Subject:

Ocean Surface Waves

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OCEAN SURFACE WAVES[1]

by H. S. Chen

1. INTRODUCTION

Since it was implemented on October 12, 1994, the NOAA version of the Wave Model (WAM) (hereafter referred to as the NOAA/WAM) replaced the NOAA Ocean Wave (NOW) model which was developed from Greenwood et al (1985) as the National Meteorological Center (NMC) global wave model.

During the last five decades, wind wave forecasts have improved significantly from the empirical approaches based on Sverdrup and Munk (1947) and Bretschneider (1958) to the spectral approaches based on the radiative transport equation (*e.g.* SWAMP Group 1985). At present, the most advanced spectral model for research and forecast is the so-called third generation[2] wave model of which the WAM is an example (WAMDI Group 1988). The Ocean Products Center (OPC) has continuously made systematic efforts to test and develop models based on prediction accuracy, computational efficiency and sound wave dynamics, and to employ them to produce operational forecasts. The NOAA/WAM is a third generation spectral wave model. In contrast the NOW model is a second generation[3] spectral wave model.

This TPB describes the NOAA/WAM briefly and the wave guidance products which are being disseminated. This guidance consists of significant wave height, H_s, which combines sea and swell; mean wave direction; mean wave period; and directional wave spectra at selected grid points. Guidance is available in both graphic and alphanumeric form. The reader is referred to *World Meteorological Organization (WMO) Report No.702* (1988) for wave definitions, measurements and modeling.

The bulletins and graphics of the new guidance follow the same formats shown in TPB No. 388 (Esteva and Kidwell 1990), except for the following differences:

(1) The new wave frequency (period) values and their corresponding bandwidth are different from those in TPB No. 388. The number of new wave frequencies is 25 (compared with 15 for the NOW model).

(2) In the new guidance, the mean wave direction and mean wave period are used. This is because these parameters are more stable and are closer to what an observer reports than those previously used.

(3) There are fewer alphanumeric bulletins on the 1200 UTC cycle than the 0000 UTC cycle because of limitations on AFOS and agreements reached between the NWS Eastern and Western Regional and the NWS National Headquarters.

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[1]OPC Contribution No. 92

[2]A third generation wave model uses the most updated wave dynamics in wave generation, wave dissipation, and nonlinear energy transfer with no limitation on wave growth.

[3]A second generation wave model uses dynamics in wave generation, but the nonlinear energy transfer mechanism is over-simplified, and the wave growth is artificially limited by the Joint North Sea Wave Project (JONSWAP) spectrum.

2. NOAA OCEAN WAVE FORECAST MODEL (NOAA/WAM)

Global ocean wave forecasts are operationally generated at the NMC by using the NOAA/WAM model. Fields of directional frequency spectra in 12 directions and 25 frequencies are generated in 3-h intervals up to 72 hours. The 12 directions begin at zero degrees to the north and have a directional resolution of 30 degrees. Note that there were 24 directions used in the NOW model. The 25 frequencies begin at the lowest frequency of 0.04177 Hz and have each frequency followed by a logarithmic increment of 0.1 times the frequency; *i.e.*, if f_1 = 0.04177 Hz and f_n is the nth frequency, then $f_{n+1} = 1.1f_n$ where n = 1, 2, 3, ..., 24. Explicitly, they are 0.04177 Hz (23.94 s), 0.04595 Hz (21.75 s), 0.05054 Hz (19.78 s), ..., 0.41145 Hz (2.43 s). Table 1 shows the periods associated with these frequencies as the logarithmic center of a bandwidth of frequencies.

Wave spectral data are available on a 2.5- by 2.5-degree latitude/longitude grid for deep water ocean points between latitude 67.5 degrees South to 77.5 degrees North. At present, the lowest sigma layer winds from the NMC analysis and aviation version of the global forecast system (AVN) (Kanamitsu *et al.* 1991) are adjusted to a height of 10 m by using a logarithmic profile and are used to drive the ocean surface waves. Analyzed wind fields from the previous 12 hours at 3-h intervals are used for a 12-h wave hindcast. Winds from the AVN at 3-h intervals out to 72 hours are used for the 72-h wave forecasts which are produced twice daily for the 0000 and 1200 UTC cycles.

Significant wave height statistics for the NOAA/WAM model are better than those of the NOW model. Figure 1 shows their bias and root-mean-squared error (RMSE) for the 24-, 48-, and 72-h forecast based on wave measurements from National Data Buoy Center (NDBC) fixed buoys. Additional comparisons in Chen (1991 and 1993) also show similar results. A technique for buoy and European Research Satellite number 1 (ERS1) altimeter data assimilation was implemented for the NOW model in the fall of 1993. Even with the improvements due to the incorporation of these assimilated data, the bias and RMSE scores indicate the NOAA/WAM forecasts are more skillful than those of the NOW model. Data assimilation has not been introduced to improve the NOAA/WAM model forecast yet, but it will be eventually.

Table 1. The logarithmic center periods and their corresponding band widths for the frequencies used in the WAM model.

Center Period (sec)	Band Width (Hz)
23.94	0.0021
21.75	0.0044
19.78	0.0048
17.99	0.0053
16.35	0.0058
14..86	0.0064
13.51	0.0071
12.28	0.0078
11.17	0.0085
10.15	0.0094
9.23	0.0103
8.39	0.0114
7.83	0.0125
6.93	0.0138
6.30	0.0151
5.73	0.0166
5.21	0.0183
4.74	0.0201
4.30	0.0222
3.91	0.0244
3.56	0.0268
3.23	0.0295
2.94	0.0324
2.67	0.0357
2.43	0.0187

3. AVAILABLE PRODUCTS AND DISSEMINATION

The ocean surface waves are calculated for grid points covering the whole globe, excluding land, the North and South poles area, and inland water bodies, such as Great Lakes, Chesapeake Bay, Mediterranean Sea, *etc.* The calculated waves are disseminated graphically via AFOS and facsimile for selected areas, and in alphanumeric format via AFOS for selected grid points.

a. AFOS Graphics

Gridded charts of H_s, mean wave direction[4], and mean wave period[5] are disseminated on AFOS and on the AFOS Graphics Service of the FOS. The data are displayed on a Northern Hemisphere map background (AFOS map background B01). The charts extend from 10 degrees to 70 degrees North latitude and 20 degrees to 180 degrees West longitude for H_s and mean wave direction. Mean wave periods are transmitted only for the Pacific portion of these latitudes and longitudes.

To avoid crowding and to reduce the size of the graphic products, information is plotted at every other model grid point. Numeric values of H_s (to the nearest foot) and mean wave period (to the nearest second) are given, and arrows show the wave direction. The size of the characters and length of the arrows are somewhat reduced above 50 degrees North latitude.

The H_s is a measure of the combined sea and swell wave height. It is a statistical quantity defined as the average of the one-third highest waves in a given wave record. Since the human eye biases toward the higher waves in a confused sea, visual estimates correspond to an approximation of this definition. It has been shown that the H_s is related to the sum of the frequency-directional components in a wave energy spectrum (Neumann and Pierson 1966).

