Data-Enhanced Modeling of Sea and Swell on the Continental Shelf

William C. O'Reilly and Thomas H.C. Herbers
U.S. Naval Postgraduate School
Dept. of Oceanography, Code OC/He
(510) 642-6776 FAX: (510) 643-8934 bor@coast.ucsd.edu
(408) 656-2917 FAX: (408) 656-2712 herbers@oc.nps.navy.mil

James M. Kaihatu, Y Larry Hsu, Paul A. Hwang, and W. Erick Rogers
Oceanography Division, Naval Research Laboratory
Stennis Space Center, MS 39529-5004
(601) 688-5710 FAX: (601) 688-4759 kaihatu@nrlssc.navy.mil
(601) 688-5260 FAX: (601) 688-4759 hsu@tides.nrlssc.navy.mil
(601) 688-4708 FAX: (601) 688-5997 phwang@nrlssc.navy.mil
(601) 688-4727 FAX: (601) 688-4759 rogers@wateree.nrlssc.navy.mil

Leo H. Holthuijsen and Nico Booij
Dept. of Civil Eng., Delft University of Technology
P.O. Box 5048, 2600 GA Delft, the Netherlands
31-15-2784803 FAX: 31-15-2784842 L.Holthuijsen@ct.tudelft.nl
31-15-2786938 FAX: 31-15-2784842 N.Booij@ct.tudelft.nl

Robert T. Guza
Center for Coastal Studies
Scripps Institution of Oceanography
La Jolla, CA 93093-0209
phone: (619) 534-4333 FAX: (619) 534-0300 email: rguza@ucsd.edu

Award #'s: N0001499WR30009, N0001499WX30036, N00014-98-1-0019

LONG-TERM GOAL

Our long-term goal is to contribute to the accurate prediction of surface gravity wave generation, propagation, and dissipation in coastal regions through the combined use of measurements and models.

OBJECTIVES

Our objective is to develop improved wave propagation, dissipation, and data assimilation schemes for shallow water wave models used on large (continental shelf) scales. In the process of developing the wave data assimilation techniques, we will identify the types of wave data (eg. remotely sensed or in situ) and measurement locations (e.g. at the offshore model boundary or in the nearshore) that provide the most useful constraints on model predictions.

APPROACH

Our approach for improving wave propagation and dissipation schemes scheme is to test viable methods with analytic solutions, controlled simulations, and finally field data comparisons. The most promising higher order schemes are being implemented in the SWAN model and validated using several historical data sets from the U.S. East and West coasts to insure its applicability to a wide range of environmental conditions and geographic settings. Our approach to adding data assimilation capabilities to shallow water models is to: 1. identify the types of wave measurements available on or near the continental shelf, 2: relate these measurements to a model's spectral output with as few additional assumptions as possible, and 3: assimilate this information using methods that are computationally feasible for use in future operational products.

WORK COMPLETED

Wave Propagation

Development and testing of higher-order propagation schemes have been completed. Two schemes have been found to be the most appropriate candidates for inclusion into the SWAN model: the scheme of Stelling and Leendertse (1992) (referred to here as the "Stelling" scheme) and the SORDUPI (Second ORDer Upwind Implicit) scheme. The Stelling scheme is nominally of greater accuracy, but comes at a higher computational cost in stationary (time-independent) runs of the model. It is thus recommended for large - scale *non*stationary model operation (in which the increase in computational cost is nominal) or small-scale stationary operation over complex bathymetry. The Stelling scheme has been shown to greatly enhance the fidelity of modeling swell propagation over rugged bathymetry. The SORDUPI scheme is significantly more accurate than the present SWAN propagation scheme with only a modest increase in computational time and can be used for larger, regional applications of the model (in either stationary or nonstationary modes).

