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SATELLITE DATA ASSIMILATION IN THE WAVE MODEL 3G-WAM

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ABSTRACT

A number of hindcast experiments with the third-generation wave model 3G-WAM have been carried out during the SEASAT period to test the mutual consistency of wind and wave data provided by SEASAT scatterometer, altimeter and SAR sensors. Generally the wave model data are reasonably consistent with altimeter wave heights. In order to reduce occasional regional deviations between observed wave information and simulated spectral wave energy density an assimilation method is developed to locate and estimate the wind corrections responsible for the wave data deviations. The assimilation system is tested under various situations and is currently being prepared for application to the ERS-1 SAR wave data.

Keywords: Assimilation, wave model 3G-WAM

1. Introduction

The motivation for the development of an data assimilation scheme using satellite data derived from active microwave sensors (radar altimeter, synthetic aperture radar (SAR) and scatterometer) is to make optimal use of these globally received ocean surface data for climate studies and weather and wave forecasting. Assimilating wind and wave data into atmospheric and surface gravity wave models will improve the prediction of the sea state, which is particularly desirable in strong storm situations. Conversely, reliable knowledge of the sea state is needed to convert remotely sensed signals into geophysical quantities.

The global third generation wave model 3G-WAM provides a valuable base for an operational assimilation system (WAMDIG, 198:). The wave model calculates the evolution of the two-dimensional spectral wave energy density directly from the energy balance equation without prior restrictions on the spectral shape. As the significant wave height of a fully developed sea state is approximately proportional to the square of the friction velocity, the wave model wave heights represent a sensitive indicator of errors in the wind stress fields.

The quality of the satellite wind and wave data obtained from SEASAT (July to October 1978), and GEOSAT (1985 to 1989) had been assessed by comparison with ground truth observations and model data (e.g. Atlas et al., 1987; Woiceshyn et al., 1987; Fedor and Brown, 1982; Hasselmann et al., 1988; Hasselmann and Hasselmann, 1991; Romeiser, 1992). The mutual consistency of remotely sensed wind and wave data for wave forecasting has been investigated in a hindcast study using the SEASAT data (Bauer et al., 1992). The WAM model was driven by differently analysed gridded wind fields with and without assimilated scatterometer winds. The computed wave heights were validated against the altimeter wave heights. Some systematic differences in wave heights could be attributed to various shortcomings in the wind fields. Previous findings were confirmed that low winds were underestimated and high winds overestimated by the scatterometer algorithm.

For a preliminary assimilation experiment a hindcast situation was chosen in which the modeled wave heights were underestimated up to 30%, in the southern hemisphere due to poorly determined wind stress fields. SEASAT altimeter wave heights were continuously inserted during the wave model integration, improving the model prediction where observations were available. From the altimeter wave heights correction factors were determined and applied to the two-dimensional energy spectra in a region of influence around the measurement position. However, the relaxation time of the error correction was relatively short (about five days) since the incorrect wind fields which created the errors was not modified. The assimilation scheme should therefore be extended to include a correction not only of the wave field but also of the wind field.

2. Assimilation using an impulse response function approach

The most general data assimilation approach is the adjoint method. The cost function expressing the deviation between the model and the data is minimized in an iterative procedure involving alternate integrations of the model equations forwards and the adjoint model equations backwards (Thacker and Long, 1988). However this method appears computationally too expensive for operational applications. In the following, we propose an alternative simpler assimilation method.

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We define the cost function as the distance between observational data D^0 and the corresponding model counterpart $\hat{D}$ weighted by the error covariance matrix M of the data including a penalty term, with an appropriate weighting matrix S for the differences between the initial wind data $\vec{u}$ and the corrected wind data $\hat{\vec{u}}$:

$$J = (\hat{D} - D)^T M^{-1} (\hat{D} - D) + (\hat{\vec{u}} - \vec{u})^T S^{-1} (\hat{\vec{u}} - \vec{u}) \quad (1)$$

The control variables for the minimization are the model friction velocities. For simplicity it is assumed that the error values of the different data are uncorrelated. The cost function is then normalized with the standard deviation of observational errors, yielding to a straightforward least squares problem:

$$J = \sum_p (\hat{D}_p^0 + \hat{d}_p - D_p)^2 + \Psi \sum_q [(u_q)^2 + (v_q)^2] \quad (2)$$

where D_p denote the observed data at positions p, $\hat{d}_p$ the modification of the model data, $\hat{D}_p^0$ the model first-guess and (u_q, v_q) the corrections of the friction velocity vector at specified influence locations q.

