Assimilation of Synthetic-Aperture Radar Data into Navy Wave Prediction Models

David T. Walker
Earth Sciences Group, Veridian ERIM International
P.O. Box 134008, Ann Arbor, MI 48113-4008
phone: (734)994-1200 x2987 fax: (734)994-5824 email: dwalker@erim-int.com

David R. Lyzenga
Earth Sciences Group, Veridian ERIM International
P.O. Box 134008, Ann Arbor, MI 48113-4008
phone: (734)994-1200 x2683 fax: (734)994-5824 email: lyzenga@erim-int.com

Contract No.: N00014-98-C-0012

LONG-TERM GOAL

To develop methods utilizing synthetic aperture radar (SAR) data to improve predictions for the littoral zone obtained from Navy wave forecasting models — in this case the SWAN model of Booij, Ris & Holthuijsen (1999).

OBJECTIVES

There are three basic objectives to this program: (1) to develop a forward prediction capability for the expected value of the SAR-image spectrum, with the SWAN wave-spectrum prediction as input; (2) to develop methods to bring the SWAN-based SAR-spectrum prediction into agreement with satellite-based SAR observations by adjusting the SWAN model inputs; and (3) to validate the improvement in the results from the SWAN model against ground-truth data.

APPROACH

The accuracy of the predictions obtained from the SWAN model is limited by (among other things) inaccuracies in the specification of the model inputs (initial conditions, boundary conditions, and forcing). The information contained in SAR images of ocean waves can potentially be used to improve the predictions, by guiding modifications to the model inputs so as to obtain the best agreement between the observed SAR-image spectrum and the SAR-image spectrum predicted from the wave spectrum output from the SWAN model. For the calculation of the SAR-image spectrum corresponding to a given SWAN prediction of the wave spectrum, the approaches used are the fully nonlinear mapping approach of Hasselmann & Hasselmann (1991). The approach used to bring the predicted SAR-image spectrum into agreement with the observed SAR-image spectrum relies on the variational framework outlined by Le Dimet & Talagrand (1986) which corresponds to the strong-constraint formalism of Bennett (1992). This procedure is iterative in nature and is applied until the difference is minimized.

WORK COMPLETED

During FY 00, a variational approach for assimilating wave spectrum observations into the SWAN model was developed and validated for a spatially uniform incident wave spectrum. A variational SAR assimilation algorithm was implemented as well. An adjoint form for the general nonlinear three-wave and four-wave interactions was developed, and the adjoint SWAN model code was modified to accommodate a spatially varying incident wave spectrum.

RESULTS

The main accomplishment of the current fiscal year is the validation of a variational assimilation approach for wave spectrum observations using an adjoint to the SWAN model of Ris *et al.* (1999) and the implementation and testing of a variational SAR assimilation algorithm using the adjoint to the Hasselmann & Hasselmann (1991) model. Both of these approaches assume that the incident wave spectrum is spatially uniform, and in the adjoint SWAN model, the three- and four-wave interactions are neglected. In addition to these main developments, the codes have been modified to handle spatially varying incident wave spectra, and the adjoints representations of the three- and four-wave interaction terms have been developed.

Assimilation of Wave Spectrum Observations into the SWAN Model

Using the approach described in Le Dimet & Talagrand (1986) and Bennett (1992) a formal adjoint to the SWAN model was developed. The resulting equations are similar in nature to the SWAN model equations; i.e. transport equations including spatial and spectral advection with source terms. The source terms include ones corresponding to those in the SWAN model (wind input, white-capping, bottom friction, depth-induced breaking, and nonlinear wave-wave interactions) and an additional term proportional to the difference between wave spectrum observation and a previous SWAN prediction for some number of locations. Modifications were made to the SWAN code to allow solution of the adjoint form of the equations, along with appropriate I/O modifications and memory management to allow the observations to be input into the code. The current version of the SWAN adjoint neglects the nonlinear source terms, and stationary conditions are assumed.

The following problem has been examined, and is presented in detail in Walker (2000): Given a wave spectrum observation at a single spatial location in a geographical region, determine the incident wave spectrum, and the corresponding prediction of the wave field for the entire region, which yields results which match the observation. In order to test specifically the assimilation algorithm, a forward prediction using a known input spectrum was run using the SWAN model for the region around the US Army Field Research Facility (FRF) at Duck, N.C. The predicted wave spectrum for a given location was extracted and used as an 'observation' (in this case, the spectrum from the location of the FRF 8 m array was chosen). The observations were then used as input to the adjoint SWAN model. The solution of the SWAN adjoint at the open boundary indicates the adjustment to the incident wave spectrum required to improve agreement between the predicted spectrum and the observations. Starting from an assumed zero incident wave spectrum, the algorithm proceeds as follows: 1) the adjoint SWAN model is run, with the observed wave spectrum as input; 2) the incident wave spectrum is adjusted based on the adjoint solution; 3) the forward SWAN model is run using the 'improved' incident wave spectrum; 4) the adjoint model is run again with the difference between the predicted and observed wave spectrum as input. Steps 2–4 are repeated until the difference between the predicted and observed wave spectrum is minimized, and the incident wave spectrum ceases to change.

