PACIFIC BASIN WIND-WAVE MODELS:
The generation and propagation of low frequency energy

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Abstract: An overview of global wave modeling methods currently used by the U.S. Navy is presented, and the advantages and disadvantages of various approaches are discussed. Two Pacific Basin swell events are presented for illustration, one typical of winter events at the California coast, the other typical of summer swells. The WAM model performs poorly in both cases. Model underprediction of wave generation is the primary source of error for the winter swell, while wave propagation errors explain the poor performance for the summer swell. A new approach for reducing error associated with propagation is proposed. Test results for a canonical case are discussed.

INTRODUCTION

As an introduction, we will in the next three sections discuss the state-of the-art for modeling wind generated gravity waves on ocean basin scales by way of detailing three wave models, their assorted difficulties/shortcomings, and means of dealing with these problems.

WAM MODEL

The Wave Action Model **(**WAM), Cycle 4, (Komen et al. 1994) is the last open-source version of WAM. It is the model presently used for global wave forecasts at the Naval Oceanographic Office (or "NAVO", www.navo.navy.mil). This model is noteworthy for being created, tested, validated, and improved by a large number of researchers over a period of many years. WAM is described in terms of the wave action density spectrum. In Cartesian coordinates, this is

$$N(x,y,\sigma,\theta) = E(x,y,\sigma,\theta)\big/\sigma\ , \qquad (1)$$

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where N is the spectral action density, E is the energy density, σ is relative frequency, θ is direction, and x and y are geographic coordinates. Or, in spherical coordinates, this is

$$N(\varphi,\lambda,\sigma,\theta)=E(\varphi,\lambda,\sigma,\theta)/\sigma, \quad (2)$$

where φ is latitude and λ is longitude. It is governed by the action balance equation:

$$\frac{\partial}{\partial t}N+\frac{\partial}{\partial x}\dot{x}N+\frac{\partial}{\partial y}\dot{y}N+\frac{\partial}{\partial\sigma}\dot{\sigma}N+\frac{\partial}{\partial\theta}\dot{\theta}N=\frac{S}{\sigma} \quad (3)$$

or

$$\frac{\partial}{\partial t}N+(\cos\varphi)^{-1}\frac{\partial}{\partial\varphi}\dot{\varphi}\cos\varphi\,N+\frac{\partial}{\partial\lambda}\dot{\lambda}N+\frac{\partial}{\partial\sigma}\dot{\sigma}N+\frac{\partial}{\partial\theta}\dot{\theta}N=\frac{S}{\sigma}. \quad (4)$$

Here $\dot{x}$ denotes wave action propagation speed in x-space (which is the x-component of group velocity: $C_{gx}(\sigma,\theta)$), $\dot{\varphi}$ denotes wave action propagation speed in φ-space, etc. S/σ is the total of source and sink terms. In deep water, there are three active source/sink terms: wind input, dissipation, and nonlinear interactions.

The model generally performs well in small to moderately sized basins, such as the North Atlantic. The model has high skill when predicting the wave height of local wind seas, and moderate skill when predicting the peak period of local wind seas and wave height of young swell. However, if one looks at performance at lower frequencies (swell) in the Pacific Basin, the model skill is significantly reduced. There appear to be a number of WAM model deficiencies that contribute to its poorer performance in large basins:

WAM Wave Generation

WAM is not particularly skillful at predicting the frequency distribution of wave energy near its source, particularly in the case of intense mid-Pacific storms with a relatively small geographic "footprint". We discuss this further in the winter storm case study section. Note that in terms of geographic distribution of wave height (total energy), errors associated with inaccurate frequency distributions will (due to physical dispersion) become much more apparent as the energy radiates from its source (as swell).

WAM Geographic Resolution

The Naval Oceanographic Office runs the global wave model (which serves as the Pacific Basin model) at a one degree geographic resolution. This is sufficient to resolve a great majority of wind fields. However, it is insufficient resolution to include island groups such as Hawaii and Polynesia. Islands obviously play an important role in blocking swell; omission of islands or inadequate resolution of islands will lead to errors in their lee (most often, overprediction of swell).

WAM Geographic Diffusion

WAM uses a first order geographic propagation scheme. Combined with the coarse geographic resolution, this leads to considerable diffusion when propagation distances are large (e.g. greater than 5000km). In the absence of other effects (e.g. nonlinear source/sink terms, directional spreading, and blocking by land), diffusion is mass-conserving, smoothing a wave field as it propagates, so an underprediction at one location (or time) would tend to be accompanied by an overprediction at another location (or time). This is, in fact, the trend observed by Wittmann and O'Reilly (1998). Since the process of dispersion will also spread energy geographically during propagation, it is often difficult to distinguish *real* dispersion from *artificial* diffusion without looking at individual components of the wave spectra.

