AN OPERATIONAL SPECTRAL WAVE FORECASTING MODEL FOR THE GULF OF MEXICO[1]

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1. INTRODUCTION

Until recently, the NWS has been issuing wave forecast guidance for the Gulf of Mexico using a model developed by the Techniques Development Laboratory (TDL). The model empirically relates the significant wave height and period to wind speed, fetch and duration. The model performance was found to be inadequate in terms of accuracy and consistency of forecasted wave fields. Furthermore, wave forecasts are needed for both the deep (offshore) and shallow (coastal) areas of the Gulf. In each of these areas the dynamics of the wave physics are quite different and the empirical model cannot take these effects into account.

There are two operational global models which also routinely forecast wave conditions for the Gulf. They are the Fleet Numerical Oceanography Center Global Spectral Ocean-Wave Model (GSOWM) and the NOAA Ocean Wave (NOW) model. These models employ dynamical spectral wave forecasting techniques. However, in addition to being global scale models with coarse horizontal resolution, they are only applicable to deep water cases. The effects of bottom conditions on the modification of the wave spectrum are not considered in these models.

In order to improve and extend NMC's wave forecasting capability over the coastal areas of the Gulf of Mexico, a regional spectral ocean wave model, applicable for both deep and shallow waters of the gulf has been implemented recently. Model performance has been evaluated by means of statistical error analysis of the significant wave height forecasts against measurements at NDBC buoys in both deep and shallow water of the gulf. The result of evaluation along with an intercomparison with other deep water wave models forecasts are presented in this paper.

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2. WAVE MODEL CHARACTERISTICS

The present model is an adaptation of the model developed by Duffy and Atlas (1984) to the Gulf of Mexico. The essential governing equations and computational procedures follow the model described by Golding (1983). The model solves the energy balance equation of the form

$$\partial E/\partial t = - \nabla \cdot (VE) - \partial\{(V \cdot \nabla\theta)E\}/\partial\theta + I + D + N \tag{1}$$

where $E(f, \theta)$ is the spectral density of the wave field, V the group velocity and θ is the wave direction, and where I represents energy input from winds, D energy loss due to whitecapping and bottom effects and N the redistribution of energy within the wave spectrum due to conservative nonlinear wave-wave interactions. The equation is solved in four stages in the following order: propagation, refraction, growth and dissipation, and nonlinear interaction.

In computing wave propagation, Golding (1983) used a modified Lax-Wendroff integration scheme while Duffy and Atlas have chosen a two-step, third order scheme suggested by Takacs(1984) to minimize numerical dissipation and dispersion. At grid points adjacent to the coast, this scheme, however, cannot be used because it uses values from two grid points away from the central grid. At these points, simple upstream differencing scheme is used assuming that no waves would be reflected from the shore. The wave refraction effect in shoaling water of varying depth is computed according to Golding (1983). The procedure involves using centered differences to compute the water depth derivatives and using upstream dufference to solve the refraction portion of the wave energy equation in flux form.

The growth of waves driven by input surface winds, I, is modelled according to conventional linear and exponential terms representing, respectively, an excitation by turbulence fluctuation in the surface wind and the coupling of existing waves with mean shear flow in the marine boundary layer.

The wave energy dissipation in deep water due to whitecapping is determined according to a formulation involving the entire spectrum as described by Hasselmann (1974). In shallow water, in addition to the calculation of bottom friction loss of wave energy formulated by Collins (1972), a computation of energy loss due to bottom percolation proposed by Shemdin et al. (1980) is included in the present model.

The nonlinear wave-wave energy transfer is considered in a parameterized and empirical manner. Firstly, a wind-sea spectrum is defined as that part of a spectrum that is : (1) above 0.8 of the peak frequency and (2) within 90 degrees of direction of wave propagation and wind direction. This wind-sea spectrunm is then forced to conform to a modified JONSWAP spectrum based on the assumption that nonlinear interactions will always act to bring the wind-sea spectrum back to the modified JONSWAP-shape spectrum. This modified JONSWAP spectrum incorporates the saturation range in water of arbitrary depth suggested by Thornton (1977) and a cosine square angular spreading function with the original JONSWAP spectrum (Hasselmann et al.,1973).

The peak frequency is determined through an iterative procedure involving empirical equations.

At present, the model has twenty frequency bands ranging from 0.04 to 0.42 Hz and twelve direction bands. The Gulf of Mexico is assumed to be an enclosed ocean basin. Thus incoming waves from the Yucatan Straight and the Straight of Florida are ignored. The grid mesh is 37x27 with a grid interval of 55 km and the computational time step is 30 minutes. The model has been running daily on the NMC Cyber 205 computer generating wave spectra at three hour intervals out to 48 hours. The required wind input at a height of 10 meters above the sea surface is derived from the NMC Regional Analysis and Forecasting System (Hoke, 1984). A modified two layers boundary model described by Cardone (1969) incorporates stability effects due to air-sea temperature difference. The wind field forecast is made at six hour intervals.

