WEATHER BUREAU
Systems Development Office
Techniques Development Laboratory
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Interim Report on Sea and Swell Forecasting

Technical Memorandum WBTM TDL-13

U.S. DEPARTMENT OF COMMERCE / ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

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WEATHER BUREAU

TECHNIQUES DEVELOPMENT LABORATORY

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(Continued on inside back cover)

U. S. DEPARTMENT OF COMMERCE

ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

WEATHER BUREAU

Weather Bureau Technical Memorandum TDL-13

INTERIM REPORT ON SEA AND SWELL FORECASTING

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INTERIM REPORT ON SEA AND SWELL FORECASTING

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ABSTRACT

Work in the Techniques Development Laboratory during the past year on sea and swell forecasting is summarized. The computer programs being adapted for operational use and the test forecasts for a five day period in May 1967 are described.

INTRODUCTION

Weather Bureau Planning Report No. 4, Marine Weather Service Planning Study [1], is a guide for the implementation of improved services which will support maritime interests. The operational requirements for information on ocean waves are specified to include the description of wave conditions out to 48 hours in advance. Wave information up to 6 days ahead is specified as a requirement for planning. To meet these requirements, Planning Report No. 4 recommends technique development on the prediction of waves.

The waves observed on the surface of the ocean are of two types, sea and swell. Wind waves or sea refer to the waves under the influence of the local wind at the time of observation. Swell are the ocean waves previously generated which have propagated out of their generating area. Swell are more regular and generally have longer periods than wind waves.

There are two general approaches to wind-wave and swell forecasting; the "singular" method and the "spectrum" method. The basic difference between the two general types of wave forecasting as pointed out by Hubert [3], is that the "singular" method yields a single forecast value such as significant wave height, whereas the "spectrum" method yields a specification of the wave spectrum.

The singular method consists of relationships to express wave variables such as significant wave height and period as functions of meteorological variables like wind speed and wind duration. The spectrum method specifies the wave components as they are generated by meteorological conditions and propagate through the ocean.

Several reasons why a singular method is being adapted for Weather Bureau use are:

1. The height, period, and direction of the significant waves are variables the Weather Bureau should forecast. The complete directional wave spectrum is not required. The singular method defines the waves adequately for most users.

2. The singular method is far simpler, less expensive, and easier to program for a computer.

3. The singular method which is being adapted applies to the entire grid of the National Meteorological Center (NMC).

4. Comparison of the two methods for a short test period in 1966 by the Naval Oceanographic Office showed them to be about equally good in the forecasting of significant wave heights. The largest errors in wave forecasts are caused by errors in the forecasts of wind fields and not by the wave forecast method being used.

HISTORICAL BACKGROUND

Computer-produced forecasts of sea conditions began at the Joint Numerical Weather Prediction Unit (JNWP) in July 1956 [2]. These calculations were for wind waves without the consideration of swell. Swell was not included for two reasons; the problem is simpler without considering swell, and swell is less important than wind waves in most areas. The surface winds used in the calculations were determined from the 1000-mb. pressure-height forecasts of JNWP.

The height of wind waves depends on wind speed, fetch length, and duration time. Fetch is the area of water over which the wind blows in essentially a constant direction. The duration time is the time the wind blows in essentially the same direction over the fetch. A fully developed sea has the maximum height which can be generated by wind of a given force. The first experiments assumed that the waves would be fully developed. This is accomplished by assuming fetch length and duration time to be sufficient for the waves to attain maximum height for the particular wind speed.

The relationship used for the height of the fully developed sea was:

$$H = \frac{A}{g} V^2$$

where H is wave height,
A is constant,
g is gravitational attraction,
and V is wind speed.

In this calculation, 70% of the 1000-mb.-level geostrophic wind was used as V.

Hubert [2] reported that the prognoses of wave heights were "far from good" but "not completely discouraging." The experiment showed that high waves were generally predicted too high and that low waves were generally predicted too low. The discrepancies were possibly explained by assuming the minimum fetch and duration for fully developed seas and by not including swell.

The next step was to consider the duration time of the wind. The wave height relationships of Pierson, Neumann, and James [4] for duration times of 6, 18, 30, and 42 hours were used. The wind direction at each computation point was checked for a direction change of 25° in determining the duration time. This consideration of duration time improved the wave-height calculations.

During March 1957, a two-class duration model was used for 24-hour wave forecasts. The duration was approximated as either 6 hours or 24 hours as indicated by the wind direction of the 12-hour 1000-mb. forecasts.

The conclusions reached after 9 months of testing at JNWP included:

1. Consideration of two classes of duration time led to improved forecasts over the assumption of minimum duration time for fully developed seas. However, improvement can be attained by a closer determination of the duration time.

2. The assumption of unlimited fetch is not too restrictive but probably should not be made in areas of strong offshore flow.

3. Refined wave forecast methods should include the propagation of swell.

Work was continued on the development of wave forecasting techniques at the Fleet Numerical Weather Facility (FNWF) by W. E. Hubert, E. M. Carlstead, N. M. Stevenson and others [6].

The experimenters have noted that the proper specification of the forecast wind fields is of overriding importance for accurate forecasting of wave conditions. It appeared that errors in the forecast wind fields caused greater errors in the forecasts of wave conditions than any other identifiable factor.

WEATHER BUREAU INTEREST

During 1964, the National Meteorological Center (NMC) with the cooperation of FNWF, programmed the wind-wave program for use on the IBM 7094. The method of swell propagation was not programmed. This wave program was not completely developed to the operational stage.

In 1966, when the Techniques Development Laboratory (TDL) became interested in wave forecasting, the decision had to be made whether to:

1. Program the swell propagation method to be used with the 1964 wind-wave program developed at NMC, or

2. Adapt the 1966 version of the FNWF wind-wave and swell programs, which recently had been improved, for Weather Bureau use.

A test was set up to compare the two systems of wind-wave forecasts. NMC prepared wind-wave forecasts based on meteorological input from the Primitive Equation (PE) Model during May and June of 1966. Comparison of these wave forecasts with the available wave observations for the ocean station vessels (OSV) was made by TDL. Comparison of the wind-wave forecasts for the same times by FNWF was made with the observations. The FNWF forecasts were supplied by the Fleet Weather Central, Suitland. Only FNWF forecasts for 12 and 36 hours were available. During the three-month period, sixteen sets of wind-wave forecasts were made at NMC. The forecasts were for 0, 12, 24, and 36 hours after time of calculation. Copies of the synoptic ship reports including the wave observations were made available by the Communications Branch of NMC. Observations were available from ships A, B, C, D, E, I, J, K, and M in the North Atlantic and N, P, and V in the North Pacific.

