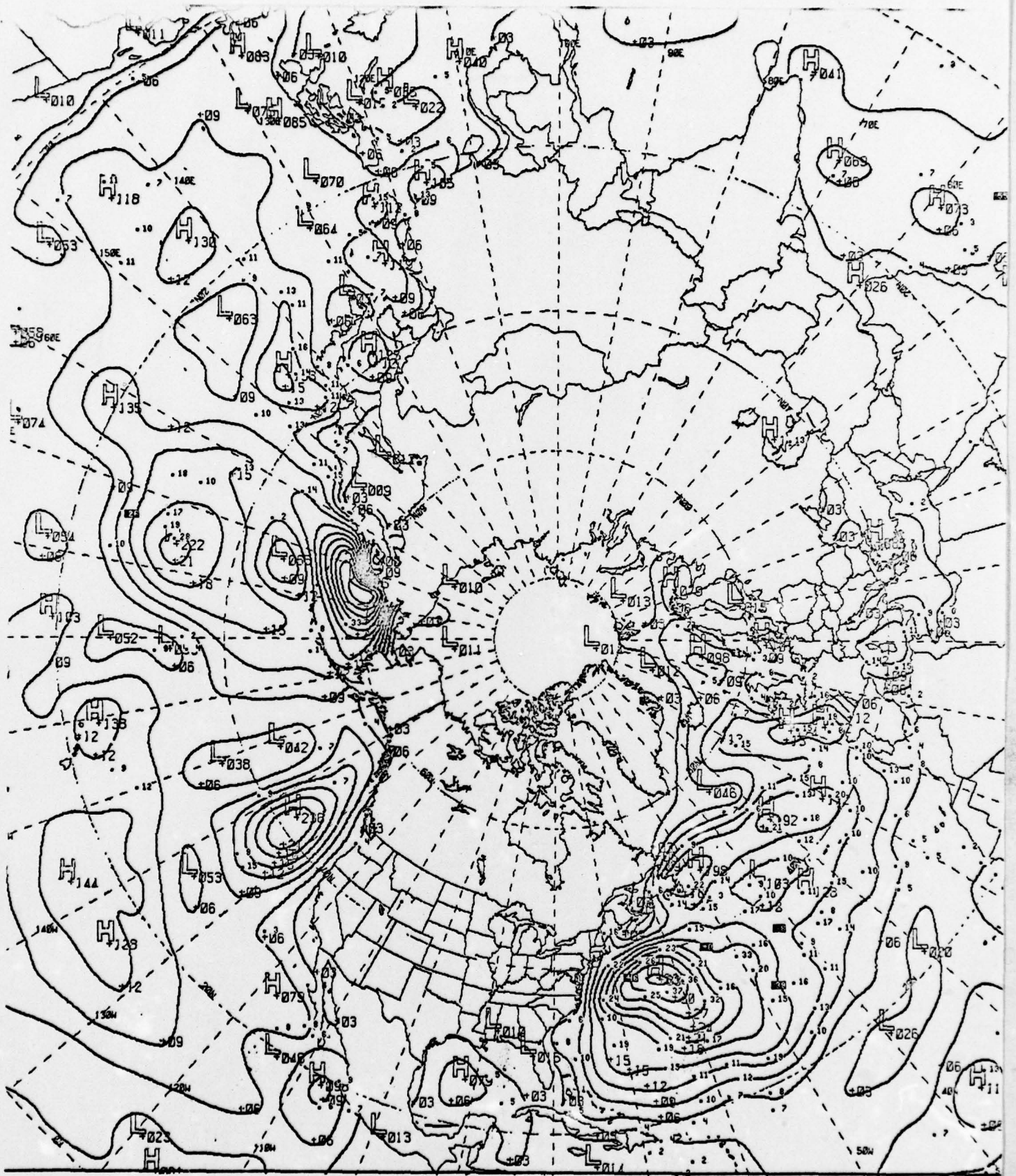


Figure 8 FIBWH analysis of significant wave height for 12Z 30 JAN 79
 No. of reports: 366