The first order, upwind, explicit scheme of WAM has the unfortunate characteristic of *strongly* favoring propagation along computational grid axes (i.e. diffusion is reduced in these cases). The problem is typically reduced (slightly) by offsetting angular bins by half of the directional bin width ($\Delta\theta/2$). This will tend to make diffusion large for all directional bins, as opposed to being large for all but a few axial bins.

Diffusion is especially problematic where large gradients exist in the wave field, e.g., in the lee of an island. Therefore, if an island group is large enough to be represented in the computational grid, and a diffusive propagation scheme is employed, *real* and persistent reductions in wave energy in the shadow of the island are poorly represented.

WAM Spectral Resolution (and the "Garden Sprinkler Effect")

The NAVO global WAM uses 25 frequency bins and 24 directional bins (a 15° angular bin width). This is sufficient resolution for the source/sink term formulations used by WAM. However, it leads to problems during propagation over large distances (e.g. greater than 5000km). As a wave energy field is propagated throughout the model domain, it will ideally spread out via physical dispersion (different wave components travelling different speeds and directions) along great circle routes in a continuous geographic pattern. However, unless the spectral resolution is sufficiently fine, the discrete representation of the spectra will lead to discrete geographic peaks and valleys in the wave field. This is the "Garden Sprinkler Effect" (e.g. SWAMP group 1985), henceforth denoted "GSE". The GSE related to directional resolution is typically much more noticeable than that related to frequency resolution.

In the WAM model, there is a fortuitous cancellation of errors with the GSE discontinuities being smoothed by the diffusion of the first order scheme, resulting in dispersion which is more realistic in appearance. Numerical diffusion is not controllable in the WAM model; and in some cases, even the first order diffusion is insufficient to mask the GSE.

WAVEWATCH III

WAVEWATCH III (Tolman (1991), henceforth denoted "WW3") has its origins in the earlier versions of the WAM model, but has been developed independently over the last decade with the goal overcoming various inherent limitations of the WAM model numerics (some are described below). WW3 is used operationally by NOAA (U. S. National Oceanic and Atmospheric Administration) and the U.S. Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC).

WW3 Wave Generation

WW3 calculates nonlinear interactions (S_{nl}) using the same algorithm as WAM (Discrete Interaction Approximation,DIA, Hasselmann et al. 1985), with minor adjustments. Wind input (S_{in}) and dissipation (S_{ds}) are calculated according to Tolman and Chalikov (1996) (with some modifications). The latter physical formulations are more complex than those of WAM, but often similar in result. WW3 physics tend to be more empirical, but produce fewer artificial problems. For example, the dissipation of WAM is dependent on spectrum-averaged parameters (e.g. mean steepness), leading to anomalous behavior with bimodal frequency distributions; whereas WW3 does not have this problem.

WW3 Geographic Resolution (Blocking by Islands)

The NOAA and FNMOC global implementations of WW3 use geographic resolution similar to NAVO WAM (1-1.25°). This is insufficient to represent blocking by islands. However, Tolman (2001, these proceedings) is implementing an alternative to high resolution: treating sub-grid islands as partially transmitting obstacles. This is a sensible, numerically cost-effective approach that could significantly improve model accuracy in the vicinity of islands. However, it will not allow resolution of fine-scale wave shadow features ($< \approx 1°$ in latitude and longitude), produced down-wave of islands, to persist for more than one or two grid points. The end result is something akin to a high resolution model with nonphysical diffusion into the wave energy shadow in the immediate lee of an island group.

It should also be noted that geographic resolution is important insofar as the accuracy of propagation schemes tends to be strongly dependent on resolution.

WW3 Geographic Diffusion

For geographic propagation, WW3 uses the "QUICKEST" scheme (Leonard 1979, Davis and Moore 1982) with the "ULTIMATE" total variance diminishing limiter (Leonard 1991). The QUICKEST scheme is explicit and conditionally stable. For one-dimensional problems, the scheme is 3rd order accurate. Extension of the one-dimensional scheme to two dimensions is implemented using a split time step approach (e.g., x-propagation, rollover, y-propagation, rollover, etc.). For large-scale modeling (e.g. grid spacing greater than 25km), this two-dimensional scheme is an excellent mix of accuracy and cost. In the context of ocean wave modeling, it is uncertain whether the ULTIMATE limiter contributes much to the overall accuracy.

WW3 Spectral Resolution (and the "Garden Sprinkler Effect")

The diffusion error of the QUICKEST scheme is not sufficiently large to mask the GSE, especially that associated with directional spreading. This is countered using the Booij and Holthuijsen (1987) method, which is to explicitly add diffusion (via finite differencing) in a manner consistent with real dispersion. The stability criterion of the method is unfortunately a function of grid spacing to the second power (e.g. Δx^2), so cost rapidly increases with higher resolution. Tolman (2001, these proceedings) proposes two alternative approaches. To date, the more successful of the two involves using the Booij and Holthuijsen method, but instead of using a finite differencing of diffusion terms, it mimics diffusion by spatial averaging. Thus, there is no stability criterion.

