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THE OPERATIONAL PERFORMANCE OF THE FLEET NUMERICAL OCEANOGRAPHY CENTER GLOBAL SPECTRAL OCEAN-WAVE MODEL

An operational 72-hour global wave forecast is made at the Fleet Numerical Oceanography Center, but because of the inaccuracy and scarceness of suitable wave observations, the wave forecast remains uninitialized by any observations. Present model performance is given here so we can learn what degree of improvement might be expected should directional wave spectral observations from satellites become available.

INTRODUCTION

Knowledge of the sea state is very important to naval operations and maritime activities. A forecast of surface-wave conditions at sea aids ship routing, allowing measurable reduction of fuel costs, and can help to lessen or entirely eliminate costly damage to ship structures caused by wave action.

At the Fleet Numerical Oceanography Center (FNOC), the numerical modeling of waves began in the mid-1960s by applying a Singular Wave Model.[1] This model was replaced in the mid-1970s by the northern hemisphere Spectral Ocean Wave Model (SOWM).[2] In June 1985, the SOWM was succeeded by the Global Spectral Ocean Wave Model (GSOWM), which is the world's first (and only) operational global wave model. Because of its global coverage, it was able to provide a 72-hour wave forecast off the southern tip of Chile for the SIR-B experiment.

Only a brief synopsis of the physics in GSOWM is given here; Pierson[3] provides a much more detailed account. The wave growth mechanism, that of Inoue,[4] modifies and combines the Miles[5] instability mechanism with the Phillips[6] resonance theory. Thus, GSOWM does not incorporate the more recent developments in wave theory, such as spectral overshoot and nonlinear wave-wave interactions. The growth equations predict the evolution of the one-dimensional spectrum rather than of the directional spectrum. The directional spectrum is inferred by spreading the resulting wave energy for wind sea over the directional bins of the model as the fourth power of the cosine of the angle between the spectral component and the wind. Wave energy is dissipated for spectral components traveling against the wind by an empirical function of energy, frequency, and angle relative to the wind. No dissipation occurs for spectral components that are unopposed by the wind. Finally, wave energy is propagated along great-circle paths at the group velocity of each spectral component.

Much about the modeling of waves in GSOWM is the same as that in SOWM. However, there are four important differences: first, GSOWM has twice the angular resolution of SOWM, resolving 24 directions instead of 12; second, GSOWM uses an entirely different grid—a 2.5 degree spherical grid instead of the icosahedral gnomonic grid used by SOWM— and thus the average spacing between grid points is smaller for GSOWM than for SOWM; third, GSOWM has an improved energy-conserving propagation scheme; and fourth, GSOWM is global, allowing waves to propagate across the equator.

When GSOWM replaced SOWM, the wind model that provides the winds to the wave model was also replaced. The performance of the new wind model is significantly better, but it clouds the issue of how much GSOWM is improved over SOWM because the performance of the improved wind model improves the performance of the wave model. Clancy et al.[7] give more details about recent improvements in the wind model.

GSOWM is not initialized by observations; it provides its own initial conditions by integrating the spectral history file from the prior wave analysis forward in time. The directional wave spectrum modeled by GSOWM is rarely observed by any measurement system, is not sufficiently abundant, and is not available in near real time for model initialization. Although FNOC has been modeling the directional wave spectrum operationally since 1974, the difficulty of observing the spectrum has prohibited its verification completely until the SIR-B experiment in October 1984 (see the article by Beal elsewhere in this issue). Even then, the spectrum was observed for only five days. However, the results are promising. The remote sensing of the two-dimensional spec-

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trum with the synthetic aperture radar and/or the Radar Ocean Wave Spectrometer (see the Jackson articles, this issue) may be the most practical and cost-effective approach to providing global validation of wave models.

PERFORMANCE OF MODELS

Figure 1 is an example of a GSOWM wave chart for October 10, 1984, during the SIR-B experiment. Northwest of the experiment site (55.5°S, 82.5°W), GSOWM shows an eastward-traveling wave system, with a maximum significant wave height $H_{1/3}$ of 24 feet and a primary period of 14 seconds.

Figures 2a-d show the type of verification that is performed monthly at FNOC for the surface wind and wave models. The moored buoys from the NOAA Data Buoy Center (NDBC) are used to provide observations of the frequency spectrum, significant wave height, and wind speed. The 1-sigma error level of the buoy-reported significant wave height is 0.5 meter. The colored lines are least-squares regression lines. The plots are for buoys located in the Gulf of Alaska (46001, 46002, 46003, 46004, 46006) and off the Hawaiian Islands (51001, 51002, 51003, 51004). The time period is for March 1985.

