Abstract

The Spectral Ocean Wave Model (SOWM) has been an operational product at Fleet Numerical Oceanography Center since the mid 1970s; the Global Spectral Ocean Wave Model (GSOWM) was developed to replace it. An operational test of GSOWM, using buoy, ocean-weather-station, and ship-reported wave-height data for verification, was conducted during the winter of 1984/85 by several components of the Naval Oceanography Command. This test indicated that GSOWM was superior to SOWM and that both models exhibited root-mean-square significant-wave-height errors on the order of 1 m. Wave-height errors deduced from the ship observations were comparable to those calculated from the buoy data. The GSOWM scatter index, determined from the buoy and ocean-weather-station data and defined as the standard deviation of the model-predicted wave-height error divided by the mean observed wave height, averaged 0.34.

As a result of the study reported here, GSOWM replaced SOWM as the U.S. Navy's operational wave model in June of 1985. Examples of GSOWM output, illustrating both the capabilities and shortcomings of the model, are presented.

1. Introduction

Prediction of surface waves on the ocean is a problem of great practical interest as sea state impacts virtually all aspects of naval operations, as well as a variety of commercial maritime activities. Thus, real-time forecasting of waves with numerical models has received emphasis in recent years, with operational models now being run by no less than 12 agencies around the world.

Fleet Numerical Oceanography Center (FNOC) pioneered these efforts through the application of a singular wave model in the mid 1960s (Hubert, 1964; Hubert and Mendenhall, 1970; Schwartz and Hubert, 1973) and a spectral model in the mid 1970s (Lazanoff et al., 1973; Lazanoff and Stevenson, 1975). This latter model, the Spectral Ocean Wave Model (SOWM), was based on the observational and theoretical work of W. J. Pierson and coworkers, and has been the mainstay of the navy's operational wave-prediction capabilities for the past 10 years. Real-time SOWM output has been available to civilian interests since 1981 via the Navy/NOAA Oceanographic Data Distribution System (NODDS; see Lazanoff, 1983a; SAI, 1984; Duernberger, 1985).

In addition to its real-time application, SOWM has been used to generate a wave climatology to aid in ship design and other activities (Lazanoff and Stevenson, 1978). SOWM has been documented and compared to a variety of other wave models through idealized numerical experiments by McLaren Plansearch (1985).

From both practical experience and scientific study, as summarized by Pierson (1982), the SOWM has proved to be a very useful model. Nevertheless, SOWM suffers the limitations of coverage restricted to the Northern Hemisphere, poor angular resolution, and an awkward grid and propagation algorithm. Recognizing these limitations and anticipating increasing computer power, FNOC began to contract for the development of the Global Spectral Ocean Wave Model (GSOWM) in the late 1970s. Full implementation of GSOWM was completed in the fall of 1984, and an operational test, pitting GSOWM against SOWM, was conducted the following winter to coincide with the period of highest waves in the Northern Hemisphere. This test involved comparison of GSOWM- and SOWM-predicted significant-wave heights with observations from moored buoys and ocean weather stations, and the subjective evaluations of product users who received parallel output from the two models. The purpose of this paper is to provide a brief technical description of GSOWM, highlighting its similarities and differences with SOWM, presenting the results of the operational test, and showing examples of GSOWM output.

2. Description of the model

a. Output fields and grid

Like the SOWM, GSOWM is a discrete spectral model whose basic output consists of directional wave-energy spectra for a finite set of direction-frequency bins. GSOWM employs 24 direction bins compared to 12 for SOWM, and thus has twice the angular resolution (15°) of SOWM. This alone represents a significant improvement, as the 30° resolution of
SOWM has long been considered a potentially serious shortcoming (Lazanoff and Stevenson, 1975; Salfi and Pierson, 1977). GSOWM uses the 15 spectral bins shown in Table 1, which are the same used by SOWM.

The following output fields are derived from the GSOWM directional wave spectra: significant-wave height, maximum-wave height, whitecap probability, primary and secondary wave direction, and primary and secondary wave period. The significant-wave height and maximum-wave height are calculated as integral functions of the spectra, under the usual assumption of a Rayleigh wave-height distribution. The calculation of whitecap probability is based on the work of Ross and Cardone (1974). Finally, the primary and secondary directions and periods are given simply by the directions and periods defining the primary and (if present) secondary local maxima in the directional energy spectrum.

GSOWM functions on the standard FNOC 2.5° latitude by 2.5° longitude spherical grid in a global band extending from 77.5°N to 72.5°S. This sets it quite apart from SOWM, which runs on an icosahedral gnomonic grid for the Northern Hemisphere only (see Pierson, 1982). In addition, the average spacing between gridpoints in GSOWM is slightly smaller than that of SOWM for the Atlantic and Pacific Basins. The GSOWM grid spacing in the Mediterranean, however, is much coarser than that of the Mediterranean submodel of SOWM (see Lazanoff et al., 1973). Therefore, the Mediterranean component of SOWM has been retained for operational use. Note that the derived output fields discussed above are transformed to a variety of map projections before distribution to users.

b. Wave growth, dissipation, and angular spreading

The equations for wave growth, dissipation, and angular spreading relative to the wind direction in GSOWM are essentially identical to those of SOWM, and will not be reproduced here. We will instead provide a brief synopsis of the physics used in the model and note that a detailed presentation and discussion of these equations can be found in Pierson (1982).

