CHAPTER 371

The Use of Data Assimilation to Improve Wave Hindcast Results

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Abstract

A sequential data assimilation scheme was used to assimilate wind speed and direction measured at land and buoy platforms into a modeled wind field over the Gulf of Mexico during January 1996. The resulting wind field is more accurate than the modeled field alone for locations near the coast where winds are affected locally by transition from land to water. The assimilated winds result in improved hindcasts of wave height over modeled winds alone when compared to wave measurements from buoys.

Introduction

Data assimilation is the process of incorporating observations of a dynamic system into a model of the system. In the context of wave modeling, this is the process of incorporating observed wind and/or wave information into a wave model or the results from a wave model. At this stage of wave model development, the most significant and timely improvement in the accuracy of model results lies in the combination of measurements and model results.

The Wave Information Study (WIS) at the Coastal and Hydraulics Laboratory (CHL) has developed and is applying a WIS Data Assimilation System (WDAS) to make optimal use of data collected under the Coastal Field Data Collection Program at CHL. The objective is to improve the accuracy of hindcast results, especially in high energy events where available wind fields and/or present wave models are sometimes not sufficiently accurate.

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Accuracy of Present Wave Models

Cardone et al. (1996) conclude that first, second, and third generation wave models presently in use give equivalent results when used to hindcast extreme wave heights in two severe storms off the U.S. East Coast. Their conclusion is based on comparison of model results to measurements from nine buoys. They also note that all models underestimate the highest waves over 12 m. Tracy and Cialone (1996) provide statistics from comparison of results from the same second generation model used by Cardone et al. to 16 buoys off the U.S. East Coast for one year, 1994. They conclude there is little bias in wave height and peak period results from the model compared to measurements, and root mean square differences are about 0.5 m and 2 sec, respectively. Until a significant improvement in wave modeling emerges, the most expedient approach to improved accuracy is the use of data assimilation in wave hindcasting.

Assimilation Techniques

All data assimilation techniques attempt to improve the results of a model by using some method to minimize the difference between model results and a set of observations of model variables, spaced closely in location and time to model values and considered more accurate than model values. Data assimilation approaches can be grouped into two general categories. One is referred to as sequential and the other variational.

Sequential techniques use observations to improve model results only at the time the observations occur; that is, current observations are discarded as soon as assimilated. Their success increases with the number of observations in space each time data are assimilated. A number of different approaches are included in the sequential method. These are, in ascending order of complexity, direct insertion, blending, nudging, optimal interpolation, successive corrections, and Kalman filtering.

The adjoint method is a commonly used variational approach. It considers a set of observations in space over a certain time interval which by ergodicity is equivalent to a distribution in probability space. Again, the objective is to minimize the difference between model results and observations or a cost function. This is done by solving a set of equations consisting of the model equations and adjoint equations. The adjoint equations are formed by differentiating the cost functions with respect to a control variable and setting the result equal to zero. This differentiation can be very difficult due to the dynamical coupling between state variables in the cost function and control variables, for example, wave height and wind speed, respectively.

Hubertz, Thompson, and Wang (1996) provide a summary of recent studies which employed these techniques to improve wind, wave, and water level/current model results. The WDAS employs a sequential technique similar to optimal interpolation which allows assimilation of vector or scalar measurements from random points on a latitude, longitude grid with model data and interpolation to a target grid using minimization of a quadratic form to provide fit and smoothness.

WIS Data Assimilation System

Application of the system consists of three steps. First, available measurements pass through a quality control filter to ensure only valid data are used and they are consistent in characteristics, e.g., units, conventions, elevation, etc. Second, a target grid is specified upon which the results of the assimilation process will be available for use. Randomly spaced measurements and/or data from a model are interpolated to this target grid. Finally, a set of equations (one for each target grid point) is solved which minimizes the difference between input data and final values on the target grid. The equations allow a weight for data type if one type of data is considered more important, and a smoothing weight on a derivative constraint to control smoothness of the final field. The equations to be solved have the form

$$w_d(F_d - F)^2 + \beta^2[(\delta F/\delta x)^2 + (\delta F/\delta y)^2] = Minimum$$

where F refers to a vector or scalar variable, d to input data, w a weight, β a smoothing parameter, δ the derivative operator, and x, y the longitudinal and latitudinal directions, respectively. The equations are solved with a Gauss-Seidel iteration scheme. Details of the system are provided by Oceanweather Inc. (1996).

Results - Time Series at a Point

Wind speed and direction from buoys and coastal land stations in the Gulf of Mexico were assimilated into an approximate 1 degree latitude, longitude background wind field from the National Meteorological Center (NMC) during January 1996. Figure 1 shows the locations of measured and modeled wind data. Measured data locations are indicated by either the alphabetie Coastal-Marine Automated Network (CMAN) designation or the National Data Buoy Center (NDBC) numeric identifier. Modeled National Center for Environmental Prediction (NCEP) wind results are indicated by the meteorological wind barb symbols.