The direction reported is the mean wave direction averaged over the all spectral wave components. In the absence of a wind sea at a location due to very light local winds, the arrow will indicate the direction of the mean swell. The period reported is the mean wave period averaged over the all spectral wave components. Period is the reciprocal of the frequency. Charts are produced for the 12-, 24-, 48-, and 72-h wave forecasts for 0000 and 1200 UTC. Table 2 shows the product identifiers and titles of the AFOS graphics. Figures 2, 3, and 4 show examples.

b. Alphanumeric Spectral Message

Directional spectral bulletins are transmitted for 10 selected grid points, four locations in the Atlantic and six in Pacific (refer to Table 3) and have a total of 60 alphanumeric messages at 0000 UTC and 26 alphanumeric messages at 1200 UTC. At 0000 UTC, bulletins FZPZ41 KWBC (AFOS PIL NMCOSWSP1) and FZPZ42 KWBC (AFOS PIL NMCOSWSP2) containing directional spectra for Pacific locations (47.5°N, 125.0°W) and (45.0°N, 125.0°W) respectively provide forecasts at 6-h intervals from 0 to 48 hours plus the 60-h projection. Bulletins of wave directional spectra at the other locations provide forecasts every 12 hours from 12 to 60 hours. At 1200 UTC, bulletins for the two Pacific locations provide forecasts at 6-h intervals from 0 to 24 hours. Bulletins at the other locations provide forecasts at 12 and 24 hours.

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[4]The mean wave direction is given by $\bar{\theta} = \arctan(b/a)$; $= E^{-1}\iint \cos\theta F(\omega,\theta)\,d\omega d\theta$; $b = E^{-1}\iint \sin\theta F(\omega,\theta)\,d\omega d\theta$, *where* E is the total energy; F is the spectral density; ω is the frequency, and θ is the direction.

[5]The mean wave period is given by $\bar{\tau} = 2\pi / \bar{\omega}$, *wher* is the mean frequency.

Currently, the alphanumeric bulletins are sized to use a maximum of 15 frequencies. To reduce the number of frequencies from 25 to 15, the two highest and lowest frequencies were not used and other frequencies were combined to give the frequencies found in Table 4. When approved by the AFOS Data Review Group after consultation with the Eastern, Southern, and Western Regions of the NWS, the bulletins will be expanded to include all 25 frequencies forecast by the NOAA/WAM.

The format of the alphanumeric spectral bulletin gives the variance in each of the frequency/period bands and directional bands in the body of the message . The variance values are in meters squared x 1000. An example of a spectral bulletin generated from the NOAA/WAM is depicted in Fig. 5.

The first line of the message header below the WMO header line gives the model run date/time (YYMMDDHH), the latitude and longitude of the model grid point, the model cycle time (0000 or 1200 UTC), the model run date, and the projection (TAU).

Row and column headings are shown on the far left and top, respectively, of Fig. 5. Rows or columns with all zero values are omitted (again to reduce the volume of the transmission). The row headings are the (logarithmic) center period of the band in seconds. The column headings are the center direction of the directional band. Frequency spectral densities can be obtained by dividing the variances by the corresponding band width (in Hz) in Table 4.

Table 2. Product identifiers (PILs) and descriptions of AFOS graphic wave products.

AFOS PIL	Product Description
	Significant Wave Height
NMCGPH0O1	12H AVN Significant Wave Height
NMCGPH0P1	24H AVN Significant Wave Height
NMCGPH0R1	48H AVN Significant Wave Height
NMCGPH0T1	72H AVN Significant Wave Height
	Mean Wave Direction
NMCGPH0O2	12H AVN Mean Wave Direction
NMCGPH0P2	24H AVN Mean Wave Direction
NMCGPH0R2	48H AVN Mean Wave Direction
NMCGPH0T2	72H AVN Mean Wave Direction
	Mean Wave Period
NMCGPH0O3	12H AVN Mean Wave Period
NMCGPH0P3	24H AVN Mean Wave Period
NMCGPH0R3	48H AVN Mean Wave Period
NMCGPH0T3	72H AVN Mean Wave Period

c. Facsimile graphics

Two Mercator charts containing wave information are distributed over the facsimile circuits. One chart displays gridded wind barbs and values of H_s in feet; the second chart displays arrows showing the mean wave direction and the mean wave period in seconds. The charts cover different geographical areas and are disseminated over the corresponding circuits as shown in Table 5.

Charts for 12, 24, 48, and 72 hours are transmitted for 0000 and 1200 UTC. Two panel charts (12/24 hours and 48/72 hours) are displayed per facsimile slot except for the Honolulu circuit, which displays a single panel chart per slot.

Examples of these charts are given in Figs. 6 through 11. As in the AFOS charts, the mean wave directions and mean periods are shown in the figures. When there is no wind sea, the mean direction and mean period of the swell are shown

Table 3. Geographical area, AFOS product identifiers (PILs) and descriptions, WMO headers, latitude (° N) and longitude (° W) for which alphanumeric spectral bulletins are transmitted.

AFOS PIL	Description	WMO Header	Lat (° N)	Lon (° W)
	WSFO Washington, D.C.[1]			
NMCOSWSA1	Spectral Wave Energy, Atlantic Ocean, 35.0N - 72.5W	FZNT41 KWBC	35.0	72.5
NMCOSWSA2	Spectral Wave Energy, Atlantic Ocean, 37.5N - 70.0W	FZNT42 KWBC	37.5	70.0
NMCOSWSA3	Spectral Wave Energy, Atlantic Ocean, 40.0N - 67.5W	FZNT43 KWBC	40.0	67.5
	WSFO Miami, Fl.[1]			
NMCOSWSA5	Spectral Wave Energy, Atlantic Ocean, 25.0N - 85.0W	FZNT45 KWBC	25.0	85.0
	WSFO San Francisco, Calif.[2]			
NMCOSWSP1	Spectral Wave Energy, Pacific Ocean, 47.5N - 125.0W	FZPZ41 KWBC	47.5	125.0
NMCOSWSP2	Spectral Wave Energy, Pacific Ocean, 45.0N - 125.0W	FZPZ42 KWBC	45.0	125.0
NMCOSWSP3	Spectral Wave Energy, Pacific Ocean, 42.5N - 130.0W	FZPZ43 KWBC	42.5	130.0
NMCOSWSP4	Spectral Wave Energy, Pacific Ocean, 35.0N - 122.5W	FZPZ44 KWBC	35.0	122.5
NMCOSWSP5	Spectral Wave Energy, Pacific Ocean, 32.5N - 120.0W	FZPZ45 KWBC	32.5	120.0
NMCOSWSP6	Spectral Wave Energy, Pacific Ocean, 27.5N - 122.5W	FZPZ46 KWBC	27.5	122.5

[1]Spectral Wave Bulletins transmitted over the Domestic Data Service of FOS and the eastern and southern loops of the AFOS network.
[2]Spectral Wave Bulletins transmitted over the Domestic Data Service of FOS, the southern and western loops of the AFOS network, and to the USAF via Offutt AFB and Tinker AFB.