The hindcast studies have demonstrated that the mean model wave heights are close to the observations. In an assimilation system in which the wave field is updated continuously it can be expected that the local first-guess energy density will not deviate too far from the true state. A small deviation of the model data $\hat{d}_p$ can be linearly related to a small deviation of the wave energy $f_p(\vec{k})$ as function of wavenumber $\vec{k}$ by the transfer function $A(\vec{k})$:

$$\hat{d}_p = \sum_{\vec{k}} A(\vec{k}) f_p(\vec{k}) \quad (3)$$

Changes of the spectral wave energy due to a wind modification can formally be represented by an impulse response function which depends however, on the sea state field. In this case the impact of changes of the friction velocity components $(u_q(\vec{k}), v_q(\vec{k}))$ on the wave spectrum $f_p(\vec{k})$ can be given by a linear relation:

$$f_p(\vec{k}) = W_p^u(\vec{k}) u_q(\vec{k}) + W_p^v(\vec{k}) v_q(\vec{k}) \quad (4)$$

Thus the cost function can be expressed as a quadratic function of the linearized spectral perturbations $f_p(\vec{k})$.

In general, a modification of the wave spectrum $f(\vec{k}; \vec{x}, t)$ at a position $\vec{x}$ and a time t can be described as the response of the system due to the effect of a friction velocity forcing $(u(\vec{x}', t'), v(\vec{x}', t))$ acting at position x' and time t':

$$f(\vec{k}; \vec{x}, t) = \int\int\int d\vec{x}', dt' [G^u(\vec{k}; \vec{x}, t, \vec{x}', t') u(\vec{x}', t') + G^v(\vec{k}; \vec{x}, t, \vec{x}', t') v(\vec{x}', t')] \quad (5)$$

where G^u, G^v are impulse response (Green) functions of the linearized system. It can be shown that to an acceptable approximation G^u, G^v can be represented as δ-functions in space and time, so that Eq. 5 reduces to Eq. 4. The index p refers to the position $\vec{x}_p$ and time t_p of the observation, while q denotes the point and time of maximal influence of the wind field perturbation on the spectral component $f_p(\vec{k})$. The influence point of each spectral component is determined by the wave age $\tau(\vec{k})$.

The problem is reduced to the computation of the impact functions $W_p^u(\vec{k})$ and $W_p^v(\vec{k})$ given in Eq. 4 and of the wave age $\tau(\vec{k})$. $W_p^u(\vec{k})$ and $W_p^v(\vec{k})$ are obtained by integration of the wave transport equation for small spectral perturbations:

$$\frac{D}{Dt} W_p^u(\vec{k}) = \beta^u(\vec{k}) + \lambda(\vec{k}) W_p^u(\vec{k}) \quad (6)$$

$$\frac{D}{Dt} W_p^v(\vec{k}) = \beta^v(\vec{k}) + \lambda(\vec{k}) W_p^v(\vec{k}) \quad (7)$$

The forcing terms on the right-hand sides $\beta^u(\vec{k})$ and $\beta^v(\vec{k})$ express the impact due to changes of the friction velocity on the spectral energy close to the spectral peak, whereas the term $\lambda(\vec{k})$ represents a damping of the perturbations due to dissipation and nonlinear transfer.

The wave age $\tau(\vec{k})$ describes the time at which the wave component last received a significant impact by the wind forcing. It is small for short wind generated waves and larger for swell.

The relation between the control variables $(u_q(\vec{k}), v_q(\vec{k}))$ and the model data $\hat{d}_p$ is obtained from Eqs. 3 and 4:

$$\hat{d}_p = \sum_{\vec{k}} B_p^u(\vec{k}) u_q(\vec{k}) + B_p^v(\vec{k}) v_q(\vec{k}) \quad (8)$$

where

$$B_p^u(\vec{k}) = A(\vec{k}) W_p^u(\vec{k}) \quad (9)$$

$$B_p^v(\vec{k}) = A(\vec{k}) W_p^v(\vec{k}) \quad (10)$$

and is substituted into the cost function Eq. 2. The minimum of the cost function is given by the solution of:

$$\frac{\partial J}{\partial u_q(\vec{k})} = 0 \quad (11)$$

$$\frac{\partial J}{\partial v_q(\vec{k})} = 0 \quad (12)$$

which yields:

$$u_q(\vec{k}) = R_p B_p^u(\vec{k})(D_p - \hat{D}_p^0) \quad (13)$$

$$v_q(\vec{k}) = R_p B_p^v(\vec{k})(D_p - \hat{D}_p^0) \quad (14)$$

where

$$R_p = \left[\Psi + \sum_{\vec{k}'} \left\{(B_p^u(\vec{k}'))^2 + (B_p^v(\vec{k}'))^2\right\}\right]^{-1} \quad (15)$$

The assimilation method was tested in various twin experiments using synthetic wind fields with one containing errors. As example, Fig. (1) shows the correct friction velocity field of an idealized cyclone and Fig. (2) the friction velocity deviations ($\approx 20\%$ underestimation), while Fig. (3) and (4) show a true spectrum and a spectral deviation respectively, at an exemplary measurement point. The wind stress errors inferred by the assimilation of 12 correct spectra at measurement points typical of two ERS-1 SAR wave mode passes are presented in Fig. (5).