Correlation coefficients (r) and root-mean-square-errors (RMSE) were determined for the sets of forecasts made by NMC and FNWF. Persistence forecasts were also evaluated. The coefficients are shown in graphical form in figure 1A. Root-mean-square-errors are shown in figure 1B. There is a decay of correlation and an increase of RMSE with increasing time of forecasts. The 12- and 36-hour forecasts by FNWF were somewhat better than the NMC 12- and 36-hour forecasts. Correlation coefficients, forecast means, observed means, standard deviations, and root-mean-square-errors of forecasts and observations of wave heights for 0, 12, 24, and 36 hours are shown in table 1. The reason for the different number of sets of data for the different forecasts periods is that some of the observations were missing or otherwise not usable. Comparison of the means of the forecasts and observations indicates the NMC forecasts were generally too low. The FNWF forecasts means were much closer to the observed means. These comparisons led to the decision to adapt the 1966 version of the FNWF wind-wave and swell programs as described by Hubert [3] for use with the meteorological forecasts of the NMC Primitive Equation Model. These programs are based on the Sverdrup-Munk forecasting system described in H. O. 601 [5].

THE FNWF WIND-WAVE PROGRAM (1966 VERSION) AS ADAPTED BY THE WEATHER BUREAU

The FNWF wind-wave program is used for calculating the significant wave height and the significant wave period. Significant wave height is defined as the average height of the one-third highest waves. Significant wave period is the average period of the one-third highest waves.

Calculations are made for points of the NMC octagonal grid as shown in figure 2. The program is given information which specifies which of the grid points are land or polar ice, so that wave forecasts will be made only for ocean areas. The distribution of land and ice is also considered in determining fetch length restrictions.

The wave forecasts are based upon the NMC Primitive Equation Model 1000-mb.-level wind calculations. The winds for the 18-hour period prior to the time of the wave forecast are considered. Our first experiments used the winds at 3-hour intervals. Therefore to make a wind-wave forecast for time T, the winds at times T, T-3, T-6, T-9, T-12, T-15, and T-18 hours are used.

For any particular forecast time wind data are obtained from:

1. The current PE output tape,

2. A wind-history tape generated from the PE output tape 12 hours earlier,

3. A wind-history tape generated from the PE output tape 24 hours earlier.

The duration of the wind is determined by comparing the wind direction at time T with that at time T-3, T-6, etc., until a wind shift of more than 22° is found. The duration is therefore determined to be 0, 3, 6, 9, 12, 15, or 18 hours.

Once the duration at a grid point is determined, an effective wind speed is calculated for that duration time. The effective wind speed is a weighted mean such that the more recent winds are weighted most heavily. Each wind included is weighted so that it contributes as much as all of the earlier winds in the calculation.

The expressions for wave height and period are:

$$H = K_1 V^2 D + K_2$$

$$T = V (K_3 + K_4 D) + K_5$$

where H is significant wave height,

T is significant wave period,

V is effective wind speed,

D is duration of wind, and

K's are constants.

These relationships are shown graphically in figures 3 and 4.

At computation points near land or ice, consideration is given to the possibility of fetch limitations. A determination is made in the upstream direction from each computation point for the existence of land or ice within approximately 1 or 2 grid lengths. If land or ice is found within 1 grid length, the wave height is reduced to 70% of its value. Land or ice between 1 and 2 grid lengths causes the wave height to be reduced to 90% of the computed value.

Wind-wave calculations are made for +00 hr., +12 hr., +24 hr., and +36 hr. from the time of the latest PE output. Variables which can be printed out include effective wind speed, significant wave height, period, and direction.

THE FNWF SWELL PROGRAM (1966 VERSION) AS ADAPTED BY THE WEATHER BUREAU

Calculations are made for ocean points of the NMC octagonal grid. The program is given a map factor at each grid point. These map factors are used to determine the map projection distance the swell travels, since this distance is a function of latitude.

The swell forecasts are based upon the +00 hour forecast of the wind-wave program. A minimum travel time of 30 hours is required before a wind wave is considered to have moved from its generation area to become a swell. Therefore, to make a swell forecast for time T, wind waves at times T-36, T-48, T-60, T-72, and T-84 hours are used.

For any particular forecast time wind-wave data and swell data are obtained from:

1. A wind-wave history tape generated from a previous run of the swell program.

2. A wind-wave tape generated from the wind-wave program.

3. A swell history tape generated from the previous run of the swell program.

Starting from the oldest field on the wind-wave history tape (T-84 hours), each wind wave having a height greater than 5 feet is considered as a potential swell. A preliminary swell travel distance is computed. Swell travel distance (d) depends on group velocity of the swell (C_g) and the travel time (t) in the following form:

$$d = C_g \times t$$

The group velocity (C_g) depends upon the period of the swell as shown here:

$$C_g = A \times T_f$$

where T_f is the period of the swell,

and A is a constant.

The expression for approximate swell travel distance therefore is:

$$d = C_1 T_F t m$$

where d is distance traveled,

T_F is the period of the swell,

t is travel time,

m is the map factor at point of generation,

and C_1 is a constant.

Once the preliminary travel distance has been computed, a search is made along the entire path of the wave. If land or ice has been specified within 0.72 grid lengths of the path of the wave, the wind wave is discarded.

Each wave train is allowed to spread 15 degrees either side of the center line of travel. A more accurate travel distance is computed for each grid point over water (affected point) within a 30 degree spread about the center line of swell propagation. The expression for computing this distance is the same as the expression for approximate swell travel distance, except m is replaced by $\overline{m}$, where $\overline{m}$ is an average map factor over the area traveled. The affected point is then tested against a distance requirement. This requirement is that the affected point lie within the range of travel distance of the swell for the particular forecast period. If this requirement is satisfied, swell period and height are computed for the affected point by the following expressions:

$$T_D = (T_F^{\,2} + C_2 t)^{\frac{1}{2}}$$

$$H_D = H_F \left(T_D / T_F \right)^{C_3}$$

where T_D is the period of the swell,

T_F is the period of the wind wave,

t is travel time from generating point to affected point,

H_D is the swell height,

H_F is the initial wind-wave height,

and C2 and C3 are constants.

Since any grid point can be hit by many swells, only the greatest swell height is retained at the affected point.

An overall wave condition, a combined-height field, is constructed as the square root of the sum of the squares of the wind-wave and swell heights.

Swell calculations are made for +00, +12, +24, and +36 hours. Variables which can be printed out include combined wave height, swell height, period, and direction.

TEST PERIOD (MAY 5 - 10, 1967)

Ten sets of wind-wave forecasts were made at twelve-hour intervals beginning at 12Z on May 10, 1967. These forecasts were based upon the 1000-mb. level U-wind components and V-wind components from the NMC Primitive Equation Model. Forecasts were made for +0, +12, +24, and +36 hours after the times of PE model output.