Wave Dissipation

Spectral models typically use the formulation for steepness-limited deep water dissipation of Hasselmann (1974) and Komen et al. (1984):

$$S_{dis}(\sigma,\theta) = -C_{ds}\left(\frac{\tilde{s}}{\tilde{s}_{PM}}\right)^{m}\tilde{\sigma}\left(\frac{k(\sigma)}{\tilde{k}}\right)^{n}E(\sigma,\theta)\,, \qquad (1)$$

where C_{ds} is a coefficient of proportionality, $\tilde{s}$ is the overall wave steepness, $\tilde{s}_{PM}$ is the steepness of the idealized fully-developed (infinite fetch and duration) wave spectrum of Pierson and Moskowitz (1964), m and n are free parameters, $\tilde{\sigma}$ is the mean relative frequency of the entire spectrum, and $\tilde{k}$ is the mean wavenumber of the spectrum.

Komen et al. (1984), determine the "best" C_{ds} and n to achieve the Pierson-Moskowitz spectrum. They suggest n=1. C_{ds} is dependent on the definition of $\tilde{\sigma}$ and $\tilde{k}$ used, so we will not discuss the actual value (for sake of brevity). With the existing whitecapping procedure, this same dissipation formula is applied to all spectral components, even though intuitively one would expect that sea and swell are dissipated by very different physical processes.

We've tested two modest modifications to the standard dissipation formulation, meant to correct underprediction of low frequency energy which we consistently observe in hindcasts using the model across continental shelves (modeling on scales of 200-500km).

By repeating the Komen et al. (1984) tuning process, it can be shown that the "ideal" value of n for achieving the Pierson-Moskowitz limiting condition is between 1 and 1.5. Using a value of n greater than unity would have the effect of increasing dissipation on higher frequencies, while decreasing the dissipation of lower frequencies. Increasing n requires a corresponding increase in C_{ds} in order for the model to achieve stable growth under duration- and fetch-unlimited conditions. Through numerical experiments, we find that for n=1.5, C_{ds} must be increased by a factor of 1.9 to achieve this asymptote. This retuning of C_{ds} to satisfy the Pierson-Moskowitz condition unfortunately will often lead to underprediction of total energy under more realistic (i.e. fetch- or duration-limited) conditions.

We've applied the modified dissipation terms in the SWAN model for a wind event that occurred during the SandyDuck experiment (Duck, N.C.) on Sept. 24 1997. The sea conditions were swell-dominated until around 0300UTC Sept. 24 when a front passed and a moderate wind-sea growth event occurred, lasting approximately 12 hours, and peaked at $U_{10}\approx$10m/s. We modeled this event with a 300x500km computational domain, with a nested grid close to shore. SWAN model results were compared to buoy measurements on the North Carolina shelf (NDBC buoy 44014 located at the 47m depth contour).

By comparing temporal variation at individual frequencies, we had a clear indication of where error occurs (e.g. Fig. 1). In general, the use of a higher n value in (1) produced only modest differences in energy level, though the change was almost always an improvement. At lower frequencies, dissipation was less with n=1.5; near the peak, the higher C_{ds} appears to counterbalance the effect of higher n; at higher frequencies, the higher n and C_{ds} both contribute to greater dissipation, as one would expect.