The growth mechanism used in the model is basically that of Inoue (1967), which modifies and combines the Miles (1957) instability mechanism and the Phillips (1957) resonance theory. This approach parameterizes the wave-energy growth as a function of the one-dimensional spectra (produced by summing the directional spectra over direction) and the instantaneous wind speed, with each component in the one-dimensional spectra growing independently of the others. Thus the model is linear in the sense that it does not attempt to explicitly represent the nonlinear interactions of the wave field which produce the frequency downshift of the spectra (e.g., Barnett, 1968). It fits into the class of models termed decoupled propagation (DP) models by the SWAMP (Sea Wave Modeling Project) Group (1985).

The resonance mechanism dominates during the initial phase of wave growth, producing a linear growth in wave energy with time. The instability mechanism governs the behavior during the latter stages, yielding an exponential increase of energy with time. Growth of each spectral component is slowed as it approaches the Pierson and Moskowitz (1964) fully developed spectrum which is taken as the upper bound for the growing wave energy, except at high frequencies where it is exceeded by the Kitaigorodskii (1961) spectrum, which then becomes the upper bound. Thus, the model is unable to represent the spectral-overshoot effect observed by Barnett and Wilkerson (1967). Like SOWM, the model uses forward time differencing with a three-hour time step.

Dissipation of wave energy for spectral components traveling against the wind is accomplished according to an empirical function of wave energy, frequency, and angle relative to the wind (Cardone et al., 1976). The dissipation rate increases with the wave energy and frequency, and decreases with angle between the waves and the wind. No dissipation occurs for spectral components that are unopposed by the wind.

The growth equations predict the evolution of the one-dimensional spectra rather than that of the directional spectra. Therefore, the resulting wave energy must be spread over the model's direction bins to produce two-dimensional (i.e., directional) spectra. This is done with an empirical function of wind speed, frequency, and angle relative to the wind. The spread decreases with decreasing frequency and varies essentially as the fourth power of the cosine of the angle between the spectral component and the wind for low frequencies.

c. Wave propagation algorithm

Both GSOWM and SOWM propagate energy along great-circle paths at the frequency-dependent group velocity for deep-water waves. The numerical algorithms used to accomplish this, however, differ significantly between the two models. GSOWM uses an energy-conserving downstream-interpolation technique (Greenwood and Cardone, 1977), while SOWM uses a hybrid numerical scheme employing velocity gradient and jump techniques as described by Pierson et al. (1966). The GSOWM algorithm is implemented in the form of a time-invariant propagation table which specifies the fraction of energy propagated from each spectral component to all other spectral components at the surrounding gridpoints, rigorously conserves energy, and accurately simulates the natural dispersion of discrete frequency bands. The SOWM technique requires computationally expensive logic, does not conserve energy exactly, and generally encounters difficulties in propagating energy across the edges of adjacent triangular subprojections of the icosahedral gnomonic grid. The GSOWM algorithm is expected to be particularly superior in the case of low-frequency long-range swell propagation.

d. Initial conditions and wind forcing

The basic prognostic variable of GSOWM, the directional wave spectrum, is not presently observed synoptically by any measurement system. Hence, the initial conditions for GSOWM forecasts are not provided by observations. Instead, in analogous fashion to SOWM, the model provides its own initial state in the form of a spectral history file of predicted wave energy produced by integrating the model forward in time. This hindcast initial state is updated four times per day using the most accurate winds available, and great emphasis is placed on maintaining its continuity.

The low-level winds that force GSOWM are produced by the Global Surface Contact Layer Interface (GSCLI) system.
The GSCLI is a parameterization that relates analyzed and forecast synoptic-scale variables predicted by the Navy Operational Global Atmospheric Prediction System (NOGAPS; Rosmond, 1981) model to the small-scale variables that determine the turbulent-flow regime in the surface-contact layer. The governing equations for this methodology are described in Mihok and Kaitala (1976) and are consistent with those used in the Planetary Boundary Layer Northern Hemisphere (PBLNH) system, which produced the winds for SOWM from the same NOGAPS synoptic-scale input. Both GSCLI and PBLNH compute mean vertical profiles of wind, temperature, and moisture as functions of a stability parameter, the Monin-Obukhov length. Winds input to the GSOWM and SOWM are computed at 19.5-m height. These winds contain an integration constant which has the effect of increasing their speed for unstable stratification (air colder than water) and decreasing their speed for stable stratification (air warmer than water). The GSOWM and SOWM can therefore treat the 19.5-m wind as though the constant-flux layer is always neutrally stratified. This is a computational advantage allowing the effects of stability to be precisely included in a calculation of the surface friction velocity which involves only a quick iterative solution of the logarithmic wind law for neutrally stratified conditions. See Cardone (1969) for the details of this approach.