4. EVALUATION

An evaluation of the NOAA/WAM and the NOW model was carried out from October 1992 through January of 1994. The results are shown in Fig. 1, already introduced in Section 2. The results show the NOAA/WAM to be as good as or better than the NOW model at 24 hours and better than the NOW at 48 and 72 hours. Comments from the high seas forecasters at NMC/NCEP indicate the overall wave patterns are more realistic as well.

5. REFERENCES

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Table 4. The logarithmic center periods and their corresponding band widths for the frequencies used in the alphanumeric AFOS bulletins.

Center Period (sec)	Band Width (Hz)
18.84	0.0101
16.35	0.0058
14.86	0.0064
13.51	0.0071
12.28	0.0078
11.17	0.0085
10.15	0.0094
9.23	0.0103
8.39	0.0114
7.63	0.0125
6.60	0.0289
5.46	0.0349
4.51	0.0423
3.55	0.0807
2.94	0.0324

Table 5. Geographical coverage, circuits, and slots of charts disseminated on facsimile (FAX).

Geographical Coverage	Facsimile Circuit	Facsimile Slots (dir/per)	Facsimile Slots (Wind/H_s)
50.0N- 2.5S/ 10.0W-110.0W	San Juan FAX	J191 & J192	J086 & J087
57.5N-10.0N/ 60.0W-180.0W	DIFAX	D106 & D107	D104 & D105
62.5N-35.0S/112.5W-130.0E	Honolulu FAX	H113, H114, H115 & H116	H165, H166, H167 & H168
60.0N-17.5N/105.0W-155.5E	Alaska FAX	A058 & A059	A121 & A122

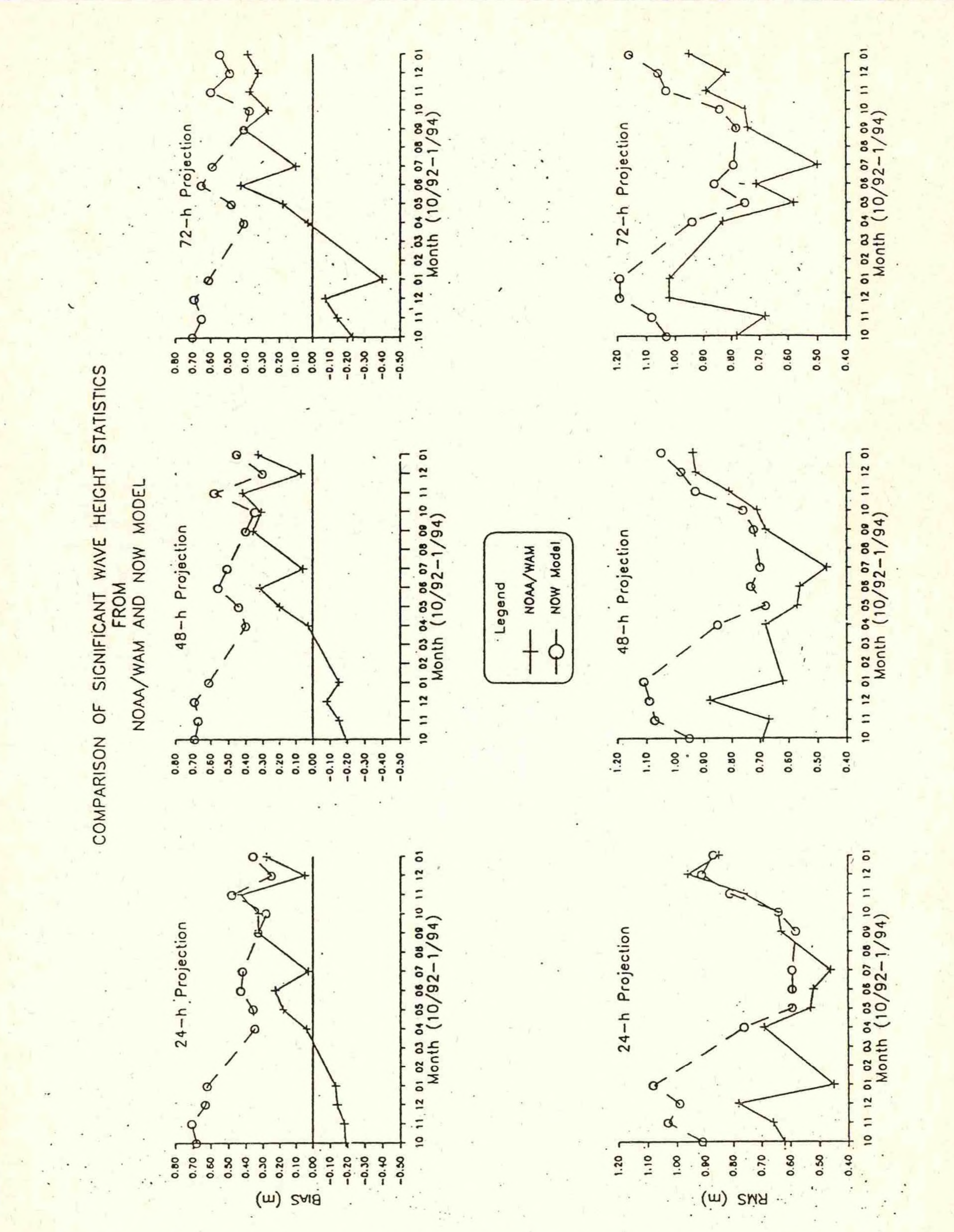

Figure 1. Bias and root mean squared error of NOAA/WAM and NOW models computed with respect to NDBC buoy observations.