One drawback of the Booij and Holthuijsen (and derivative) techniques is the need for a user-specified "wave age". The level of diffusion added is controlled by this wave age parameter. For an operational forecast model, this is somewhat awkward. We do not know of any automated method for specifying this parameter in a physically meaningful way. The GSE-countering method of Lavrenov and Onvlee (1995) is a possible alternative to the Booij and Holthuijsen method. The former promises to eliminate the need for specifying wave age, as the diffusion strength is locally defined. We do not know how well this works in practice.

NAVY SWELL MODEL

The Navy Swell Model is being developed at the Scripps Institution of Oceanography (W. O'Reilly) and the Naval Research Laboratory at Stennis Space Center (L. Hsu). Where WAM and WW3 are Eulerian (finite difference) models, the Navy Swell Model is Lagrangian, using backward ray tracing for propagation. Thus, propagation inside the Swell Model can be considered exact. No source/sink terms are calculated internally; instead the model uses a time history of WAM global source/sink output for information on wave generation and dissipation. The forecast is calculated at any user-specified arrival location. Below are the notable advantages/disadvantages of this model.

Advantages

1) Long range forecasts. The forecast ranges of the Eulerian wave models, as implemented, do not extend past the forecast range of the atmospheric forcing (5 days typically). The Swell Model is intended for implementation with forecast range well beyond that (e.g. 20 days) by allowing the 5-day forecast swell energy to continue propagating across ocean basins. [We note that it is possible to calculate similar 20 day forecasts using a Eulerian model. However, because the 5-20 day range is a propagation-only problem, the Swell Model is more efficient and more accurate for this application.]
2) The model provides much higher directional resolution (1° vs. 15° for WAM) and no diffusion.
3) Excellent representation of blocking by islands. A 5' resolution topography is used. With this resolution, details of blocking by even relatively small islands can be properly represented.
4) Speed. The model is very fast, particularly if one is interested in output at just a few points.
5) Scientific tool. The model is a method (albeit indirect) of determining the origin of errors in the Eulerian models. Also, it is potentially a very useful tool for studying swell attenuation.

Disadvantages

1) Dependence on WAM. WAM is not being "corrected" by the Swell Model's perfect propagation. Therefore, any source/sink information drawn from the WAM model has been corrupted by inaccurate propagation in the WAM model. This is likely to be a second-order error given that wave generation/dissipation in the WAM model is not very sensitive to the presence of a background swell.
2) Having two models which do the same thing. In cases where both Swell Model and WAM model forecasts exist, interpretation of the two results is inconvenient and requires a certain level of sophistication of the end user. Combining the two forecasts, to provide forcing for a smaller scale model, can be problematic.
3) Lack of "big picture". There are no plans to use the Swell Model to provide output on a regular grid, e.g., for the entire Pacific Basin. The model is designed for use at a few forecasts locations of interest. Producing model output at thousands of locations would be very inefficient compared to standard global models.

WAM CASE STUDY: CALIFORNIA WINTER

The NAVO WAM nowcast (analysis) is compared to data from NDBC (NOAA) buoy 46059, located in deep water (4600m depth) off the California shelf, west of San Francisco for the month of January 2001. We find the following:

1) Skill of WAM for predicting wave height (total energy) is marginal. For the typical wave condition (H_{m0}=2-5m), WAM usually underpredicts H_{m0} by around 25% during this period. For the large events (6-8 events, H_{m0}=5-14m), WAM underpredicts H_{m0} by around 30-50% (e.g. for a 14m event, WAM analysis is 7m).
2) Skill of WAM for predicting spectral density at lower frequencies (0.05-0.07Hz) is poor, greatly underpredicting energy for the entire month.

3) Skill of WAM for predicting spectral density at higher frequencies (0.08-0.15Hz) is fair, with a slight underprediction on average, for the entire month.

During the winter months, swells are predominately from the north Pacific. In the days leading up to the 14m event on Jan. 11, WAM shows two significant wave events in the north Pacific. The western event is characterized by large amounts of low frequency energy, while the eastern event generates only small amounts of low frequency energy. The latter is the event that corresponds to the 14m wave height measurements. Inspecting the forcing for these two storms (FNMOC NOGAPS output), we see that they are of roughly equal intensity (maximum wind speeds around 20-25m/s), but the western event is much larger and of slightly longer duration.

This leads us to two possible conclusions:

1) The forcing is wrong. NOGAPS is predicting a small storm in the northeast Pacific, whereas the storm is actually much larger (i.e. as large as the storm in the northwest Pacific).
2) The generation mechanisms in WAM are flawed insofar as WAM badly underpredicts low frequency energy for small, intense wind events. In order to generate large quantities of low frequency energy, WAM requires a very large fetch, whereas in nature, such a large fetch is not necessary.