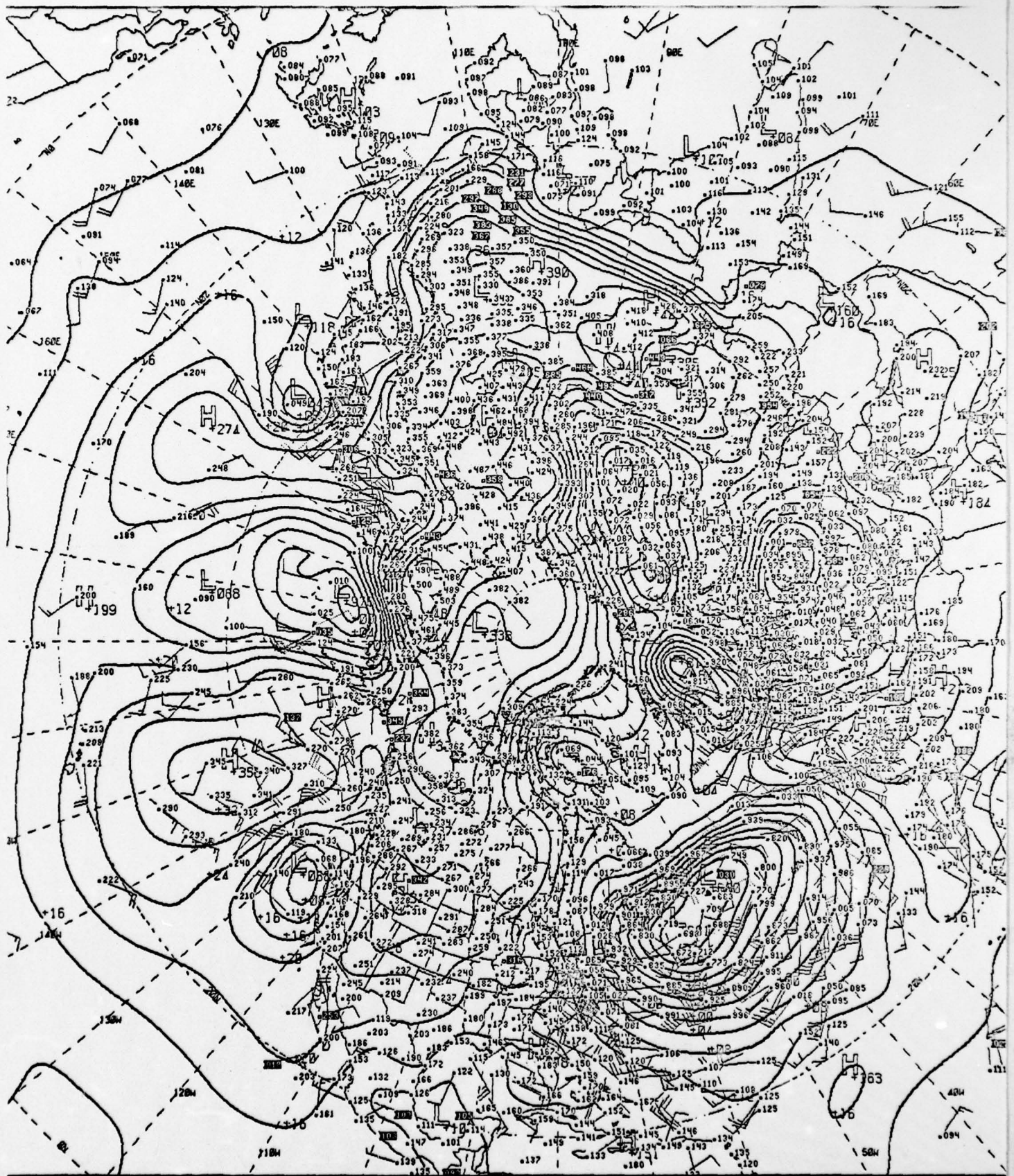


Figure 9 Sea-level pressure analysis for 18Z 30 JAN 79 No. of reports: 4689

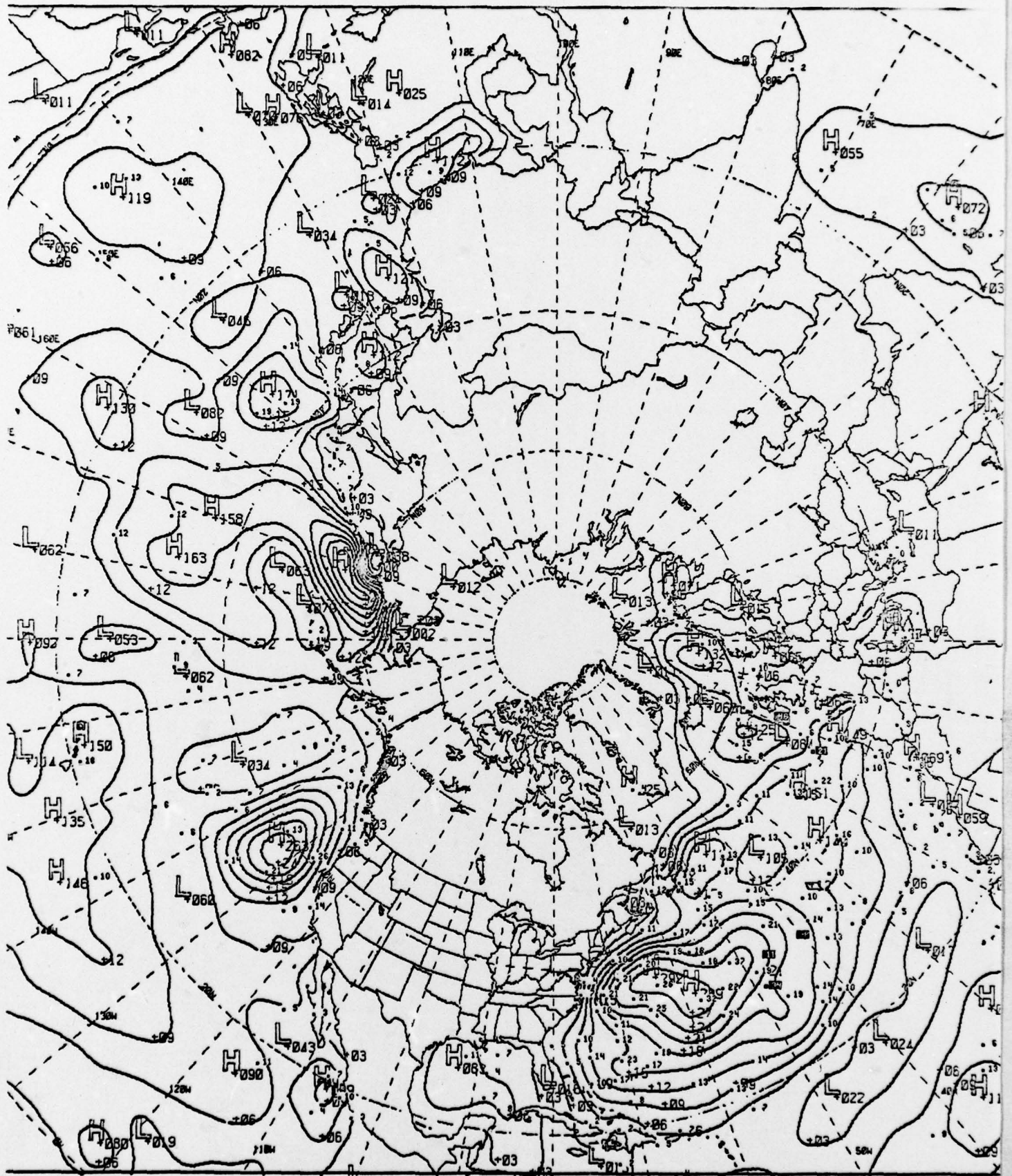


Figure 11 FIBWH analysis of significant wave height for 18Z 30 JAN 79
 No. of reports: 366