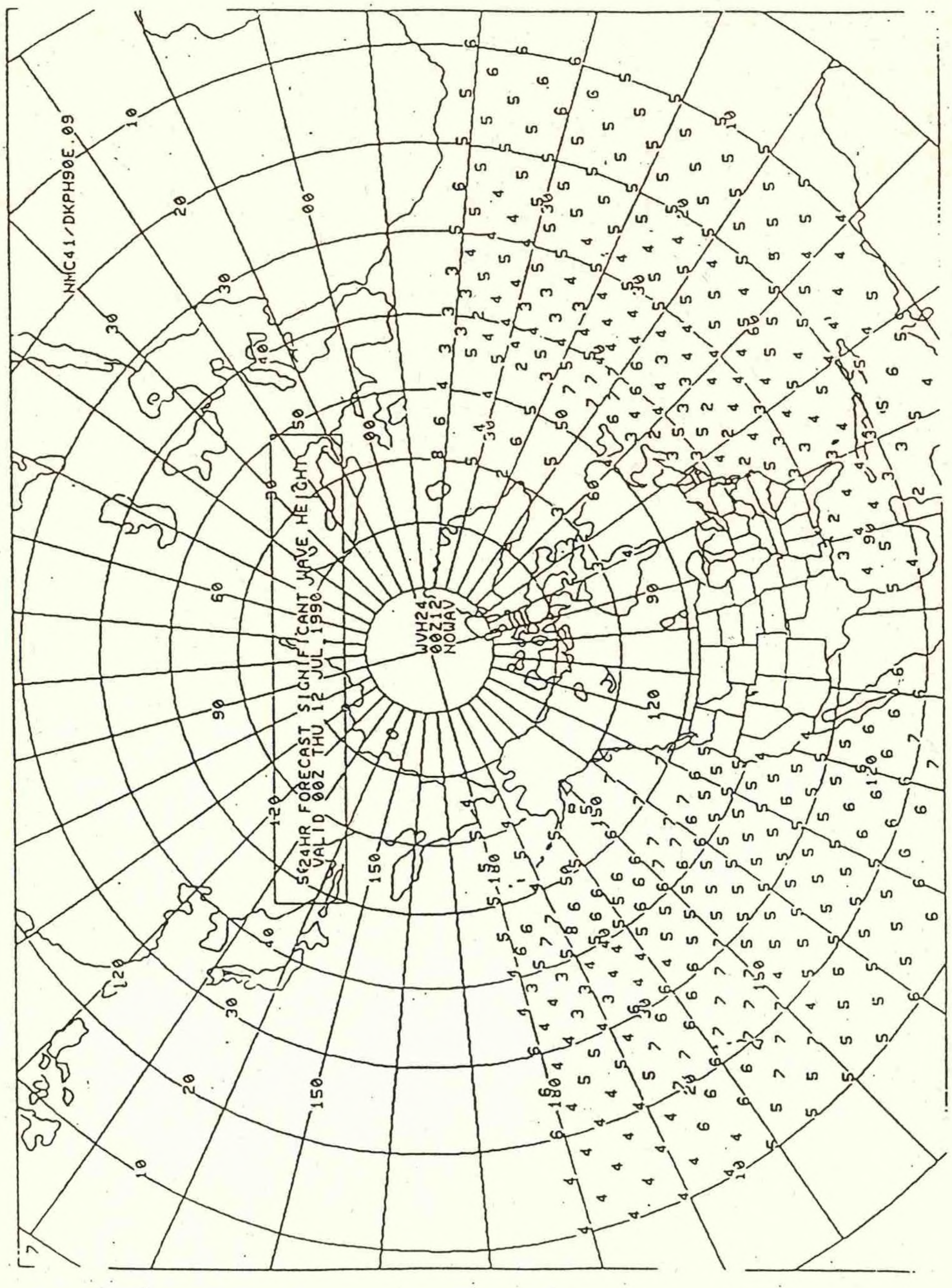

Figure 2. Sample AFOS graphic of WAM gridded values of significant wave height (H_s) in feet.

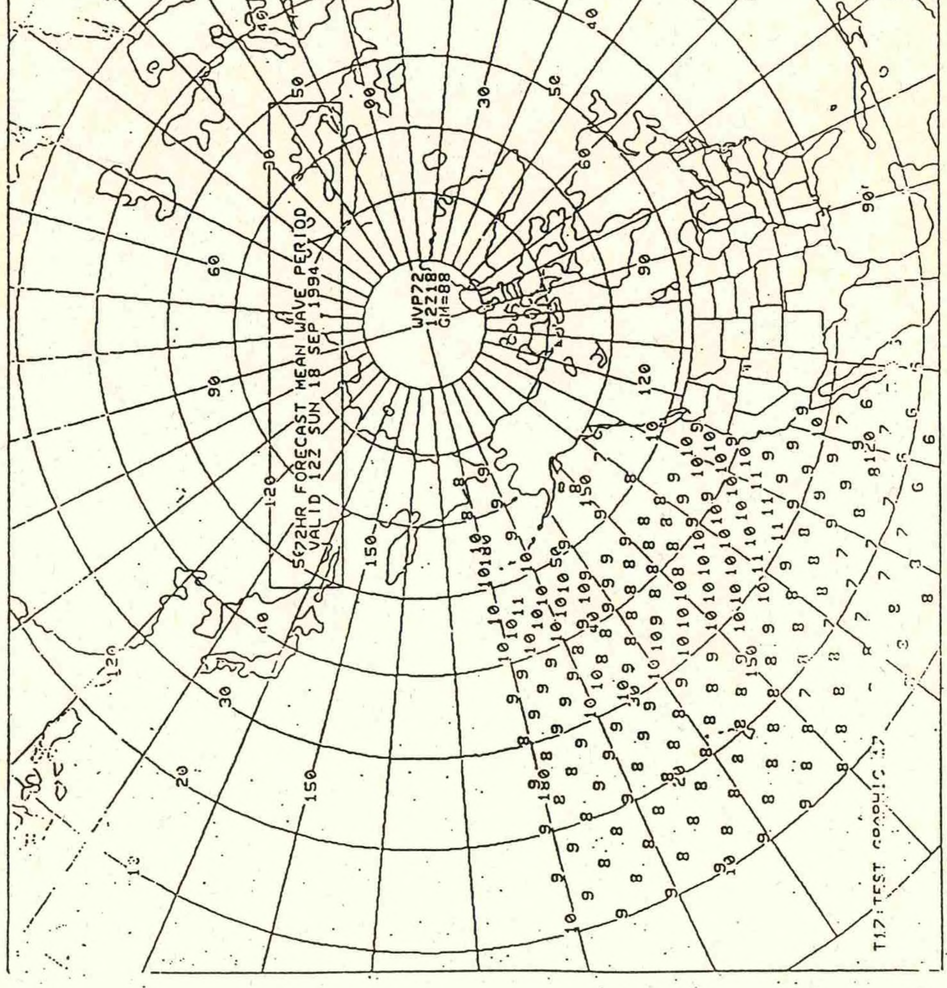

Figure 3. Sample AFOS graphic of WAM gridded mean wave direction arrows.

