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Quantifying the Role of Wind Field Accuracy in the U.S. Navy's Global Ocean Wave Nowcast/Forecast System

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14. ABSTRACT

This report documents the second part of an investigation to determine the relative importance of various sources of error in the two global scale models of wind-generated surface waves used operationally by the U.S. Navy (the first part of the investigation is documented in an earlier NRL report; a short review of that earlier report is given herein). Here, we focus primarily on the impact of wind forcing (provided by an atmospheric model and/or data assimilation system) on the WAVEWATCH-III model. We use the time period of January 1-February 8, 2002 in global WAVEWATCH-III hindcasts, forced by three different types of wind analyses, one being the operational global surface wind analyses produced by Fleet Numerical Meteorology and Oceanography Center. Modeled total wave heights are compared to buoy and altimeter data (ERS-2 and TOPEX) locally, regionally, and globally. Based on these and earlier comparisons, it is credible that errors associated with wind forcing dominate the total error in the Navy's contemporary (circa January/February 2002) operational global wave model nowcast/forecast system. However, since the operational surface wind product is periodically improved, the relative magnitude of wind forcing error can be expected to change over time.

15. SUBJECT TERMS

Swell; WAVEWATCH-III; NOGAPS; QuikSCAT; Scatterometer; Wind-waves; Gravity-waves; Altimeter; ERS-2; TOPEX; Buoy; Suface winds

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QUANTIFYING THE ROLE OF WIND FIELD ACCURACY IN THE U.S. NAVY'S GLOBAL OCEAN WAVE NOWCAST/FORECAST SYSTEM

Author's note: This document will also appear in the CD-ROM Proceedings of the 7th International Workshop on Wave Hindcasting and Forecasting (October 21-25, 2002, Banff, Alberta, Canada). This NRL Memorandum Report serves as the print publication for the manuscript.

1. INTRODUCTION

At U.S. Navy operational centers (Naval Oceanographic Office [NAVO] and Fleet Numerical Meteorology and Oceanography Center [FNMOC]), the models used for nowcasting and forecasting wind-generated surface waves at oceanic scale are the third generation models WAM, Cycle 4 (henceforth "WAM4", see Günther et al. 1992, Komen et al. 1994, and references therein) used at NAVO, and WAVEWATCH-III (henceforth "WvW3", see Tolman 1999[1] and references therein). This type of model is subject to various sources of error, which can be grouped into three broad categories: 1) wave model numerics and resolution, 2) wave model physical formulations, and 3) wind forcing (provided to the wave model by an atmospheric model and/or data assimilation system). It is well known that wave models are very sensitive to wind forcing. However, it is less clear how the relative accuracy of the contemporary Navy operational surface wind product affects the global wave model. The objective of this study is to unravel the role of wind field accuracy in the U.S. Navy's global ocean wave nowcast/forecast system, versus other sources of error.

1.1 Background: Numerics and resolution

In the WAM model (Cycles 1-4), a first order, upwind, explicit scheme is used for propagation of wave energy. This leads to significant diffusion and phase error, which is the numerics/resolution issue that is generally thought to be of greatest importance in the WAM model. For example, Bender (1996) concludes that the first order scheme is responsible for much of the negative bias in swell predictions in regional WAM hindcasts (WAM Cycle 2, Australian region). WvW3 uses a higher order propagation scheme (see Tolman 1995). WAM4 relies on numerical diffusion to mask problems associated with coarse spectral discretization, whereas WvW3 uses somewhat more accurate methods to deal with the problem (namely that of Booij and Holthuijsen 1987). Additional refinement and improvement to propagation are new features of WvW3, version 2.22 (see Tolman 2001, Tolman 2002b), which is not yet operational at FNMOC.

1.2 Background: Physical formulations

The time rate of change in spectral density in the third generation wave model is controlled by propagation (advection) terms and by source/sink terms (physical formulations). In deep water, the total source/sink term S is dominated by three terms, $S \approx S_{in}+S_{nl}+S_{ds}$: input by wind (which can be negative in the case of WvW3), four wave nonlinear interactions, and dissipation, respectively. The physics of WAM4 are described in Janssen (1991) and Komen et al. (1994); the physics of WvW3 are described in Tolman and Chalikov (1996), with minor refinement of the Tolman and Chalikov physics being described in Tolman (1999). The WvW3 formulations of S_{in} and S_{ds} are quite different from those of WAM4. With regard to the S_{nl}, there is only a minor difference. The S formulation of Tolman (1999) will henceforth be denoted as "TC" (Tolman and Chalikov) physics. For the most part, the physical formulations of these two models are based on earlier works, some of which are not referenced herein.

The life cycle of a wave train can be divided into a "growth stage" and "propagation stage". During the growth stage, all three source sink terms are important. In order to accurately predict wave growth, all three terms must be skillful, or at least must be tuned such that shortcomings in any one term will tend to be compensated by other term(s). At the propagation stage, once swells are sufficiently dispersed such that the amplitude-to-wavelength ratio is small, nonlinear interactions are insignificant. Also, local wind speeds are generally not high enough to transfer momentum to the swells (i.e. $S_{in} \leq 0$). Thus, only attenuation is important. In WAM4, attenuation is represented by the S_{ds} term. In WvW3, it is represented by combined S_{in} and S_{ds} (both negative).

[1] This reference is the user's manual for version 1.18 of WvW3, which is the version presently used at FNMOC.

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1.3 Background: Wind forcing

We include three wind analysis sources in our comparisons herein:

1) NOGAPS ("Navy Operational Global Atmospheric Prediction System", see Hogan and Rosmond (1991) and Rosmond et al. (2002)) analyses. NOGAPS is used by the operational Navy (FNMOC and NAVO) to force the global wave models (WvW3 and WAM4, respectively), so relevance to this study is obvious. We assemble the forcing fields using one analysis field every twelve hours, with the three hour, six hour, and nine hour forecasts providing intermediate forcing (i.e. twelve-hour cycle and three-hour interval). We refer to these as "analyses", though strictly speaking, they are a mix of analyses and very short-range forecasts.
2) NCEP (National Centers for Environmental Prediction) analyses (see e.g. Kanamitsu 1989 and Caplan et al. 1997), which are a product of the GDAS ("Global Data Assimilation Scheme") and the MRF (aviation cycle of the Medium Range Forecast) model. These are used to force NCEP's operational global wave model (WvW3). It is included to compare the Navy's operational product with another mainstream, operational product. As with the NOGAPS analyses, these fields are provided by NCEP with a three-hour interval, on a twelve-hour cycle.
3) NOGAPS analyses, with NOGAPS wind vectors replaced by "QuikSCAT" measurements (PODAAC 2001) at appropriate times/locations. (These are the "L2B, W6" wind fields described in Rogers 2002.) The method used to generate these fields is simple and crude, but the fields are useful tools to better understand the impact (on the wave model) of the deviation of NOGAPS from measurements. We refer to these fields as "blended QuikSCAT/NOGAPS" or "L2W6" analyses. Any method of constructing wind component maps on a uniform space-time grid from satellite measurements is expected to suffer from temporal collocation (sampling) error to some extent (see Schlax et al. 2001). However, this type of error should be fairly random (i.e. bias, if it exists, is small). Systematic biases may exist in the QuikSCAT vectors themselves, but we expect that such errors are small (there is a limited validation in Rogers (2002), using buoy measurements). These analyses are created with a three-hour time interval.

Except in cases where we indicate that wave model results are from operational products, all wave model results presented were run in hindcast mode (not real-time).

2. APPROACH

Our approach for arguing/determining the relative impact of various sources of error is as follows:

1) Investigation of numerics/resolution: Determine scenarios/situations in which numerics and resolution play an important role in the total wave model error. Since we have the ability to practically eliminate error associated with numerics and resolution, this can be straightforward and conclusive.
2) Investigation of physical formulations at the generation stage: Create hindcast scenario(s) in which a) wind field error is not expected to produce significant bias (i.e. predominately random error) and b) physics of swell attenuation and numerics of swell propagation are not relevant (i.e. young swells). Model performance is therefore a check on skill of physical formulations at the generation stage.
3) Investigation of physical formulations at the propagation stage: Determine scenario(s) in which models with similar forcing, numerics, and resolution, but different physical formulations produce dramatically different results. In this circumstance, the competing physical formulations cannot both be correct. Comparison to data may lend insight with regard to relative skill of the physical formulations.
4) Using models with similar physics, numerics, and resolution, determine sensitivity to wind field specification method. If one method provides consistently better results, attempt to determine whether this is due to more accurate wind fields, or due to counterbalancing of errors (e.g. by direct comparison to wind measurements).

3. INVESTIGATION: NUMERICS AND RESOLUTION

Wittmann and O'Reilly (1998) and Rogers (2002)—through the use of a great circle wave ray-tracing tool developed by Dr. W.C. O'Reilly (Scripps Institution of Oceanography)—demonstrated that the diffusion associated with the first order scheme of WAM is unlikely to be a first order source of error in the Navy's global WAM4 implementation, even if only older swells (which are the wave components most affected by diffusion) are considered[2]. The WvW3 model provides the option of employing higher order propagation numerics (and other, related improvements), so the impact of this issue is diminished further. Rogers (2002) also demonstrated that resolution (both geographic and spectral) is unlikely to be a first order source of error, though geographic resolution *is* expected to play an important role in some locations. Supporting information and discussion of other numerics/resolution issues can be found in Rogers (2002).

4. INVESTIGATION: PHYSICAL FORMULATIONS, GENERATION STAGE

Rogers (2002) studied the skill of the Navy global wave models in hindcasting young swells generated by the strong extratropical storms which are common in the north Pacific during the winter season using two simulations (January 2001 and January/February 2002). The results suggest that, given accurate forcing, both WvW3 and WAM4 are reasonably skillful at predicting young, low frequency (e.g. <0.08Hz) energy. The basic question asked was: "given a surface wind field with little or no bias, does the wave model produce wave energy with comparable bias?" In general, hindcasting the young swells, the models seemed quite well behaved in this regard. The bias of wind fields was determined by comparison to scatterometer data (in the case of the NOGAPS and NCEP fields), and by limited comparison to winds measured by buoys. Prediction of low frequency energy is generally more difficult than prediction of total energy; both models show even greater skill when comparing energy from a larger portion of the spectrum (e.g. energy less than 0.3 Hz, not shown).