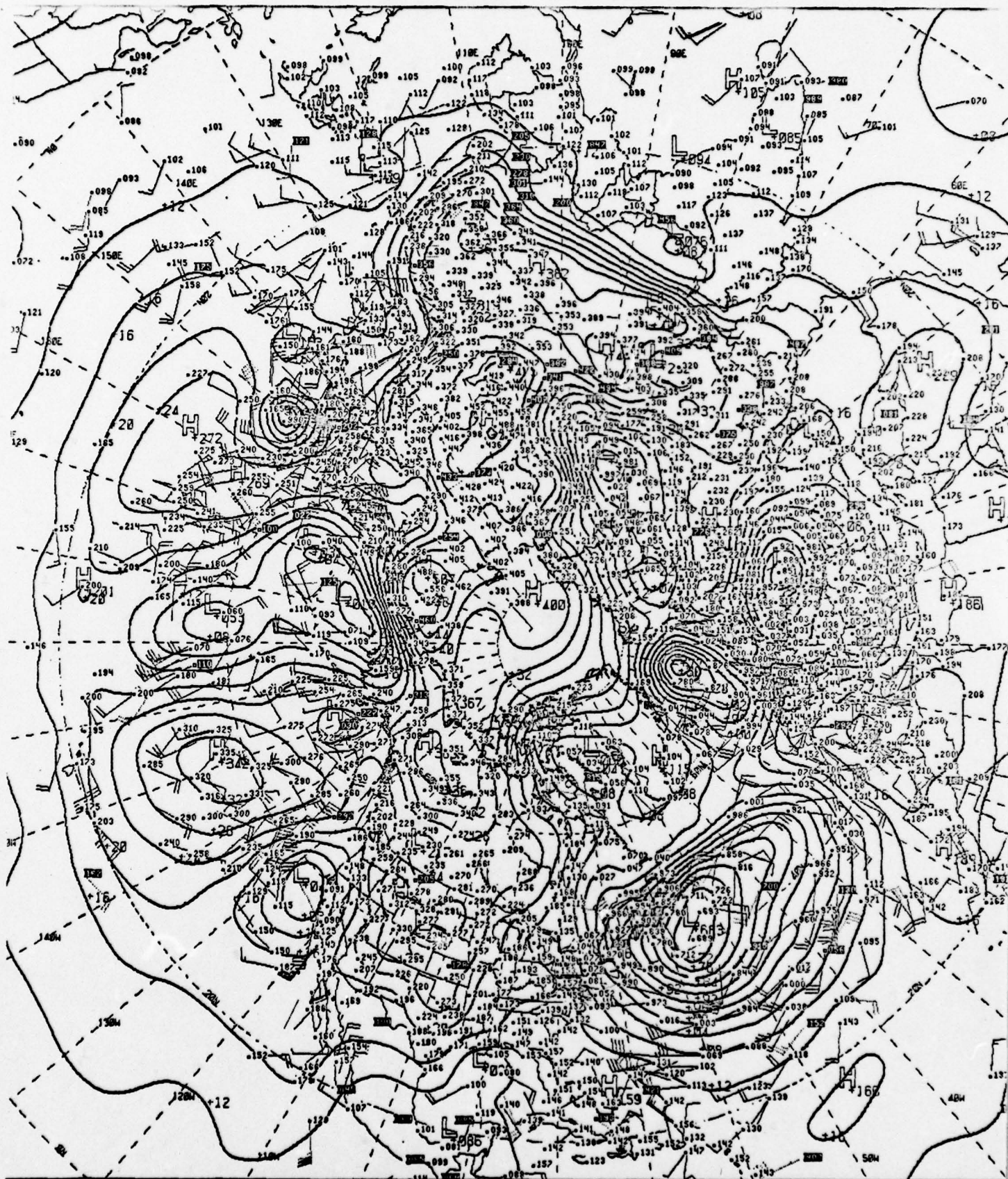


Figure 12 Sea-level pressure analysis for 00Z 31 JAN 79 No. of reports: 4945

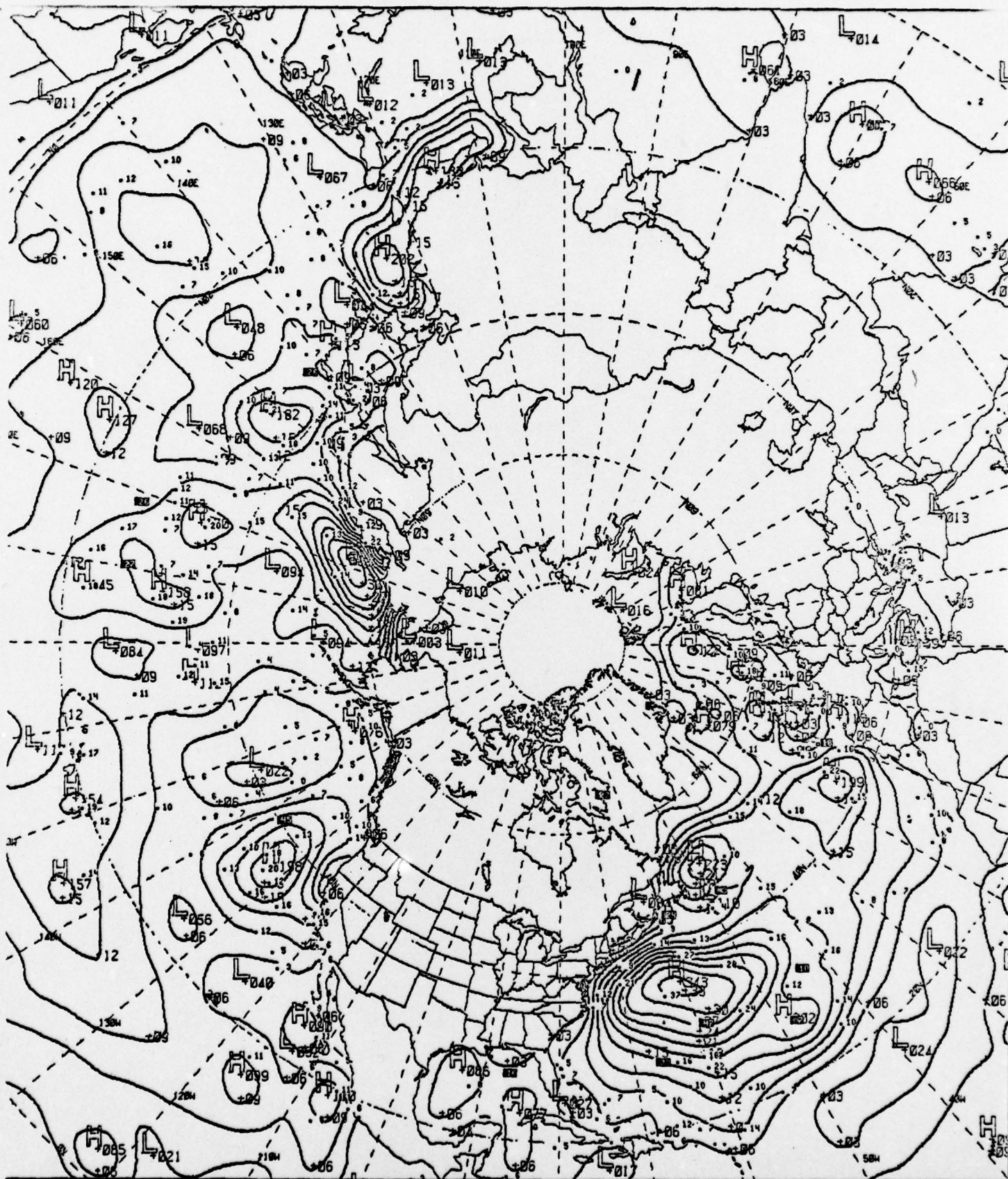


Figure 14 FIBWH analysis of significant wave height for 00Z 31 JAN 79
 No. of reports: 424