These forecasts were compared to the observations made at the Ocean Station Vessels (OSV). The observations were from ships A, B, C, D, E, I, J, K, and M in the North Atlantic and N, P, and V in the North Pacific. Forecasts for the OSV locations were estimated from the forecasts at nearby grid points. Some OSV forecasts were determined from the height forecasts at one grid point. Others were determined from two or four grid points. Figures 5 and 6 show the grid points at which wave-height forecasts were averaged to determine forecasts for OSV locations. The statistics on these forecasts as compared to the OSV observations are shown in table 2. The mean of the forecast heights is slightly higher than the mean of the observations for each of the forecast periods, +0, +12, +24, and +36 hours. Comparison of the root-mean-square errors (RMSE) between this set of forecasts and those of the 1966 test case - NMC and FNWF forecasts - is shown in figure 7. Unfortunately, these two tests were made during different years. At least they were made about the same time of year. (May - June 1966 and May 1967). It was not practical to repeat the methods tested in 1966 in May of 1967. The curves of RMSE indicate the FNWF method to be slightly better than the TDL method for twelve hour forecasts and the TDL forecasts to be slightly superior for thirty six hour forecasts.

Considering the subjectivity of the wave observations used for this verification and the different time periods of the calculation, the only conclusion that can be reached at this point is that the FNWF and the TDL methods have about the same accuracy for the mid-latitudes where the Ocean Station Vessels are located.

Further evaluation of the TDL test forecasts was made by superimposing on surface synoptic charts the areas of high waves. These charts are filed in TDL. In the temperate zone the areas of high waves are oriented as expected in relation to the location of extratropical storms. At low latitudes the forecast wave heights were much too high. These high wave forecasts resulted from the high wind forecasts by the PE model during the test period.

Since few ships report swell conditions, it is not practical to compare the forecast swell with the observed swell. However, swell height contours and directions were plotted on weather maps for a comparison with the wind waves and weather conditions at the time the swells were generated. In all cases the comparisons were favorable.

FEASIBILITY OF USING SIX-HOUR WIND INPUT

Because the regular NMC output of the PE Model is for six-hour intervals, it would be more practical and economical to base wave forecasts upon wind forecasts made for six-hour intervals.

The wind-wave program was modified to accept six-hour winds instead of three-hour winds. In the wave computations this change results in a more crude approximation of the duration time. Duration times are determined to be 0, 6, 12 or 18 hours.

The ten sets of forecasts for May 5 - 10 were repeated using six-hour wind input. Very little difference resulted in the wave forecasts. Statistics on these forecasts are shown in table 3. A scatter diagram of the +36-hour wave-height forecasts for the OSV locations based on six-hour winds compared to those based on three-hour winds is shown in figure 8. The decision reached from the comparison of the forecasts made with three-hour winds and with six-hour winds is that we can base our wave forecasts upon winds at six-hour intervals.

FUTURE PLANS

The next step is to make a series of forecasts during the winter months. These forecasts will be the basis upon which to make slight adjustments in the empirical constants in the wave forecasts relationships. It is expected that these adjustments will tune the system for operational use with the PE model wind input at six-hour intervals.

ACKNOWLEDGMENTS

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3. Hubert, W. E., "Operational Forecasts of Sea and Swell," 1st U. S. Navy Symposium on Military Oceanography, U. S. Naval Oceanographic Office, Washington, D. C., June 1964, pp. 113 - 124.

4. Pierson, W. J., G. Neumann, and R. W. James, Practical Methods for Observing and Forecasting Ocean Waves by Means of Wave Spectra and Statistics, U. S. Navy Hydrographic Office, Publication No. 603, 1955.

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6. U. S. Navy, U. S. Naval Weather Service Computer Products Manual, Published by Direction of the Chief of Naval Operations, NAVAIR 50-16-522, March 1967.

TABLE 1. STATISTICS ON THE FORECAST AND OBSERVED WAVE HEIGHTS FOR TESTS MADE DURING MAY AND JUNE 1966

		+ 00 Hours		
NMC Forecasts to Observed Heights		r = 0.62		
		Mean	Stand. Dev.	RMSE
(150 sets)	NMC Forecasts	3.0 ft.	2.2 ft.	3.9 ft.
	Observed Heights	5.4 ft.	3.9 ft.	
		+ 12 Hours		
NMC Forecasts to Observed Heights		r = 0.47		
FNWF Forecasts to Observed Heights		r = 0.60		
Persistence Forecasts to Observed Hgts.		r = 0.64		
		Mean	Stand. Dev.	RMSE
(138 sets)	NMC Forecasts	2.9 ft.	2.0 ft.	4.7 ft.
	Observed Heights	5.9 ft.	4.1 ft.	
(101 sets)	FNWF Forecasts	6.5 ft.	3.1 ft.	3.6 ft.
	Observed Heights	6.3 ft.	4.5 ft.	
(118 sets)	Persistence Forecasts	5.5 ft.	3.8 ft.	3.5 ft.
	Observed Heights	6.0 ft.	4.3 ft.	
		+ 24 Hours		
NMC Forecasts to Observed Heights		r = 0.41		
Persistence Forecasts to Observed Hgts.		r = 0.37		
		Mean	Stand. Dev.	RMSE
(153 sets)	NMC Forecasts	3.0 ft.	2.1 ft.	4.4 ft.
	Observed Heights	5.7 ft.	3.7 ft.	
(121 sets)	Persistence Forecasts	5.5 ft.	4.0 ft.	4.3 ft.
	Observed Heights	5.7 ft.	3.7 ft.	
		+ 36 Hours		
NMC Forecasts to Observed Heights		r = 0.32		
FNWF Forecasts to Observed Heights		r = 0.49		
Persistence Forecasts to Observed Hgts.		r = 0.19		
		Mean	Stand. Dev.	RMSE
(154 sets)	NMC Forecasts	2.9 ft.	2.1 ft.	4.5 ft.
	Observed Heights	5.4 ft.	3.9 ft.	
(113 sets)	FNWF Forecasts	4.9 ft.	3.2 ft.	4.0 ft.
	Observed Heights	5.6 ft.	4.3 ft.	
(117 sets)	Persistence Forecasts	5.4 ft.	3.9 ft.	4.7 ft.
	Observed Heights	5.1 ft.	3.5 ft.	