There were some behavioral differences between WvW3 and WAM4, but in terms of skill, differences were insignificant. To illustrate this, an example comparison is shown in Figures 1a,b. Here, output from global hindcasts (January 1 – February 8, 2002) are compared to data collected by a buoy offshore of the U.S. west coast. "Low frequency wave height" is plotted, which is a fictitious wave height calculated from the variance of the wave spectrum below some frequency, 0.06Hz in this case. Rogers (2002) made similar young swell comparisons using one other hindcast (January 2001), two other locations (further offshore of the U.S. west coast), two other frequency ranges ("up to 0.08Hz" and "up to 0.10Hz"), and other model/forcing combinations.

This result is consistent with that of Cardone et al. (1996), who find that, given accurate forcing, oceanic scale wave models such as WAM4 are quite accurate at predicting strong wave events, up to a (total) wave height of around 12m.

5. INVESTIGATION: PHYSICAL FORMULATIONS, PROPAGATION STAGE

Rogers (2002) similarly studied skill at predicting medium-age (e.g. 4-6 days old) swells and old (greater than 8 days old) swells using a hindcast of July 2001. This hindcast was inconclusive with regard to the models' skill at the generation stage, but differences between the attenuation occurring during the propagation stage were surprisingly large, indicating that attenuation is not well represented in one or both of the models. Comparison to buoy data led to the (very tentative) conclusion that attenuation is underpredicted in the WAM4 model. Figures 2a-b show example comparisons. The swells are generated in the southern Pacific Ocean. The Christmas Island buoy measures them 4-6 days after generation. The California buoys measure the swells more than 8 days after generation. "O(1) numerics" refers to the first order, upwind, explicit scheme. "UQ numerics" refers to the higher order propagation that is the default option of WvW3. WAM4 physics refers to physics of Janssen (1991) and others (see Komen et al. 1994). "TC physics" refers to physics of Tolman and Chalikov (1996).

The observation that swells may be under-dissipated in the WAM4 model is consistent with observations made by Tolman (2002a), who further suggests that WAM4 may benefit from a wave-to-wind momentum feedback (i.e. negative S_{in}), as present in WvW3.

Note that even if swell attenuation is improved in the Navy WAM4, this will not necessarily translate into an improvement in error statistics globally. If low frequency energy is being under-generated (e.g. due to winds that are biased low at high wind speeds), then underprediction of attenuation might actually improve statistics. Further, since (natural) dispersion is more relevant to older swells, accurate prediction of frequency and

[2] Note that though diffusion (and similar issues, such as spectral resolution) may have small impact on statistical error measures (relative to other sources of error), it can have a more significant impact on qualitative measures of skill, such as the ability to produce realistic swell dispersion, as seen in graphical images.

directional distribution at the source is that much more crucial. Unfortunately, the ability of models to predict these finer details reliably is questionable.

6. INVESTIGATION: WIND FORCING

The accuracy of wind forcing is obviously important to a wave model nowcast or forecast. For example, Cardone et al. (1996) suggested that error in contemporary operational wave model nowcast/forecast systems was dominated by errors in wind analyses and forecasts. Herein, our objective is to determine whether this holds true for present (circa 2002), operational Navy systems.

Rogers (2002) compares NOGAPS and NCEP analyses to QuikSCAT measurements in the northeast Pacific during January 2001 and in the south Pacific during July 2001. It is found that both analyses tend to be biased low at high wind speeds, but the bias is relatively slight with the NCEP analyses and quite significant in the NOGAPS analyses, particularly in the northeast Pacific comparison. We have made global comparisons for January 1 through February 8 2002; these similarly suggest that strong surface wind events in NOGAPS analyses are biased low. This comparison is presented in Appendix A.

Rogers (2002) investigates the sensitivity of the January 2002 hindcast case to wind forcing using time series comparisons of low frequency wave height similar to those in Figures 1-2. In the January 2002 hindcasts, Rogers (2002) only looked at the wave climate in the north Pacific, so it was essentially a hindcast of the low frequency energy generated by the strong extratropical storms typical of this time and location. Here, we take an alternate tack, by including not only local comparisons, but also regional and global comparisons. In order to have data at locations not within the coverage of the U.S. and Canadian buoy networks, we use the TOPEX/POSEIDON altimeter data (henceforth denoted "TOPEX"; for description see Fu et al. 1994)[3] and ERS-2 (European Remote Sensing Satellite 2). The comparison thus differs further from Rogers (2002) insofar as it is of total wave heights, which is the wave quantity that is inferred from altimeter measurements. All subsequent hindcast comparisons are for January 8 through February 8, 2002.

All altimeter data presented in this paper is what is known as "Fast Delivery" (FD) or "Interim Geophysical Data Records" (IGDR) altimetry. This is the near-real-time altimeter product. None of the comparisons use the other type of altimeter product, which is referred to as "offline" or "Ocean PRoduct" (OPR) data[4]. During this study, large inconsistencies between the buoy data, FD TOPEX, and FD ERS-2 became apparent, suggesting the need for some type of calibration/correction. Thus, in our comparisons of hindcast wave model output to altimeter data, we use the FD altimetry, with calibrations provided by David Cotton (of Satellite Observing Systems). These calibrations, and their impact on the comparisons are described in Appendix B. Henceforth, the calibrated altimeter products are referred to as "FDC" data.

Comparisons of WvW3 hindcasts to (corrected) ERS-2 are not presented in graphical form, but statistics are given in Table 1, along with statistics for the buoy and TOPEX comparisons. To summarize, the wave comparisons made in subsequent sections are:

- Operational FNMOC WvW3 analyses (forced by NOGAPS analyses) vs. buoy data (graphics generated monthly; samples for January 2002 reproduced here in Figure 5).
- Operational FNMOC WvW3 analyses (forced by NOGAPS analyses) vs. FD ERS-2 (graphics generated monthly; February 2002 reproduced here in Figure 12).
- WvW3 hindcasts (forced by three different types of analyses) vs. buoy data for the period of January 8 through February 8, 2002 (Figure 3; statistics in Table 1).
- WvW3 hindcasts (forced by three different types of analyses) vs. FDC TOPEX data for the period of January 8 through February 8, 2002 (Figures 4, 6-11); also statistics in Table 1).

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[3] For a description of the altimetry products used herein (TOPEX/POSEIDON and ERS-2), see http://www7320.nrlssc.navy.mil/altimetry/index.html.

[4] The offline products include additional processing. In the case of TOPEX, the acronym "GDR" (Geophysical Data Record) is also used for the offline product (distinguished from "IGDR"). In the case of TOPEX *wave heights*, there is little, if any difference between IGDR and GDR. In the case of ERS-2 wave heights, the difference between FD and OPR wave heights is substantial. Note that the additional processing of the offline products does not imply that calibration is not needed for the product.

- WvW3 hindcasts (forced by three different types of analyses) vs. FDC ERS-2 data for the period of January 8 through February 8, 2002 (statistics in Table 1).

It is well known that error statistics have a seasonal cycle, especially when only one hemisphere (northern or southern) is included in a particular comparison (see e.g. Bidlot et al. 2002, Fig. 4). Thus, it is important to keep in mind that some of our January/February comparisons correspond to summer *or* winter conditions, while other comparisons for this time period correspond to summer *and* winter conditions, depending on the region covered.

6.1 Local comparison

To get a rough idea of the confidence limits of the altimeter data, we first make a comparison that can be crosschecked against a comparable buoy comparison. For the location, we use buoy 46006 (west of northern California), since it is well removed from the continental shelf (nearer the shelf, fetch-limited conditions are expected to increase variation along the altimeter track, which weakens comparisons). Figures 3a,b shows a scatter plot of model wave heights (from wave hindcasts forced by wind analyses) vs. buoy wave heights. Here, wave heights of both buoy and model are calculated from the spectrum up to 0.3Hz, so they include both low and high frequencies. The root mean square errors ("rmse"), regression[5] y-intercept ("b"), regression slope ("m"), and the bias (mean error) corresponding to the highest 15% of measured wave heights ("$\gamma_{15\%}$") are indicated on the plot. The points included in the bias calculation are to the right of the vertical line. Figures 4a,b shows a scatter plot of model vs. altimeter wave heights. Here, the wave heights shown are simply the total wave height reported by the model and altimeter. Both Figures 3 and 4 suggest that (as expected) the difference in wave model result, from using one type of operational wind product to another, is quite large. With regard to model skill, the comparisons are fairly consistent. The buoy data and the FDC TOPEX data both suggest that the NOGAPS-forced model has a moderate negative bias. Further, they both suggest that the WvW3 model forced by blended NOGAPS and QuikSCAT has a moderate positive bias. The NCEP-forced model has the smallest bias (positive). Comparisons with FDC ERS-2 altimeter wave heights show similar results (Table 1, Location 46006).

The comparison of the NOGAPS-forced model to buoy data (Figure 3a) is consistent with comparisons produced by FNMOC for their operational model in this region during this time: see Figure 5, which also compares buoy-measured winds to NOGAPS analyses. Note that NDBC buoy 46006 is included in the "northeast Pacific" grouping. The degree of bias in the FNMOC buoy comparisons varies significantly by region (for example, the models' skill is relatively good in the northeast Pacific grouping). See "http://www.fnmoc.navy.mil/PUBLIC/MODEL_REPORTS/MONTHLY_MODEL_SUMMARY/" for other comparisons.

6.2 Regional and global altimeter comparisons

Figures 6-11 show comparisons of the two models to FDC TOPEX data for the north Pacific (Figure 6), equatorial Pacific (Figure 7), south Pacific (Figure 8), the entire Pacific (Figure 9), the north Atlantic (Figure 10), and the entire globe (Figure 11). (Figure B2b in Appendix B shows a global comparison similar to Figure 11, except with FDC ERS-2 data.) In each plot, the vertical line indicates the lower bound of data used in the bias ("$\gamma_{15\%}$") calculation. FDC ERS-2 statistics are shown in Table 1. All of these comparisons suggest a significant negative bias in the NOGAPS-forced model, consistent with the north Pacific buoy comparisons. The NCEP-forced model also has a consistent negative bias (thus differing from the local comparison), but it is generally smaller than that of the NOGAPS-forced model. The model forced by blended NOGAPS/QuikSCAT data has a consistent positive bias, but as with the NCEP-forced model, bias is relatively small.