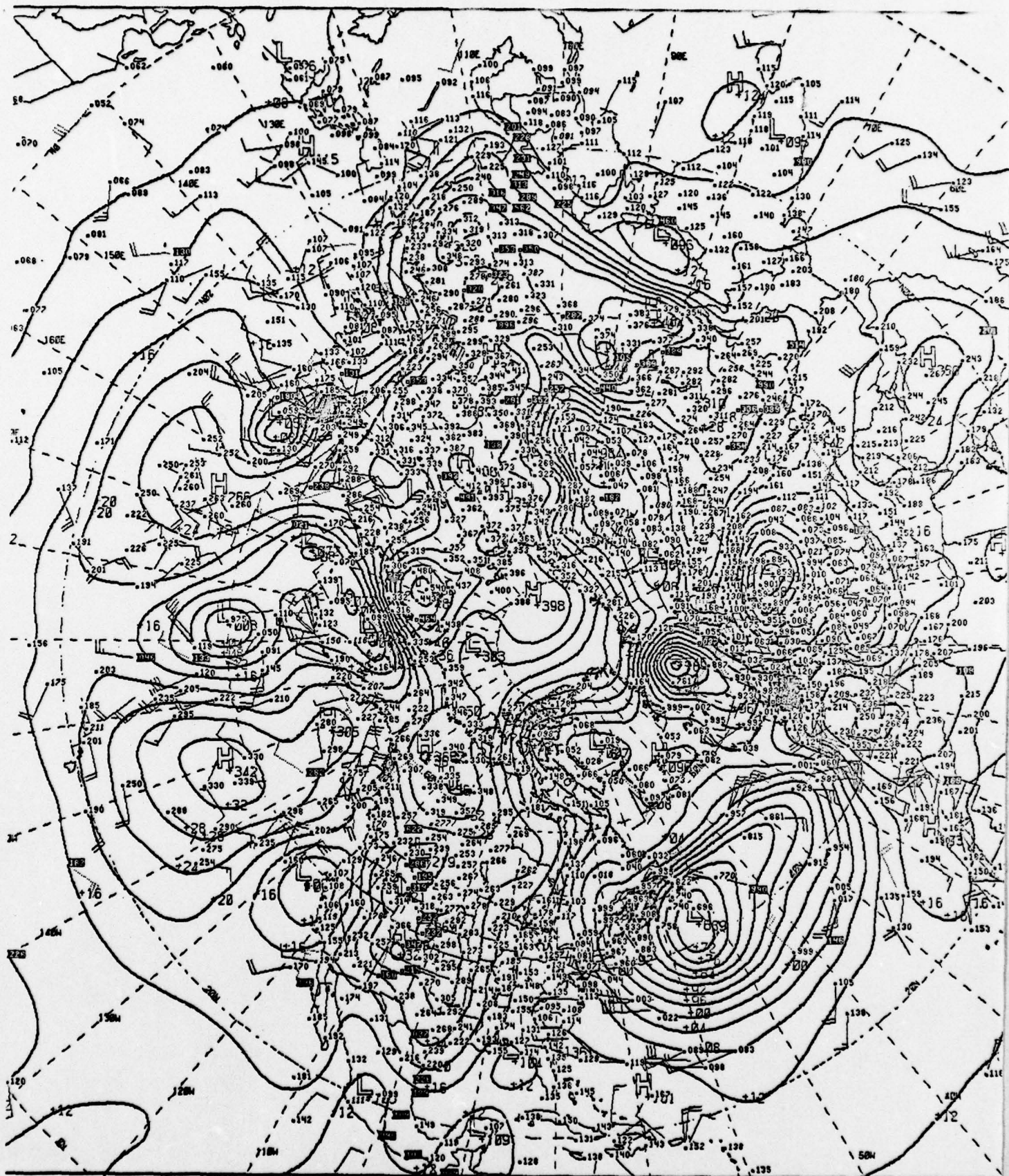


Figure 15 Sea-level pressure analysis for 06Z 31 JAN 79 No. of reports: 5005

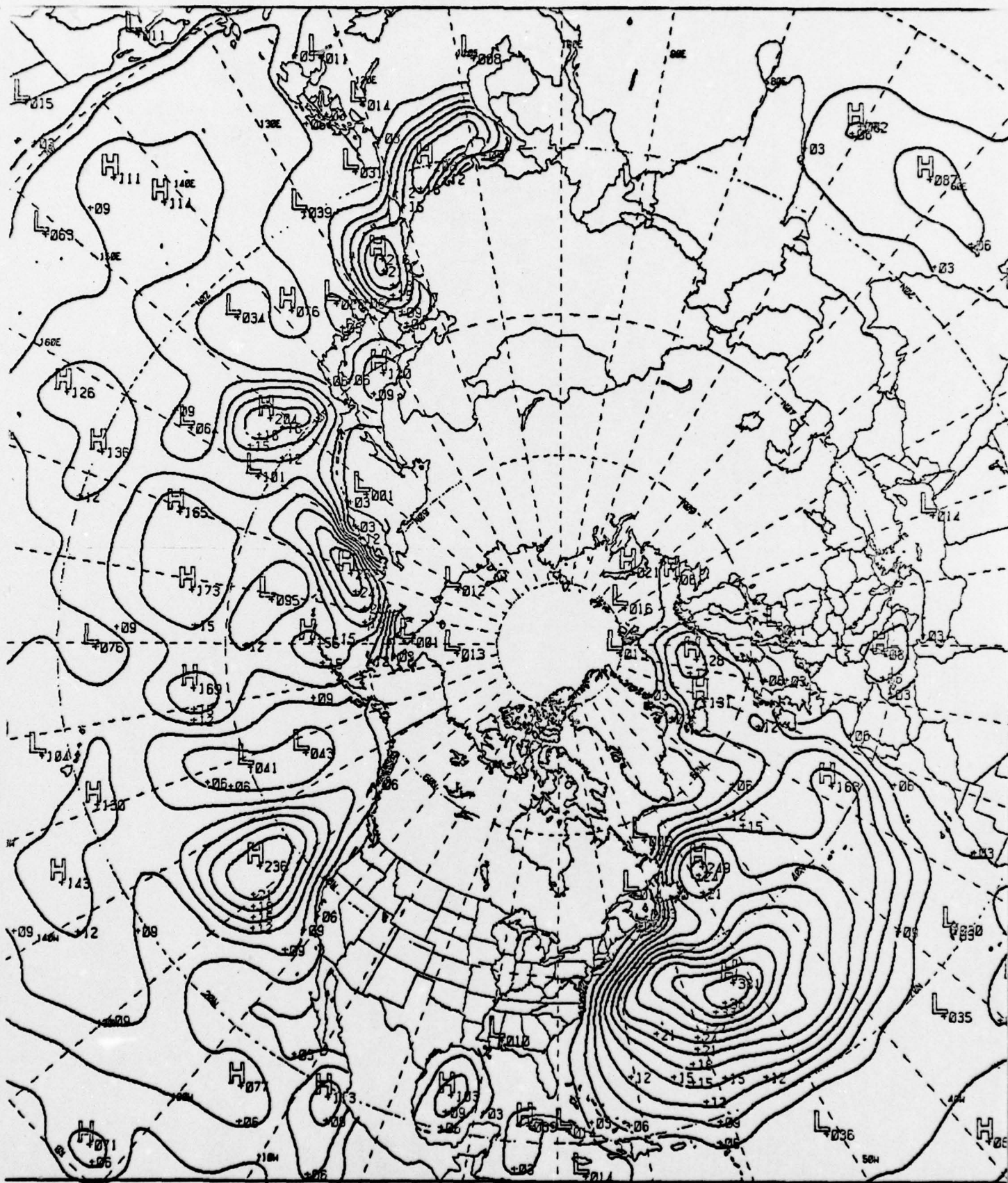


Figure 16 SOWM-derived significant wave height for 06Z 31 JAN 79



Figure 17 FIBWH analysis of significant wave height for 06Z 31 JAN 79
 No. of reports: 297

4.2 Verification Statistics

The verification of fields based on comparisons with concurrent observations has been discussed by Holl⁶. A Field Verification System (FVS) based on Holl's concepts currently is being developed and implemented by MII on behalf of FNWC.⁷ The verification statistics presented in this Section have been produced by an experimental version of this field verification system which, as yet, has not been progressed to the point of satisfying design requirements. Nevertheless the verification statistics for FIBWH (and SOWM) given below represent the first application of the new system. As pointed out by Holl, the interpretation of field verification statistics contains many pitfalls--interpretations which are intuitively "obvious" can lead to false inferences concerning bias and error.

The field verification statistics shown in Figs. 18 through 21 are based on comparisons of observed values with field values at the location of the observed value--for every observed value, H_R , there is an associated FIBWH value, H^* , and an associated SOWM value, H . Figures 18 through 21 show field verification statistics for each of the four analysis times presented in Section 4.1. Each figure contains two pairs of tables, the upper pair for $H_R:H^*$, the lower pair for $H_R:H$.

Referring to Fig. 21 by way of example, the first table in each pair, the scatter diagram, is obtained by assigning observed values and field values to classes. The class range is ± 1.5 feet and center value of the