An example of the results from Walker (2000) is shown in figure 1, for a case where the 'observations' were a single wave spectrum from the location of the FRF 8 m array, taken from SWAN model results for a given incident wave spectrum. Figure 1 shows the iteration history for the significant wave height, peak frequency, and dominant wave direction at the 8 m array location, as well as the 'true' directional spectrum and the estimated directional spectrum. From these results it is clear that the procedure converges smoothly to an estimate of the incident wave spectrum which yields results at the 8 m array which are in good agreement with the observations. The final result indicates that a good estimate of the incident wave spectrum has been obtained via the assimilation process.

Assimilation of SAR Data into the SWAN Model

To assimilate SAR data into the SWAN model, an adjoint to the Hasselmann & Hasselmann (1991) SAR spectrum model was developed. This adjoint SAR model computes an adjustment to the wave spectrum based on the difference between the observed SAR-image spectrum and the predicted image spectrum, obtained using the current estimate of the wave spectrum. This adjustment is then used as the effective difference between the predicted and 'observed' wave spectrum, for input to the adjoint SWAN model. To verify the adjoint SAR model it has been exercised in a stand-alone mode in order to determine whether the wave spectrum could be estimated directly from the SAR image (Lyzenga 2000).

For the adjoint SAR model, the effective difference between the actual and predicted wave height spectrum (i.e. the 'observation' source term in the adjoint SWAN model) is estimated to be

$$\delta S(\vec{k}) = \varepsilon[S_{im}(\vec{k}) - \hat{S}_i(\vec{k})][R_{sar}(\vec{k}) + R_{sar}(-\vec{k})]$$