TABLE 2. STATISTICS ON FORECAST AND OBSERVED WAVE HEIGHTS USING TDL METHOD WITH THREE HOUR WINDS FOR THE TEST PERIOD OF MAY 5 - 10, 1967

+ 00 Hours

	Mean	Stand. Dev.	RMSE	r
Forecast	4.9 ft	3.6 ft	3.3 ft	0.51
Observed	4.4	3.0	(104 sets)	

+ 12 Hours

	Mean	Stand. Dev.	RMSE	r
Forecast	6.0	4.3	4.2	0.47
Observed	4.4	3.0	(107 sets)	

+ 24 Hours

	Mean	Stand. Dev.	RMSE	r
Forecast	5.5	3.6	3.5	0.50
Observed	4.4	3.0	(108 sets)	

+ 36 Hours

	Mean	Stand. Dev.	RMSE	r
Forecast	4.9	3.2	3.4	0.44
Observed	4.4	3.1	(110 sets)	

TABLE 3. STATISTICS ON FORECAST AND OBSERVED WAVE HEIGHTS USING TDL METHOD WITH SIX HOUR WINDS FOR THE TEST PERIOD OF MAY 5 - 10, 1967

+ 00 Hours

	Mean	Stand. Dev.	RMSE	r
Forecast	5.9 ft	4.0 ft	3.8 ft	0.53
Observed	4.4	3.0	(104 sets)	

+ 12 Hours

	Mean	Stand. Dev.	RMSE	r
Forecast	6.3	4.1	4.2	0.49
Observed	4.4	3.0	(107 sets)	

+ 24 Hours

	Mean	Stand. Dev.	RMSE	r
Forecast	5.8	3.8	3.8	0.49
Observed	4.4	3.0	(108 sets)	

+ 36 Hours

	Mean	Stand. Dev.	RMSE	r
Forecast	5.1	3.4	3.5	0.43
Observed	4.4	3.1	(110 sets)	

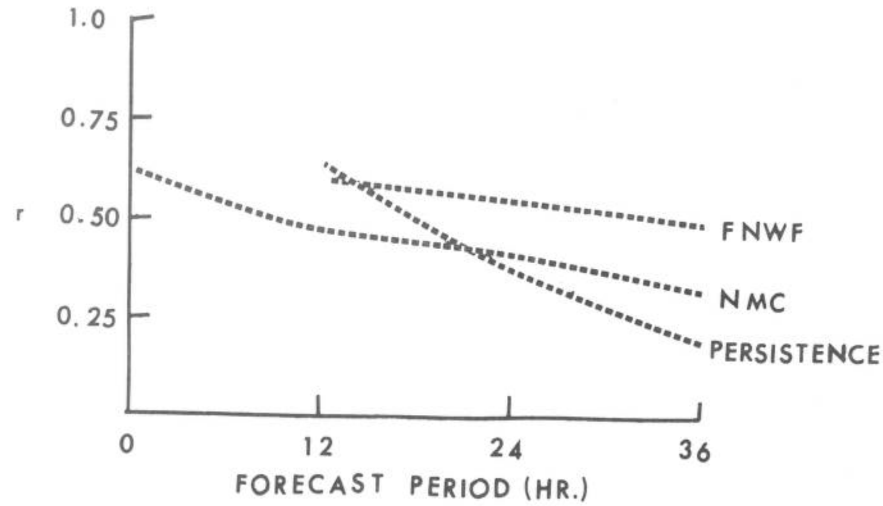

Figure 1A. Correlation coefficients of forecast wave height to observed wave height versus forecast period for the calculations for May and June 1966.

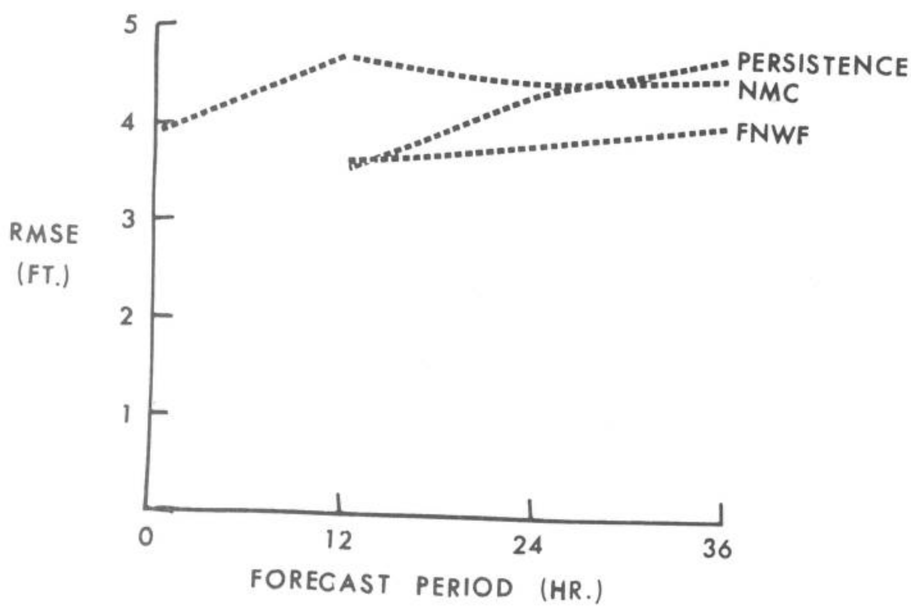

Figure 1B. Root mean square error of wave height forecasts versus forecast period for the calculations for May and June 1966.