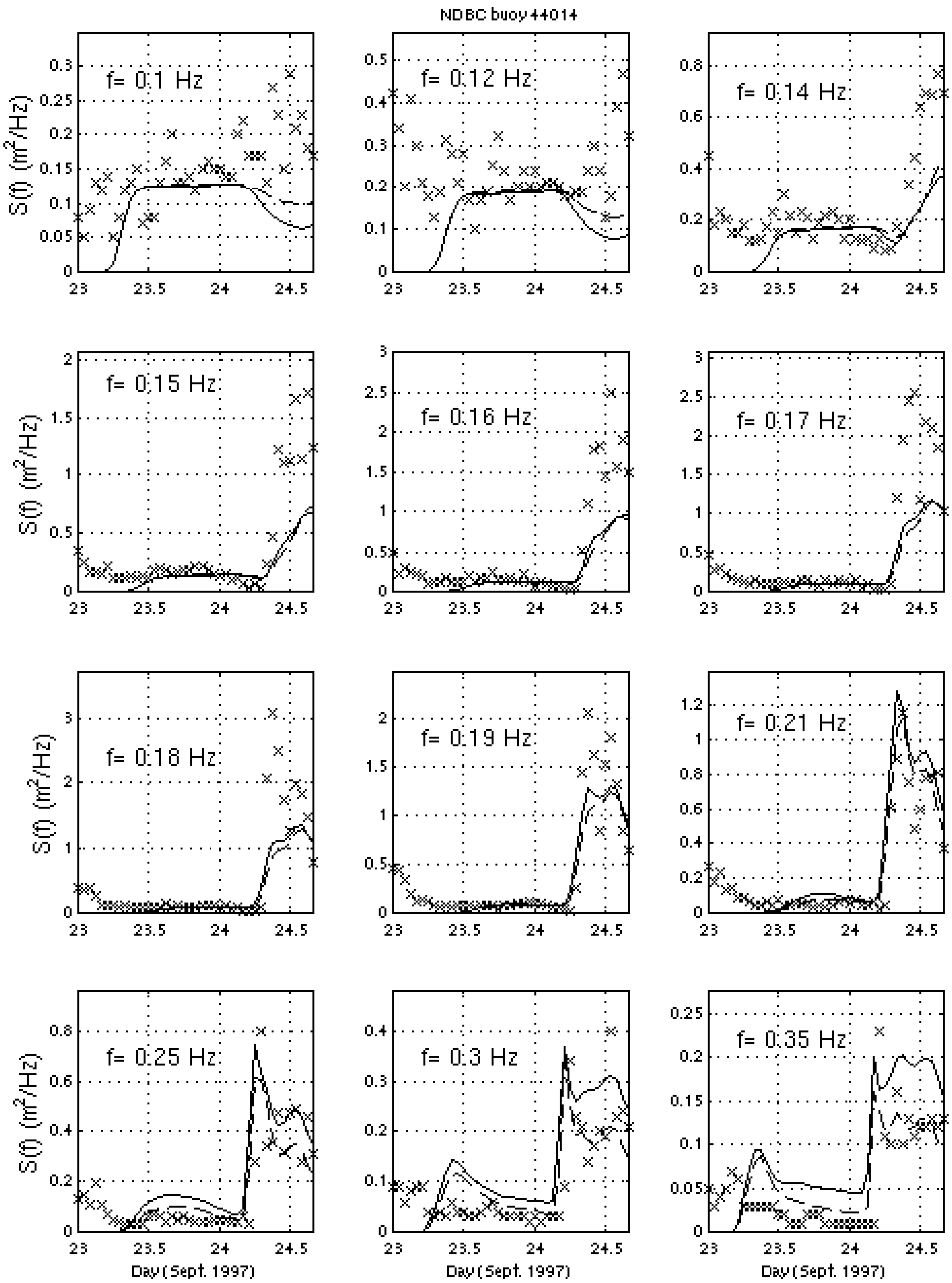

Fig. 1 Comparison of SWAN frequency spectra time series to data from NDBC buoy 44014. "x", data; solid line, model with n=1; dashed line, model with n=1.5.

Two items are of particular interest. The first is the behavior of the lowest frequency shown (0.10 Hz, Fig. 1) when the wind sea event occurs: a significant decrease in the model's energy at this frequency is observed. The decrease is due to the mean steepness term, $\tilde{s}$, in (1). When the wind sea arrives, the mean steepness of the spectrum increases, and therefore S_{ds} (as it is applied to the entire spectrum, including 0.10 Hz) increases. This is clearly nonphysical; one cannot expect the existence of wind sea to have this drastic an impact on swell frequencies over such short time/space scales. And indeed, in the buoy data, we see that low frequency energy (0.10 Hz) actually increases during this time (this may or may not be related to the wind event).

The second item of interest is model's underprediction of energy at frequencies below 0.2 Hz during the wind event. It is difficult to say with great certainty that this is due to inaccuracy of S_{dis}, and not S_{in} or S_{nl}. We do, however, feel that this is most likely the case.

Swell Dissipation.