3. FORECAST PERFORMANCE EVALUATION

Wave data are acquired from buoy measurements in the Gulf of Mexico operated by NOAA Data Buoy Center. The buoy station 42001 on deep water is located at about the center of the Gulf (25.9N, 89.7W), midway between stations 42002 (26.0N, 93.5W) and 42003 (26.0N, 85.9W). The station 42015 (30.1N, 88.2W) is on a water depth of 16 m, 5 nm south of Dauphin Island near Mobil, Alabama. The wave data analyzer (WDA) wave measurement system mounted aboard a deep water buoy, consisting of an axial linear accelerometer, provides spectral estimates with a bandwidth 0.02 Hz and degrees of freedom of 48. The frequency bands range from 0.01 up to a cut-off frequency of 0.39 Hz. The upper and lower bounds of the 90% confidence interval are, respectively, 1.36 and 0.69 of the estimated value. At station 42015 is a pitch-roll directional wave-measuring buoy comprises a data acquistion control and telemetry (DACT) directional wave analyzer (DWA) system. The directional-frequency spectrum has a frequency bandwidth 0.01 Hz with center frequencies ranging from 0.03 to 0.35 Hz and the degree of freedom 24 (Steel and Lang, 1988). The upper and lower bounds of the 90% confidence interval are therefore 1.52 and 0.58, respectively. The wave data and other data such as wind speeds and directions were encoded and relayed to NMC via the Geostationary Operational Environmental Satellite (GOES). The anomometer height is 10 meter above the mean sea level.

The statistical error analysis is performed for the significant wave height forecasts of each model interpolated to the buoy locations at forecast hours : +12 Z, +24 Z, +36 Z and +48 Z using the concurrent buoy measurements as common validation standard. Willmott(1982) has suggested a series of statistical indices which should be calculated since no single index can adequately describe model perfomance. In this study, the analysis consists of the monthly mean bias error $BIAS$, correlation coefficient $CORR$, mean square error MSE as well as its systematic and unsystematic proportions of magnitudes $(MSE)_s$ and $(MSE)_u$. These indices take the form

$$BIAS = N^{-1}\Sigma(P_i - O_i) \tag{2}$$

$$MSE = N^{-1}\Sigma(P_i - O_i)^2 \tag{3}$$

$$(MSE)_s = N^{-1}\Sigma(\hat{P}_i - O_i)^2 \quad (4)$$

$$(MSE)_u = N^{-1}\Sigma(P_i - \hat{P}_i)^2 \quad (5)$$

$$CORR = \left\{\Sigma[(P_i - \bar{P})(O_i - \bar{O})]\right\} / \left\{\Sigma(P_i - \bar{P})^2\Sigma(O_i - \bar{O})^2\right\}^{1/2} \quad (6)$$

where N is the number of data points and, $\hat{P}_i = a + b\,O_i$, in which a and b are the intercept and slope of the least squares regrression, respectively, and where $\bar{P}$ and $\bar{O}$ are the means values of model predictions and measurements, respectively.

The MSE or its square root ($RMSE$) summarizes the mean difference in the units of P and O . The MSE comprises two parts, i.e., $MSE = (MSE)_s + (MSE)_u$. For a good model, the systematic difference, from the model should approaches zero while the unsystematic difference approach MSE.

Figures 1 shows monthly statistics of the significant wave height forecasts of the present Gulf of Mexico wave model (GMEX) from October 1987 through February 1989 for the projection hour +24Z at deep water location -NDBC 42001. The statics shown in these figures include bias, root mean square error, correlation coefficient and the ratio of systematic root mean square error to total root mean square error. Also shown in Figure 1 are the results of other model forecasts, i.e., NOW model, GSOWM and TDL model.

In comparison with other models, the GMEX model tends to under- predict the significant wave height (SWH) in deep water while the NOW model and GSOWM tend to over-predict SWH. The TDL model also has shown negative bias for most months during the period when it was operative. Monthly root mean square error of the GMEX model is comparabl with other models except September 1988. During that month, two hurricanes past through the gulf (Hurricane Florence and Hurricane Gilbert) and the wave height is over-predicted as a result of over-forecast of wind speed by Cardone's boundary layer wind model (1969). This is expected because the model is not designed for hurricane wind prediction. The graph which shows the monthly variation of correlation coefficient indicates that GMEX performs, in general, more consistent with measurements than other models.

The sources of systematic error in the wave height prediction are the result of inperfection in the wave model itself and/or the input wind from the wind model. Monthly variation of the ratio of systematic root mean square error $(RMSE)_s$ to the total $RMSE$ is presented for both wave height and boundary wind predictions. It is of interest to observe that the parterns of their variations are quite similar. It suggests that errors in the wind prediction is a major souce that contributes to the error in the wave prediction, at least, in deep water.