Figure 2a shows the SOWM winds to be scattered and biased high. The errors are significant. The slope of the least-squares fit is 0.41 while the intercept is 7.03 meters per second. The root-mean-square error (rms) is 4.23 meters per second.

Figure 2b shows the GSOWM winds to be improved over SOWM, though they are still far from perfect. Both the scatter and the positive bias are reduced. The slope of the least-squares fit is 0.72 while the intercept is 3.11 meters per second. The rms error is 2.62 meters per second. The reader should note that the wind observation made by the buoy is for only 8 minutes, while the FNOC-modeled wind is averaged over 3 hours. This comparison of an 8-minute observation to a 3-hour average is not entirely justified and is a source of some of the scatter evident in Figs. 2a and 2b.

Figure 2c shows the significant wave height ($H_{1/3}$) verified against the NOAA buoys. The SOWM waves are scattered and biased high, evidencing a direct correlation with the same problems in the modeled winds. (Here we have a good example of how errors in modeled winds introduce errors in modeled waves.) The slope of the least-squares fit line is 0.77 while the intercept is 1.73 meters. The rms error is 1.43 meters. Figure 2d shows GSOWM to be an improvement, with less scatter and a lower bias. The slope of the least-squares fit line is 0.89 while the intercept is 0.66 meter. The rms error is 0.90 meter.

Figure 3 shows a variety of time series at one buoy location (that of buoy 46002, off the coast of Oregon) during November 1985. Modeled $H_{1/3}$, wind speed, and wind direction are plotted every 12 hours and are identified by boxes. The buoy observations of the same parameter are identified by circles. The time series at the bottom of the figure is the buoy-observed air-sea temperature difference. The negative value occurring during most of the month indicates that the boundary layer was largely unstable in November. The rms error in the winds was 2.52 meters per second and the rms error in the waves was 0.71 meter. It should be noted that the errors are small enough to be about equal to the accuracy of the buoy observations. Taken as a whole, the time series shows that when the winds are accurately modeled, the numerical modeling of waves without any initialization through observations can also be quite good.

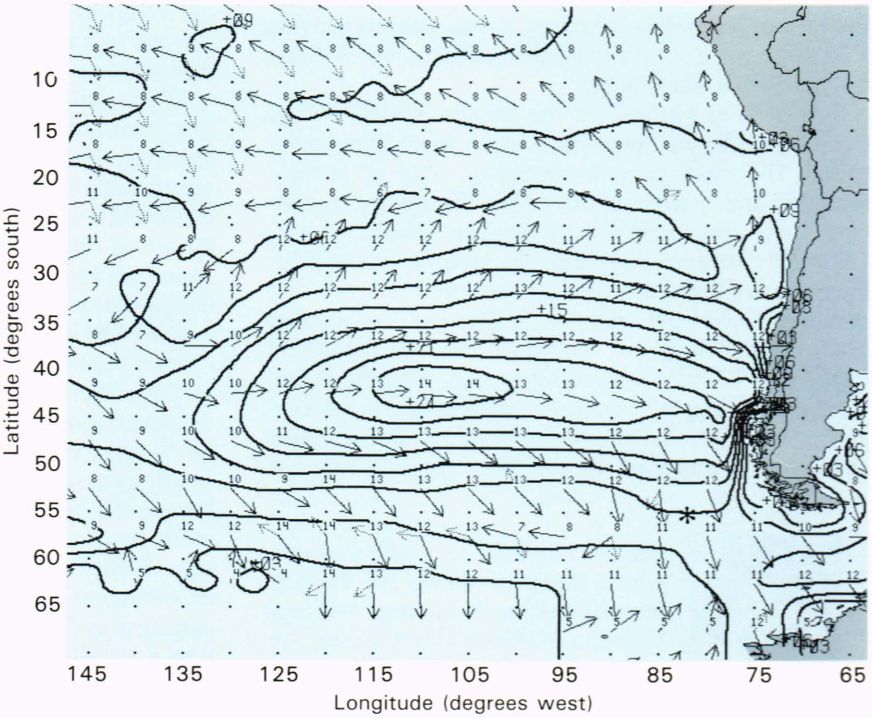

Figure 1—GSOWM wave chart during the SIR-B experiment. The contours are of significant wave height $H_{1/3}$ in feet with a 3-foot contour interval. The dark arrows indicate the primary wave direction, and the occasional faint dotted arrow, the secondary wave direction. The integers show the primary wave period in seconds. The asterisk marks the general location of the SIR-B experiment.