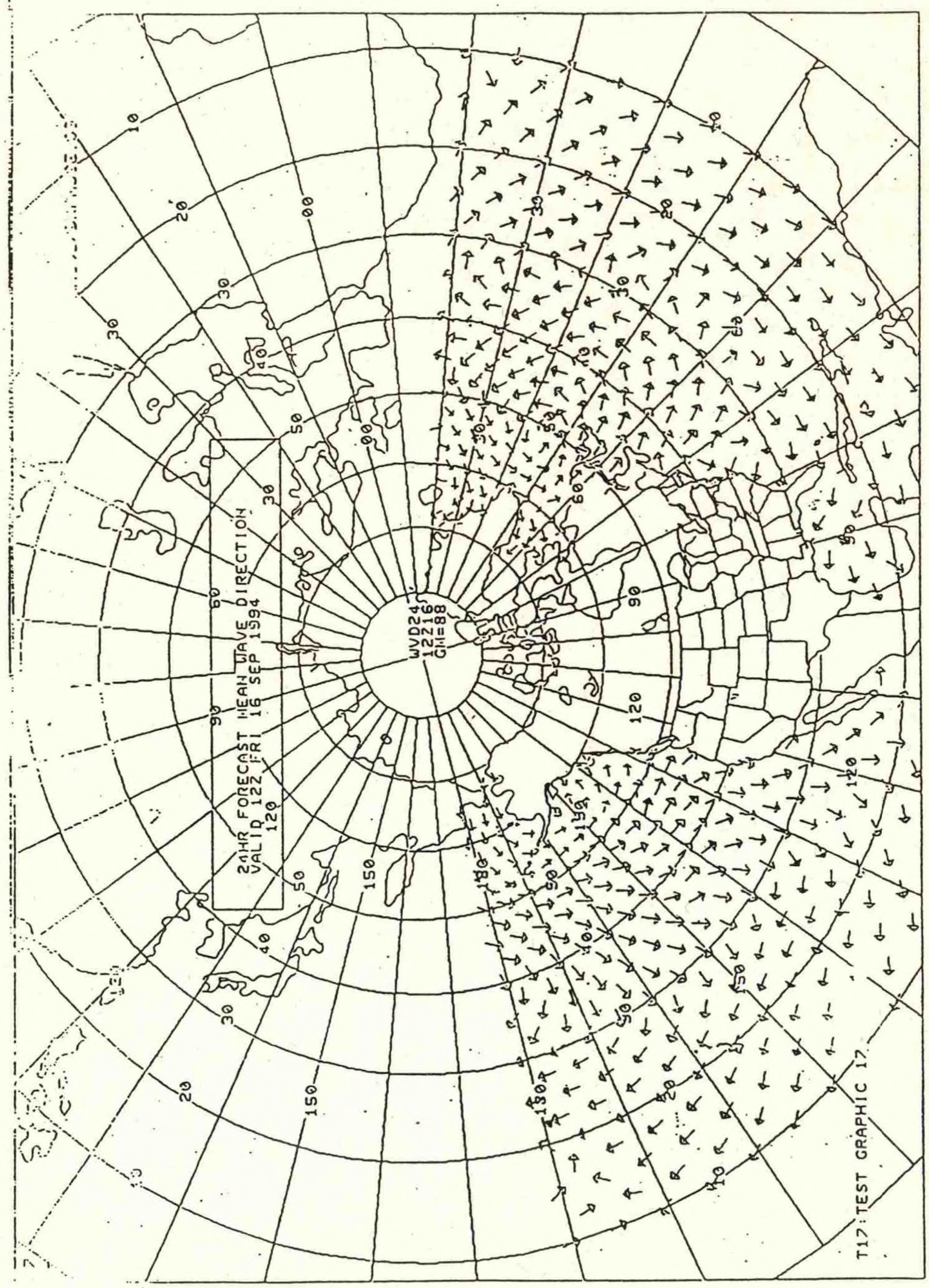

Figure 4. Sample AFOS graphic of WAM gridded mean wave periods in seconds.