⁶Holl, Manfred M., 1978; "The Verification of Fields based on Comparison with Concurrent Observations (A Critical Review of OPL2)", Design Study (Contract No. N00228-78-D-4316, 7R-13, Fleet Numerical Weather Central), Meteorology International Incorporated, Monterey, California, 35 pp.

⁷"Correction and Improvement of the OPL2 Verification Statistics Package", Contract No. N62271-79-M-0471, Fleet Numerical Weather Central, MII Project M-240.

Ship Reports: FIBWH

Scatter Diagram										Class Means					
	39									*	39	24.0	2	T	9
	26									*	36	31.3	3	T	0
	33									* 1 1	33	23.7	3	37.5	2
	30									1 1 2	30	22.8	3	31.3	4
	27									1 1 1	27	19.4	9	25.3	3
	24									1 1 1 1 1	24	20.1	5	24.3	5
A	21									1 1 2 2 1 1 1 1	21	17.5	12	21.6	11
N	18	1								1 1 1 7 4 2 1	18	17.0	23	17.5	24
A	15									1 2 5 4 7 4 1	15	13.2	44	14.8	40
L	12									1 3 4 4 4 1	12	11.7	59	11.5	38
Y	9									2 4 4 5	9	9.8	70	9.7	50
S	6									4 4 3	6	6.6	34	6.2	72
I	3									3 3 1 1 1 1	3	4.4	59	4.4	55
S	0									1 1 1 1	0	5.8	5	5.7	4
	0									5 12 18 24 30 35	CL	ANA	N	REP	0
	2									0 0 0 0 0 0					

376 reports. HM = 10.4 ALG = -0.2 ABS = 2.5 RMS = 3.7

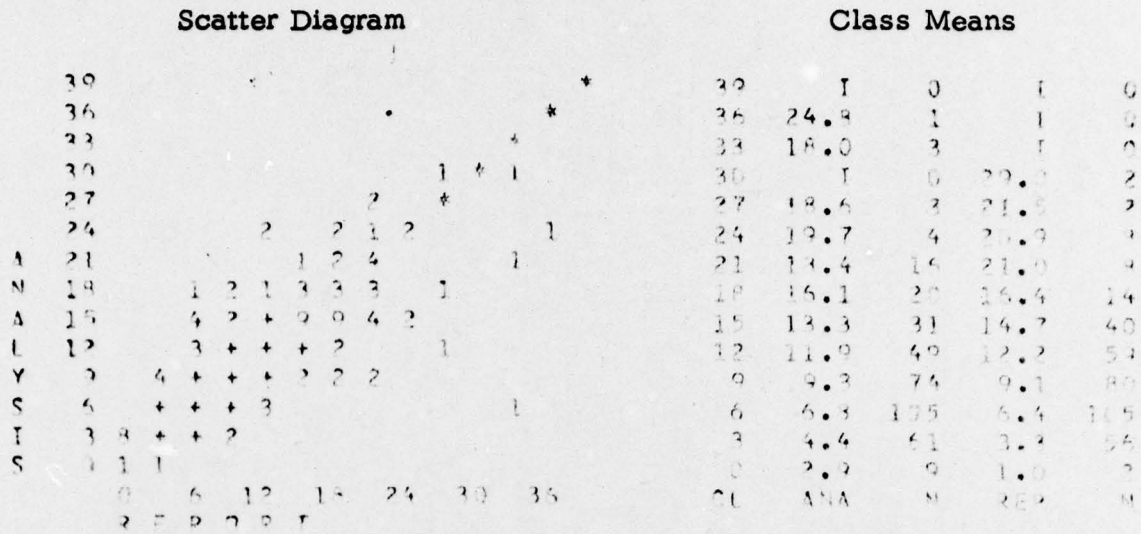
Ship Reports: SOWM

Scatter Diagram										Class Means					
	39									*	39	27.1	2	T	9
	26									*	26	29.3	3	T	0
	33									*	33	25.3	3	T	0
	30									2 1 3 1	30	24.4	3	22.1	7
	27									4 2 3 2 1 2	27	17.3	5	19.0	14
	24	1								1 2 3 1 1 1 1	24	20.6	5	16.6	11
A	21									1 5 2 5 6 4 1 1 1	21	16.5	12	16.5	26
N	18									2 2 6 7 4 6 1	18	12.5	23	12.5	28
A	15									1 3 3 6 4 1 2	15	13.6	44	14.9	20
L	12									2 6 4 8 2 2 1	12	11.9	59	11.3	43
Y	9									4 4 4 3 1 2	9	10.2	70	9.5	74
S	6									1 4 4 4	6	6.4	34	7.7	68
I	3									2 2 7 4 1	3	4.5	59	6.0	42
S	0									1 1 1 1	0	5.0	5	5.4	27
	0									6 12 18 24 30 35	CL	ANA	N	REP	0
	2									0 0 0 0 0 0					