Measured data are available every hour while NCEP data are available at a 6-hour interval. The NCEP data are interpolated in time to every hour. NCEP values are removed within a specified radius of measured values to give added influence to the measured data. Figure 2 provides an example of the difference between modeled NCEP data, measured data from the buoy and the assimilation product WDAS using both NCEP modeled and buoy data at the grid point closest to the buoy. The WDAS and buoy data are almost identical reflecting the influence of the assimilation process at the grid point closest to the buoy. The NCEP model data depart from the other two most notably at times of higher wind speeds, which in these cases are due to fronts moving offshore. These are at approximately hours 175, 275, 450, and 650 in Figure 2.

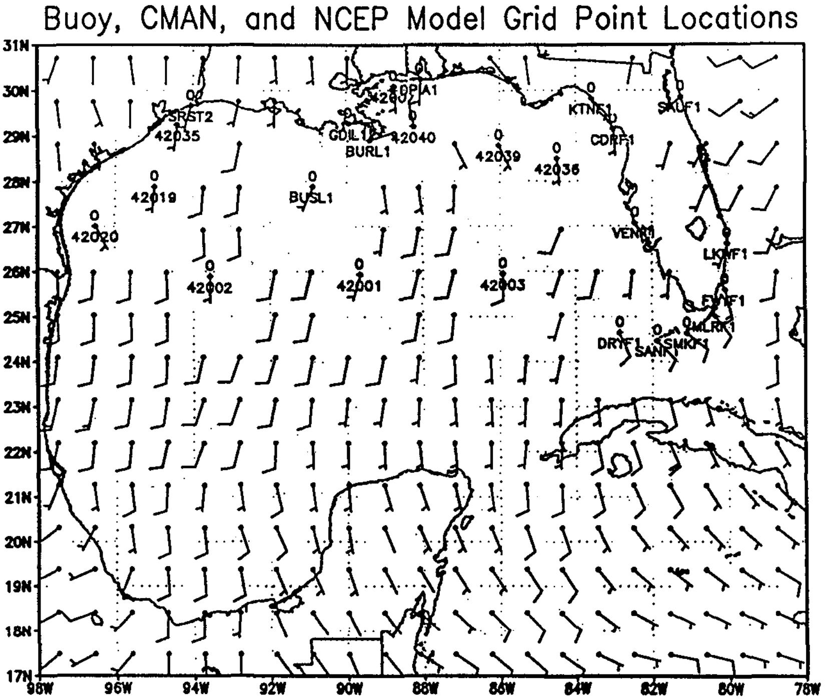

Figure 1. Locations of Measured and Modeled Wind Data

Wind fields from NCEP and from the assimilation process were input to the WISWAVE model to hindcast wave conditions over the Gulf of Mexico during January 1996. The hindcast results were then compared to wave measurements made at the buoys shown in Figure 1. Hindcast wave height results at the grid point closest to the buoy and measured values at the buoy are compared in Figure 3. Wave heights are overestimated at the same times wind speeds are overestimated, the NCEP winds being higher with respect to hindcast values using assimilation with measurements at the buoy. The first 50-75 hours in Figure 3 represent the "spin-up" of the model and should not be used to compare differences in wind input. At other times there is little difference between using NCEP winds and the assimilated wind product.

In general there was little improvement in hindcast wave height and peak period using the assimilated winds over using the NCEP winds alone, as measured by monthly values of bias and root mean square differences at the eight buoys recording wave information during January 1996. However, these monthly statistics mask cases where