It can be argued that swell should not be dissipated by the same mechanism by which wind sea is dissipated (i.e. via steepness-limited breaking). Indeed, it is debatable as to whether swell is dissipated significantly by *any* process. The first step toward treating the dissipation of sea and swell differently would be to deactivate the dissipation of swell. The mechanism described in (1) can subsequently be replaced by another mechanism (e.g. an eddy viscosity formulation). This leaves the question of "how does one define swell?". One option would be to base this on the wave age used by the model's S_{in} formulation. For example, in the case of SWAN, which uses the Komen et al. (1984) formulation for wind input, S_{in}, if

$$28\frac{U_*}{c}\cos(\theta_{wv}-\theta_{wd})<\psi\ , \tag{2}$$

then that particular wave component (described by c and θ_{wv}) would be considered swell. (Here, U_* is the friction velocity, c is the wave phase speed, θ_{wv} is the wave direction, and θ_{wd} is the wind direction.) With a value of ψ=1.0, any wave component which is not being actively forced by S_{in} would be considered swell. A value of ψ<1.0 would be more conservative (i.e. would have a less drastic impact on model results).

If a model were to properly handle the dissipation of swell as a process distinct from the dissipation of wind sea, what impact would this have on results? By disallowing the breaking of swell using a method such as (2), we can gain some insight into this question. For this case, we do not need to be concerned with how swell *does* dissipate, since we can safely assume that swell does not dissipate significantly at the short time/space scales of this problem. The more difficult problem is how to separate the sea and swell.