Preliminary studies of the GSOWM/GSCLI and SOWM/PBLNH winds have been conducted with measurements from National Oceanic and Atmospheric Administration (NOAA) data buoys used for validation. Surprisingly, GSCLI has verified better than PBLNH, even though the physics of the two systems are essentially the same. Reasons for this may stem from the following: 1) GSCLI is a recoded version of PBLNH wherein the application of the engineering enhancements for the thermal-wind effect, the advective modification of the air-sea temperature difference, and the gradient-wind adjustment to the surface geostrophic wind are computed in a more-concise fashion; 2) the GSCLI contains a diagnostic package which permits constant comparison with the FNOC marine-wind analysis and thus more-accurate tuning of the physical processes in 1) above; and 3) PBLNH is subjected to extratropical-wind bogus adjustment (i.e., subjective modification of winds by FNOC personnel) not currently in GSCLI.

In any case, no attempt is made to force both GSOWM and SOWM with exactly the same winds. The GSCLI winds are regarded as an integral part of the GSCLI system, and the operational test described here is also considered an implicit test of the GSCLI model.

e. Run schedule

Like its predecessor the SOWM, GSOWM runs four times per day, producing a 72-hour forecast on the 0000 GMT watch and a 48-hour forecast on the 1200 GMT watch. Output fields are saved at 12-hour intervals during each forecast period, and are normally available for distribution near 0600 GMT and 1800 GMT. The off-time runs at 0600 GMT and 1800 GMT simply hindcast the spectra forward in time to maintain continuity of the history file. They do not produce a forecast or any derived output fields.

The overall GSOWM jobstream functions on three mainframes; the wind forcing is produced on the CYBER 175, the wave-forecast model is initialized on the CYBER 730 and run on the CYBER 205, and the derived output fields are generated on the CYBER 730. A 72-hour forecast requires approximately three minutes of CP time and 16 million words of mass storage on the CYBER 205 (approximately 60 million operations per second) and eight minutes of CP time and six million words of mass storage on the CYBER 730 (approximately eight million operations per second). A 72-hour forecast by SOWM requires approximately 162 minutes of CP time and seven million words of mass storage on the CDC 6500 (approximately two million operations per second).

3. Verification techniques

a. Statistical comparison with buoy observations

The NOAA Data Buoy Center (NDBC) maintains a number of moored buoys which provide observations of one-dimensional wave spectra and significant-wave height several times per day (Hamilton, 1980). The significant-wave heights are calculated as an integral of the spectrum, exactly as is done in GSOWM and SOWM. The one-sigma error level of the buoy-reported significant-wave heights is 0.5 m (Hamilton, 1980).

Significant-wave heights from the GSOWM- and SOWM-hindcast initial states were verified against the NDBC buoy observations in the northwestern Atlantic and northeastern Pacific. This was done by interpolating the model-predicted wave heights to the buoy locations shown in Fig. 1, and comparing with the reported values in real time.

A number of statistical parameters were calculated for both models, including root-mean-square error (RMSE), systematic mean-square error (MSEs), unsystematic mean-square error (MSEu)(see Willmott, 1981, 1982), and the scatter index (S; see Janssen et al., 1984). The statistic MSEs is the mean of the squared differences between the observed wave heights and the least-squares regression line through the scatter of model-predicted versus observed wave heights. The statistic MSEu is the mean of the squared differences between the model-predicted wave heights and the regression line. Systematic errors in models tend to be concentrated in MSEs, while unsystematic errors and noise in the observations tend to be concentrated in MSEu. The two statistics are related to RMSE according to RMSE = (MSEs + MSEu)1/2. The scatter index S is simply the standard deviation of the difference between predicted and observed wave heights divided by the mean observed wave height. In general, the closer RMSE, MSEs, MSEu, and S are to 0, the better the model result. These statistics were generated separately for the northwestern Atlantic and northeastern Pacific (combining all data from the buoys in each region) from 30-day accumulations of data.

b. Statistical comparison with ocean-weather-station observations

Several ocean weather stations are maintained in the northwestern Atlantic via a multinational effort coordinated by the WMO. These stations report significant-wave height in real time with accuracy comparable to that of the NDBC buoys.

Commencing 1 January 1985, significant-wave heights from the GSOWM- and SOWM-hindcast initial states were interpolated to the positions of ocean stations CHARLIE,
LIMA, and ROMEO (see Fig. 1) and compared against the reported wave heights. The same statistical parameters listed in the previous section were also calculated from these data. As before, the statistics were based on 30-day accumulations of data grouped together from the stations in the region.

c. User evaluation of GSOWM- and SOWM-output products

Evaluation of GSOWM and SOWM output was done by four of the Naval Oceanography Command’s five Regional Oceanography Centers: Naval Western Oceanography Center, Pearl Harbor; Naval Eastern Oceanography Center, Norfolk; Naval Polar Oceanography Center, Suitland; and Naval Oceanography Command Center, Guam. Predictions of significant-wave height and primary wave direction from both GSOWM and SOWM were transmitted to the Regional Centers twice per day during the period 18 December 1984 through 8 February 1985 via the Naval Environmental Data Network. Qualitative and quantitative evaluation of these products was done with emphasis on their value for direct support of fleet operations in each center’s area of responsibility. A “blind” test approach was not taken. Thus, the evaluators always knew which model produced which output. Summaries of these findings were forwarded to FNOC at the end of the test period and will be discussed in the next section. Though perhaps somewhat subjective, this component of the verification process was quite meaningful and important as it involved synoptic evaluation of the model over large domains and came from the primary customers for the GSOWM output products.