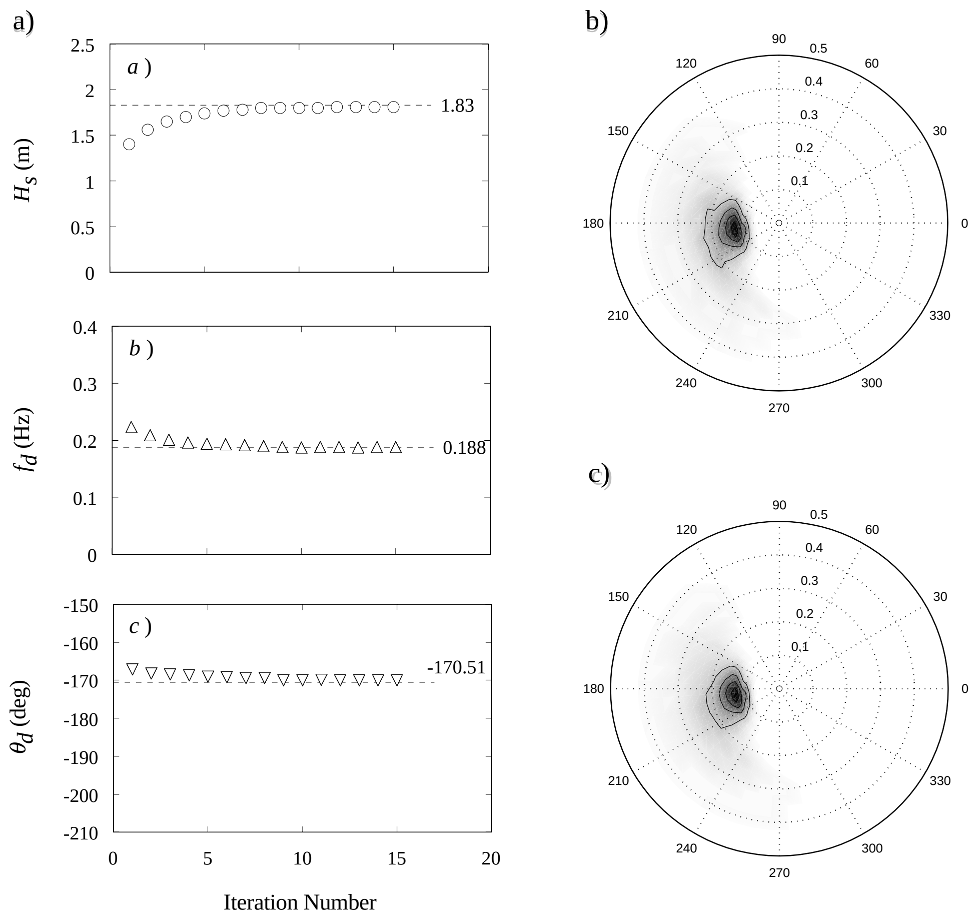

Figure 1 Results for assimilation of a single wave spectrum observation at the FRF 8 m array location into the SWAN model. a) iteration history of the significant wave height H_s, peak frequency f_d , and dominant wave direction θ_d all at the 8 m array location (the dashed lines indicate the correct values); b) wave spectrum observation at 8 m array location used for assimilation; c) estimated wave spectrum for 8 m array location.

where $S_{im}(\vec{k})$ is the observed image spectrum, $\widehat{S}_i(\vec{k})$ is the predicted image spectrum using the current estimate of the wave spectrum, and $R_{sar}(\vec{k})$ is the quasi-linear SAR transfer function. This expression is a first approximation to the full adjoint SAR model. The assimilation process was initiated using zero as the first estimate of the wave spectrum.

Tests were done using an actual ERS SAR image collected over Duck, North Carolina on 05 March 1997. Figure 2 shows the SAR image with the SWAN computational grid overlaid on it. The SAR image was subdivided into non-overlapping sub-images and Fourier transformed to obtain the SAR image spectra for assimilation. For each iteration of the assimilation algorithm, the wave spectra for the region were calculated using the SWAN model using a give incident wave spectrum, and the corresponding SAR-image spectra were calculated using the Hasselmann & Hasselmann model. The difference between the estimated SAR-image spectra and the actual SAR-image spectra was input to the adjoint SAR spectrum model, with its results being input to the adjoint SWAN model. From the solution of the adjoint SWAN model, an adjustment to the incident wave spectrum is calculated; the incident wave spectrum is then adjusted, and the procedure is repeated until the disagreement between the predicted and observed SAR-image spectra is minimized.

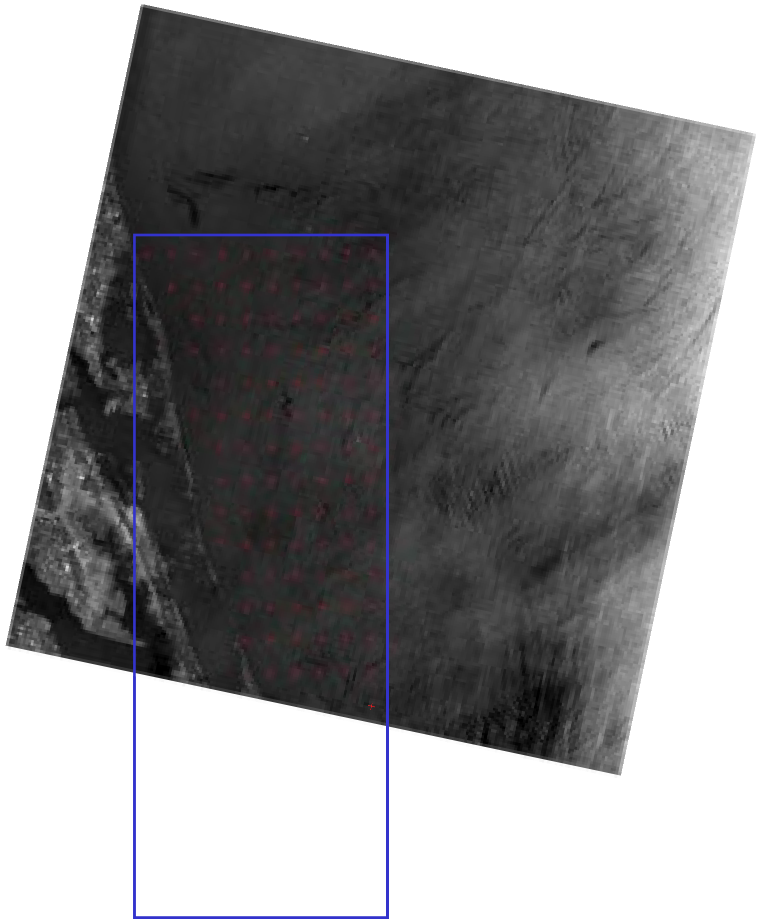

Figure 2 SWAN computational grid overlaid on an ERS SAR image for 05 March 1997.