376 reports. HM = 10.4 ALG = -0.1 ABS = 4.4 RMS = 5.8

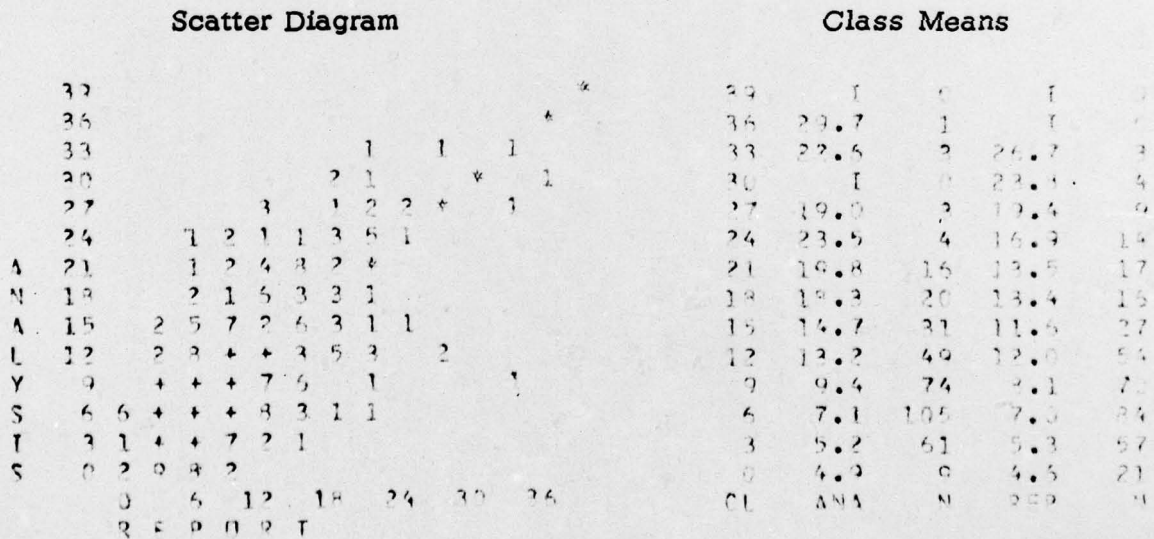
Figure 18 Significant wave height verification statistics for 12Z 30 JAN 79. See text for explanation.

Ship Reports: FIBWH



375 reports. HM = 9.3 ALG = 0.0 ABS = 2.4 RMS = 3.4

Ship Reports: SOWM



375 reports. HM = 9.3 ALG = 0.8 ABS = 4.0 RMS = 5.3

Figure 19 Significant wave height verification statistics for 18Z 30 JAN 79.

Ship Reports: FIBWH

Scatter Diagram										Class Means								
30										*	30	I	0	I	0			
36										*	36	23.6	2	I	0			
33										* 1	33	12.2	2	37.3	1			
30										*	30	14.7	1	I	0			
27			1				2	1			27	16.0	6	22.3	4			
24				1			*	1			24	17.0	7	20.5	2			
A 21		1					2	1			21	15.9	12	17.3	4			
N 18			2	3	5	1	5	1			18	13.5	16	16.7	19			
A 15		1	2	2	3	9	+	2	2	1	1	1	1	15	12.7	49	17.2	35
L 12		1	+	+	+	+	2							12	10.9	66	11.6	82
Y 9		4	+	+	+	+	7	2	1		3	1		9	9.3	83	9.6	130
S 6	1	+	+	+	+	6		1						6	7.5	126	6.4	101
I 3	5	+	+				3							3	4.5	62	4.0	54
S 0	4	3						1	1					0	2.3	10	5.9	9
	0	6	12	18	24	30	36							CL	ANA	N	REP	N
	2	F	D	0	3	I												

439 reports. HM = 9.2 ALG = -0.3 ABS = 2.5 RMS = 3.8

Ship Reports: SOWM

Scatter Diagram										Class Means								
30										*	30	I	0	I	0			
36										*	36	25.9	2	I	0			
33										*	33	11.4	2	24.0	2			
30										1 *	30	15.3	1	32.5	2			
27		1					1	*			27	16.2	6	14.3	3			
24			2	4	3	1		1	1		24	19.1	7	15.2	12			
A 21		2	1	1	1	2		1			21	14.8	12	13.8	9			
N 18			3	2	5	+	1	4	1		1			18	12.0	16	15.0	29
A 15		1	5	7	3	5	3	1	1		1			15	13.0	49	12.4	27
L 12		4	+	+	+	+	3	5	2	1	3			12	10.5	65	11.3	64
Y 9		1	1	+	+	+	+	3	2					9	8.9	83	13.0	72
S 6	3	+	+	+	+	+	+	2		1	1			6	7.2	126	8.2	129
I 3		+	+	+	+	4	2	1						3	4.8	62	6.5	54
S 0	6	+	+	+	2	1			1					0	2.5	10	4.6	39
	0	6	12	18	24	30	36							CL	ANA	N	REP	N
	2	F	D	0	3	I												

439 reports. HM = 9.2 ALG = -0.5 ABS = 4.2 RMS = 5.6

Figure 20 Significant wave height verification statistics for 00Z 31 JAN 79.

classes ranges from 0 to 39 feet. Thus a class of 9 feet includes heights from 7.5 feet to 10.5 feet. (Class 0 is singular in that it contains heights from 0 to 1.5 feet.) The numbers in the body of the scatter diagram show the number of paired-values falling into each element of the diagram. For example, for the $H_R:H^*$ diagram, there was one case where a reported wave height of 6 feet (actually 4.5 to 7.5 feet) corresponded to an analyzed wave height of 12 feet (10.5 to 13.5 feet). Numbers of cases greater than or equal to 10 are indicated by "+"--thus, referring to the $H_R:H$ diagram, there were 10 or more cases where a reported wave height of 12 feet corresponded to a SOWM height of 6 feet. The diagonal of the scatter diagram (the line given by $H_R = H^*$ or H) is completed by "*" where no reports occur.