4. Operational test results

a. Results of comparison with buoy observations

The buoy verification statistics for the northwestern Atlantic and northeastern Pacific are summarized in Tables 2–4. The plus-or-minus limits indicate approximate 90 percent confidence intervals, and \( N \) is the number of observations used in the statistical calculations. The GSOWM RMSE averaged 0.93 m, which was about 30 percent less than that of SOWM. GSOWM exhibited its lowest RMSE (0.73 m) in the northwestern Atlantic during February, which reflected a very low systematic mean-square error (MSE).

The scatter index, \( S \), is a standard parameter for intercomparing wave models. The GSOWM scatter index ranged from 0.28 to 0.45 in the northwestern Atlantic and northeastern Pacific. The SOWM scatter index ranged from 0.38 to 0.52 and was always greater than that of GSOWM.

b. Results of comparison with ocean-weather-station observations

The ocean-weather-station verification statistics for the northeastern Atlantic are also included in Tables 3 and 4. All the statistics clearly favored GSOWM over SOWM, though both models performed poorly here. The GSOWM root-mean-square wave-height error averaged 1.78 m, while that of SOWM averaged 2.68 m. The wave-height predictions from both models were biased high at the ocean stations. To a great extent, the poor performance of both models in this region was a result of inaccuracies in the wind forcing. For example, during January, the winds which drove the wave models were biased high \( 1 \text{ m}\cdot\text{s}^{-1} \) and exhibited root-mean-square errors in the range of \( 4-6 \text{ m}\cdot\text{s}^{-1} \) relative to the wind observations at the ocean stations. In addition, as might be expected, the mean January observed wind in this region was relatively high (approximately \( 10 \text{ m}\cdot\text{s}^{-1} \)). Since significant-wave heights tend to vary as the square of the
wind speed, the effect of wind errors on the wave field is amplified in areas of persistently high winds, as was the case for the northeastern Atlantic.

Finally, note that the average GSOWM scatter index S, deduced from all the buoy and ocean-weather-station results presented in Tables 2-4, was 0.34. As discussed by Ewing (1980) and Janssen et al. (1984), this verification parameter varies typically between 0.20 (sophisticated models forced by very accurate winds) and 0.60 (operational models forced by less-accurate winds). Thus, based on the buoy and ocean-weather-station data, GSOWM appears to perform quite well for an operational system.

c. Results of user evaluations

All four of the Regional Oceanography Centers participating in the evaluation compared GSOWM and SOWM significant-wave heights against hand analyses of combined sea height (defined as \([\text{sea height}]^2 + [\text{swell height}]^2\)^{1/2}) produced from real-time sea and swell observations reported by ships. Root-mean-square wave-height errors were calculated using the analyzed combined sea heights for verification.

Naval Eastern Oceanography Center, Norfolk, evaluated the models in the North Atlantic between 35°N and 57°N. Based on a sample size of about 250, the GSOWM root-mean-square wave-height error was 0.91 m while that of SOWM was 1.10 m. This center also reported that GSOWM generally appeared superior to SOWM in forecasting both the size and location of high-seas warning areas.

Naval Polar Oceanography Center, Suitland, evaluated the models in the Davis Strait, Denmark Strait, Norwegian Sea, Barents Sea, and Greenland Sea areas. A total of 117 ship reports were available from these areas, yielding root-mean-square wave-height errors of 0.91 m and 1.10 m for GSOWM and SOWM, respectively. This center also reported that GSOWM consistently depicted wave heights and patterns southwest and west of Iceland more accurately than SOWM. They also noted, however, that GSOWM tended to underpredict wave heights and perform worse than SOWM in the Norwegian Sea.

Naval Oceanography Command Center, Guam, evaluated the models in the Sea of Japan, the South China Sea, the Kuroshio Area, and the Philippine Sea. Based on a sample size of 1600, the root-mean-square wave-height errors in these regions were 0.90 m for GSOWM and 1.07 m for SOWM. This center also reported that GSOWM, unlike SOWM, did not tend to produce extreme sea heights around Taiwan and Luzon. They also noted, however, that for observed seas over about 4 m in the Sea of Japan and Philippine Sea, SOWM appeared to be more accurate, with GSOWM underpredicting wave heights.

Naval Western Oceanography Center, Pearl Harbor, concentrated on the eastern North Pacific between 30°N and 45°N. Based on a sample size of approximately 160, the root-mean-square wave-height error for GSOWM averaged 1.19 m in this region, while that of SOWM averaged 1.41 m. This center also reported that the horizontal gradients of significant-wave height predicted by GSOWM appeared more realistic than those of SOWM.