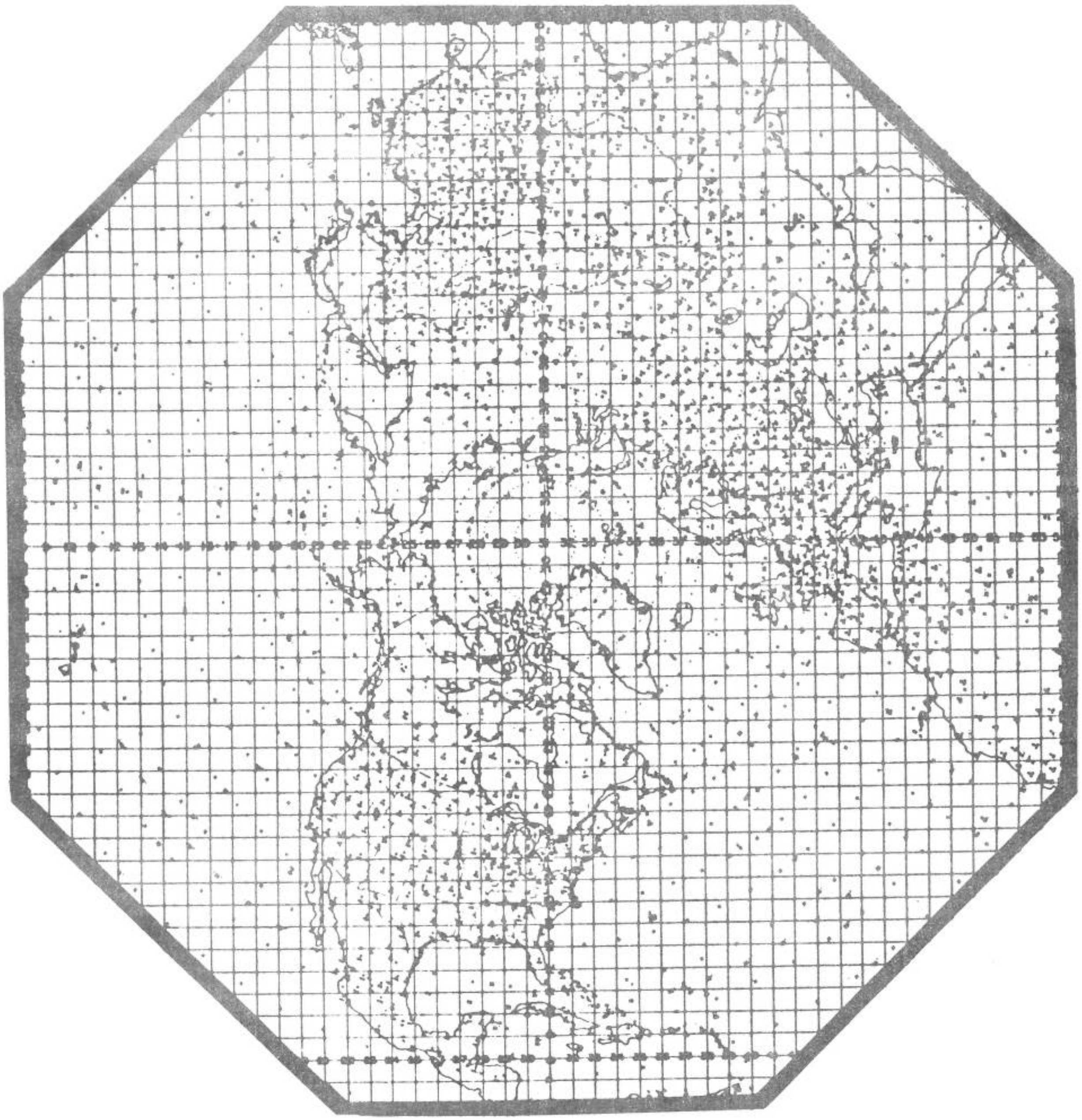

Figure 2. National Meteorological Center 1977 point grid used for computation.

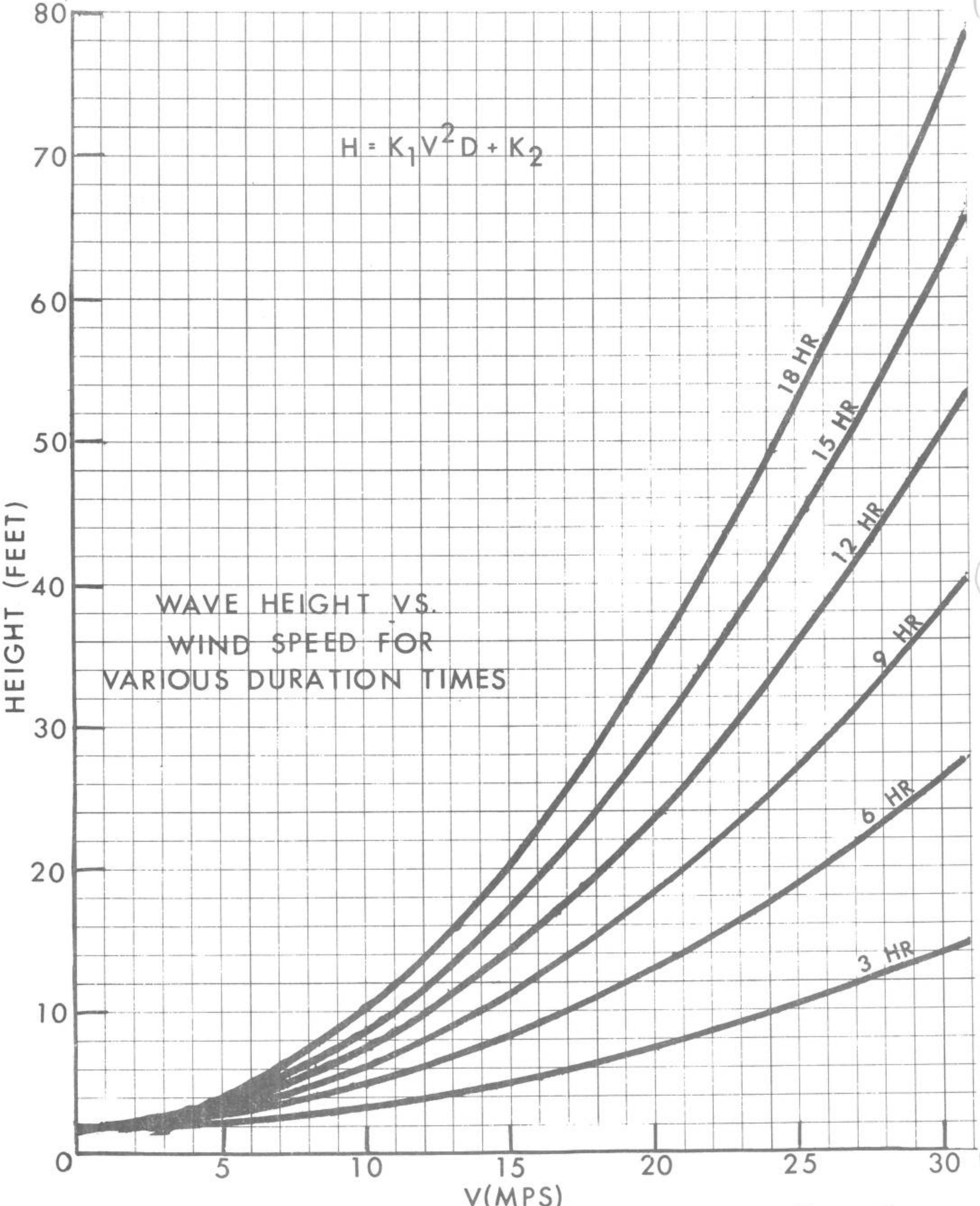
H = K1V2D + K2
WAVE HEIGHT VS. WIND SPEED FOR VARIOUS DURATION TIMES
HEIGHT (FEET)
V(MPS)
18 HR
15 HR
12 HR
9 HR
6 HR
3 HR
0
5
10
15
20
25
30
40
50
60
70
80

Figure 3.