The second table in each pair, under "Class Means", shows:

- Column 1 -- class, 0-39 ft, class range ± 1.5 feet.
- Column 2 -- analyzed (or SOWM) height for each report class. (Thus, for the upper table of Fig. 21, the mean value of H^* for all reported heights in the class of 12 feet was 10.9 feet.)
- Column 3 -- the number of reports, N , for each report class (43 for the example quoted above).
- Column 4 -- mean report height for each analyzed class. (Thus, for locations where a report was available, and the analyzed value was 12 feet, the mean height of the reports was 12.7 feet.)
- Column 5 -- the number of reports, N , for each analysis class (49 for the above example.)

These class means should be interpreted with care. In general it can be seen that for class wave heights of 12 feet or more, the mean

analysis, SOWM and reported wave heights are lower than the class value, whereas for class wave heights of 9 feet or less, the mean analysis, SOWM and reported wave heights are higher than the class value. This arises from the distribution of the bivariate sample around the overall sample mean which is about 9-10 feet. (See Holl⁶.)

Along the bottom of each pair of tables is provided a number of statistical measures--HM, ALG, ABS and RMS. Reports used in compiling these measures (the first number given) exclude all cases where the absolute difference between the field value (FIBWH or SOWM) and the reported value exceeds 20 feet. (The exclusion does not apply to the scatter diagrams and associated class means.) This number of reports does not necessarily correspond to the number used in the corresponding FIBWH analysis. For example Fig. 18 shows that 376 reports were used for statistical compilation whereas Fig. 8 shows that 366 reports were accepted by the analysis. FIBWH excludes reports that are objectively determined to be non-representative or in gross error.

The four statistical measures are computed from:

$$HM = \frac{1}{N} \sum_{n=1}^N H_{R_n} \quad (3)$$

$$ALG = \frac{1}{N} \sum_{n=1}^N \left(H_{F_n} - H_{R_n} \right) \quad (4)$$

$$ABS = \frac{1}{N} \sum_{n=1}^N |H_{F_n} - H_{R_n}| \quad (5)$$

$$RMS = \left(\frac{1}{N} \sum_{n=1}^N \left(H_{F_n} - H_{R_n} \right)^2 \right)^{1/2} \quad (6)$$

where H_R is the reported value of wave height,

H_F is the field value of wave height (either the FIBWH analysis value H^* or the SOWM value H), and

N is the number of wave height reports used in the summations.

ALG is the mean difference between FIBWH/SOWM values and reported values of wave height and provides an estimate of the overall bias. ABS and RMS provide measures of the scatter between reported values and corresponding analysis values.

4.3 Discussion of Results and Verification Statistics

The following values are extracted from Figs. 18 through 21:

DTG (JAN79)		N	HM	ALG		ABS		RMS	
Day	Hour			reports	feet	FIBWH	SOWM	FIBWH	SOWM
30	12Z	376	10.4	-0.2	-0.1	2.5	4.4	3.7	5.8
30	18Z	375	9.3	0.0	0.8	2.4	4.0	3.4	5.3
31	00Z	439	9.2	-0.3	-0.5	2.5	4.2	3.8	5.6
31	06Z	307	9.0	-0.4	-0.9	2.3	3.8	3.5	5.1

Considering that SOWM estimates of significant wave height are derived primarily from measurements of sea-level pressure and do not utilize observed wave-parameter data in a synoptic context, the agreement between SOWM-derived and observed values of significant wave height is remarkable. Nevertheless FIBWH fits the observed data better than SOWM both with regard to bias (ALG) and scatter (ABS and RMS).⁸ This

⁸The greater degree of scatter for SOWM also can be seen in the scatter diagrams, Figs. 18 through 21.

is to be expected because FIBWH assimilates and blends information from SOWM and observed data.

A test of an effective analysis algorithm (and of representative observed data) is that an analysis can be produced which not only fits the data but which also is reasonably "smooth" in the context of the scale of the significant features. Figures 8 through 17 show that FIBWH and SOWM both provide fields of combined significant wave height without introducing unrealistic sub-scale detail. Since FIBWH more exactly fits the observations it may be concluded that for applications where the required parameter is combined significant wave height (rather than the wave spectrum provided by SOWM), the analyzed fields provided by FIBWH are to be preferred to the fields of significant wave height derived solely from SOWM.

It also is considered that the results--analyses and verification statistics--demonstrate that ship observations are of higher quality than is sometimes believed. As noted in Section 4.1, the FIBWH analyses and verification statistics given in this Report were based on ship reports containing both sea and swell elements. The analyses were re-run using separate assembly classes for ships only reporting sea height and for ships reporting sea and swell (see Section 3). This increased the number of available observations by about 35-40%. There was no significant change in either bias or scatter. A reasonable explanation for this is that where a swell component cannot be distinguished the observer reporting only sea subjectively arrives at a representative value of combined significant wave height.

5. ENHANCING THE SOWM SPECTRUM

5.1 Introduction

In the context of combined significant wave height it has been shown that analyzed fields produced by FIBWH more closely agree with observed data than the concurrent fields produced by SOWM; the information content of the FIBWH fields is higher. As can be seen from Fig. 5, such time continuity as there is between analyses is provided solely by SOWM which is driven by diagnosed winds; significant wave height information resulting from observed data is not carried forward and accrued along the time axis and the benefits which can ensue from such a procedure are not realized.

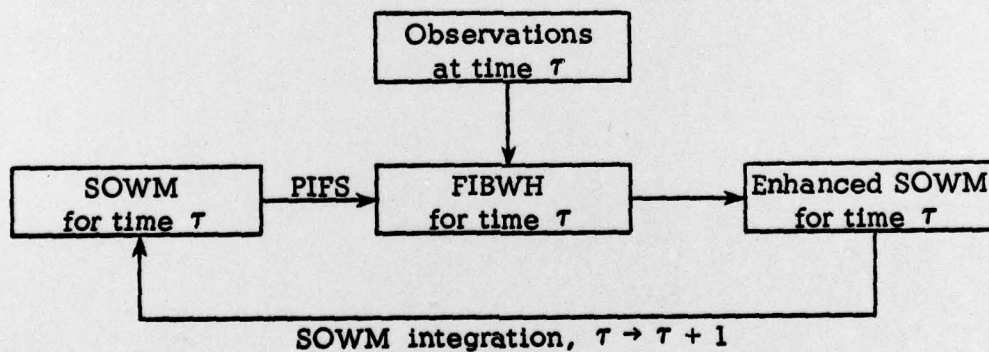
To take advantage of the improved resolution of combined significant wave height provided by FIBWH, a model is needed which is capable of assimilating the information content of each analysis and carrying it forward in time. SOWM is capable of carrying the information along the time axis; the problem is how to effect the transfer of the additional information contained in FIBWH fields to the SOWM spectrum for assimilation and accrual. Section 5.2 defines a general approach for carrying out the required process which is based on the concept of adjusting (i.e., enhancing) the SOWM spectral energy distribution, in a realistic manner, so that the resulting SOWM value of computed significant wave height conforms to the concurrent value provided by FIBWH. Based on this general approach a number of specific algorithms are suggested for evaluation. A generally-applicable method for evaluating and verifying the effectiveness of any particular algorithm is an essential component of the overall concept of enhancing the SOWM spectrum; such a method is given in Section 5.3.