[Note: Though the eastern event is “small”, it is quite well resolved by the 1° geographic resolution. Also, the temporal resolution of NOGAPS forcing provided to WAM is 3 hours, which should be sufficient.]

[Note also: Since the underprediction is mainly at the low frequencies, we can expect that if the deep water WAM results here were used to provide the boundary conditions for a shallow water wave model, the errors in wave height would get much larger (owing to shoaling).]

We feel that the second conclusion is the more likely of the two, since the NOGAPS winds would have to contain an uncharacteristically large bias towards underprediction to miss such an event. Also, the second conclusion is consistent with our experience using a similar model, SWAN (Booij et al. 1999). This model requires a large fetch and duration to reach its “fully-developed” asymptote (see, e.g. Komen et al. 1984), whereas in nature, such a large fetch and duration does not seem to be required (see, e.g., Moskowitz 1964).

Thus we conclude that the consistent underprediction of low frequency energy in WAM analyses in deep water near the California coast is predominately due to problems with the generation algorithm of WAM. Error associated with propagation is much smaller. The latter is not surprising, since propagation distances associated with winter swells are not large, being generally from the north Pacific. (In fact, the eastern Jan. 11 wind event occurs quite close to the NDBC buoy.)

WAM CASE STUDY: CALIFORNIA SUMMER

Low frequency events that occur at the California coast in the summer are typically swells generated in the south Pacific. Thus propagation distances are quite large. We compare WAM analyses to buoy data at the same location (NDBC 46059), for the month of August 2000 (not shown). Here, the result is quite different. WAM is consistently overpredicting low frequency energy. Inspecting WAM low frequency time series for the entire Pacific Basin, we see that these swells are passing through islands groups (e.g. Hawaii, French Polynesia) prior to arriving at the California buoy. These small island groups are not represented in the WAM computational grid, due to the 1° resolution. Thus, the reason for the overprediction of swell energy is clear: swells that should be blocked are not blocked.[3]

This underscores how generation-related errors cannot be properly addressed unless it is certain that propagation errors are small. Any source/sink term development effort which included the Aug. 2000-46059 comparison would have been badly misled. If we compare WAM analyses to data at a location unaffected by blocking (the Christmas Island buoy south of Hawaii), the overprediction of swell energy is not seen. In fact, the low frequency energy is generally underpredicted here (very likely due to the model's generation stage).

EXPERIMENTAL DUAL-GRID TECHNIQUE

Accurate propagation (comparable to that of the Navy Swell Model) could be achieved in the WAM model via the "brute force" technique of applying WAM at extremely high resolution in the four dimensions $(\varphi, \lambda, \sigma, \theta)$. This effectively solves the problems of resolving islands, geographic propagation scheme error, spectral propagation scheme error, and the garden sprinkler effect. However, extremely high resolution in four dimensions is not a practical solution owing to the limited hardware dedicated to running these models operationally.

Fortunately, there is one basic fact about the WAM-type models that we can exploit: while propagation benefits from this extremely high resolution, the source/sink term calculations, which are a large portion of the computational effort, do not. Thus we can employ a "dual-grid technique" wherein propagation is solved on fine grids (in four dimensions), and source/sink terms are solved on coarse grids, with transformation between the two resolutions as needed.

Though this sounds like a very simple approach, some information is lost during the transformation between fine and coarse grids, and this error accumulates with each transformation. Preservation of peaks, in all dimensions, is particularly important, and unfortunately, sometimes impossible when the peaks shift during propagation. The transformation occurs once per propagation time step. Thus it is advantageous to use as large a propagation time step as possible. Also, it is advantageous to identify frequency/directional bins as "swell" and skip the transformation/source-term/transformation process altogether. This is justifiable since "swell" (using a strict definition) does not receive energy from the wind, does not break, and does not participate in nonlinear interactions. A modified dissipation term, appropriate for swell (and cheaper than wind sea physics), can be applied on the fine grid, thus avoiding the transformation process for these components. The swell criterion can be based on, e.g. a combination of local (in geographic space) wind speed and local (in frequency space) steepness.