### Table 2. Verification statistics for December 1984.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Northwestern Atlantic GSOWM</th>
<th>SOWM</th>
<th>Northeastern Pacific GSOWM</th>
<th>SOWM</th>
<th>Northeastern Atlantic GSOWM</th>
<th>SOWM</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE (m)</td>
<td>0.77 ± 0.08</td>
<td>0.83 ± 0.09</td>
<td>1.01 ± 0.06</td>
<td>1.61 ± 0.10</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>MSE (m²)</td>
<td>0.12 ± 0.02</td>
<td>0.03 ± 0.06</td>
<td>0.20 ± 0.03</td>
<td>0.89 ± 0.12</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>MSE (m²)</td>
<td>0.48 ± 0.10</td>
<td>0.39 ± 0.08</td>
<td>0.81 ± 0.11</td>
<td>1.71 ± 0.22</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>S</td>
<td>0.45</td>
<td>0.50</td>
<td>0.29</td>
<td>0.40</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>N</td>
<td>129</td>
<td>129</td>
<td>333</td>
<td>333</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

### Table 3. Verification statistics for January 1985.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Northwestern Atlantic GSOWM</th>
<th>SOWM</th>
<th>Northeastern Pacific GSOWM</th>
<th>SOWM</th>
<th>Northeastern Atlantic GSOWM</th>
<th>SOWM</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE (m)</td>
<td>0.95 ± 0.08</td>
<td>1.31 ± 0.11</td>
<td>1.27 ± 0.08</td>
<td>1.71 ± 0.11</td>
<td>1.86 ± 0.21</td>
<td>2.76 ± 0.33</td>
</tr>
<tr>
<td>MSE (m²)</td>
<td>0.33 ± 0.06</td>
<td>0.92 ± 0.15</td>
<td>0.35 ± 0.05</td>
<td>0.47 ± 0.06</td>
<td>1.96 ± 0.46</td>
<td>4.55 ± 1.11</td>
</tr>
<tr>
<td>MSE (m²)</td>
<td>0.57 ± 0.10</td>
<td>0.79 ± 0.13</td>
<td>1.26 ± 0.17</td>
<td>2.66 ± 0.30</td>
<td>1.49 ± 0.35</td>
<td>3.05 ± 0.74</td>
</tr>
<tr>
<td>S</td>
<td>0.29</td>
<td>0.43</td>
<td>0.34</td>
<td>0.47</td>
<td>0.40</td>
<td>0.59</td>
</tr>
<tr>
<td>N</td>
<td>190</td>
<td>190</td>
<td>338</td>
<td>338</td>
<td>98</td>
<td>98</td>
</tr>
</tbody>
</table>

### Table 4. Verification statistics for February 1985.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Northwestern Atlantic GSOWM</th>
<th>SOWM</th>
<th>Northeastern Pacific GSOWM</th>
<th>SOWM</th>
<th>Northeastern Atlantic GSOWM</th>
<th>SOWM</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE (m)</td>
<td>0.73 ± 0.08</td>
<td>1.21 ± 0.14</td>
<td>0.88 ± 0.05</td>
<td>1.35 ± 0.08</td>
<td>1.71 ± 0.21</td>
<td>2.61 ± 0.32</td>
</tr>
<tr>
<td>MSE (m²)</td>
<td>0.09 ± 0.02</td>
<td>0.87 ± 0.21</td>
<td>0.13 ± 0.02</td>
<td>0.59 ± 0.07</td>
<td>1.71 ± 0.41</td>
<td>3.61 ± 0.90</td>
</tr>
<tr>
<td>MSE (m²)</td>
<td>0.44 ± 0.10</td>
<td>0.59 ± 0.14</td>
<td>0.63 ± 0.08</td>
<td>1.23 ± 0.14</td>
<td>1.22 ± 0.29</td>
<td>3.19 ± 0.80</td>
</tr>
<tr>
<td>S</td>
<td>0.32</td>
<td>0.52</td>
<td>0.28</td>
<td>0.38</td>
<td>0.34</td>
<td>0.53</td>
</tr>
<tr>
<td>N</td>
<td>102</td>
<td>102</td>
<td>386</td>
<td>386</td>
<td>94</td>
<td>94</td>
</tr>
</tbody>
</table>
5. Example GSOWM output

To illustrate some of the outputs produced by GSOWM, we consider the evolution of the wave field predicted by the model during the period 12–15 February 1985. Although the extent of the model is global, we focus on the midlatitude North Pacific in this case study to limit the discussion.

a. Synoptic weather patterns and winds for the North Pacific

Figure 2 shows analyzed surface pressure and 19.5-m winds from the FNOC operational system valid at 1200 GMT on the four days in question. Two sets of wind barbs are plotted. The darker solid barbs are the GSDL winds which drive GSOWM, while the lighter dotted barbs are from the FNOC Marine Wind Analysis.

At 1200 GMT on the 12th, the eastern midlatitude North Pacific was quiescent with a poorly developed low-pressure system in the Gulf of Alaska and a broad area of high pressure and light winds off the coast of California (Fig. 2a). The central Pacific was under the influence of a high over the Aleutians and a low centered at 35°N, 165°W. A region of 15.4 m • s⁻¹ (30-kt) winds existed northwest of the low, between these two systems. The western Pacific was dominated by a 980-mb low over the Kuril Islands. This system produced winds in excess of 15.4 m • s⁻¹ (30 kt) over a large part of the region.

By 1200 GMT on the 13th, the low previously in the central Pacific had undergone rapid deepening to less than 988 mb and moved northeastward into the eastern Pacific (Fig. 2b). At this stage, 20.6 m • s⁻¹ (40-kt) winds were present both east and west of the storm’s center, and the eastern Pacific was becoming increasingly under its influence. The low previously in the Gulf of Alaska remained weak and almost stationary. At the same time, the central Pacific was becoming dominated by high pressure and light winds as the high-pressure ridge centered over the Aleutians on the previous day extended itself much farther south. The western Pacific generally experienced decreasing winds on the 13th as the low previously over the Kurils filled and drifted northwestward.