With regard to the concept of adjusting the SOWM spectrum, the SOWM product may diverge from reality for a variety of interrelated reasons. For example the effective local wind field may not correspond, in speed,

direction and profile, to the diagnosed value utilized by SOWM; the recent evolution of actual effective winds may not be completely represented by the 3-hourly time steps of diagnosed wind used by SOWM; the wave-growth mechanisms modelled by SOWM are simplified (e.g., energy dissipation as a function of wave-wave interactions and breaking waves is not included); and there may be departures from the "ideal" values of the fully-developed spectrum empirically employed by SOWM to limit wave growth. For these reasons the SOWM product should not be regarded as inviolable and the concept of enhancing the SOWM spectrum, if substantiated by improved field verification statistics of the type presented in Section 4, should be accepted as a reasonable procedure.

5.2 A General Algorithm for Enhancing the SOWM Spectrum

In order to enhance the SOWM spectrum, a "positive feedback" of information must be provided between FIBWH and SOWM. The feedback loop may be illustrated thus:



Information is passed from SOWM to FIBWH by way of the PIFS, and from FIBWH to SOWM by an appropriate adjustment algorithm. The effects of providing such feedback between SOWM and FIBWH are:

- a. The SOWM spectrum for a particular analysis time would be enhanced by assimilating the concurrent information contained in observations;
- b. Observed information would be accumulated in the SOWM spectrum and carried forward along the time axis from one analysis to the next.

It can be seen that coupling SOWM and FIBWH in an integrated system as outlined above should result in an improved knowledge of ocean wave parameter distributions.

The SOWM spectrum at each grid point consists of a matrix containing 180 elements (12 directions x 15 frequencies), the numbers in the matrix being the energy components, $S(d,f)$, associated with a specific direction (d) and frequency (f). The significant wave height, H , defined as the average of the highest one-third waves, is given by

$$H = 4\sqrt{E} \quad (7)$$

where E is the total two-dimensional energy at a grid point. E may be obtained by summing the energy components over all directions and frequencies:

$$E = \sum_{d,f} S(d,f) \quad (8)$$

Let H^* be the analyzed value of significant wave height at a particular grid point, corresponding to the SOWM-derived value of significant wave height H . Associated with H^* there is a 12x15 matrix whose general energy component is $S^*(d,f)$. The values of the matrix elements are not known. However if the total energy at a grid point is to

be the same for the analysis value of significant wave height and the "adjusted" SOWM value, then

$$E^* = RE \quad (9)$$

where

$$E^* = \sum_{d,f} S^*(d,f) \quad (10)$$

and R is the "adjustment factor".

R is given by

$$R = \left(\frac{H^*}{H} \right)^2 \quad (11)$$

Thus

$$\sum_{d,f} S^*(d,f) = R \sum_{d,f} S(d,f) \quad (12)$$

Provision must be made to distribute the energy difference ($E^* - E$) over the elements of the matrix associated with H in a realistic and controlled manner in order to satisfy Eq. 12. For example it would not be realistic to add $(E^* - E)/180$ to each and every element of the matrix associated with H even though the adjusted value for H would then be equal to H^* .

Consider the general formula

$$S^*(d,f) = S(d,f) + rF(d,f) \cdot S(d,f) \quad (13)$$

where $F(d,f)$ is a weighting function which can be specified to direct the adjustment over the elements of the matrix in any preferred manner. $F(d,f)$ could be based on theoretical considerations or could be specified empirically. Note that the adjustment also is proportional to the value of the individual matrix elements, $S(d,f)$, the "matrix element adjustment factor" being denoted by r .

Summation of Eq. (13) over the matrix, and division by $\sum_{d,f} S(d,f)$ from Eq. (12), yields

$$R = 1 + \frac{r \sum_{d,f} F(d,f) S(d,f)}{\sum_{d,f} S(d,f)} \quad (14)$$

This permits the calculation of r at each grid point:

$$r = \frac{(R - 1) \sum_{d,f} S(d,f)}{\sum_{d,f} F(d,f) S(d,f)} \quad (15)$$

In order to determine r , $F(d,f)$ must be specified.

5.3 Specifications for F(d,f)

The simplest specification for F(d,f) is

$$F(d,f) \equiv 1 \quad (16)$$

which yields

$$S^*(d,f) = \left(\frac{H^*}{H}\right)^2 S(d,f) \quad (17)$$

It is considered that this simple specification for F(d,f) should be evaluated first and used as a reference, or benchmark, for evaluating more complex schemes.

Two other specifications for the weighting function are suggested for consideration:

$$F(d,f) \equiv F(f) \quad (18)$$

This limits the weighting function to frequency dependency for evaluation of specified distributions of F(f).

$$F(d,f) \equiv \overline{S(d,f)} \quad (19)$$

where $\overline{S(d,f)}$ is the all-years monthly mean value of S(d,f). However application of this formulation involves storage of an F matrix for each SOWM grid point.

Equation (13) is of general applicability. The forms of the weighting factor, F(d,f), suggested above are based on physical reasoning expressed empirically. However a weighting factor based on theoretical considerations could be utilized if it can be shown that it produces superior results. Evaluation procedures are outlined in the following Section.

For SOWM, FVS may be run after each time integration (e.g., $\tau \rightarrow \tau + 1$), comparing field values for H with concurrent (i.e., $\tau + 1$) observations. For the SOWM/FIBWH system, FVS may be run after each time integration (e.g., $\tau \rightarrow \tau + 1$) but before FIBWH information based on ($\tau + 1$) observations is utilized to enhance the SOWM spectrum. In this manner verification is based on independent data.

The sets of field verification statistics will reveal the effect of the additional accrued-information content of the enhanced SOWM spectrum and will show the effectiveness of the specified weighting function, $F(d, f)$, in the accrual process.