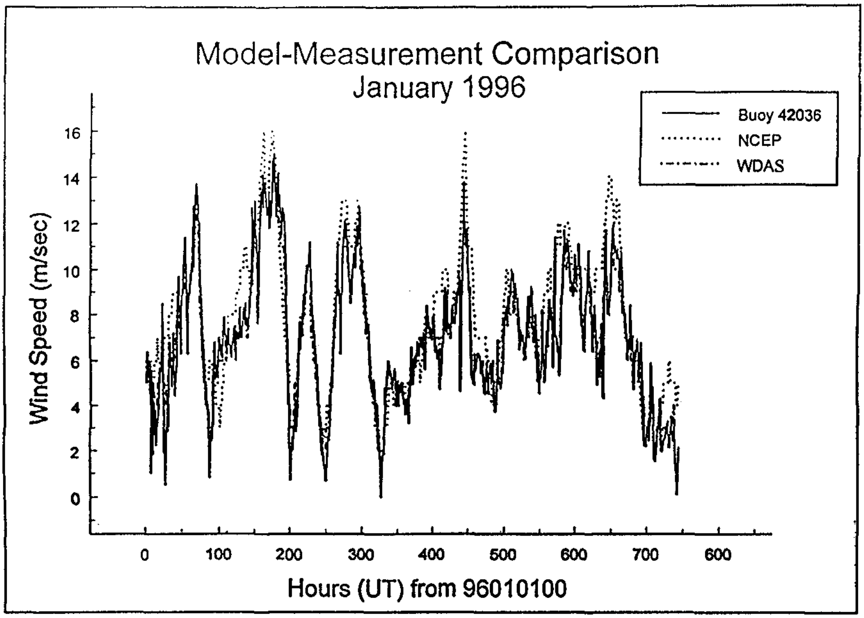

Figure 2. Wind Speed Versus Time at Buoy 42036 for Measured, Modeled, and Assimilated Data

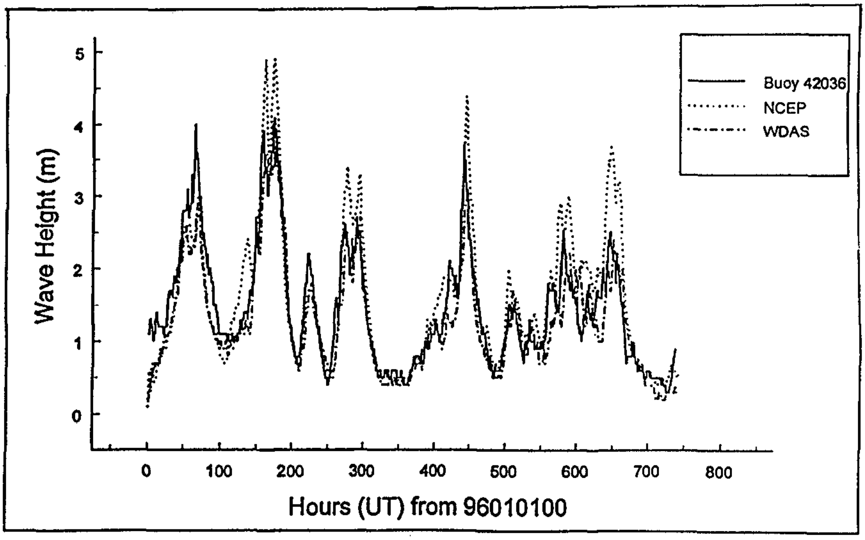

Figure 3. Wave Height Versus Time from WISWAVE Model Using Wind Input from NCEP Model and Winds from WDAS Compared to Measurements from Buoy

the NCEP winds did not accurately represent local wind speeds and directions. In these cases, improved hindcast values of wave height and peak period were obtained.

Results - Wave Height on Grid at One Time

Next, differences in hindcast wave heights over the entire grid at one time are shown for the case of using NCEP winds alone and using the product of the assimilation process. Figure 4 shows the winds over the Gulf of Mexico at 0100 UT on January 28, 1996. This corresponds to hour 650 on the previous time series plots. The contour interval is 1 m/s. Wind speed is relatively high (10 m/s) and offshore along the northwest coast of Florida. It was in this area assimilated winds were lower than NCEP winds (Figure 2) and resulted in lower wave heights of about 1 m (Figure 3).