By 1200 GMT on the 14th, the two lows in the eastern North Pacific had merged to become a major and extensive extratropical cyclone with central pressure less than 976 mb and highest winds southeast of its center (Fig. 2c). Winds in excess of 20.6 m • s⁻¹ (40 kt) occurred southeast of the storm’s center, and the entire midlatitude eastern North Pacific was dominated by the storm at this juncture. The central Pacific remained under the influence of high pressure and light winds, while a new and intense low-pressure system developed explosively in the western Pacific east of Hokkaido.

By 1200 GMT on the 15th, the storm in the eastern Pacific had begun to dissipate (Fig. 2d). Highest winds over the ocean at this time were 15.4 m • s⁻¹ (30 kt) as the central pressure in the low had increased to 992 mb. Dissipation of the system continued beyond this point, with the storm losing its identity on the 16th. Winds in the central Pacific were higher than on the previous day, as the high-pressure system dominant there earlier began to disappear. The intense rapidly growing low present in the western Pacific on the 14th now dominated the entire region as it extended its influence eastward to the central Pacific.

b. GSOWM-hindcast significant-wave height, primary wave direction, and primary wave period for the North Pacific

Figure 3 shows significant-wave height (contours), primary wave direction (arrows), and primary wave period (small numbers printed at every five degrees of latitude and longitude) from the GSOWM-hindcast initial state valid at 1200 GMT on the four days under consideration. The primary direction and period are displayed at every other model gridpoint in the zonal and meridional directions.

At 1200 GMT on the 12th, the wave field in the North Pacific was quiet for this time of the year with significant-wave heights generally in the range of 2.7–3.7 m (9–12 ft, see Fig. 3a). A variety of primary directions were present in the eastern Pacific at this point, reflecting the absence of strong local forcing. The central Pacific exhibited a local maximum in significant-wave height of 5.5 m (18 ft) centered in the area of high winds northwest of the low-pressure system at 35°N, 165°W, as well as a region of relatively low waves associated with the high-pressure system over the Aleutians. The wave field in the western Pacific was dominated by high long-period waves forced by winds from the Kuril storm. The model predicted significant-wave heights in excess of 9.1 m (30 ft) near the center of the low, and primary periods of 14–16 s over a broad area.

At 1200 GMT on the 13th, the eastern Pacific exhibited a double maximum in significant-wave height east and west of the developing low-pressure system (Fig. 3b). Significant-wave heights exceeded 7.3 m (24 ft) in the region of maximum wave height west of the storm’s center and 8.2 m (27 ft) in the region of maximum height east of the storm’s center. The primary directions in both regions reflected the local wind direction. The central Pacific showed a relative minimum in significant-wave height, consistent with the high pressure and light winds prevailing in the region at this time. Significant-wave heights in the western Pacific still showed the influence of the storm over the Kurils, although the waves had subsided considerably from the previous day as the storm weakened.

By 1200 GMT on the 14th, the wave field in the eastern Pacific was clearly being controlled by the storm in the Gulf of Alaska (Fig. 3c). The primary directions and packing of significant-wave height contours along the coast of Canada indicated that substantial wave energy was propagating onto the shore at this time; wave heights exceeded 9.1 m (30 ft) off the central coast of British Columbia. Note the discontinuity in primary direction extending from low to high latitudes at about 165°W. This was associated with swell propagating eastward from the Kuril storm of Fig. 3a and impinging on the region dominated by quasi-locally developed seas produced by the Gulf of Alaska storm of Fig. 3c. The primary periods of Fig. 3c also reflect this difference: 14–18 s for the swell from the western Pacific, 10–12 s for the waves produced by the Gulf of Alaska storm. The central Pacific continued to show a relative minimum in significant-wave height on the 14th and was characterized by long-period swell propagation from the Kuril storm. The western Pacific showed substantial shorter-period wave growth produced by the rapidly developing storm east of Hokkaido.

By 1200 GMT on the 15th, the eastern Pacific high-wave event was winding down as wave energy continued to be dis-
FIG. 2. Analyzed winds (barbs) and surface pressures (contours) from the FNOC operational system valid at 1200 GMT on the (a) 12th,
(b) 13th, (c) 14th, and (d) 15th of February 1985. Contour origin and interval is 900 mb and 4 mb, respectively.
Fig. 3. Significant-wave heights (contours) and primary wave directions (arrows) from the GSOWM-hindcast initial state valid at 1200 GMT on the (a) 12th, (b) 13th, (c) 14th, and (d) 15th of February 1985. Contour origin and interval is 0 m (0 ft) and 0.9 m (3 ft), respectively. The
small numbers printed at every five degrees of latitude and longitude are the primary wave periods in seconds.
Fig. 4. Same as Fig. 3 but for 48-h forecasts valid at 1200 GMT on the (a) 12th, (b) 13th, (c) 14th, and (d) 15th of February 1985.
sipated against the shoreline (Fig. 3d). The highest significant-wave–height contour along the coast of British Columbia was now down to 7.3 m (24 ft). The region of discontinuity in primary direction noted on Fig. 3c moved farther east as the long-period swell from the western Pacific continued to propagate eastward. The central Pacific remained as a local minimum in wave height, with the axis of the low-wave–height area now oriented NW-SE. The western Pacific showed the expanding influence of the new storm in the region. Significant-wave heights off the coast of Japan exceeded 9.1 m (30 ft).