Figure 12 shows a plot of the FNMOC operational analyses vs. ERS-2 for February 2002. These are the FD ERS-2 products (Cotton corrections are not applied).

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[5] The linear regression algorithm uses iteratively reweighted least squares with a bisquare weighting function.

7. DISCUSSION

In our comparisons, the wave models forced by NOGAPS analyses show a fairly consistent negative bias at high wave heights. We feel that much of this can be attributed to negative bias in NOGAPS analyses at high wind speeds.

The consistent positive bias with QuikSCAT forcing suggests that either a) the wave model is tuned to perform well when forced by wind fields which have negative bias at high wind speeds, b) the L2W6 fields are biased high, or c) another aspect of the L2W6 fields (e.g. spatial irregularity) leads to erroneously high wave conditions. We feel that (c) is unlikely to be the case. Extensive comparisons to in situ data (which we have not performed yet) are required to determine whether (a) or (b) are more likely explanations.

The L2W6 results and the direct comparisons to measured winds (e.g. Appendix A and Rogers 2002) suggest that the negative bias cannot be attributed to the wave model physics alone. In fact, if (for the sake of argument) the L2W6 analyses do not have any systematic bias, this hindcast indicates that the wave model physics of WvW3 leads to a small, positive bias during energetic conditions (e.g. H_{m0}=4-10m). In the case of the NOGAPS-forced and NCEP-forced models, this positive bias would partially counterbalance the larger negative bias associated with the forcing. It must be stressed, however, that if this positive bias resulting from wave model physics exists, it is small. None of our results suggest that given accurate forcing, either wave model (WAM4 or WvW3) has persistent, significant problems predicting large waves associated with extratropical storms. [Of course, they may be less skilled in the most extreme cases, such as wave heights greater than 12m, as in Cardone et al. (1996), which are not the focus of this study.]

All data sets indicate large sensitivity of wave model skill to wind forcing. This is, of course, to be expected. The skill advantage of the NCEP-forced model over the NOGAPS-forced model is consistent, but varies considerably by region. This variation may be due to differences in season, or due to the nature of data assimilation in the two atmospheric models (e.g. different weighting of buoys, which are mostly in the northern hemisphere).

In order for the hindcast comparisons to be relevant to the operational Navy, the hindcast model must be consistent with the operational model. We have addressed this (to some extent) by presenting example results from the operational model that may be compared against our results (for example compare Figure 3a vs. 5a [lower right quadrant] and Figure B2a vs. Figure 12 [left plot]). Additionally, Rogers (2002) compared the hindcast WvW3 model output to archived operational WvW3 model analyses at a single point. The discrepancies were very small and could be attributed to known (minor) differences between the models.[6]

Note that other than the very short-term (3, 6, and 9hr) forecasts used to create our forcing fields, we do not present wave model results with forecast wind fields herein. It is entirely possible that the negative bias that exists in the NOGAPS analyses (at high wind speeds) does not exist in the longer term (e.g. 72hr) forecasts. This is important since much of the wave energy in a wave model forecast is generated by wind forecasts (though much of the forecast swell energy is still generated by wind analyses).

8. SUMMARY

Our findings, based on this investigation and previous investigations, are as follows:

1) Numerics and resolution do not have a major impact on wave model error statistics. As other sources of error decrease, this situation may change. Further, there are benefits associated with more precise propagation techniques that may not be apparent in statistics.
2) When forced with accurate winds (e.g. direct forcing by scatterometer measurements), both WAM4 and WvW3 are fairly skillful at generating low frequency energy (e.g. energy from the portion of spectrum below 0.08 Hz) and, to a greater degree, total energy. Significant differences exist in the physical formulations of the two models, resulting in differences in wave growth that is evident in low

[6] For example the FNMOC WvW3 model accounts for air-sea temperature differences, whereas the NRL WvW3 model does not. Also, the NRL WvW3 models interpolated spectra to the buoy locations, whereas the other models used the nearest computational node on the 1°×1° grid.

frequency energy comparisons. However, our hindcasts suggest that the two models are very close in terms of predictive skill at the generation stage.

3) WAM4 and WvW3 exhibit very different swell attenuation, in practice. Our study suggests that WAM4 does not attenuate swell enough. Due to the limited nature of this particular investigation, the latter conclusion is very tentative. Nevertheless, it is consistent with observations of others (some of them communicated informally).
4) Negative bias in the Navy's Operational surface wind product—which is most evident at higher wind speeds—is a direct cause of negative bias in total wave energy (i.e. wave height) in the operational model. The degree of the bias appears to vary considerably by season and region. Much of the negative bias in the NOGAPS surface wind analysis can be attributed to the Emanuel cumulus parameterization in NOGAPS, implemented in April 2000. A new cloud scheme—described in detail in Teixeira and Hogan (2002)—improves the surface wind bias in the tropics (Teixeira and Hogan 2001)[7]. The horizontal and vertical resolution of NOGAPS has also been upgraded in September 2002, from T169L24 (80km horizontal resolution, 24 vertical levels) to T239L30 (50km horizontal resolution, 30 vertical levels), which will further reduce negative bias in the surface winds. Finally FNMOC plans to upgrade the NOGAPS data assimilation scheme to a three dimensional variational procedure (namely, the NRL Atmospheric Variational Data Assimilation System, "NAVDAS", Daley and Barker 2001). This scheme will include the assimilation of QuikSCAT winds and will be computed on a high-resolution grid, which will better preserve high wind features in the surface wind fields. The combination of the modified Emanuel scheme, the upgrade to T239L30, and implementation of NAVDAS are expected to lessen the negative surface wind speed bias. In a follow-up paper, we will quantify the resulting improvement to the operational global wave models, perhaps by studying January/February 2003 wave analyses and hindcasts.

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APPENDIX A

In Figure A1, we directly compare analysis wind speeds to QuikSCAT (PODAAC L2B) winds speeds, globally. Of the three types of analyses, only the NOGAPS analyses can be considered independent of the data used for "ground truth" (QuikSCAT). In mid-January 2002, NCEP began to assimilate QuikSCAT data in their operational wind product (Hendrik Tolman, personal communication). The L2W6 fields are derived from the L2B data. 25% of the measurements used in the scatter plot comparison in Figure A1c were also used in the creation of the L2W6 analyses.

If the L2B QuikSCAT data can be regarded as ground truth, then this global comparison suggests that both the NCEP and NOGAPS analyses are biased low at high wind speeds. The result is consistent with the two regional comparisons made by Rogers (2002) for January 2001 and July 2001.

The L2W6 fields are created using the following algorithm:

1) If a JPL L2B measurement is nearby (within a 1° by 1° cell) and current (within 6 hours of the analysis time, thus the "6" in L2W6)), use that measurement.
2) Otherwise, use NOGAPS value for that time/location.

When, for a given grid cell and snapshot time, more than one measurement satisfies criterion (1), the nearest measurement is used. Further discussion of the method and potential improvements can be found in Rogers (2002). Figure A1c, though it does not indicate accuracy, does provide a good check on the method used to create the L2W6 fields. The discrepancy between the raw data and the processed fields is probably due to three factors:

1) Sampling error: some (though not all) of temporal collocation error will show up as error in this comparison,
2) Model error: NOGAPS is used at times/locations where no appropriate measurement can be found. Thus, bias in the NOGAPS analyses tends to produce similar bias in the L2W6 analyses, to some extent.
3) Measurement irregularity: Some of the irregularities caused by small scale wind features measured by the SeaWinds instrument and random error associated with the function used to infer wind speed from backscatter will show up as error in this Figure A1c, since not all measurements used in the comparison were used in the creation of the analyses.

Extensive comparisons of all three wind analysis methods to in situ data seems to be called for. We hope to do this in a later study.

APPENDIX B

The Navy's Fast Delivery ERS-2 and TOPEX wave height products are obtained from NOAA (National Oceanic and Atmospheric Administration) and NAVO, respectively. We apply corrections provided by David Cotton (of Satellite Observing Systems) to these FD altimeter wave heights. The corrections are described in informal documents[9]. The calibrations performed by Dr. Cotton are designed to improve agreement with U.S., Canadian, and British buoys. Corrections are given for both wave heights and wind speeds. Only the wave height corrections are relevant to the hindcasts presented in this study.

Prior to application of these corrections, the instruments (FD TOPEX, FD ERS-2, buoy 46006) were not consistent. For example, the NCEP-forced model in the local comparison, has bias values ($\gamma_{15\%}$) of 0.55m, 0.97m, and 0.28m vs. the FD TOPEX, FD ERS-2 and buoy respectively (Table 2 shows additional comparison using the FD products). After the corrections, the instruments are much more consistent. Bias values ($\gamma_{15\%}$) for different instruments (FDC TOPEX, FDC ERS-2, buoy 46006) are usually within 0.2m, and rmse values are usually within 0.1m of each other. Consistently, the FDC TOPEX bias is higher than the FDC ERS-2 bias, suggesting that refinement of the calibration is possible (at the higher wave heights, at least). Nevertheless, the level of consistency in the FDC comparisons is very encouraging.

ERS-2 Correction

Corrections for FD ERS-2 provided by Dr. Cotton are as follows:

a) A calibration used by SOS (Satellite Observing Systems) for wave heights H_s less than 1.5m:
$$H_{FDC,SOS} = 0.143 + \sqrt{1.336 H_{FD}^2 - 0.8397}$$
b) A linear calibration used by SOS for wave height H_s above 1.5m.
c) A linear calibration created by Dr. Cotton using orthogonal distance regression, valid for wave heights greater than 1.5m: $H_{FDC,Cotton} = 1.1654 H_{FD} - 0.2026$

The Cotton document notes that (c) is more accurate than (b), but SOS opts to use (b) in order to be consistent with earlier SOS data calibration. We use (a) and (c). We make the transition at H_{FD}=1.23 in order to maintain a monotonic relation (smooth transition). Figure B1 explains.

This correction to the wave heights is substantial. Figures B2a,b show ERS-2 comparisons with and without the Cotton correction.