WAM-type models use a time step size typically in the 10-30 minute range (20 minutes in the case of NAVO's global WAM). WAM and WW3 use conditionally stable geographic propagation schemes, so with an extremely fine geographic resolution, the largest allowable time step size would be as small as 0.5-1.0 minutes. Clearly, an unconditionally stable propagation scheme is needed. One which we have tested in Cartesian coordinates is the "Non-Interpolating, Semi-Lagrangian" (NISL) scheme given in one-dimensional form by Olim (1994) and extended to two dimensions by H. Petit of Delft Hydraulics via his "product-generated" method (personal communication). The scheme has the very attractive feature of becoming more accurate with higher Courant numbers (i.e. with larger time step sizes), making it ideal for

3: WER circa 2002: More recently, I am less certain about this conclusion. Perhaps it is impossible to find the effect of inadequate blocking in the very-far-field, due to signal to noise issues. It would be better to look in the near field (e.g. Hawaii buoys), which I did not do in this case.

use with the dual-grid technique. With a large time step (e.g. 3 hours) and a very fine geographic resolution (e.g. 0.25°), the scheme is extremely accurate. Unfortunately, the scheme becomes more complex in cases where energy does not travel along straight paths (e.g. in a spherical coordinate system), requiring trajectory calculations or similar correction. An unconditionally stable setup which does not require trajectory calculations would be a combination of the first order upwind explicit scheme (of WAM, stable for Courant numbers less than unity) and the first order downwind implicit scheme (stable for Courant numbers greater than unity). Though the use of a first order scheme might sound alarming, in fact, these schemes can be quite accurate at high resolution, even when simulating the most diffusion-prone cases. And since the spectral resolution, though high, will still be finite, a little diffusion is probably a good thing (due to the small, residual garden sprinkler effect). There is a catch though: like most implicit schemes, the first order downwind implicit scheme becomes less accurate as time step size is increased. Thus diffusion may be excessive for time steps of 1-3 hours. Also, implicit schemes tend to be troublesome because of the way their matrixes are solved. Some testing of either of these two approaches is obviously required.

A large propagation time step (e.g. 3 hours) would be beneficial with regard to computation time and with regard to minimizing the frequency of transformation between grids. However, there is a limit to how large a propagation time step can be used. Artificial discontinuities may result from a wave energy moving through a wind field in a stop-and-go fashion. This depends largely on the degree of geographic variation in the wind field. Some testing is required here also, to determine the largest practical propagation time step with realistic wind fields. In any event, it would not make sense for the propagation time step to exceed the forcing interval (the NOGAPS forcing of NAVO WAM is updated every 3 hours).

It is worth noting that the DIA technique (Hasselmann et al. 1985) which is used to calculate nonlinear interactions in WAM and WW3 becomes problematic at high spectral resolution. In this sense, high spectral resolution is impossible without the dual-grid technique, another potential advantage

Demonstration Model

A model was developed as a "proof-of-concept" platform. Below is a list of its features:

1) The model, like WAM, is solved in four dimensions, with time-stepping.
2) Physics are "first generation", which are considerably simpler than the "third generation" physics used by WAM-type models.
3) The model reads in nonstationary and non-uniform wind fields for forcing (as in WAM-type models).
4) The model uses the semi-Lagrangian scheme, "NISL", described above.
5) The model is solved in Cartesian coordinates. Thus, trajectory tracing for the semi-Lagrangian scheme is not needed or implemented; also, spectral propagation is not needed or implemented.
6) The model applies the dual-grid approach in two dimensions simultaneously, either (x, y) or (σ, θ). It has not yet been extended to apply the technique in four dimensions simultaneously.
7) Blocking by islands is implemented.
8) Due to hardware memory limitations, only a 90° sector in θ-space is used. [The memory requirements of fine resolution would probably dictate a distributed memory implementation for any operational usage.]

This model was tested using a case of approximately Pacific Basin scale, with a brief, strong wind event (U_{10}=22m/s) in the southwest region of the domain, blowing toward the northeast. A background wind speed of 2m/s was used. Two islands were situated near the center of the domain. The dimensions of the fine grid were: 457 nodes in x (Δx=33km); 403 nodes in y (Δy=33km); 37 nodes in θ ($\Delta\theta$=2.5°), 103 nodes in σ (with a logarithmic distribution). A ratio of six was used between fine a coarse grids in all dimensions. In both cases (dual-grid on (x, y) and dual-grid on (σ,θ)), the model yielded a result very similar to the "brute force" approach of fine resolution in all dimensions. The speed increase with the proof-of-concept model was modest (a factor of 3-5, where the number of grid points is decreased by 36). However, this "scaling" is expected to be much better in an implementation of the technique with third generation source/sink terms, for which physics calculations account for a much greater percentage of the total computation time (recall that the physics calculations—not propagation—are being sped up via the dual-grid technique). Much further optimization can occur; for example, high frequency waves can probably be propagated at the lower resolution without much loss in overall accuracy.

DISCUSSION

Output from the U.S. Navy's implementation of the global WAM model has been compared to buoy observations in the Pacific Basin. When island blocking in WAM is not an issue, the majority of forecast error is likely an underprediction of low frequency energy. These errors can be attributed to the generation stage of the model. Clearly, any "fix" for this problem will require extensive further investigation. However, we can offer this suggestion: we feel that the model skill would benefit greatly from a source/sink term modification that would provide a more rapid approach (in time and space) to the model's "fully-developed" asymptote, at least under certain conditions. Validation with short-fetch growth curves is inadequate, as is validation under weak and moderate wind speeds, since neither produces (in nature) large quantities of the low frequency energy that dominates the error in our comparisons.