c. GSOWM-forecast significant-wave height, primary wave direction, and primary wave period for the North Pacific

Figure 4 shows 48-hour GSOWM forecasts of significant-wave height, primary wave direction, and primary wave period valid at the same times as the hindcasts presented in the previous figures. Although the hindcast wave products presented in Fig. 3 were themselves subject to error, they were undoubtedly more accurate than the forecast wave products of Fig. 4 because they were produced by more-accurate winds (i.e., analyzed winds are generally more accurate than forecast winds). Thus, comparison of Fig. 4 with Fig. 3 gives a qualitative feel for the forecast skill of GSOWM, which is of course tightly linked to the forecast skill of NOGAPS, which ultimately drives the wave model.

The GSOWM forecast valid at 1200 GMT on the 12th (Fig. 4a) gave a fair representation of the wave field in the eastern Pacific and correctly predicted a generally low level of activity. The forecast for the central Pacific was less skillful as the model missed the local maximum in wave height northeast of the low-pressure system at 35°N, 165°W discussed earlier. The forecast for the western Pacific gave a good representation of the extent and pattern of the wave field forced by the Kuril storm, but underestimated the maximum wave heights near the center of the storm.

The forecast valid at 1200 GMT on the 13th (Fig. 4b) showed a tendency toward the double-maximum structure in the eastern Pacific of Fig. 3b, but the westerly maximum was significantly underdeveloped, and the easterly maximum was centered too far south. The forecast successfully predicted the minimum in wave height for the central Pacific. The forecast for the western Pacific was quite good as it correctly predicted the general pattern of the significant-wave–height field and the decrease in wave heights from the previous day.

The forecast valid at 1200 GMT on the 14th (Fig. 4c) gave a fairly accurate representation of the significant-wave–height pattern in the eastern Pacific, but underpredicted the wave heights along the coast of British Columbia. The model successfully predicted the discontinuity in primary direction near 165°W. The forecast correctly showed a minimum in wave height for the central Pacific, as well as the dominance of long-period swell propagation from the west in this region. The forecast for the western Pacific was poor as the model substantially underpredicted wave heights generated by the rapidly developing low off Hokkaido discussed in conjunction with Fig. 2c.

The forecast valid at 1200 GMT on the 15th (Fig. 4d) was better in the eastern Pacific than on the previous day, although the wave heights along the coast of British Columbia were still underpredicted. The forecast for the central Pacific gave a fair representation of the northwest-southeast oriented minimum in wave height present there. The forecast for the western Pacific correctly predicted the broad extent of the high waves, but severely underpredicted the local maximum near the coast of Japan.

Note that most, if not all, of the GSOWM forecast errors discussed here were directly traceable to inaccuracies in the meteorological forecasts which drove the wave model. For example, the local maximum in wave height in the central Pacific at 1200 GMT on the 12th (Fig. 3a) was missed in the GSOWM 48-hour forecast because the low-pressure system centered at 35°N, 165°W on Fig. 2a was absent in the 48-hour NOGAPS forecast. As a result, forecast winds in the region of high waves were underpredicted by about 10 kt. At the same time, the wave heights near the center of the Kuril storm were underpredicted because the 48-hour NOGAPS forecast underpredicted the deepening of this low by about 4 mb, and underpredicted the winds in the region of high waves by about 5–10 kt.

Similarly, the underprediction of significant-wave heights along the coast of British Columbia in the GSOWM 48-hour forecast valid at 1200 GMT on the 14th was a result of NOGAPS underpredicting deepening of the low-pressure system in the Gulf of Alaska. The 48-hour forecast valid at this time underpredicted the deepening of the storm by 12 mb and underpredicted the winds in the area of interest by 10–15 kt. A similar situation gave rise to the underprediction of wave heights in the western Pacific on the 14th and 15th, as the atmospheric model underpredicted the deepening and the winds in the storm off Hokkaido.

Thus, the tendency for GSOWM to underpredict local maxima in forecast wave heights here is a direct result of the tendency for NOGAPS to underpredict deepening of low-pressure systems in its 48-hour forecasts. This type of behavior by NOGAPS is well documented (see Picard and Clune, 1985; Toll and Clune, 1985).

6. Summary

GSOWM is a deep-water linear discrete spectral model which represents exactly the same frequency bands and contains essentially identical physics for wave growth, dissipation, and angular spreading as its predecessor, SOWM. GSOWM functions on the same run schedule that SOWM used and produces basically the same derived output fields. GSOWM differs from SOWM in the following important ways: 1) GSOWM has twice the angular resolution of SOWM in the directional wave spectra, 2) GSOWM is defined on a spherical grid with global coverage, 3) GSOWM contains a propagation algorithm which is superior to that of SOWM, and 4) GSOWM is forced by the GSCLI winds.