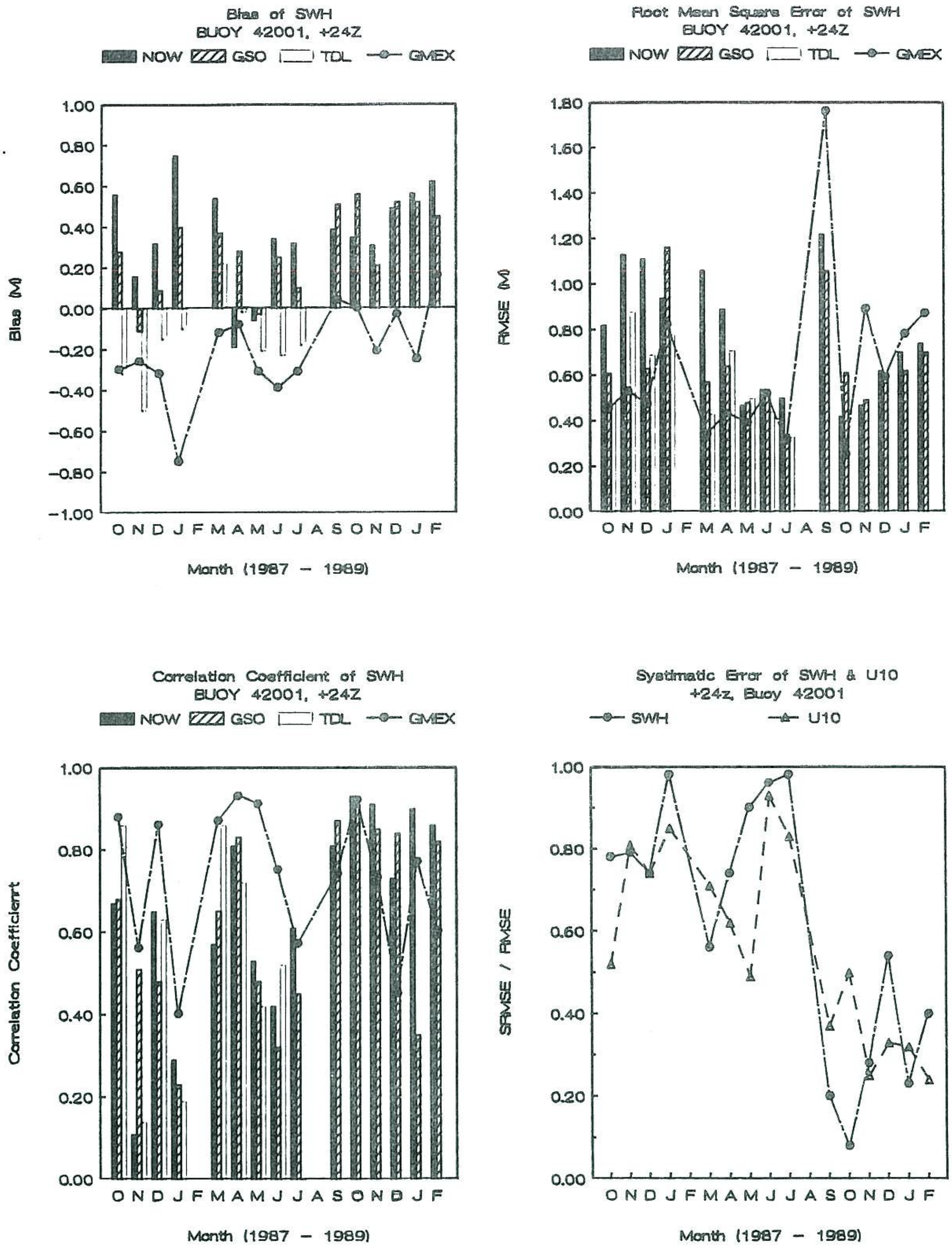

Figure 1: Monthly statistics for +24Z forecasts at a deep water location - Buoy 42001.