Two techniques for correcting propagation-related problems in WAM have been described. One technique is to use WAM in conjunction with the Navy Swell Model. This technique works well in general, but has a number of operational disadvantages described above, and is viewed as an interim solution. The other technique is to use WW3, with its higher order propagation scheme, in combination with "intelligent diffusion" to counter the garden sprinkler effect. This is a clear improvement over WAM, but falls short of a true physics-based solution.

What would the perfect ocean-scale wind-wave model be? It would be a model that propagates energy as accurately as the Navy Swell Model while simultaneously calculating the physics of wave generation, decay, and nonlinear transfers. Perfect propagation would not be the final solution, of course, since error associated with the wave generation stage would still exist. In fact, since the errors of generation and propagation are sometimes counterbalancing each other, we should not be surprised if model skill is decreased in some cases. However, solving the propagation problem is a necessary first step to addressing the generation problem. With accurate propagation, errors will become more consistent, and we can get a better sense of how and why the models' generation stage fails, and where improvements can be made.

Note that the traditional techniques for developing/tuning source/sink terms involve the use of idealized scenarios for which propagation error is not a concern. Unfortunately, source/sink terms tuned for these idealized cases tend to perform poorly when applied at oceanic scale. Thus it is clearly necessary to develop/tune source/sink terms *at* oceanic scale, which in turn, makes it necessary to have an oceanic scale model with minimal error associated with propagation.

A "dual grid" method is proposed that calculates wave generation and propagation at their appropriate spatial/temporal scales and spectral resolutions. A simple, basin-scale demonstration of this method shows promise, however, further experimentation with the scaling and exchange of information between the two grids is needed in order to assess its potential in an operational setting.

It will be possible to implement a combination of the dual-grid approach and the more approximate methods of WW3; for example, the dual-grid method for geographic dimensions and the WW3 method for dealing with negative effects of coarse spectral resolution (modified Booij and Holthuijsen (1987) technique). In order to make an informed decision in this regard, there needs to be a careful comparison of the accuracy/inaccuracy of the WW3 approximations vs. the error associated with the dual-grid technique, applied to representative ("real") test cases in the Pacific Basin. A third model employing high resolution for all operations could be used as "ground truth". Further development of the dual-grid model is obviously a prerequisite for such a comparison.

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REFERENCES

Booij, N. and Holthuijsen, L. H. 1987. Propagation of Ocean Waves in Discrete Spectral Wave Models. *J. of Comput. Physics*, **68**, 307-326.

Booij, N., Ris, R. C., and Holthuijsen, L. H. 1999. A Third Generation Wave Model for Coastal Regions; Part I: Model Description and Validation. *J. of Geophysical Res.*, **104**, 7649-7666.

Davis, R. W. and Moore, E. F. 1982. A Numerical Study of Vortex Shedding from Rectangles. *J. Fluid Mech.*, **116**, 475-506.

Hasselmann, S., Hasselmann, K., Allender, J. H., and Barnett, T. P. 1985. Computations and Parameterizations of the Linear Energy Transfer in a Gravity Wave Spectrum, II, Parameterizations of the nonlinear transfer for application in wave models. *J. Phys. Oceanogr.*, **15**, 1378-1391.

Komen, G. J., Hasselmann, S., and Hasselmann, K. 1984. On the Existence of a Fully Developed Wind-Sea Spectrum. *J. Phys. Oceanogr.*, **14**, 1271-1285.

Komen, G. J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S., and Janssen, P. A. E. M. 1994. *Dynamics and Modelling of Ocean Waves.* Cambridge Univ. Press, 532

pp.
Lavrenov, I. V. and Onvlee, J. R. A. 1995. A Comparison Between the Results of Wave Energy Propagation of the WAM Model and the Interpolation-Ray Method. *Russian Meteorology and Hydrology*, No. 3, 29-42.
Leonard, B. P. 1979. A Stable and Accurate Convective Modeling Procedure Based on Quadratic Upstream Interpolation. *Computer Methods in Applied Mechanics and Engineering*, **19**, 59-98.
Leonard, B. P. 1991. The ULTIMATE Conservative Difference Scheme Applied to Unsteady One-dimensional Advection. *Comput. Methods Appl. Mech. Eng.*, **88**, 17-74.
Moskowitz, L. 1964. Estimates of the Power Spectrums for Fully Developed Seas for Wind Speeds of 20 to 40 knots. *J. Geophys. Res.*, **69(24)**, 5161-5179.
Olim, M. 1994. A Truly Noninterpolating Semi-Lagrangian Lax-Wendroff Method. *J. of Comp. Phys.*, **112**, 253-266.
SWAMP Group 1985. *Ocean Wave Modeling*, Plenum, New York, 266pp.
Tolman, H. L. 1991. A Third Generation Model for Wind Waves on Slowly Varying, Unsteady and Inhomogeneous Depths and Currents. *J. Phys. Oceanogr*., **21**, 782-797.
Tolman, H. L., and Chalikov, D. 1996. Source terms in a Third-Generation Wind Wave Model. *J. Phys. Oceanogr.*, **26**, 2497-2518.
Wittmann, P. A. and O'Reilly, W. C. 1998. WAM Validation of Pacific Swell. Proceedings of the 5th International Workshop on Wave Hindcasting and Forecasting, Meteorological Service of Canada, 83-87.