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NMCOSWSA1
FZNT41 KWBC 082900
 90082900  LAT  35.0N LON   72.5W  00Z 29 AUG 90 TAU 60
 NOAA            DIR(FROM).   -LOCAL WIND 190.8DEG 15.5KTS
 PERIOD(TOTAL)  105 135 165 195 225 255 285
  10.9       1    1   0   0   0   0   0   0
   9.7       3    1   1   0   0   0   0   0
   8.6       6    1   2   0   1   1   0   0
   7.5       8    1   2   1   2   2   1   0
   6.3      22    1   2   2   7   6   3   1
   4.8      29    0   1   5  13   8   2   0
   3.2      14    0   1   4   5   3   1   0
  DIR(TOTAL)      6  10  12  28  20   6   1
      SIG HT   3.8FT
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NMCOSWSP1
FZPZ41 KWBC 082900
 90082900  LAT  47.5N LON  125.0W  00Z 29 AUG 90 TAU 60
 NOAA            DIR(FROM).    -LOCAL WIND 243.5DEG  8.3KTS
 PERIOD(TOTAL)  165 195 225 255 285 315 345
  18.0       1    0   0   1   0   0   0   0
  16.4       2    0   0   1   0   0   0   0
  15.0       2    0   1   1   0   0   0   0
  13.9       4    0   1   1   1   0   0   0
  12.4       8    0   2   3   2   2   0   0
  10.9       7    0   2   1   1   2   0   0
   9.7       6    0   3   1   1   1   0   0
   8.6      14    0   4   4   2   2   1   0
   7.5       9    1   2   2   1   2   1   0
   6.3       7    1   1   1   0   2   2   0
   4.8       7    1   2   1   0   1   2   1
   3.2       5    0   1   2   1   0   0   0
  DIR(TOTAL)      4  20  18  10  12   6   1
      SIG HT   3.5FT
```

Figure 5. Sample AFOS alphanumeric ocean wave spectral messages for the Atlantic Ocean (top) and the Pacific Ocean (bottom).

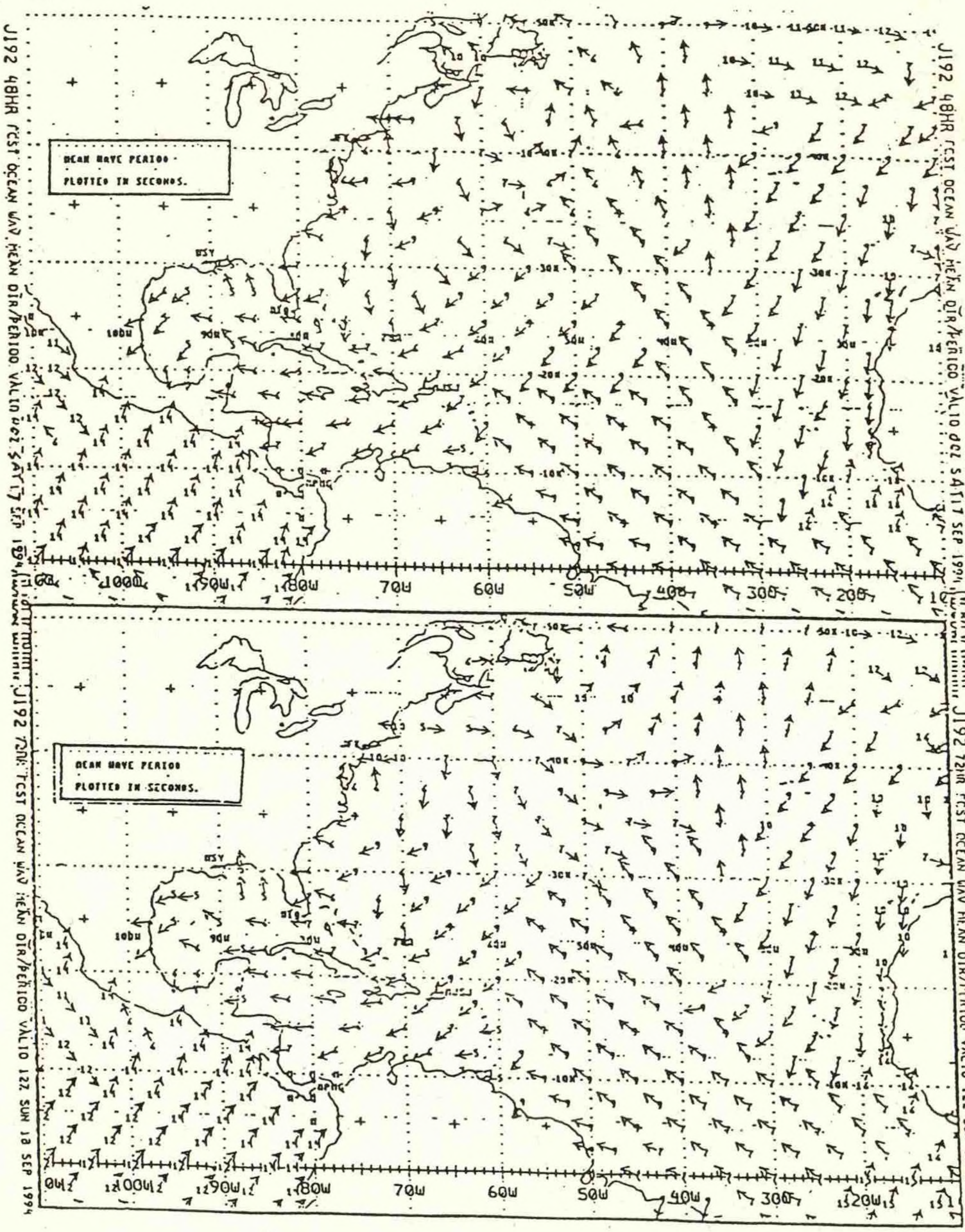

Figure 6. Sample San Juan FAX charts depicting gridded mean ocean wave period in seconds and direction for the 48- and 72-h forecasts.