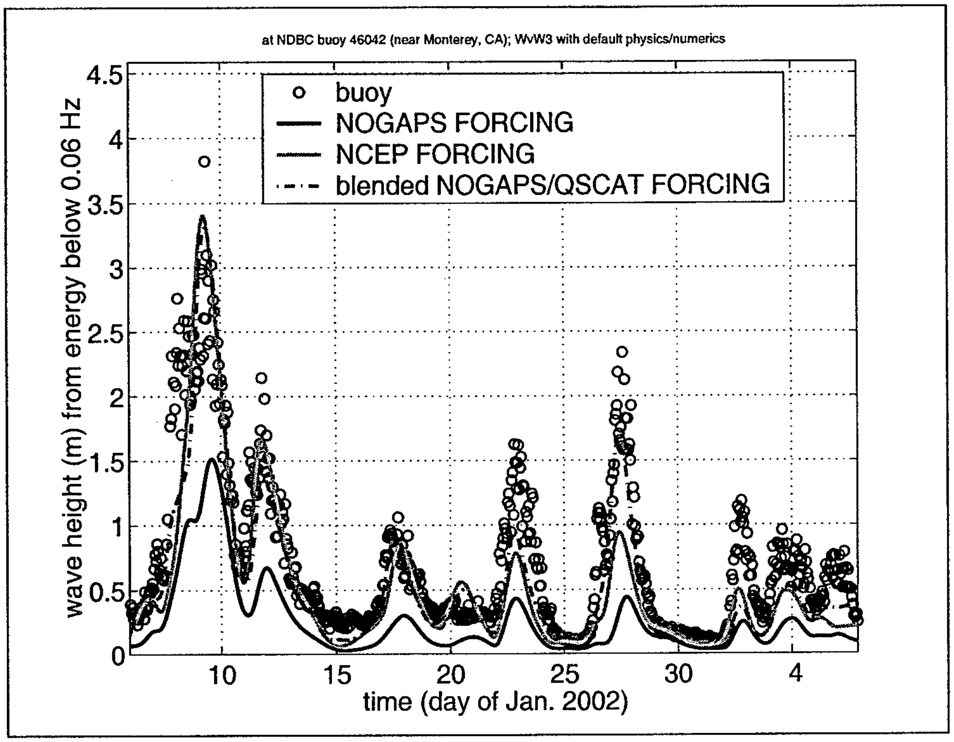
TOPEX Correction

The TOPEX correction given by Cotton is:
$$H_{FDC,Cotton} = 1.0376 H_{FD} - 0.0674.$$
Note that the magnitude of correction for TOPEX is small relative to that of ERS-2. This correction is valid for the B altimeter on TOPEX (brought into service in February 1999). The calibration for the A altimeter is different.

Related literature

There is some relevant work in the literature. For their comparisons to altimetry, Tolman et al. (2002) adjusted the FD ERS-2 wave heights using the formula: $H_{adj} = 1.09 H_{fd} + 0.03$ m. This formula was based on extensive comparison to buoy data (performed by the authors). Hwang et al. (1998) found that the FD TOPEX dataset is very accurate (approximately 0.1m RMS difference, compared to buoy wave heights) in the Gulf of Mexico region.

[9] Some of the information, e.g. the TOPEX calibration, can be found at http://www.satobsys.co.uk/Projects/CalVal .

a)


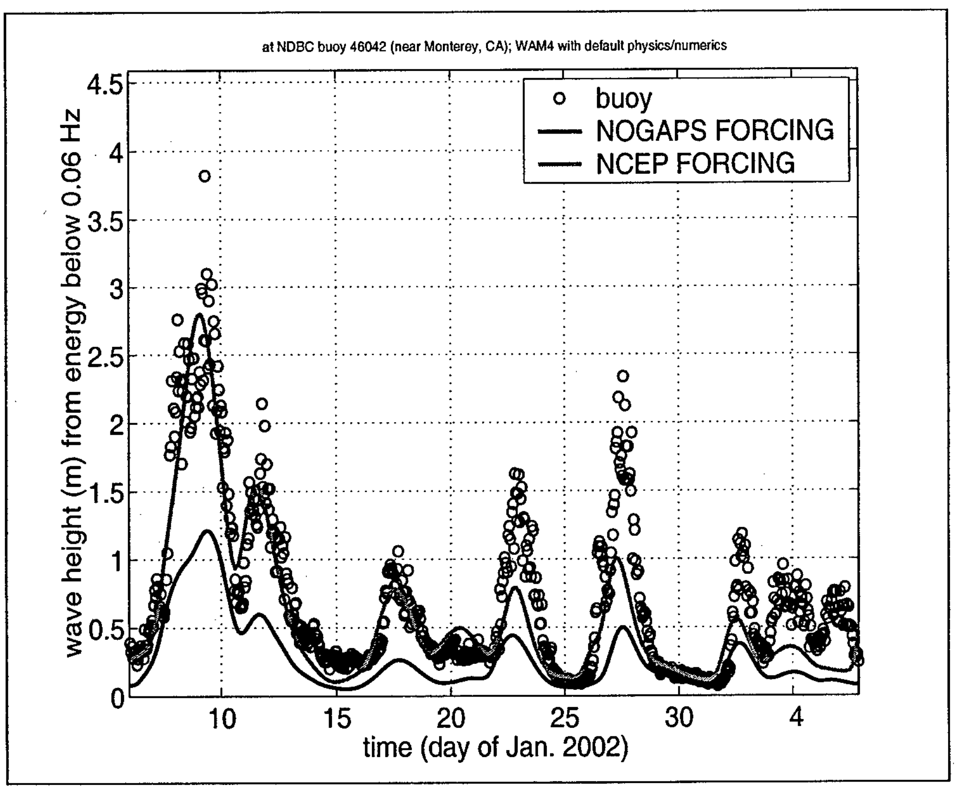
b)


Fig. 1. Comparison of wave model hindcasts vs. buoy measurements. Location is buoy 46042, near Monterey, CA. Both WvW3 and WAM4 here are applied with default physics and numerics. Forcing is provided by analyses as indicated in figure legends. A) WvW3, B) WAM4.

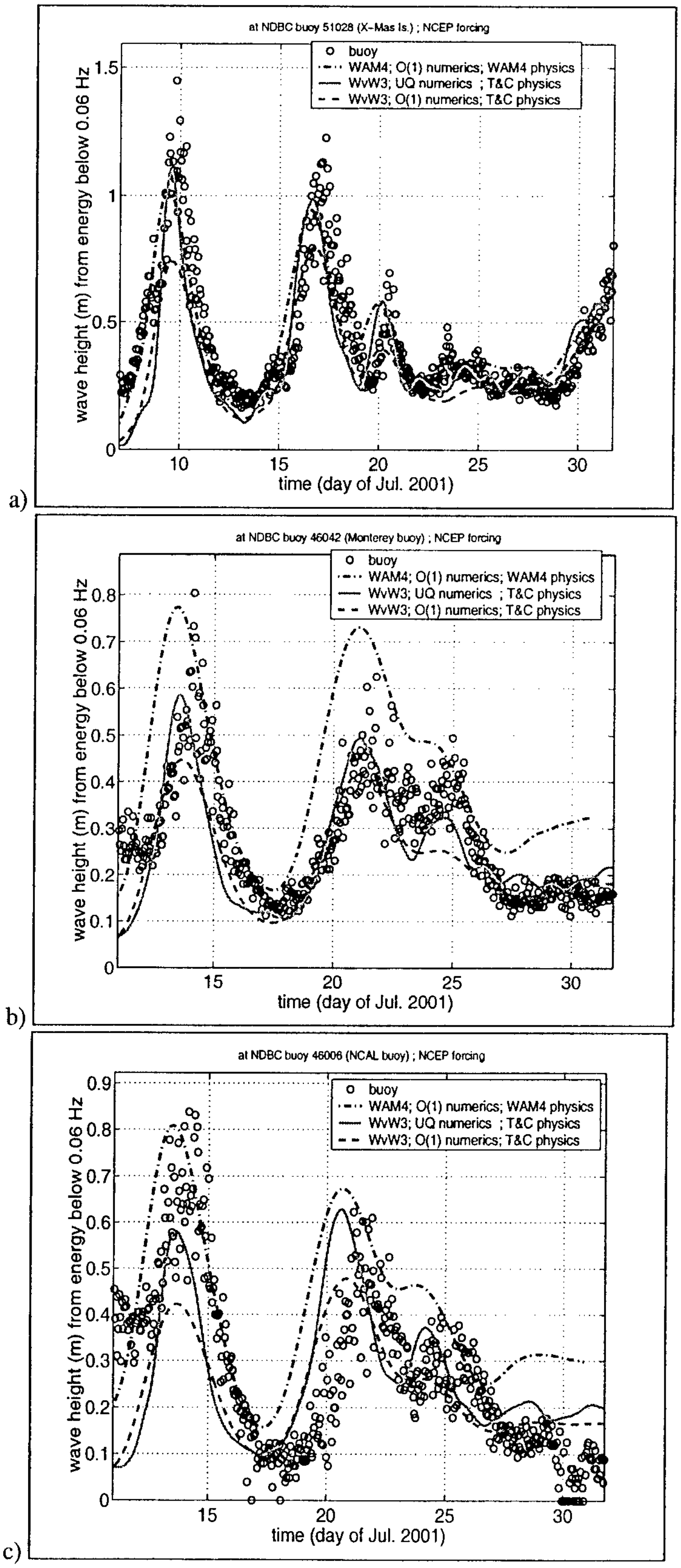


Fig. 2. Comparison of wave model hindcasts vs. buoy measurements. All models use NCEP analyses for forcing. A) Christmas Island buoy location, B) Monterey buoy, and C) northern California buoy.