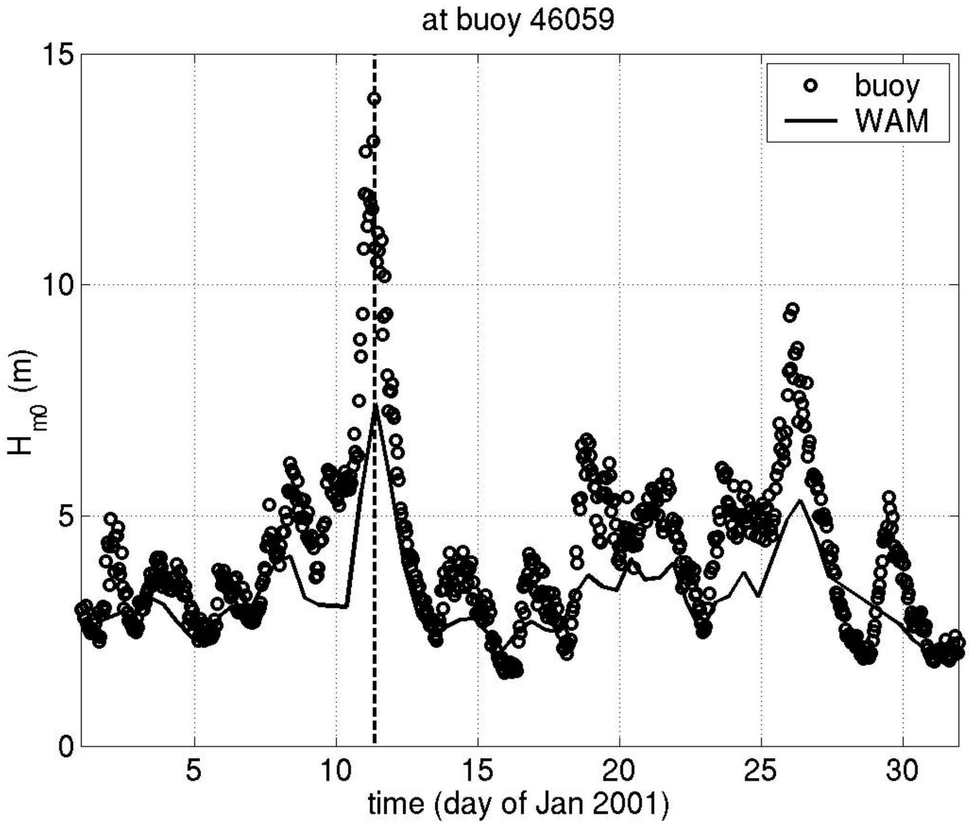

Fig. 1. Time series of zero moment wave height at location of NDBC buoy 46059 (deep water), WAM vs. buoy measurements during January 2001. Wave height is energy-based, calculated from frequencies 0.03 Hz to 0.33 Hz. The dashed vertical line indicates the instant in time that is plotted in Fig. 3 below.