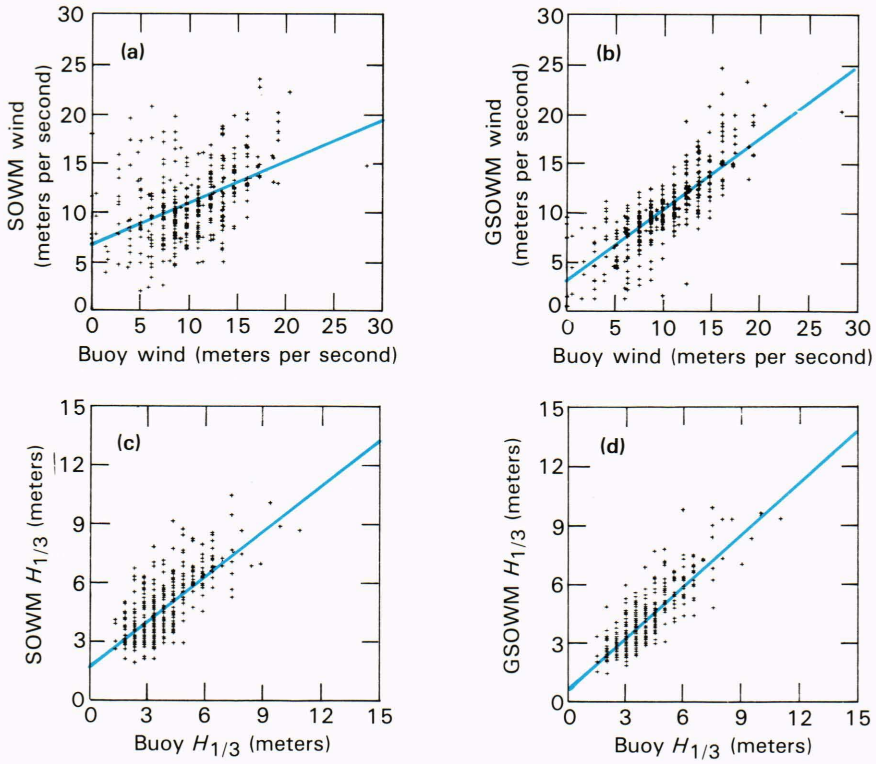

Figure 2—Scatter plots of (a) SOWM winds, (b) GSOWM winds, (c) SOWM $H_{1/3}$, and (d) GSOWM $H_{1/3}$ versus buoy observations in the Pacific Ocean for March 1985. Colored lines are least-squares regression lines.

Unfortunately, the winds are not always very good. In January 1986, the time series (not shown) for buoy 46002 reveals that the FNOC winds are often biased too high. The rms error in the winds for that month was nearly twice that for November, at 4.73 meters per second. As a result, the error in the GSOWM $H_{1/3}$ was also nearly twice as high at 1.85 meters.

SHIP OBSERVATIONS

The most abundant observations of waves are made from ships. However, the accuracy and usefulness of these observations seem always to be a matter of debate. For example, in 1985 a study was made in which the observations of waves from ships were verified against the NDBC buoys and the North Atlantic Ocean stations (C7C, C7L, and C7R). To qualify, a ship needed to pass within 1 degree of latitude and longitude of a buoy and to report during the same hour as the buoy. The total number of reports obtained in this manner was 1030. The buoys used were 51001-51004, 46001, 46003-46006, 41001, 41002, 41006, 44004, and 44008. As with the prior verification of the FNOC models, the ship-reported $H_{1/3}$ was regressed against the buoy $H_{1/3}$. The results are presented in Table 1.

In general, the ship observations showed a significant amount of scatter and were biased slightly high at about 0.5 meter. For the identical buoy observations, the same type of analysis was done for GSOWM, which is not initialized by any observations. As Table 1 shows, every statistic is better for GSOWM than for the ship reports. Therefore, the performance of GSOWM cannot be improved or even properly verified against such observations.

Table 1—Comparison of statistics derived from observations of waves by ships and modeled waves (independent of ships' observations) to observations by NDBC buoys. The performance of GSOWM is better than these observations.

	Ship $H_{1/3}$	*GSOWM* $H_{1/3}$
Least-squares slope	0.86	1.06
Least-squares intercept (meters)	0.76	0.43
rms error (meters)	1.23	1.11
Correction coefficient	0.73	0.84
Scatter index	0.47	0.39

A careful study of wave observations from ships in the southern hemisphere was made by Laing.[8] In spite of our having a better controlled data set, his results are strikingly similar to those presented here. For a period of 20 months, 2138 useable data pairs were obtained from a vessel servicing a production platform in the South Taranaki Bight (west of New Zealand). The ship observations were made within 33 kilometers of the platform. The measured $H_{1/3}$ came from a Waverider buoy. The linear regression of the ship reports on the measured values gave $H_{1/3}$ (ship) $=$ 1.17 $H_{1/3}$ (buoy) $+$ 0.60. The rms error was 1.3 meters.