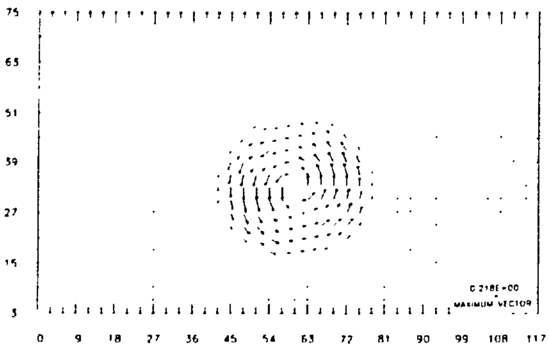

Figure 1: Correct friction velocity field

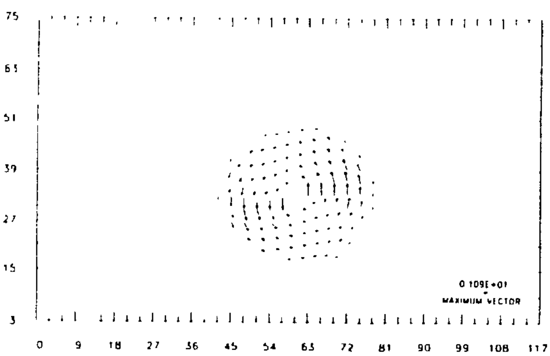

Figure 2: Expected friction velocity correction

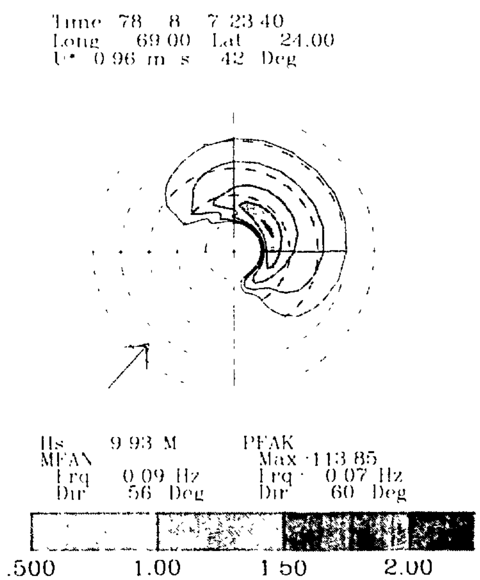

Figure 3: Correct energy density spectrum as function of frequency and direction in a logarithmic scale

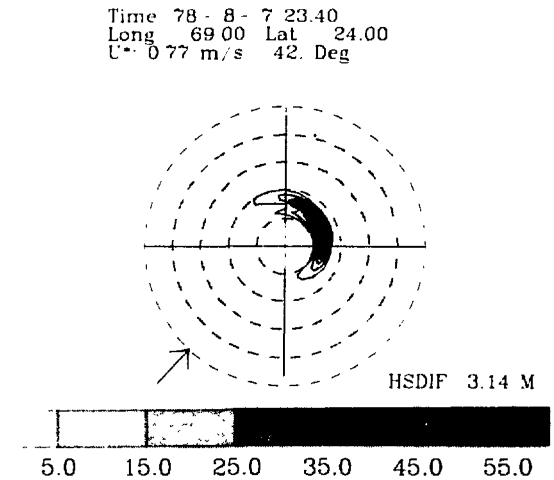

Figure 4: Energy density difference subtracting the first-guess spectrum from the correct spectrum in a linear scale

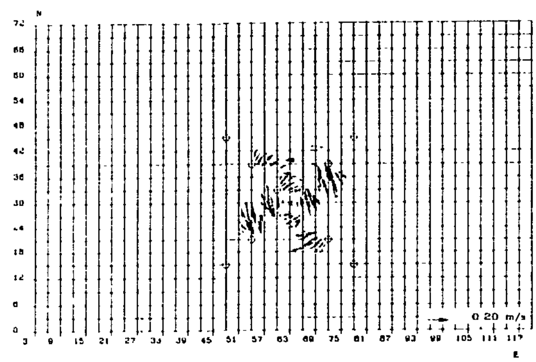

Figure 5: Inferred correction of friction velocity through the assimilation of 12 spectra from locations marked by o.

3. Conclusions

Intercomparison studies of 3G-WAM wave model hindcasts were generally reasonable consistent with observed altimeter wave heights. Regional discrepancies in the wave fields could be related in most cases to shortcomings in the analysed friction velocity fields. The proposed assimilation scheme yields non-local friction velocity corrections at the positions of maximal influence on the observed wave data. In various test cases the assimilation procedure was able to correct wind errors of the order of 20% reasonably well from non-local wave measurements.

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