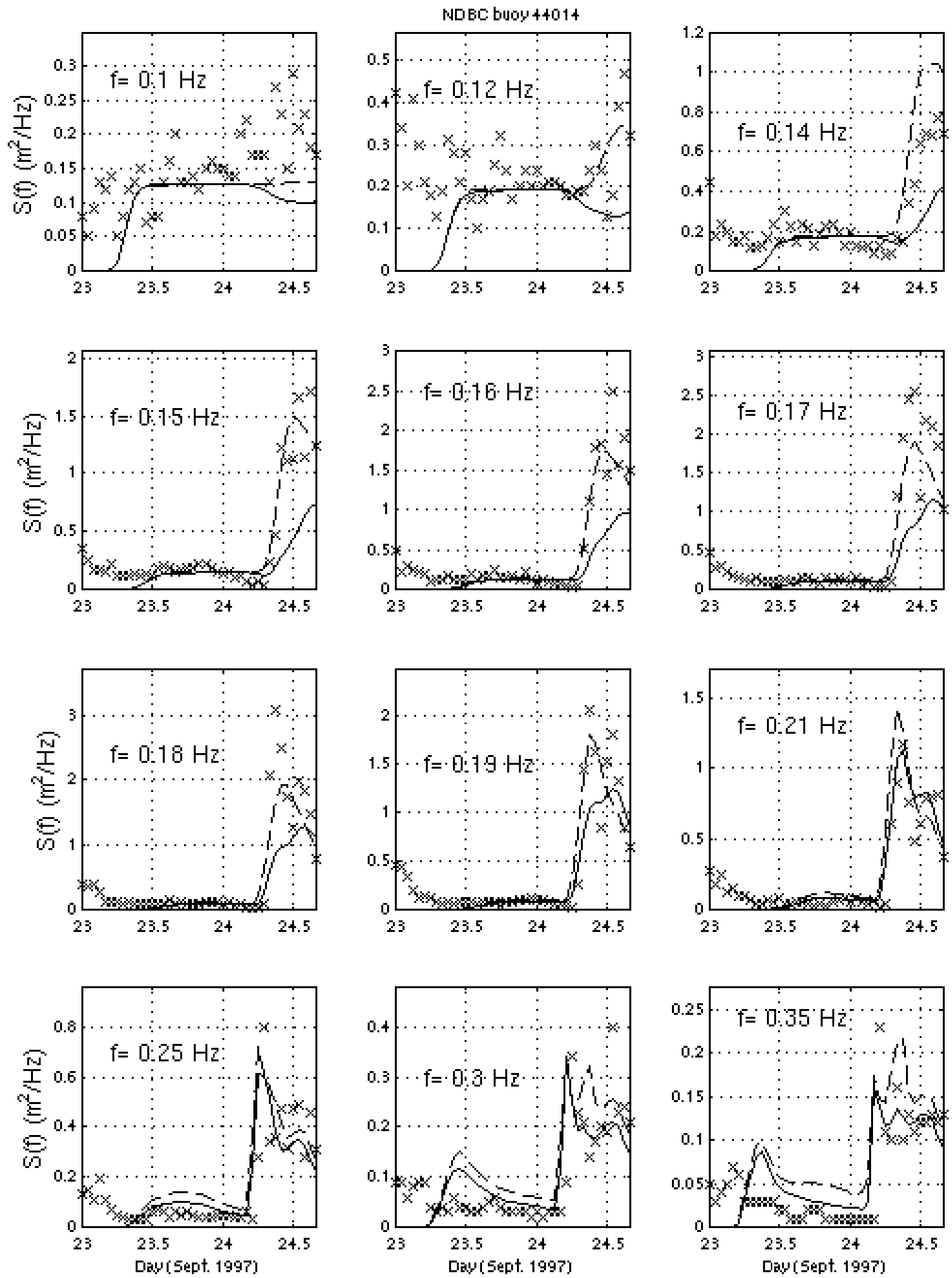

Fig. 2 Comparison of SWAN frequency spectra time series to data from NDBC buoy 44014. "x", data; solid line, model with n=1.5; dashed line, model with n=1.5, without breaking of swell, as defined in (2).

We tested (2) using the same Duck 97 field data, using a ψ value of 0.4. We note that this value was not chosen independently of the problem (unlike our choice of n and C_{ds} above), and the experiment was therefore useful for demonstrative purposes only. These results are shown in Fig. 2. We immediately noticed that 1) there is no artificial decrease in 0.1Hz energy during the wind event with the experimental model, and 2) at intermediate frequencies (0.12-0.19Hz) energy was not dissipated as quickly once it ceased to receive energy from the wind, generally correcting the underprediction of energy at these frequencies. However, at 0.14Hz, the "correction" overshot the data. This could be due to an overactive S_{in} term (which had previously been compensated by the overactive S_{dis} term), or perhaps it is due to a shortcoming in how we define swell. The idea of reducing/preventing the dissipation of swell needs further refinement. Further, we note that there are certain situations where swell might be expected to break/dissipate. A generally applicable dissipation term would need to address this.

Data Assimilation

A method has been developed to assimilate deep water directional wave buoy measurements at the continental shelf break into short-range swell forecasts for the surrounding regional coastline. The method improves the accuracy of the global, deep water wave model forecasts spectra at the shelf break before they are used to initialize a shallow water wave model. The global model spectra are reduced to frequency spectra and, at each frequency, the four lowest-order moments of the directional spectra that are measured directly by the buoy. The real-time buoy data is then used to modify the corresponding forecast model parameters over the next 12 hours, matching the buoy data exactly at t = 0 hours (the nowcast) and matching the forecast model values exactly at t = +12 hours. Data-enhanced, forecast directional spectra are then estimated from the modified parameters using the Maximum Entropy Method. The assimilation method has been validated in Southern California using deep water and coastal directional buoys maintained by the Coastal Data Information Program at Scripps Institution of Oceanography (Example, Fig.3).