CONCLUSIONS

GSOWM demonstrates a useful level of skill in its ability to forecast waves. However, the performance of

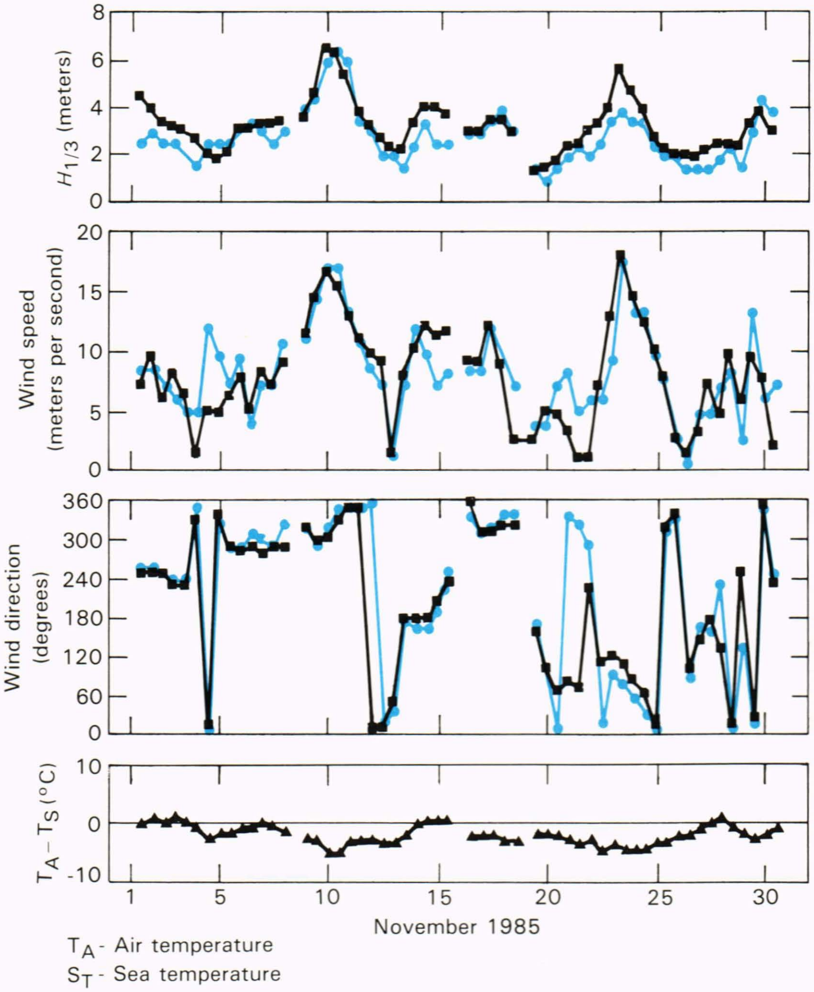

Figure 3—A variety of time series at one buoy location (buoy 46002 off the coast of Oregon) during November 1985. Modeled $H_{1/3}$, wind speed, and wind direction are plotted every 12 hours and are identified by boxes (black curves). The buoy observations of the same parameter are identified by circles (colored curves). The time series at the bottom of the figure is the buoy-observed air-sea temperature difference.

GSOWM could be improved through better knowledge of winds. The performance of wave models is clearly limited by the accuracy of the winds that drive them. Winds seem to be more difficult to model than waves. The observation of global wind fields in the early 1990s by the European Earth Resources Satellite should improve the quality of the winds, thereby improving the performance of numerical wave forecasting. It is not yet known how good the numerical modeling of waves can be if the wind fields are accurate.

Although GSOWM became operational only recently, it does not include the more recent developments in wind-wave theory such as spectral overshoot and nonlinear wave-wave interactions. A time lag exists between the development of theory and its implementation operationally. It is not yet established what degree of improvement can be expected from these more recent ideas.

Methods to achieve more accurate forecasting of spectral ocean waves look very promising. The theory of the evolution of the directional wave spectrum has progressed well over the years in spite of an almost total absence of observations. A clear need exists to observe these spectra in order to verify and initialize ocean-wave models and to increase our understanding of the spectral evolution.

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