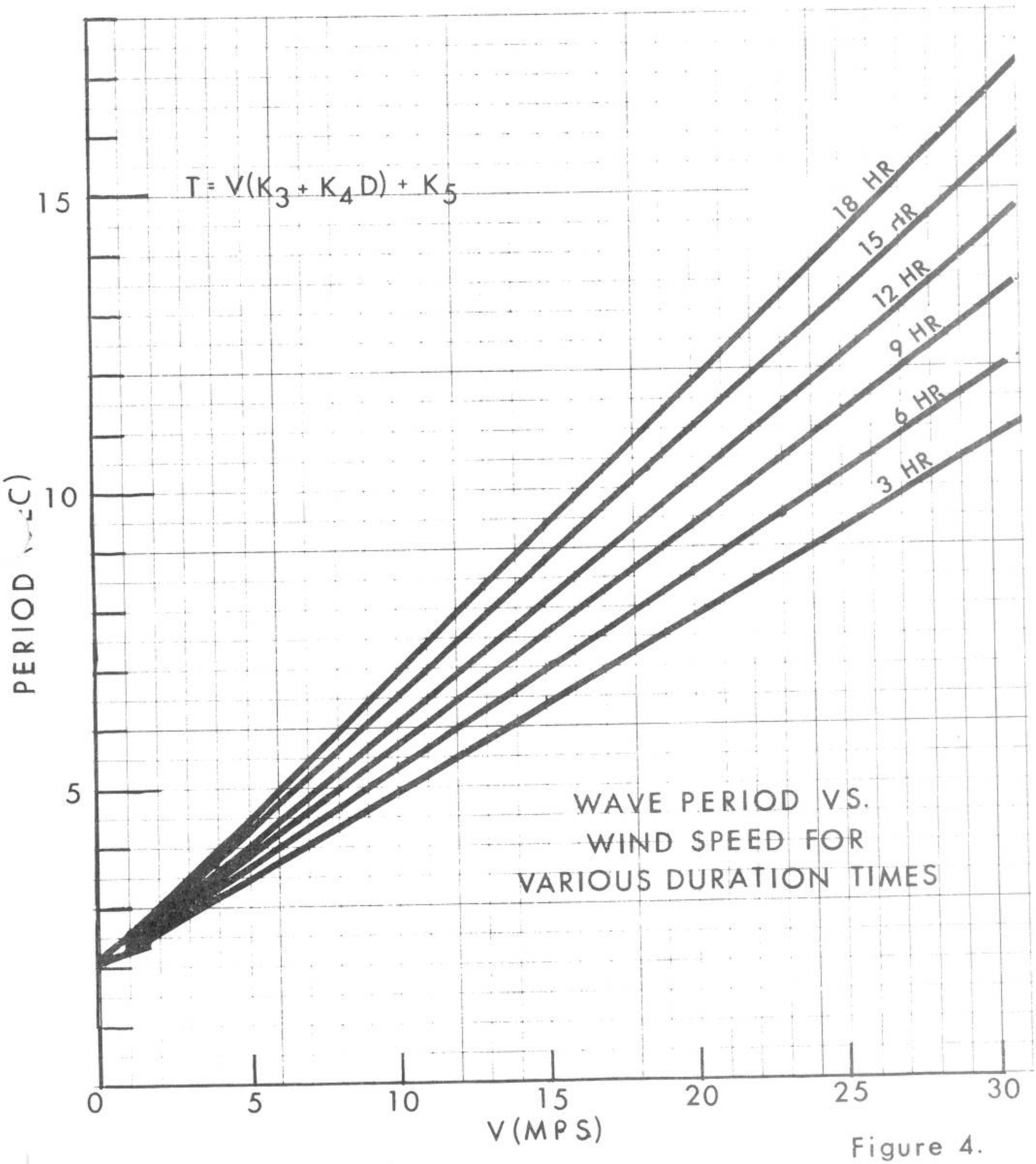
T = V(K3 + K4D) + K5
18 HR
15 HR
12 HR
9 HR
6 HR
3 HR
WAVE PERIOD VS.
WIND SPEED FOR
VARIOUS DURATION TIMES
15
10
5
0
5
10
15
20
25
30
V(MPS)

Figure 4.