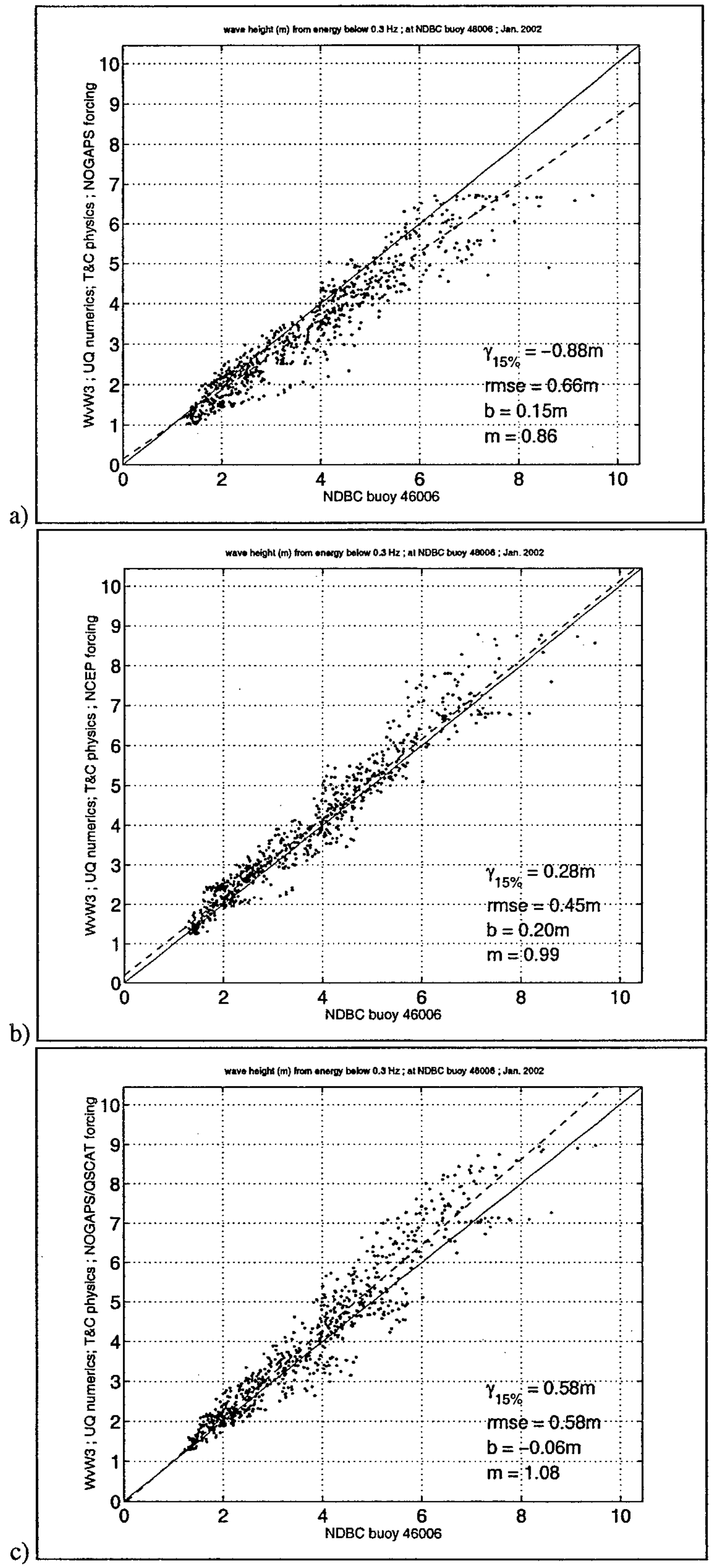


Fig. 3. Comparison of wave heights (calculated from energy below 0.3Hz): buoy 46006 (west of northern California) vs. WvW3 model hindcasts (both with identical, default physics and numerics) A) NOGAPS forcing (analyses), B) NCEP forcing (analyses), C) L2W6 analyses.

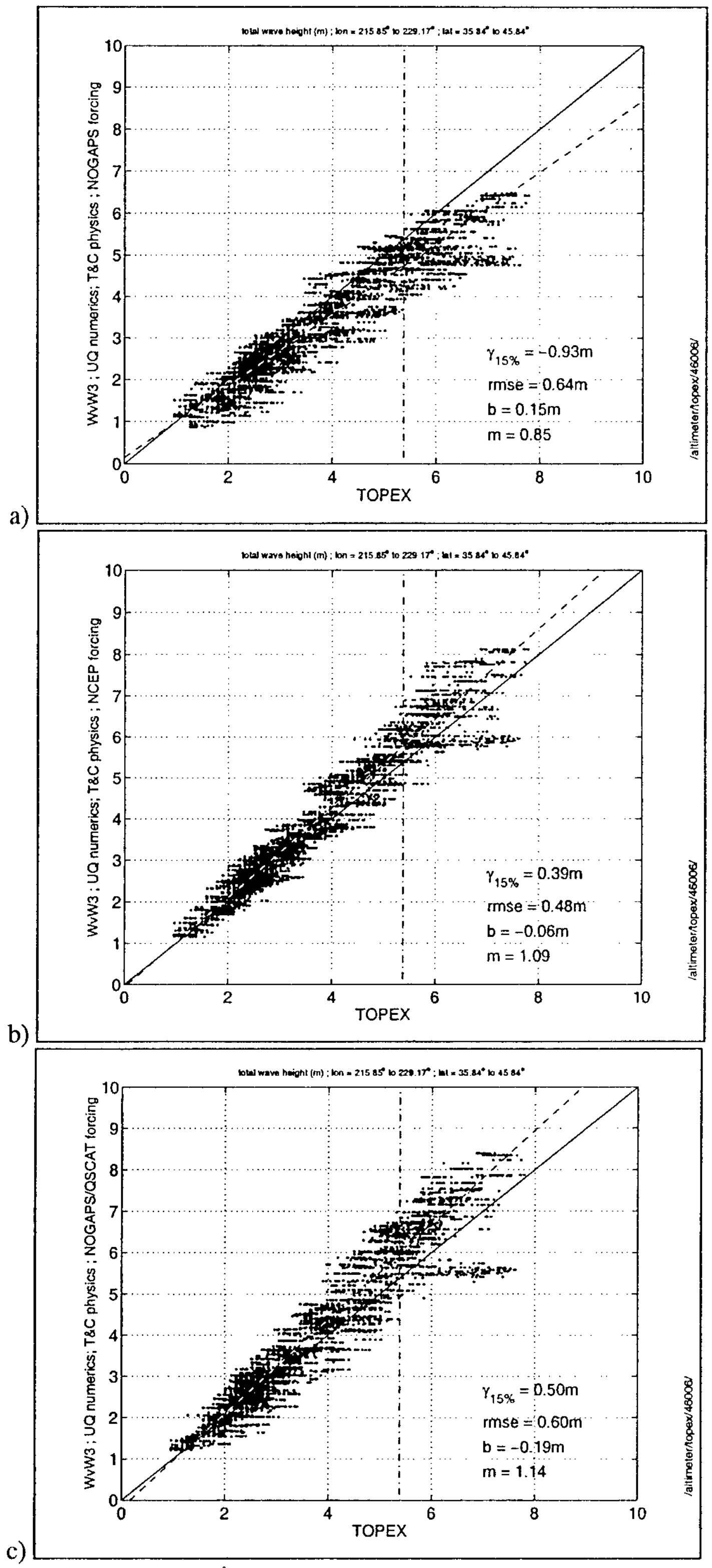


Fig. 4. Comparison of total wave heights in vicinity of buoy 46006 (buoy is west of northern California, region used is 216°E to 229°E, 36°N to 46°N): FDC TOPEX vs. WvW3 model hindcasts (both with default physics and numerics). A) NOGAPS forcing (analyses); B) NCEP forcing (analyses), C) L2W6 analyses.

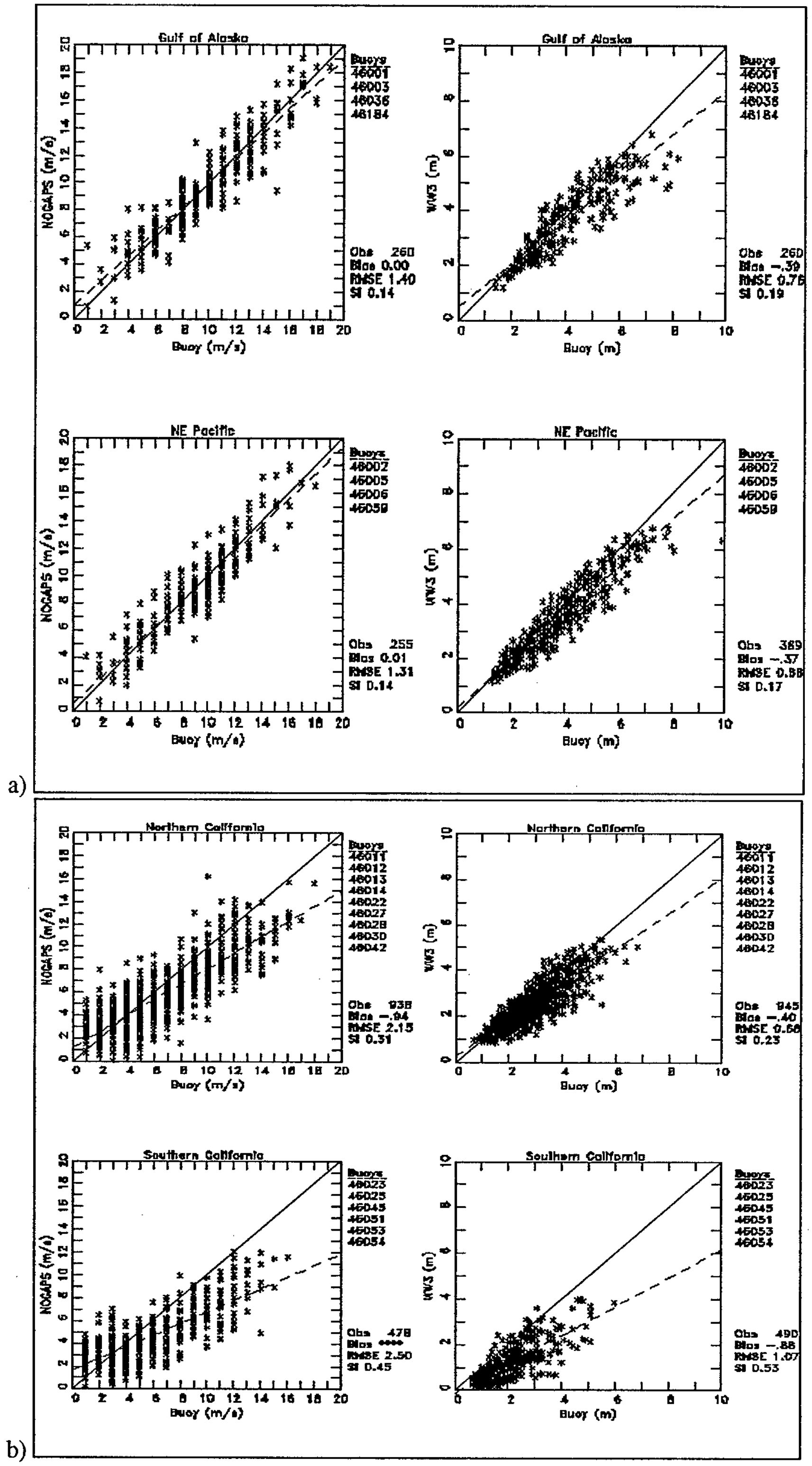


Fig. 5. FNMOC comparison for January 2002. These are the operational global wind and wave products (analyses) compared to buoys, by region. This is one of several comparisons that are made monthly. a) the "northeast Pacific" and "Gulf of Alaska" grouping, b) the "northern California" and "southern California" buoy groupings.