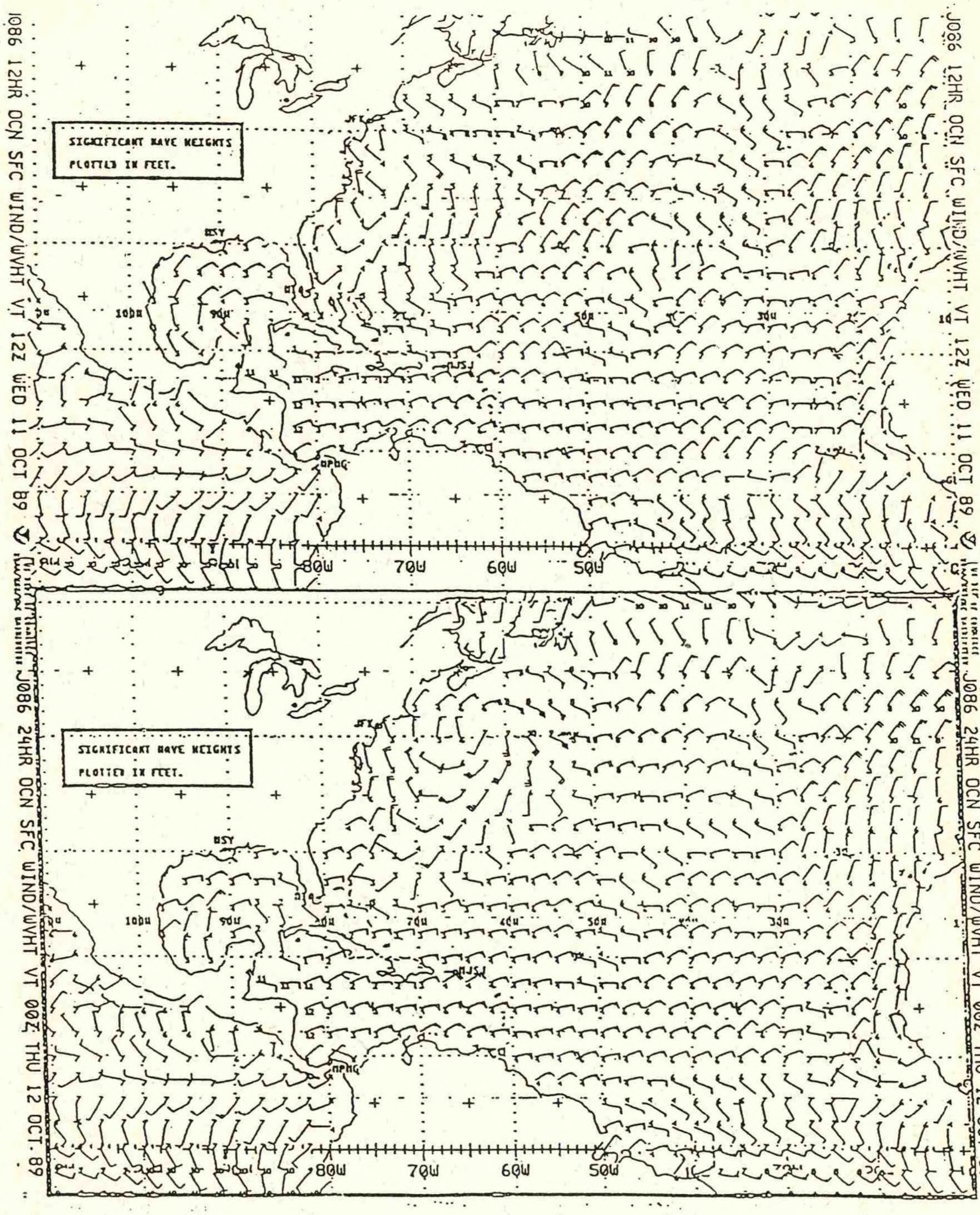

Figure 7. Sample San Juan FAX charts showing gridded values of significant wave height (H_s) in feet and wind barbs (knots) for the 12- and 24-h forecasts.

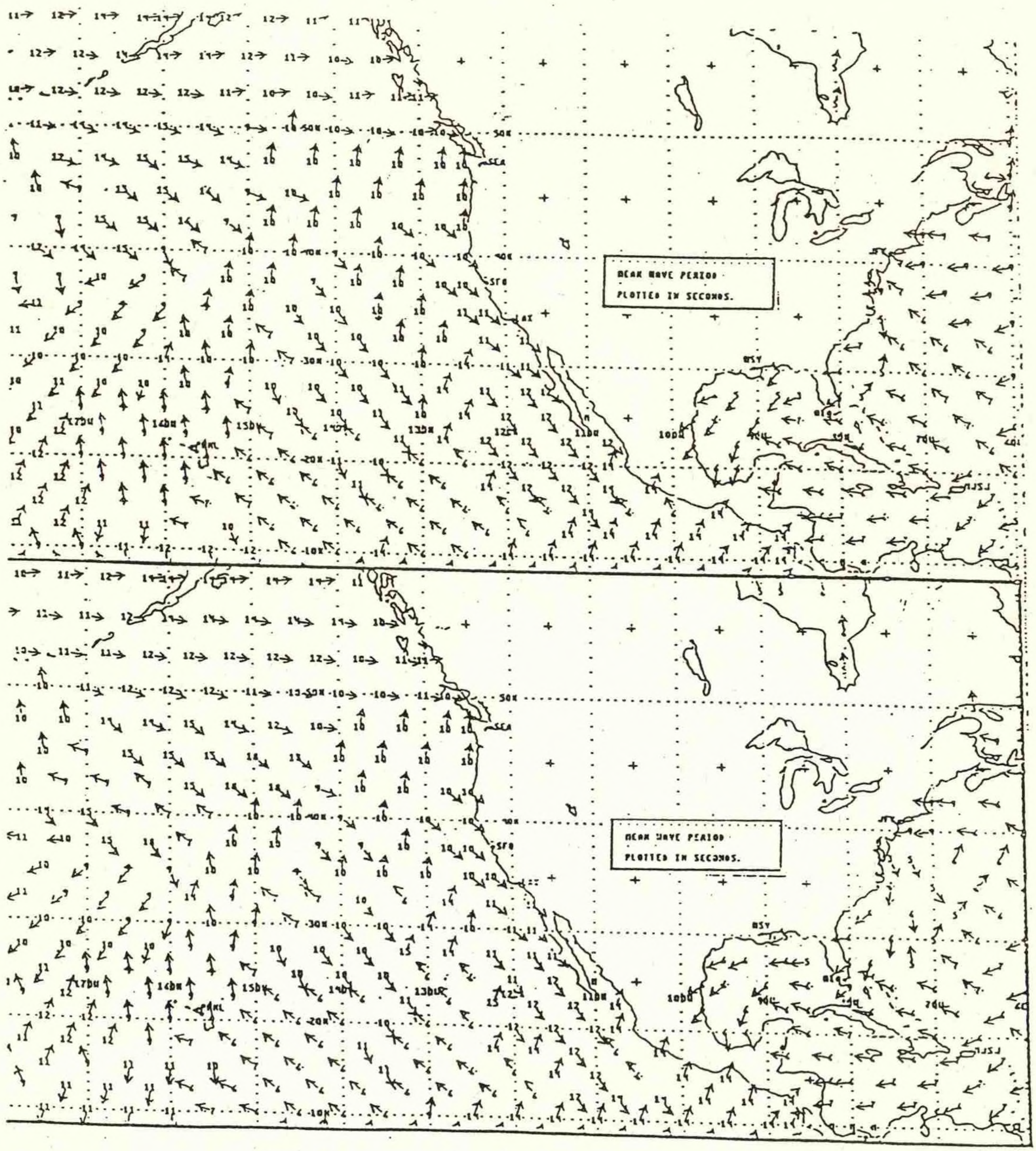

Figure 8. Sample DIFAX charts displaying gridded values of mean wave period in seconds and mean wave direction arrows.

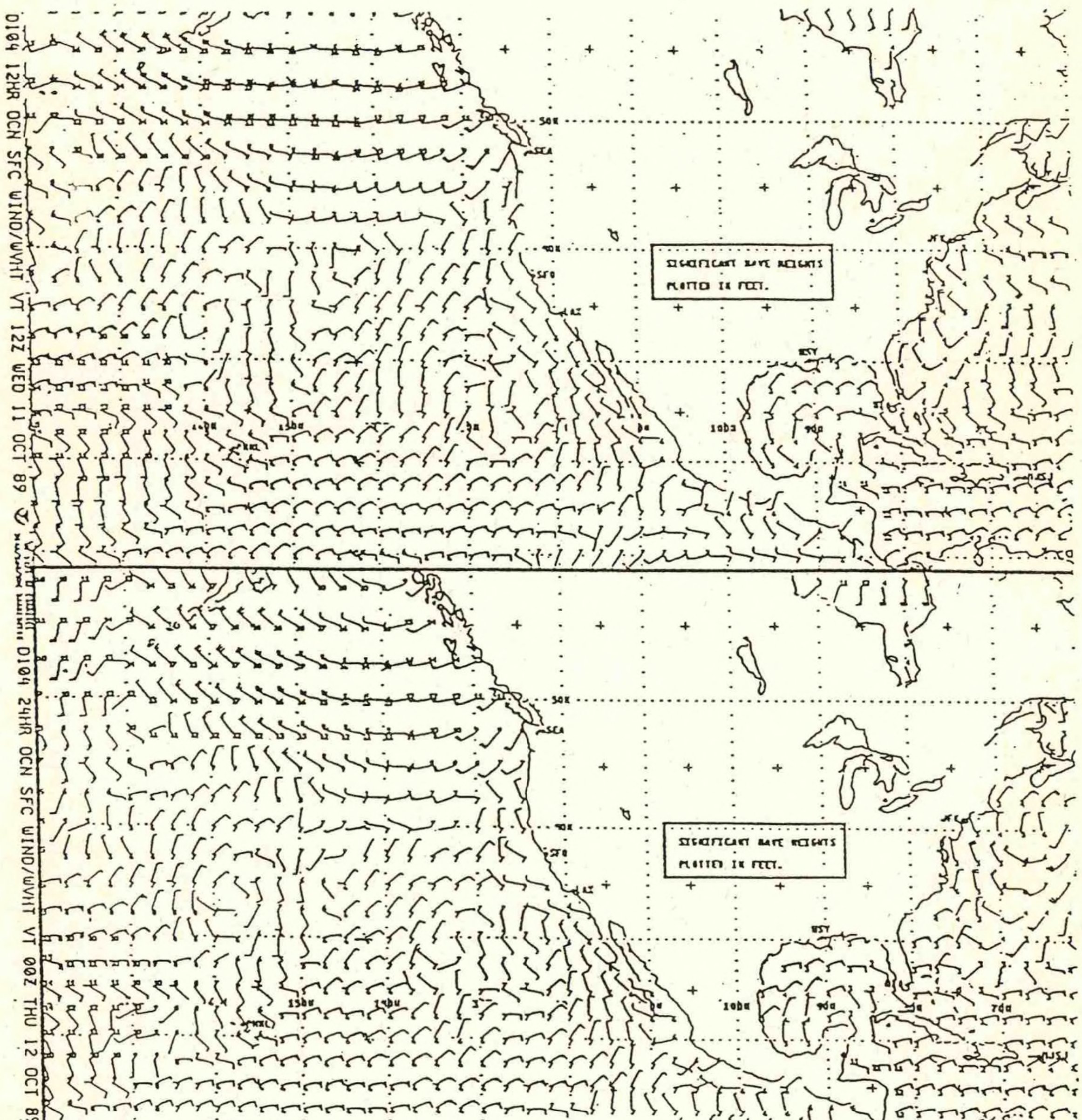

Figure 9. Sample DIFAX charts with gridded values of significant wave height (H_s) in feet and wind barbs (knots).

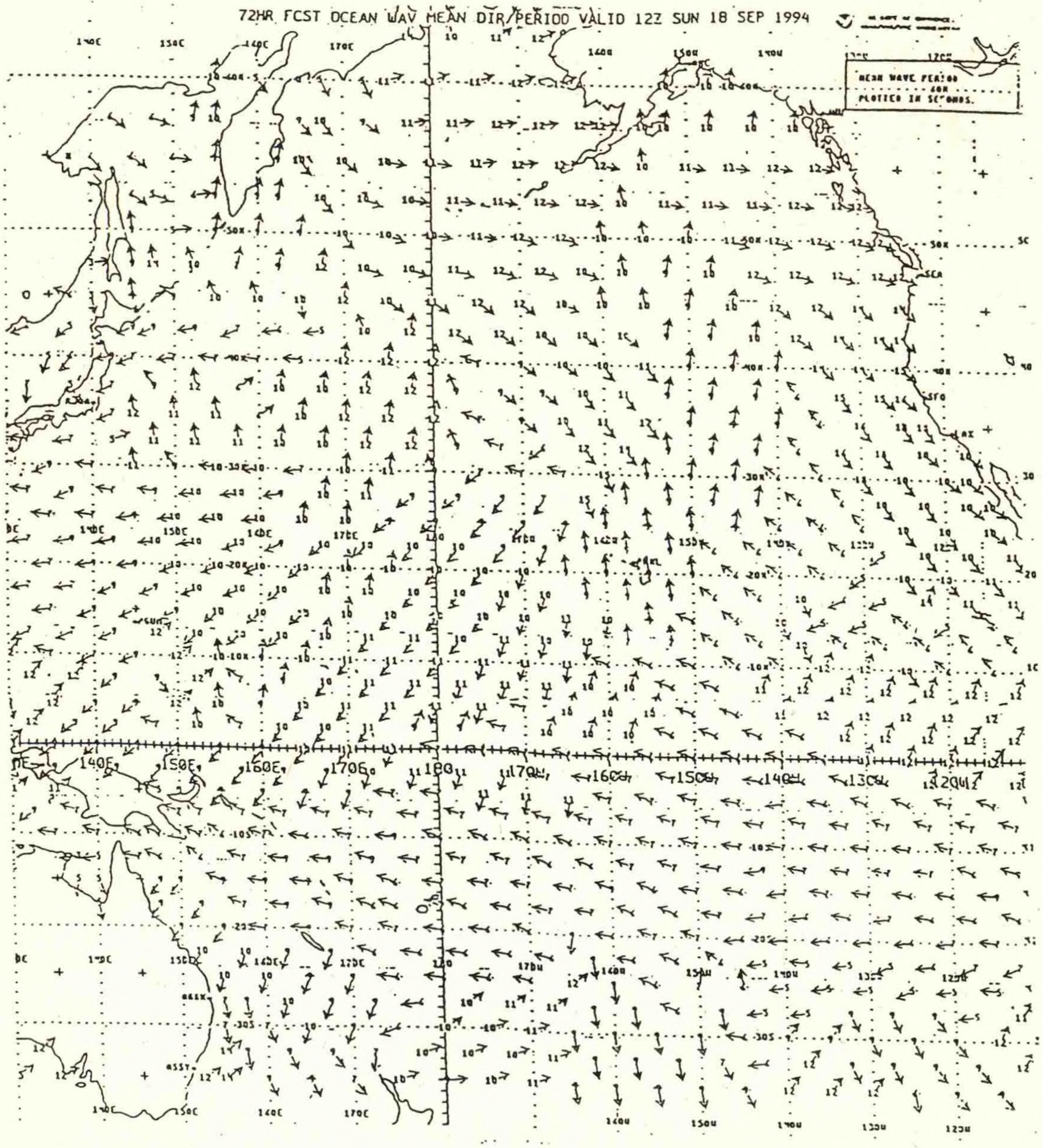

Figure 10. Sample Honolulu FAX charts depicting gridded mean wave period in seconds and mean wave direction arrows.

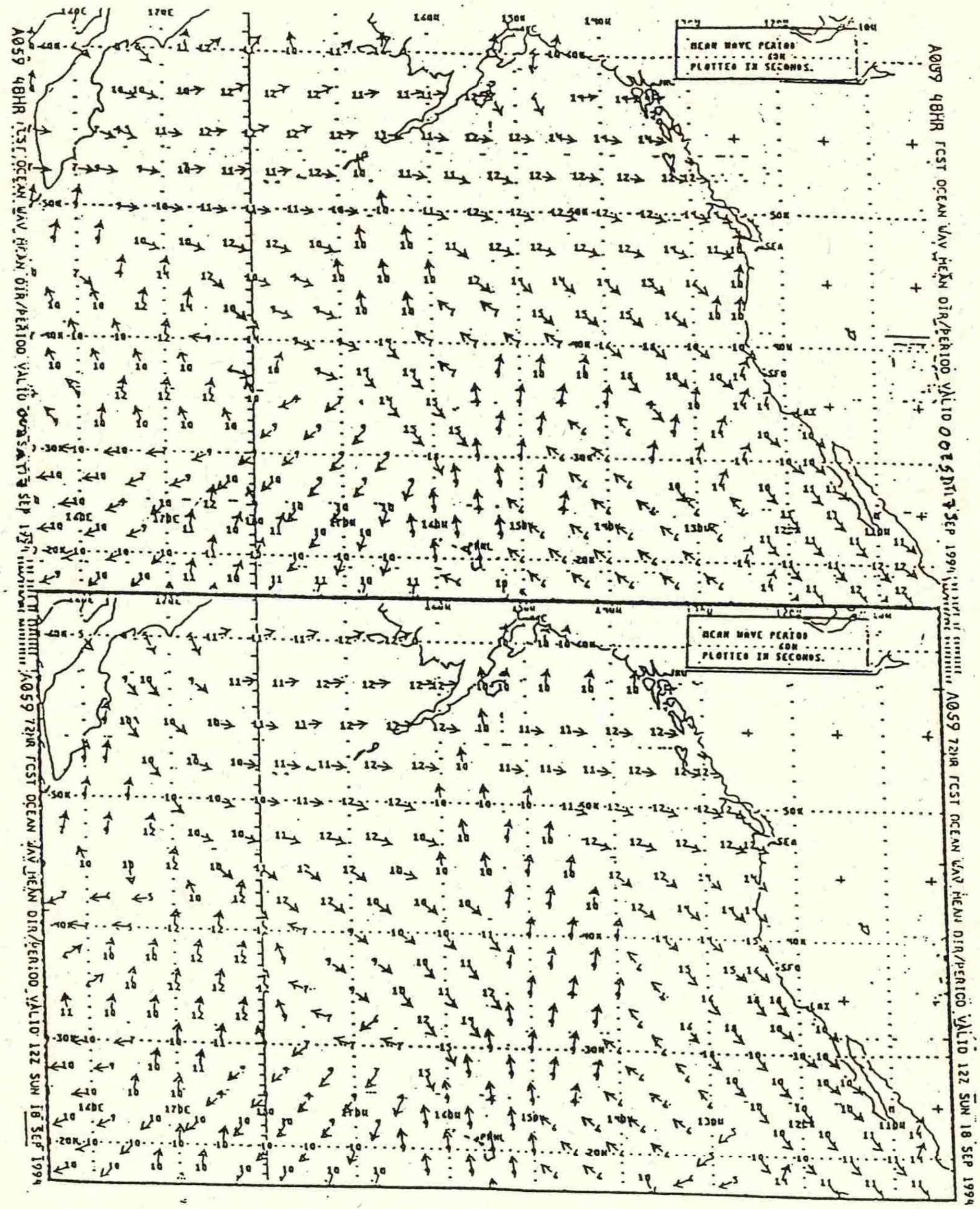

Figure 11. Sample Alaska FAX charts with the gridded mean wave period in seconds and mean wave direction arrows.