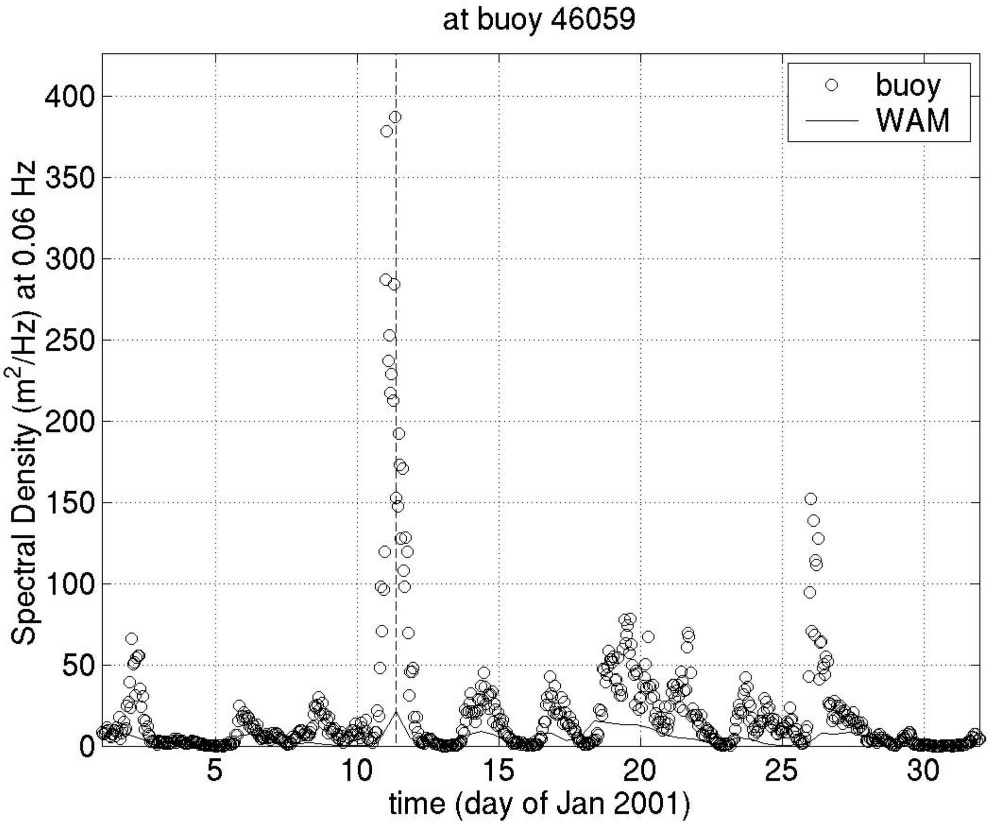

Fig. 2. Time series of 0.06 Hz spectral density at location of NDBC buoy 46059 (deep water), WAM vs. buoy measurements during January 2001. The dashed vertical line indicates the instant in time which is plotted in Fig. 3 below.

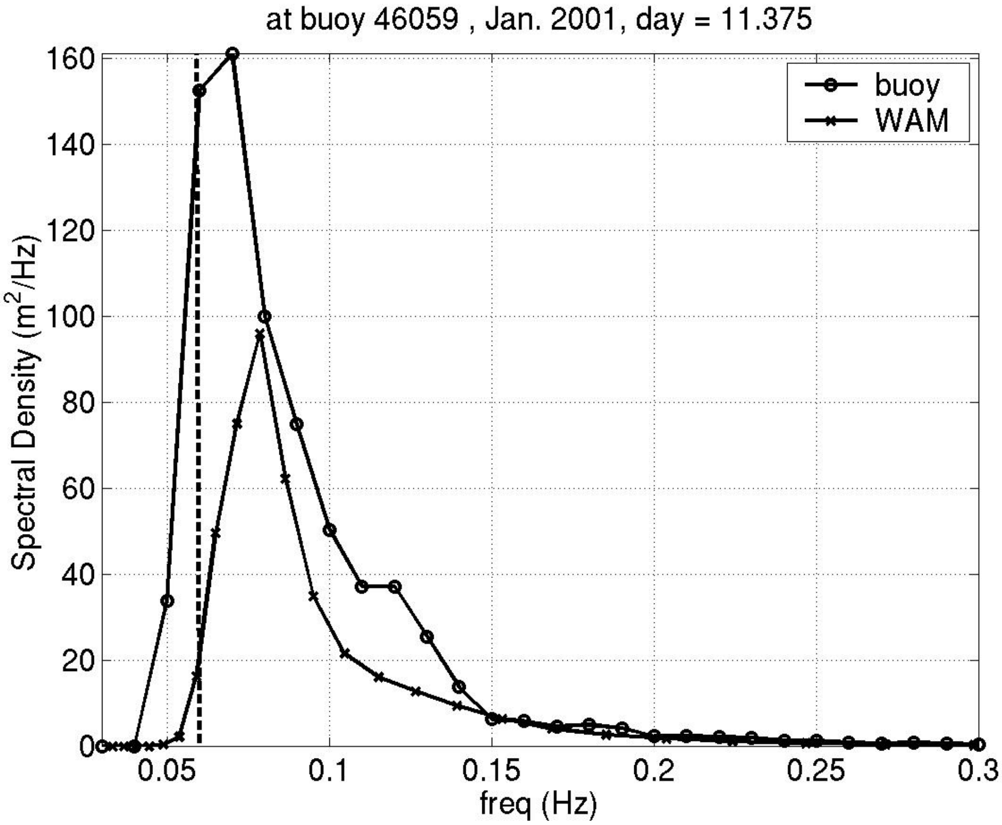

Fig. 3. Frequency distribution at location of NDBC buoy 46059 (deep water), WAM vs. buoy measurements. Time shown is Jan. 11, 2001, at 0900Z. The dashed vertical line indicates the frequency that is plotted in Fig. 2 above.