Figure 3 shows the results for this procedure applied to the data of 05 March 1997. Figure 3a shows the estimated significant wave distribution for the region. Figure 3b shows the estimated FRF 8 m array directional spectrum, while figure 3c shows the contemporaneous measured 8 m array spectrum. The agreement between the true and estimated peak wave frequency is good, as is that between the true and estimated wave direction. The significant wave height is over-estimated in the assimilation results; this appears to mainly due to the requirement that the incident wave spectrum be uniform along the boundary. This requirement is currently being relaxed in ongoing development efforts.

IMPACT/APPLICATION

Achieving the overall objectives of the program will result in an improved prediction capability for near-shore waves, allowing readily available remote sensing data to be used effectively.

TRANSITIONS

As the data assimilation capability for the SWAN model is refined, its use may be extended to other data types by other participants in the BE effort.

RELATED PROJECTS

This project is related to other efforts under the AWPP program. The SAR adjoint model described above has been extended under Contract No. N00014-98-C-0363 for use in determining wave coherence from SAR image data for application to mobile offshore base design.

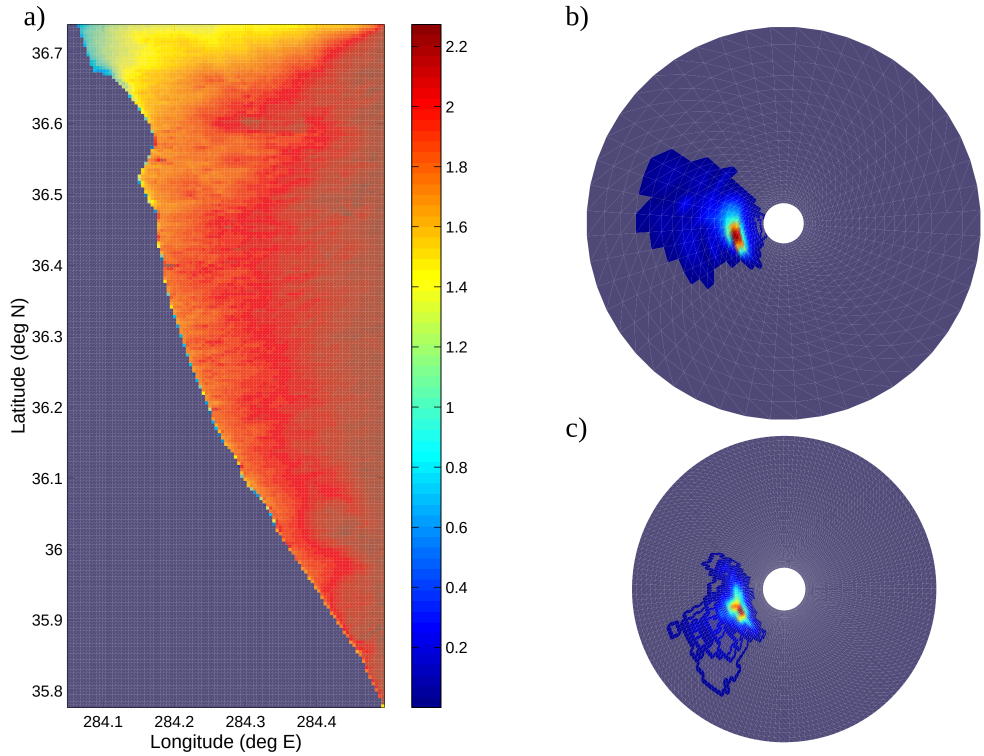

Figure 3. Results for assimilation of SAR data into the SWAN model for 05 March 1997: a) estimated significant wave height distribution; b) Estimated wave spectrum at the FRF 8 m array location (H_s = 1.84 m, f = 0.108 Hz, θ = -161.2°); measured FRF 8 m array spectrum (H_s = 1.16 m, f = 0.103 Hz, θ = -153.9°).

REFERENCES

Bennett, A.F. 1992 *Inverse Methods in Physical Oceanography*. Cambridge.

Booij, N., Ris, R.C. & Holthuijsen, L.H. 1999 A third-generation wave model for coastal regions: 1. Model description and validation. *J. Geophys. Res.* **104**, 7649–7666.

Hasselmann, K. & Hasselmann, S. 1991 On the nonlinear mapping of an ocean-wave spectrum into a synthetic aperture radar image spectrum and its inversion. *J. Geophys. Res.* **96**, 10,713–10,729.

Le Dimet, F.-X. & Talagrand, O. 1986 Variational algorithms for analysis and assimilation of meteorological observations: theoretical aspects. *Tellus* **38**A, 97-110.

PUBLICATIONS

Lyzenga, D.R. 2000 Estimation of wave height spectra from SAR images. In preparation for *J. Geophys. Res.*

Walker, D.T. 2000 Variational assimilation for near-shore waves using the SWAN model. Submitted to *J. Geophys. Res.*