An operational test of GSOWM was conducted during the winter of 1984/85. This test involved comparison of GSOWM- and SOWM-predicted significant-wave heights with observations from moored buoys and ocean weather stations, and evaluation of GSOWM output by the users of FNOC wave products. A full suite of statistical verification parameters calculated from the buoy and ocean-station observations.
clearly showed GSOWM superior to SOWM. Comparison of GSOWM and SOWM output with hand analyses of ship-reported wave data also favored the new model.

GSOWM replaced SOWM as the operational wave model at FNOC in June 1985, for all regions except the Mediterranean. This made GSOWM the world’s first global operational wave-forecast model. Output from GSOWM has been archived at FNOC since October 1984, and real-time access to the model predictions is available to commercial users via NODDS, discussed earlier. GSOWM has already been used for planning and interpretation of the Shuttle Imaging Radar Experiment (SIR-B) conducted from the space shuttle in the fall of 1984 (Beal et al., 1986).

FNOC’s immediate plans call for the implementation of a backup version of GSOWM to be run on the CYBER 860 when the CYBER 205 is down. Improvements in the wind fields used to force GSOWM will be sought via enhancements to NOGAPS in the form of a more-sophisticated objective analysis and initialization technique and increased vertical resolution. In the longer term, a Regional Spectral Ocean Wave Model (RSOWM), with horizontal resolution 0(20 km), will be developed and nested within GSOWM. When combined with suitable wind forcing, this will allow a more-accurate representation of the wave field in the vicinity of tropical cyclones and in the semienclosed seas. Finally, as a very long-range goal, the navy is interested in using data from drifting buoys and spaceborne synthetic-aperture radars to update model-predicted directional energy spectra in real time.

Acknowledgments. We thank the Naval Oceanography Command personnel who participated in this study for their efforts. We thank Professor Christopher N. K. Mooers of the Naval Postgraduate School and Dr. Vincent J. Cardone of Oceanweather Incorporated for reviewing an earlier version of the manuscript. Finally, the efforts of Mr. Leo C. Clarke of FNOC are also greatly appreciated. Without his long-term managerial and technical guidance, an operational GSOWM would not have become a reality.

References

—, L. J. Tick, and L. Baer, 1966: Computer based procedures for preparing global wave forecasts and wind field analyses capable of using wave data obtained by a spacecraft. Proc. of the 6th Naval

**announcements**

**Evaluation of NSCAT Proposals Completed**
The National Aeronautics and Space Administration (NASA) has completed its evaluation of the proposals to conduct scientific studies in oceanography and meteorology using data from the NASA Scatterometer (NSCAT). The NSCAT, an active microwave instrument designed to measure wind speed and direction near the sea surface, will provide frequent, accurate, high-resolution vector wind measurements over the oceans. Scheduled to fly aboard the U.S. Navy Remote Ocean Sensing System satellite, NSCAT’s launch is slated for late 1990.

The investigators, whose proposals were chosen by NASA, will comprise a Science Working Team. They are, Robert Atlas, Goddard Space Flight Center; R. C. Beardsley, Woods Hole Oceanographic Institution; Robert A. Brown, University of Washington; Mark A. Cane, Lamont-Doherty Geological Observatory, Columbia University; Dudley B. Chelton, Oregon State University; Peter Cornillon, University of Rhode Island; M. Crepon, Laboratoire d’Oceanographie Physique du Museum, France; Mark A. Donelan, Canada Centre for Inland Waters; Lee-Lueng Fu, Jet Propulsion Laboratory, NASA; Ross N. Hoffman, Atmospheric and Environmental Research, Inc.; William R. Holland, National Center for Atmospheric Research; W. Timothy Liu, Jet Propulsion Laboratory; James J. O’Brien, Florida State University; and James G. Richman, Oregon State University.

**meetings of interest**

7–9 July 1986. A summer engineering conference dealing with flow-visualization techniques will be held from 7 to 9 July 1986 at the University of Michigan, Ann Arbor. The principles and applications of flow-visualization techniques will be presented. Reviews will be held on application to other vehicles, flow devices, heat and mass transfer, wind-tunnel testing, aerospace, boundary-layer phenomena, combustion, atmospheres, oceanography, and medicine. Introductions to digital image processing and flow visualization by computer-generated graphics will also be given. To find out more about the conference, contact Wen-Jei Yang, Director, Engineering Summer Conferences, 300 Chrysler Center/North Campus, Ann Arbor, MI 48109-2092; telephone (313) 764-8490.

9–11 February 1987. The 2nd Multidisciplinary Conference on Sinkholes and Environmental Impacts of Karst is scheduled to be held from 9 to 11 February 1987 in Orlando, Florida. This meeting will continue the interdisciplinary communication begun at the first conference held in 1984. Technical papers and case studies are invited for the following subjects: geology and engineering studies of karst areas with emphasis on sinkholes; hydrogeology and environmental problems of karst; international examples of applied karst geology and hydrology; specific engineering considerations of karst terrain, and any additional related topics. For more information, contact Barry F. Beck, Director, Florida Sinkhole Research Institute, College of Engineering, University of Central Florida, Orlando, FL 32816.

**Deadlines Calendar**

Fellowships, grants, etc.
15 June 1986 Macelwane Annual Award (this issue, p. 539)
15 June 1986 Hanks and Orville Scholarships (this issue, p. 539)

Other
June 1986 applications for Fulbright Scholar grants (March Bulletin, p. 281)

— News Ed.