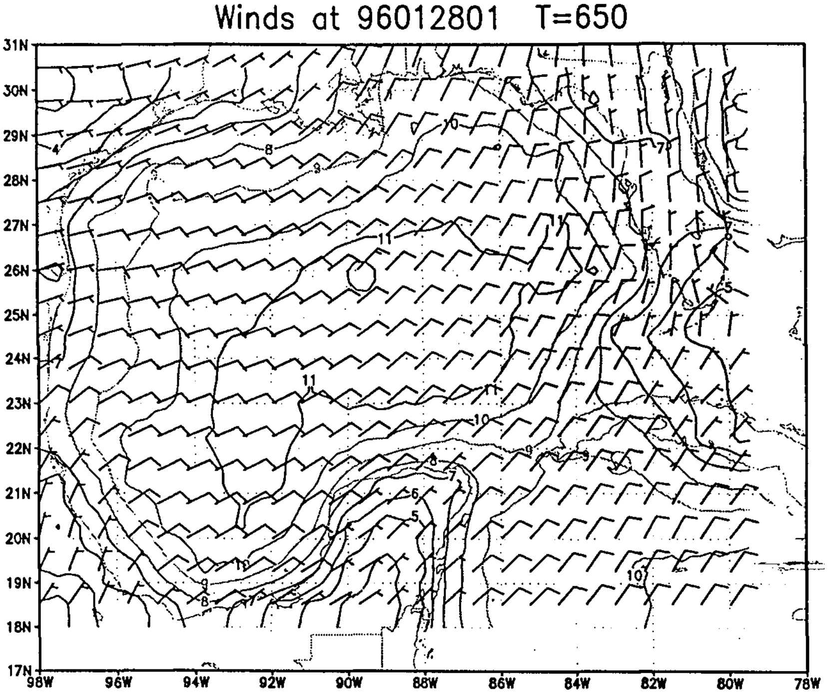

Figure 4. NCEP Wind Field Over Gulf of Mexico at 0100 UT, January 28, 1996

The difference in hindcast wave height using NCEP winds as input and using the assimilated winds as input over the whole Gulf at hour 650 is shown in Figure 5. The contour interval is 0.4 m. Most of the difference is in the northeast Gulf where the land/water boundary has an influence on offshore winds. These differences illustrate the spatial effect of assimilating data when the NCEP winds do not accurately model local conditions. Note, that in other areas differences are small indicating there is little effect of using assimilation. In these areas at this time, the NCEP winds provide accurate wave results.

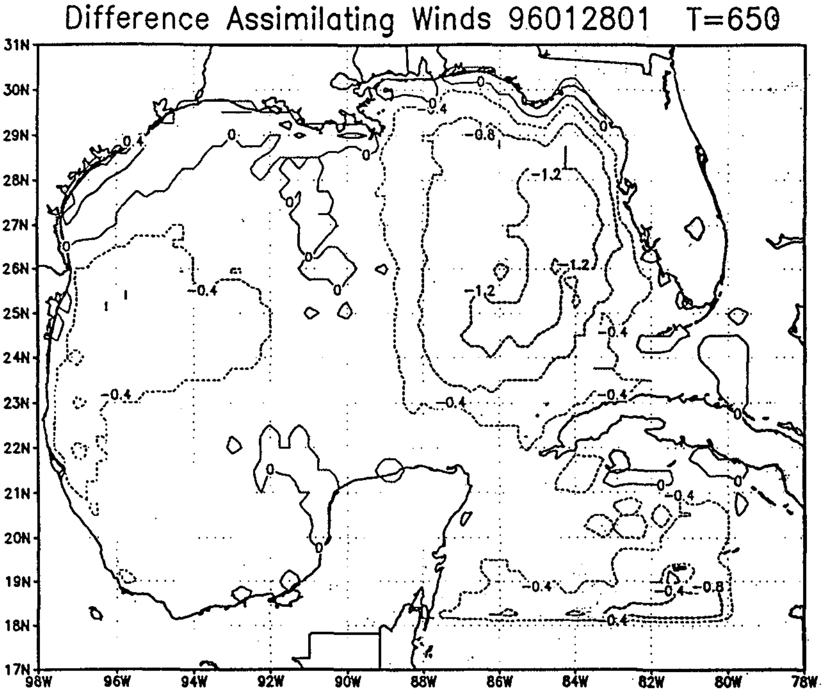

Figure 5. Hindcast Wave Heights Using NCEP Winds as Input Minus Hindcast Wave Heights Using Assimilation Winds as Input (Contour Interval 0.4)

The above applications assume correcting a wind field will lead to acceptable wave model results. If this is not the case, then the wave model is deficient, and accurate hindcast results can only be obtained by fixing the model or modifying the results by assimilating measured wave data. The WIS system can also be used in this mode using either scalar input such as wave height and peak period or vector input from wave height and direction values.

This approach can also be extended to modifying wave spectra. Typically, a WIS hindcast spectra has 20 frequency bands. For a given wave model grid over a geographic region at a given time, one has 20 stacked grids of energy densities representing the energy spectrum at each grid point. Measured energy density corresponding to model bands can be assimilated over the grid at each frequency level. This amounts to applying the system 20 times in a scalar mode using energy density. The resulting volume of data accurately reproduces the measured spectrum near the measurement point and spreads to surrounding points based on the value of a smoothing parameter.

Conclusions

At this time, first, second, and third generation wave models in use give equally good or bad results. Until advances in the theories of wave models are made, the most expedient improvement in the accuracy of wave hindcast results lies in the use of available measurements to either improve wind input or modeled wave results through data assimilation. Since accurate wave hindcast results are critically dependent on accurate winds, a system has been developed to improve hindcast wind input. The system was tested in the Gulf of Mexico using one month of modeled hindcast winds and available wind measurements from land and buoy platforms.

The system was successful in improving hindcast wave heights for certain times and locations dependent on the land/water boundary and weather systems. Improvements of up to 1 m in wave height were realized. The system will be implemented in the WIS nowcast procedure in a test mode in 1997.

Acknowledgment

This work was carried out under the Coastal Field Data Collection Program, Coastal Engineering Functional Area of Civil Works Research and Development. The Office of the Chief of Engineers, U.S. Army Corps of Engineers is acknowledged for authorizing publication of this paper.

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