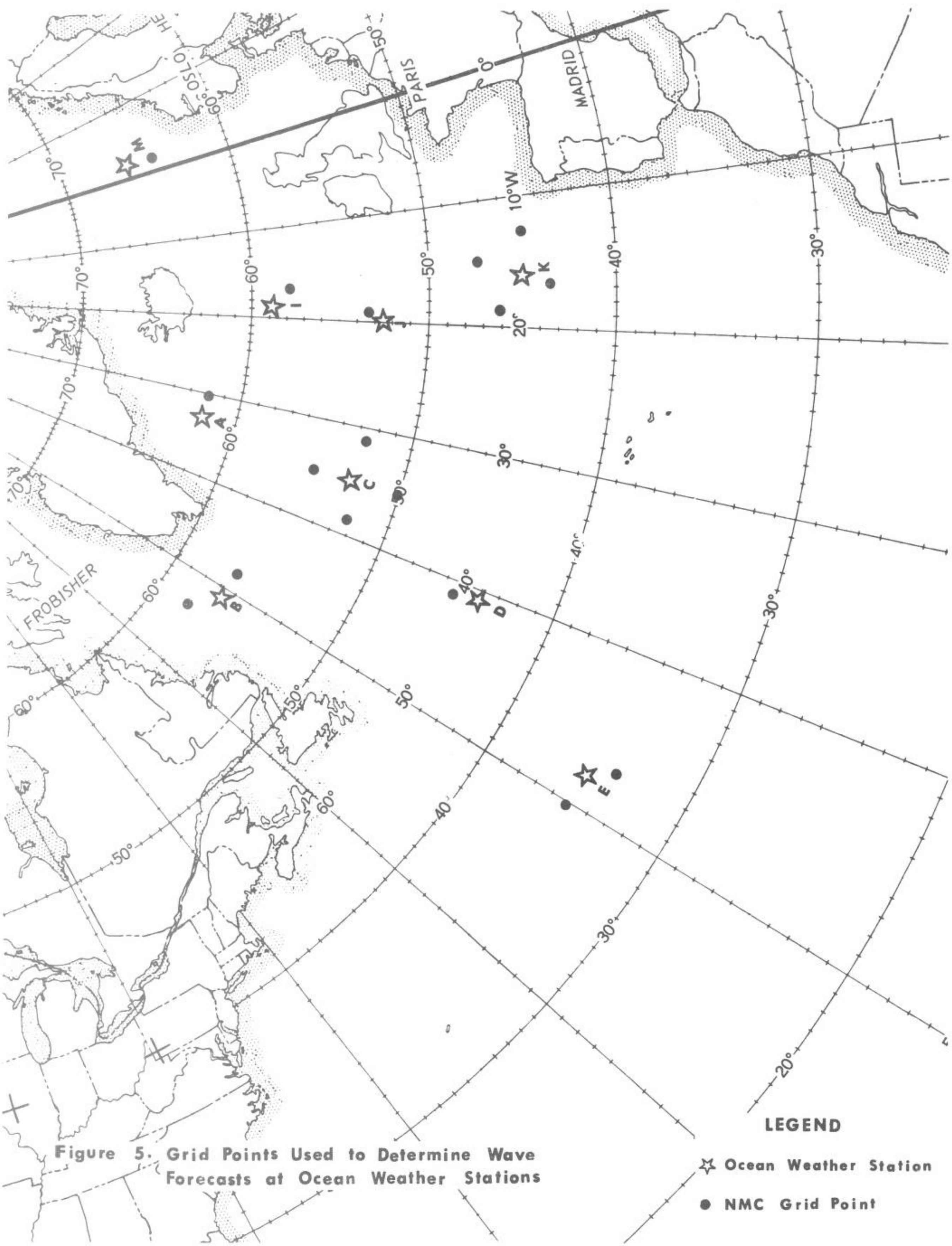

Figure 5. Grid Points Used to Determine Wave Forecasts at Ocean Weather Stations

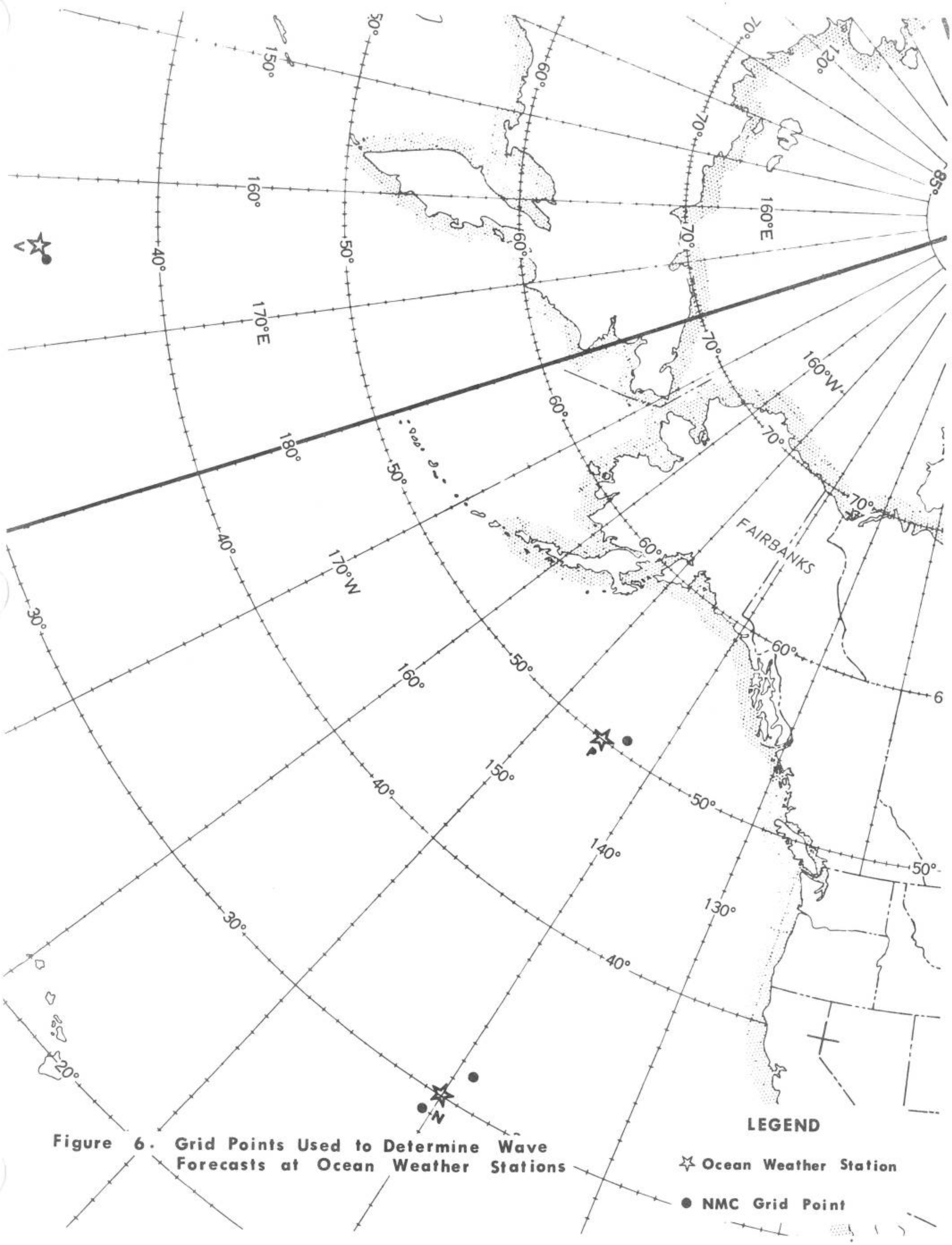

Figure 6. Grid Points Used to Determine Wave Forecasts at Ocean Weather Stations

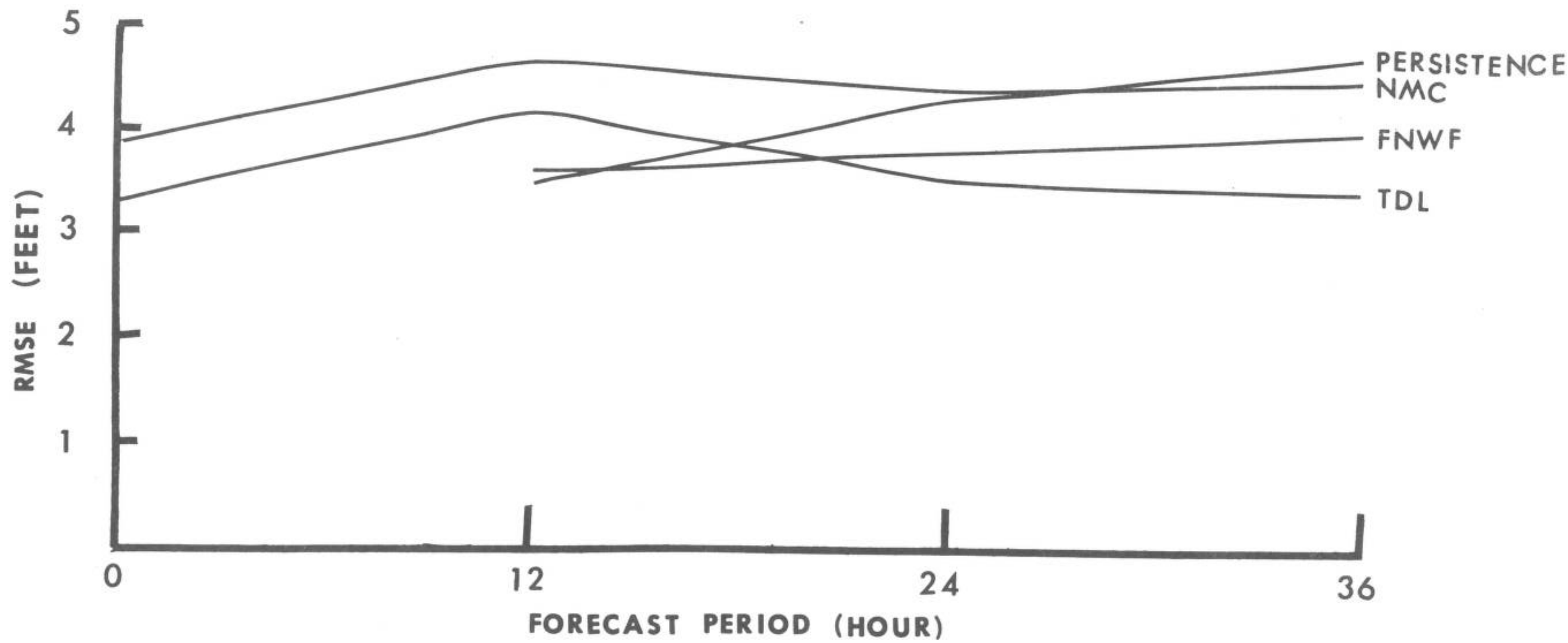

Figure 7. Root mean square error of wave height forecasts by various methods.

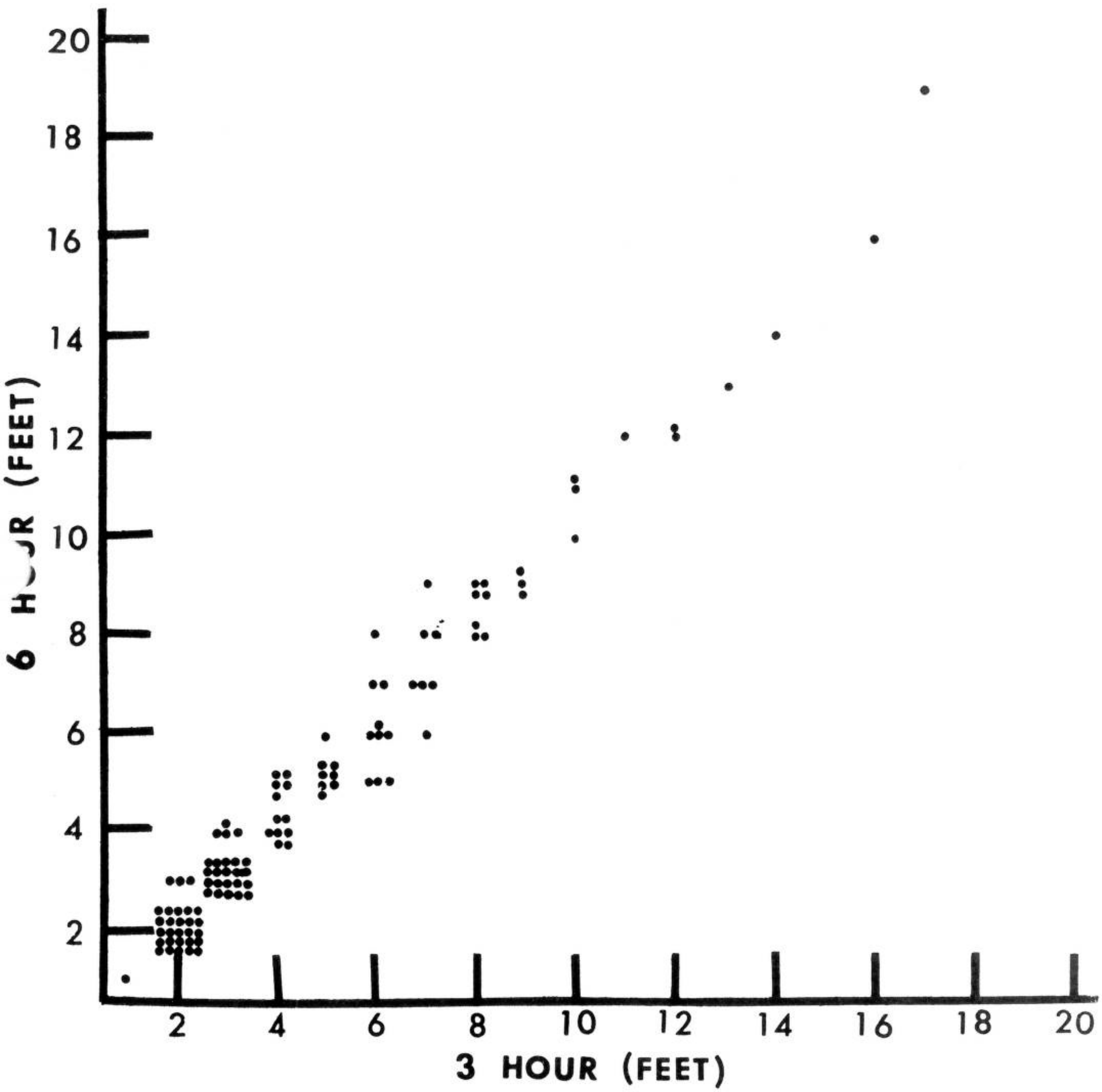

Figure 8. 36 hour forecasts of wave heights with 3 hour winds versus wave heights with 6 hour winds.

No. 8 An Experiment in the Use of the Balance Equation in the Tropics. M. A. Alaka, D. T. Rubsam, and G. E. Fisher. March 1967.

No. 9 A Survey of Studies of Aerological Network Requirements. M. A. Alaka. May 1967.

No. 10 Objective Determination of Sea Level Pressure from Upper Level Heights. W. H. Klein, F. Lewis, and J. D. Stackpole. May 1967.

No. 11 Short Range, Subsynoptic Surface Weather Prediction. H. R. Glahn, and D. A. Lowry. July 1967.

No. 12 Charts Giving Station Precipitation in the Plateau States from 700-Mb. Lows During Winter. D. L. Jorgensen, A. F. Korte, and J. A. Bunce, Jr. October 1967.