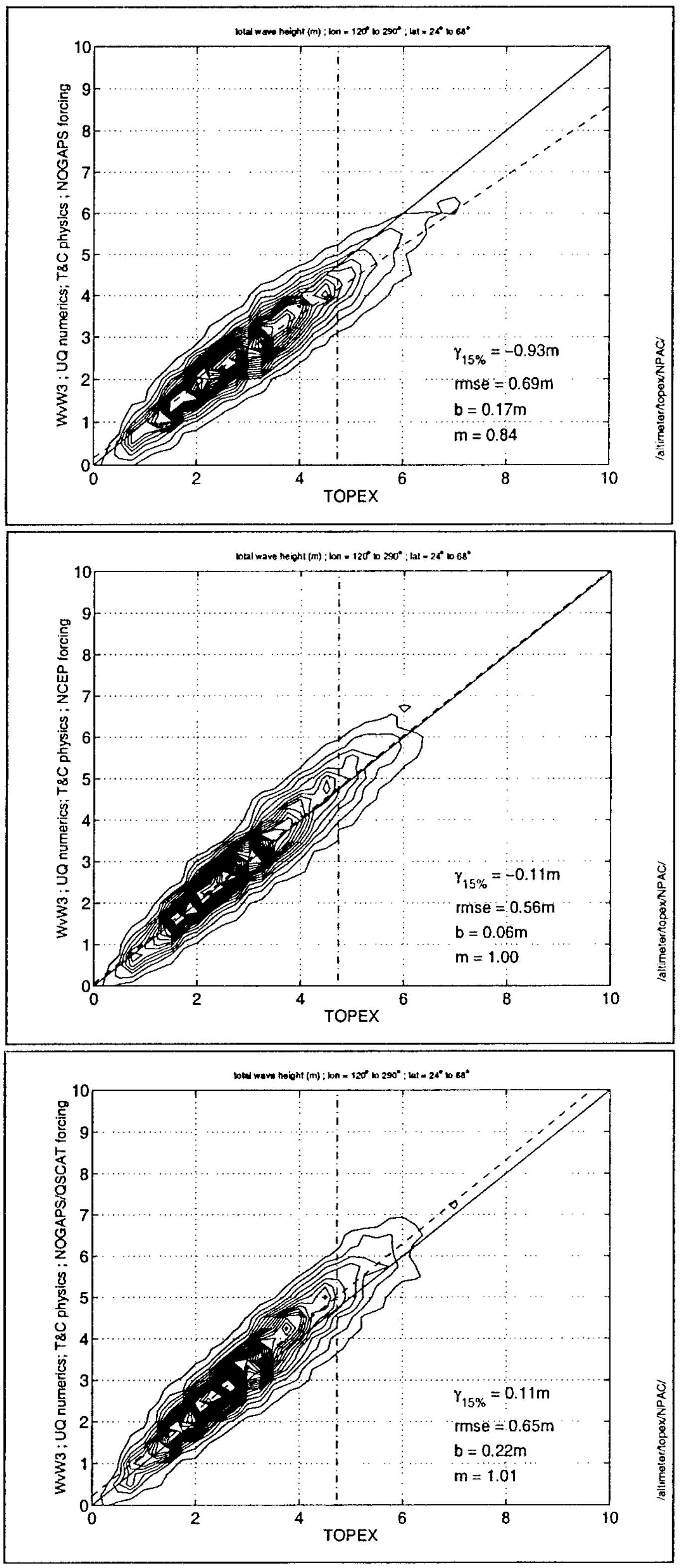
a)
b)
c)


Fig. 6. Wave height comparison of WvW3 model hindcasts (default physics, numerics) vs. FDC TOPEX for the north Pacific region (120°E to 290°E, 24°N to 68°N). A) NOGAPS forcing (analyses); B) NCEP forcing (analyses), C) L2W6 analyses.

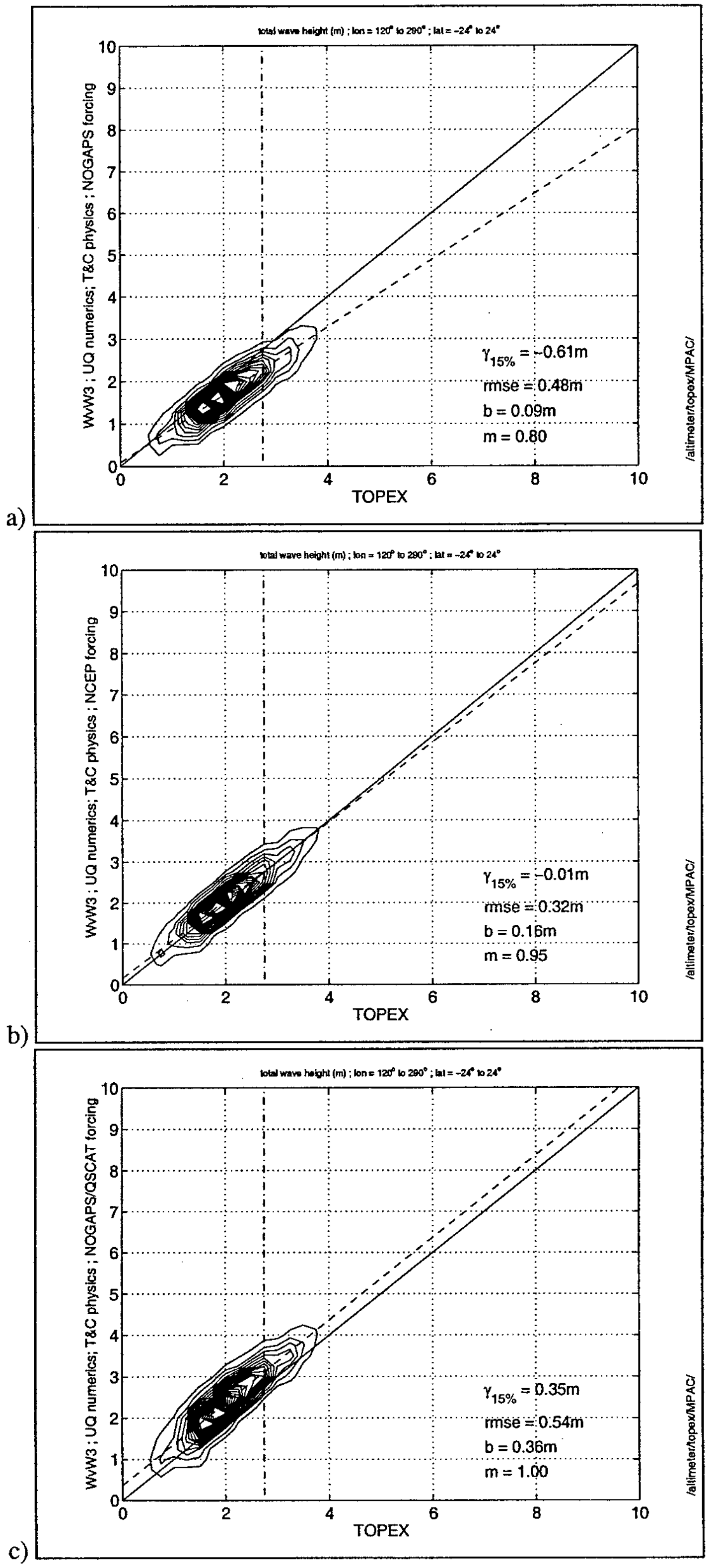
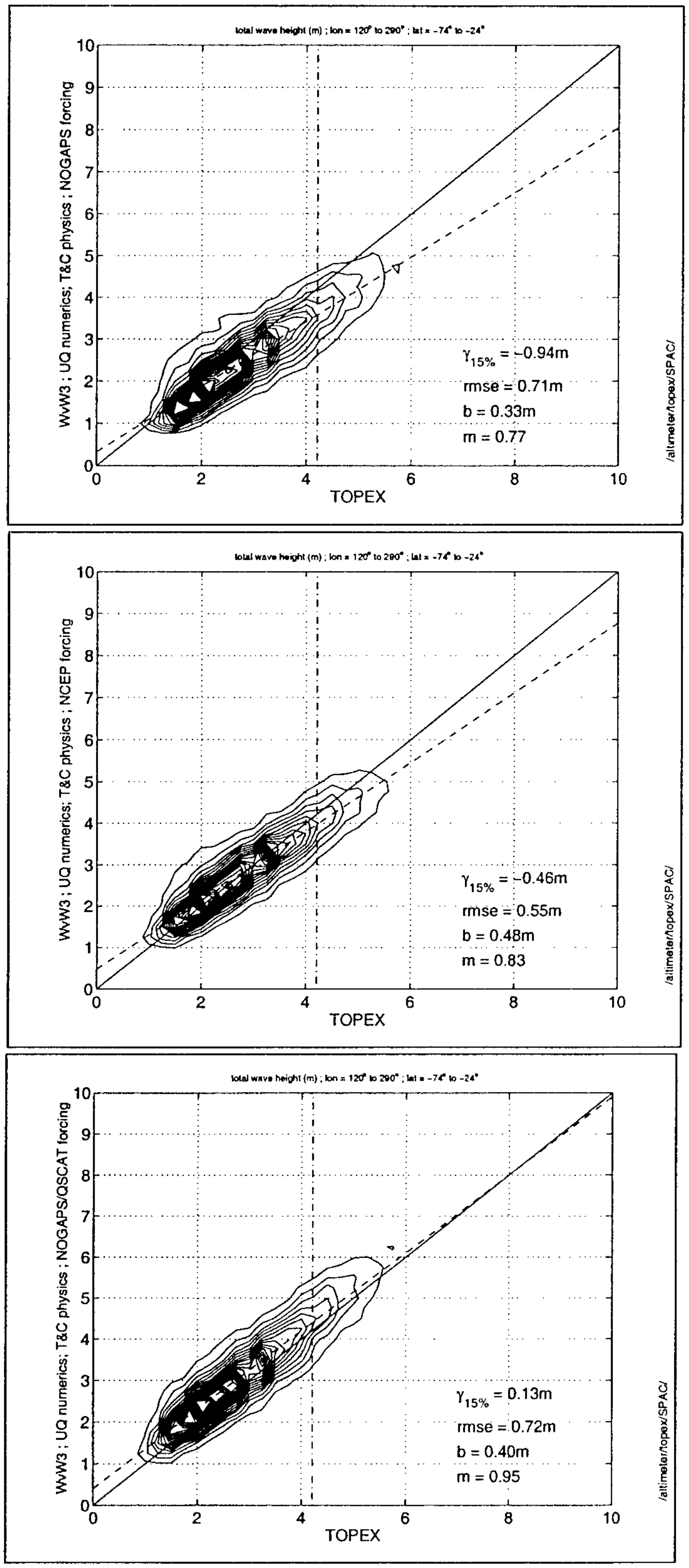