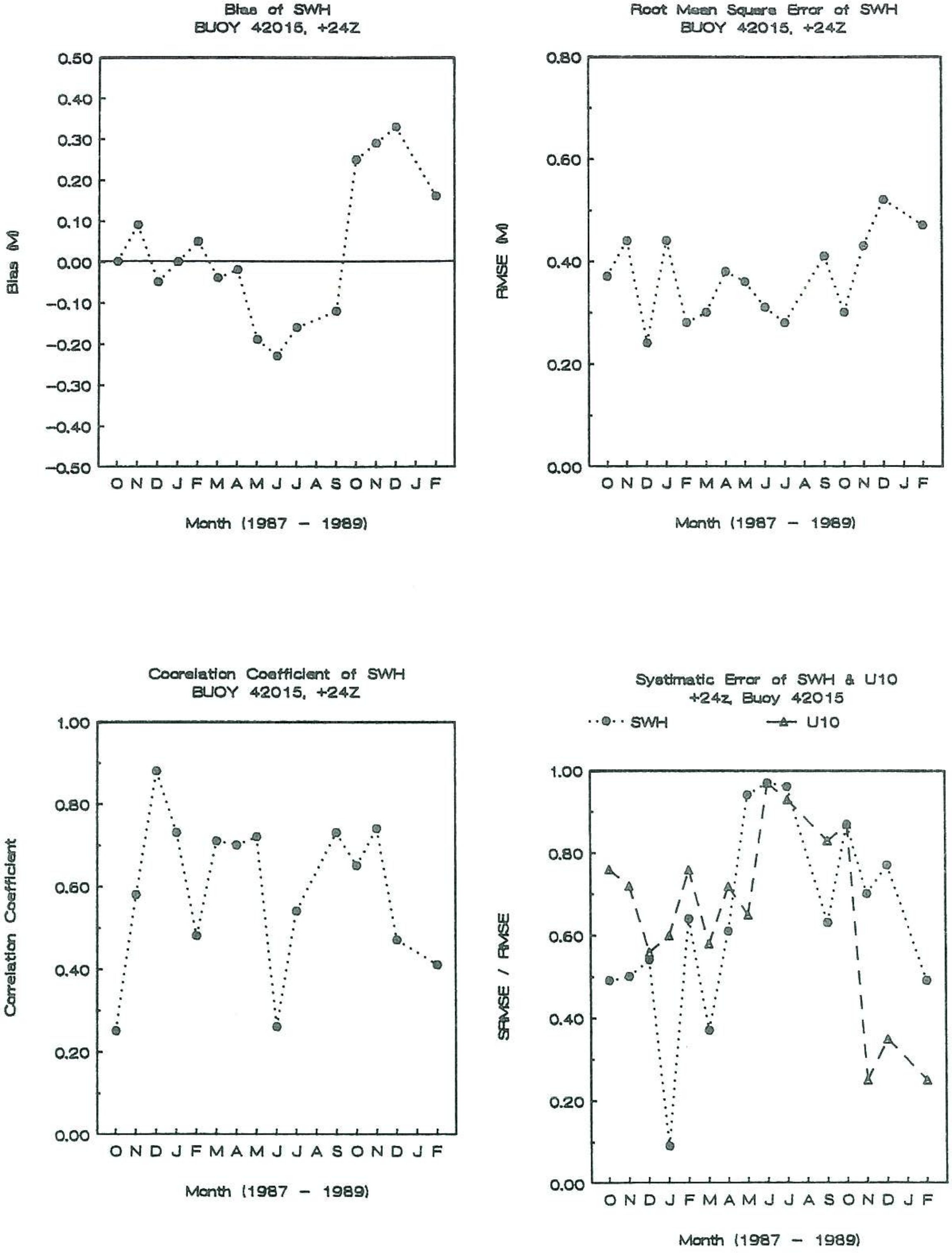

Figure 2: Monthly statistics for +24Z forecasts at a coastal water location - Buoy 42015.

Figures 2 shows monthly statistics of the GMEX model significant wave height forecasts for the same time frame and projection hour but in a water depth of 16 m - Buoy 42015.

In contrast to the deep water situation, monthly mean bias fluctuates around zero value ranging betweeen +0.30 and -0.20 meter. the maximum and meanimum vaules of RMSE during 17 months period of time is 0.55 and 0.25 meter and the mean value is 0.35 meter. Error in wind forecast associated with hurricanes Florence and Gilbert during September 1988 does not cause extreme RMSE value as what has happened in deep water situation. This seems to imply that wind is not the only dominant factor affecting coastal wave conditions. It also can be seen from a graph which shows monthly variation of systematic root mean square error of the wave height and wind speed that there is no close similarity in the patern of fluctuation, i.e., error in wave forecasts is not due to error in wind forecast alone.

4. CONCLUDING REMARKS

The performance of NMC Gulf of Mexico spectral wave forecast model has been evaluated against buoy measurements and other wave forecast models - GSOWM, NOW,and TDL models for the months from October 1987 to February 1989. The model performance evaluation presented in this paper concentrates solely on the the significant wave height forecasts. Three major error statistics, i.e., the monthly bias, root mean square error and the systematic error and a supplementary statistics - correlation coefficient are used as the evaluation standard. The results show that the GMEX model performs better than other models in deep water except during the errorneous hurricane wind forecast situation. The model performs quite well in coastal areas. Further improvement of the model can be achieved by improving wind forecasts and tuning of certain parameters involved in the model formulation.

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