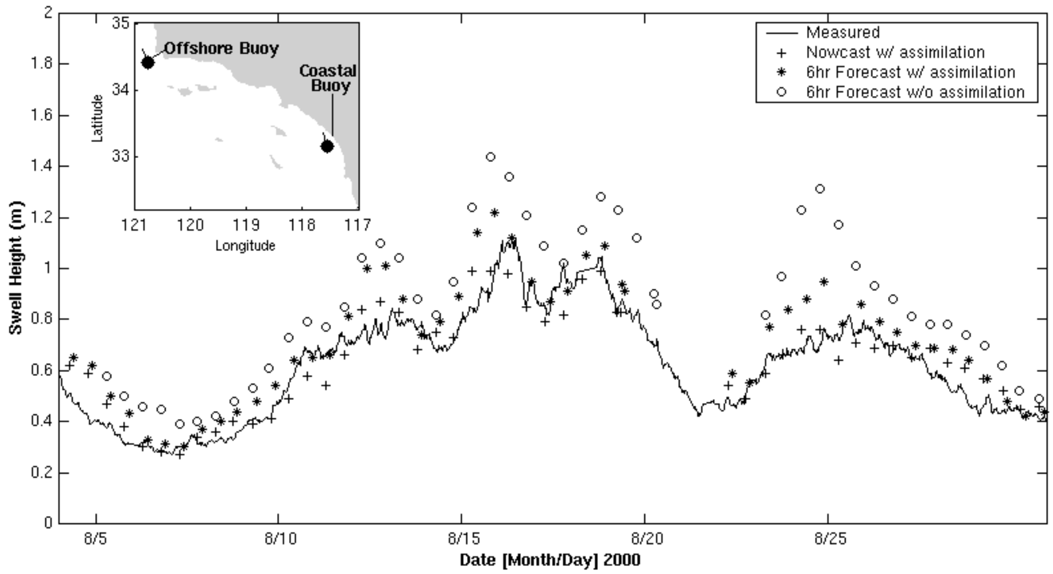

Figure 3. Validation of data-enhanced short-range coastal forecasts in the Southern California Bight (inset map, upper left) for the the month of August, 2000. 6 hour forecasts of swell height (open circles) are compared to measurements from a buoy offshore of Camp Pendleton, CA (solid line,"Coastal Buoy", map inset). The forecasts are made by initializing a shallow water refraction-diffraction model with NOAA Wavewatch-III global forecast spectra off Pt. Conception, CA (near "Offshore Buoy", map inset), and overpredict the height at Camp Pendleton. 6 hour forecasts that assimilate buoy data at the "Offshore Buoy" site (asterisks) result in a significant improvement in forecast accuracy at the "Coastal Buoy" site. Nowcasts made directly with the offshore buoy data are shown as "+" symbols.

RESULTS

Improved wave propagation and data assimilation methods have been developed for shallow water models. The model improvements have been validated with field data from Duck, N.C. and Southern California.

IMPACT/APPLICATION

The new propagation schemes will significantly enhance Navy shallow water modeling performance over large numerical domains and in areas with complex bathymetry. The new data assimilation methods have potential applications in Naval littoral operations as the use of real-time *in-situ* and remote sensing wave measurements increases at NAVO and METOC centers.

TRANSITIONS

The improved wave propogation algorithms have been incorporated into the official release of the SWAN model.

RELATED PROJECTS

1. Shoaling Waves DRI field experiment (SHOWEX).

2. Nearshore Canyon Experiment (NCEX)

3. SandyDuck field experiment

4. Duck94 field experiment

5. The Coastal Data Information Program, USACE and CA Dept. of Boating and Waterways

6. MMS Study: Modeling Waves in the Santa Barbara Channel

7. Joint work with Paul Wittmann, FNMOC-Monterey

8. Joint SPAWAR work with Larry Hsu, NRL-Stennis

REFERENCES

Stelling, G.S., and Leendertse, J.J. 1992. Approximation of convective processes by cyclic AOI methods, *Proceedings of the 2nd International Conference on Estuarine and Coastal Modeling*, ASCE, Tampa, FL, 771-782.

Hasselmann, K., 1974: On the spectral dissipation of ocean waves due to whitecapping. *Bound.-layer Meteor.*, **6**, 107-127.

Komen, G.J., S. Hasselmann, and K. Hasselmann, 1984: On the existence of a fully developed wind-sea spectrum. *J. Phys. Oceanogr.*, **14**, 1271-1285.

Pierson, W.J., and Moskowitz, 1964: A proposed spectral form for fully developed wind seas based on the similarity theory of S. A. Kitaigorodskii. *J. Geophys. Res.* **69(24)**, 5181-5190.

Tolman, H.L., and D. Chalikov, 1996: Source terms in a third-generation wind wave model. *J. Phys. Oceanogr.*, **26**, 2497-2518.

Wang, D.W., and P.A. Hwang, 2000: An operational method for separating wind sea and swell from ocean wave spectra, in review

PUBLICATIONS

Rogers, W.E., Kaihatu, J.M., Booij, N., and Holthuijsen, L.H. 1999. Improving the numerics of a third generation wave action model, *NRL Formal Report NRL-FR-7322-99-9695*. Naval Research Laboratory, Stennis Space Center, MS. 67p.