Fig. 7. Wave height comparison of WvW3 model hindcasts (default physics, numerics) vs. FDC TOPEX for the equatorial Pacific region (120°E to 290°E, -24°N to 24°N). A) NOGAPS forcing (analyses); B) NCEP forcing (analyses), C) L2W6 analyses.



a)

b)

c)

Fig. 8. Wave height comparison of WvW3 model hindcasts (default physics, numerics) vs. FDC TOPEX for the south Pacific region (120°E to 290°E, -74°N to -24°N). A) NOGAPS forcing (analyses); B) NCEP forcing (analyses), C) L2W6 analyses.

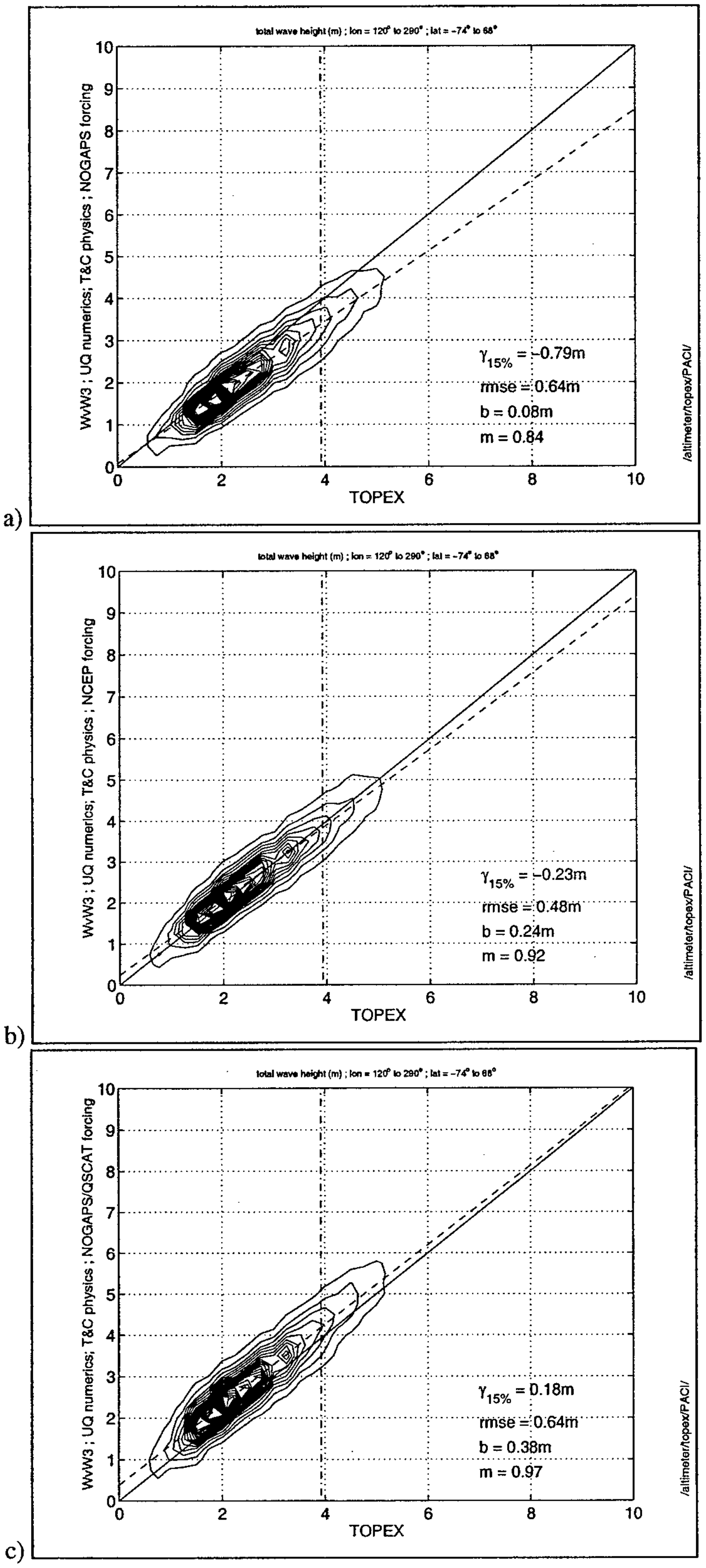
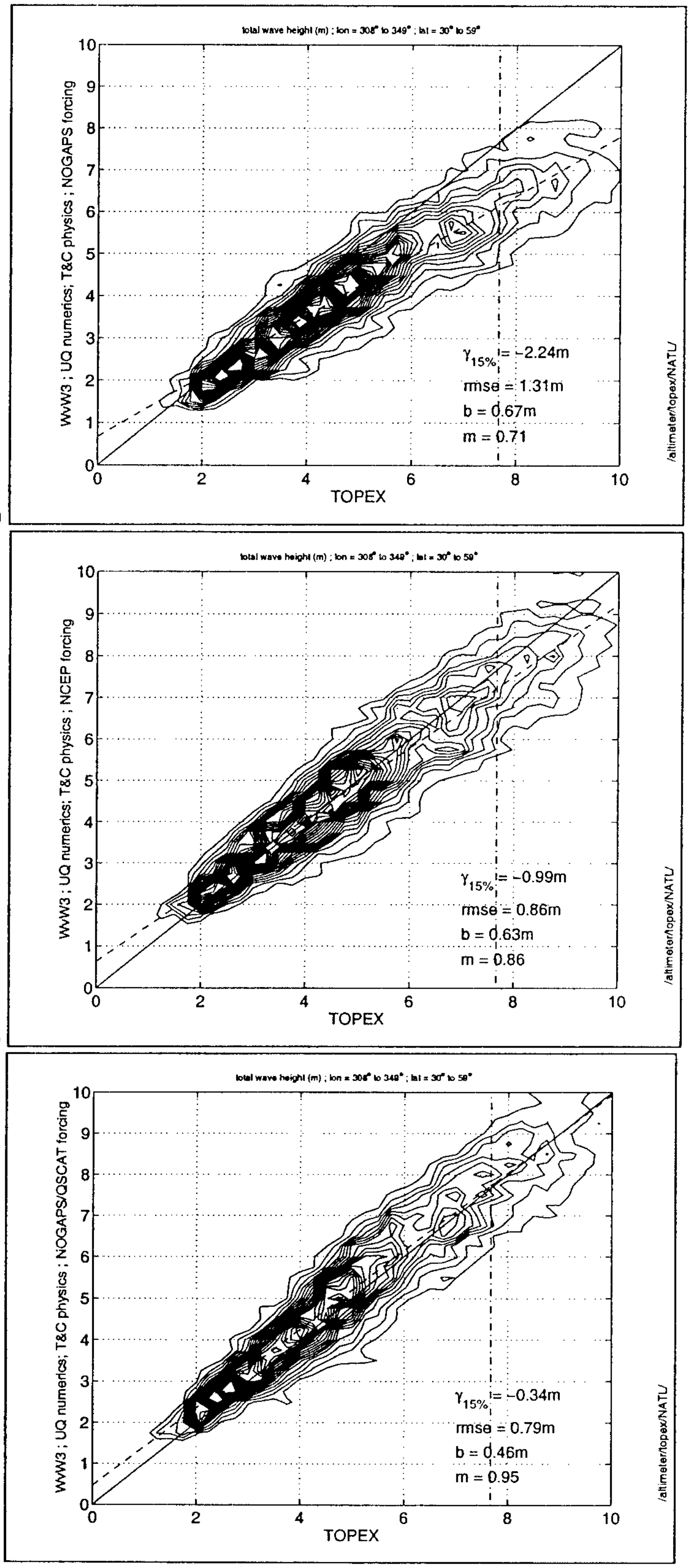


Fig. 9. Wave height comparison of WvW3 model hindcasts (default physics, numerics) vs. FDC TOPEX for the Pacific region (120°E to 290°E, -74°N to 68°N). A) NOGAPS forcing (analyses); B) NCEP forcing (analyses), C) L2W6 analyses.



a)

b)

c)

Fig. 10. Wave height comparison of WvW3 model hindcasts (default physics, numerics) vs. FDC TOPEX for the north Atlantic region (308°E to 349°E, 30°N to 59°N). A) NOGAPS forcing (analyses); B) NCEP forcing (analyses), C) L2W6 analyses.

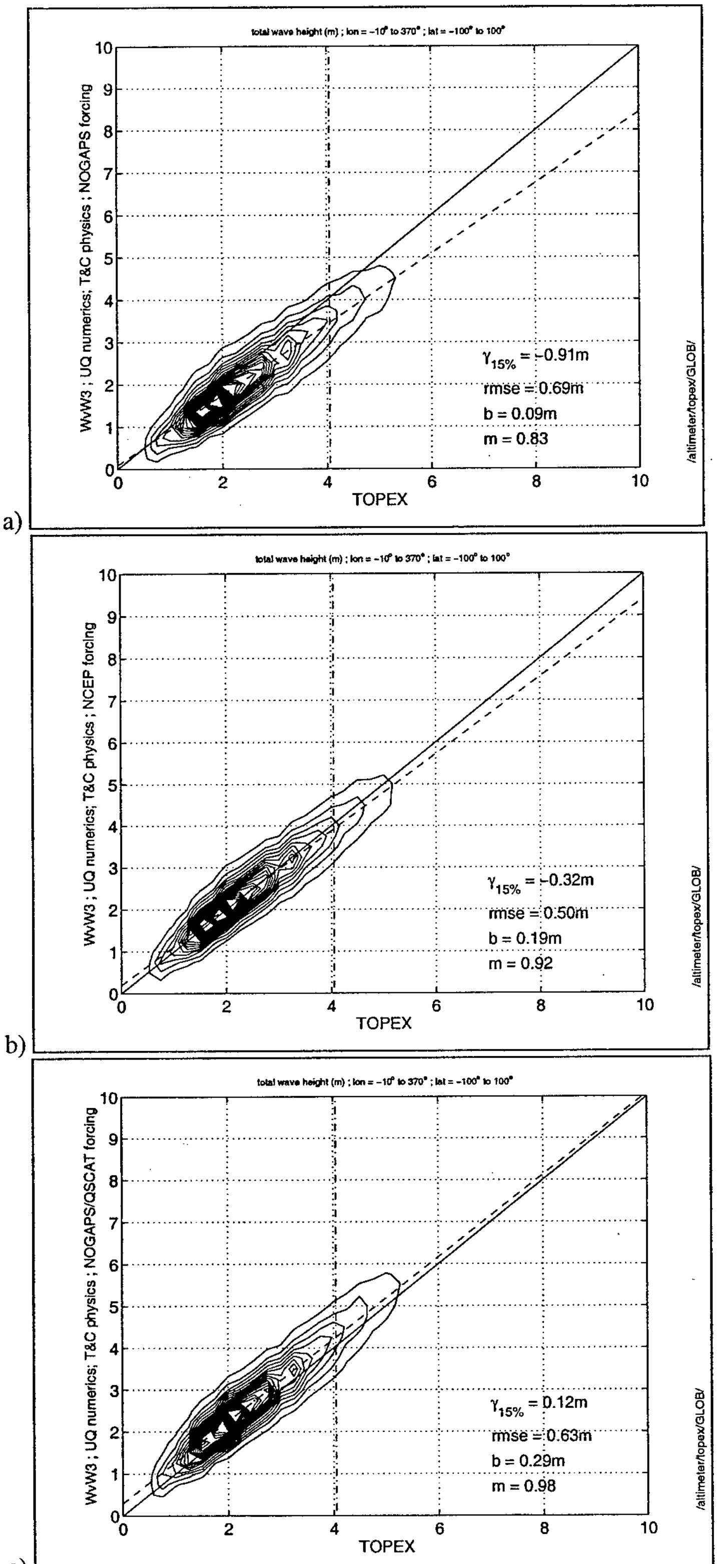


Fig. 11. Wave height comparison of WvW3 model hindcasts (default physics, numerics) vs. FDC TOPEX for the globe. A) NOGAPS forcing (analyses); B) NCEP forcing (analyses), C) L2W6 analyses.

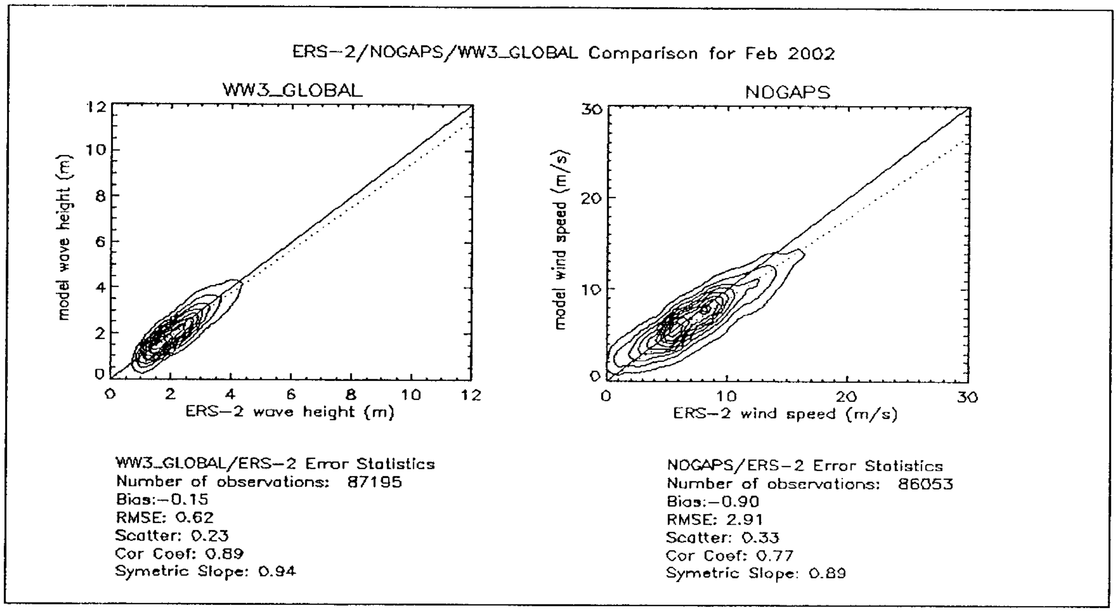


Fig. 12. FNMOC comparison for February 2002. These are the operational global wind and wave products (analyses) compared to FD ERS-2 globally. Standard definitions are used for statistics:

- Bias is the mean error.
- RMSE is the root mean square error.
- Scatter index is defined as (e.g. Cardone et al. 1995):

$$SI = \frac{RMSE}{\overline{O}},$$

- Correlation coefficient is (e.g. Cardone et al. 1995):

$$CC = \frac{\left\langle (O-\overline{O})(M-\overline{M}) \right\rangle}{\sqrt{\left\langle (O-\overline{O})^2 \right\rangle}\sqrt{\left\langle (M-\overline{M})^2 \right\rangle}}, \text{ and}$$

- "Symmetric slope" is (e.g. Bidlot et al. 2002):

$$SS = \frac{\sum M^2}{\sum O^2},$$

where overscore $^{-}$ and $\langle\ \rangle$ indicate a mean, O are observations and M are model values.

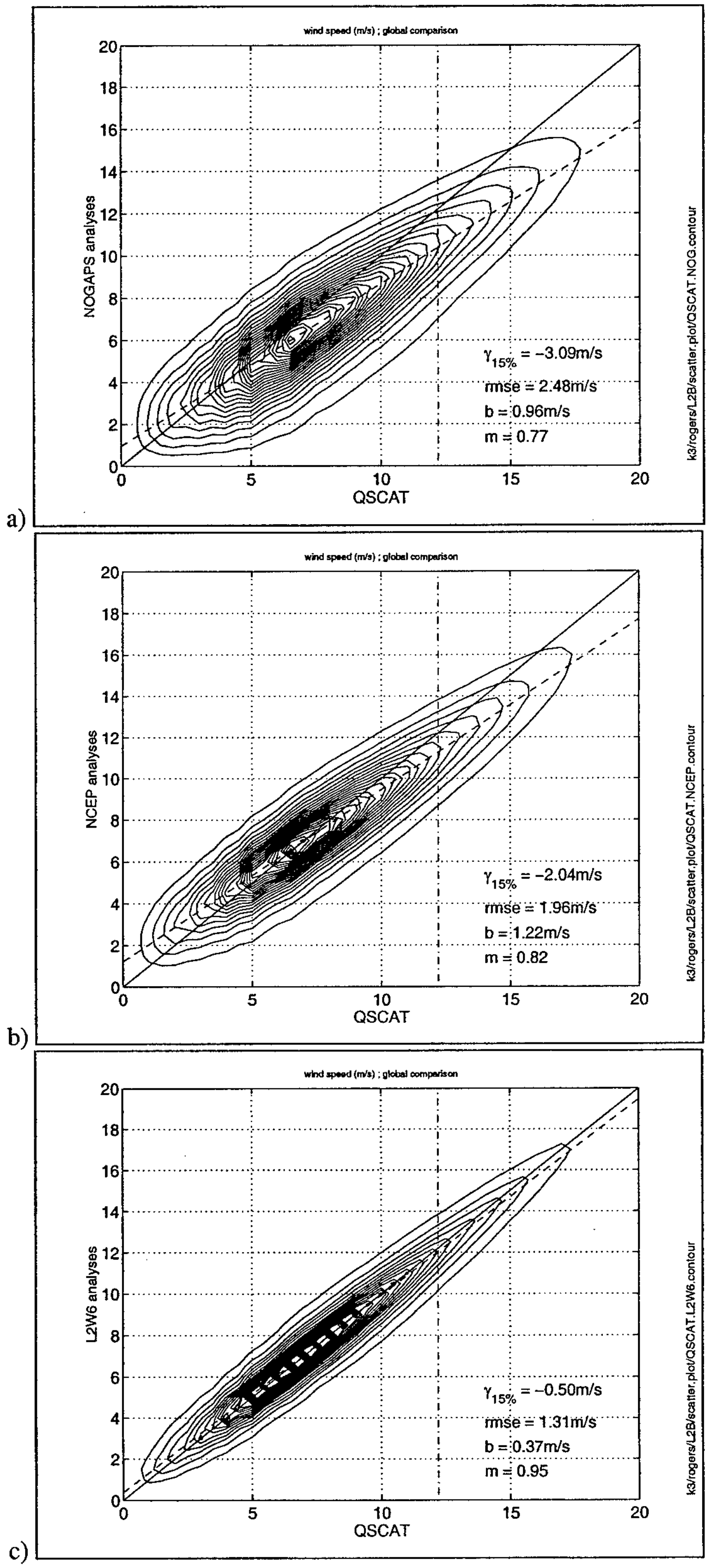


Fig. A1. Wind speed comparison of vs. QuikSCAT (PODAAC L2B) for the globe. A) NOGAPS analyses; B) NCEP analyses, C) L2W6 analyses. Only NOGAPS analyses are entirely independent of QuikSCAT data. See text for further explanation.

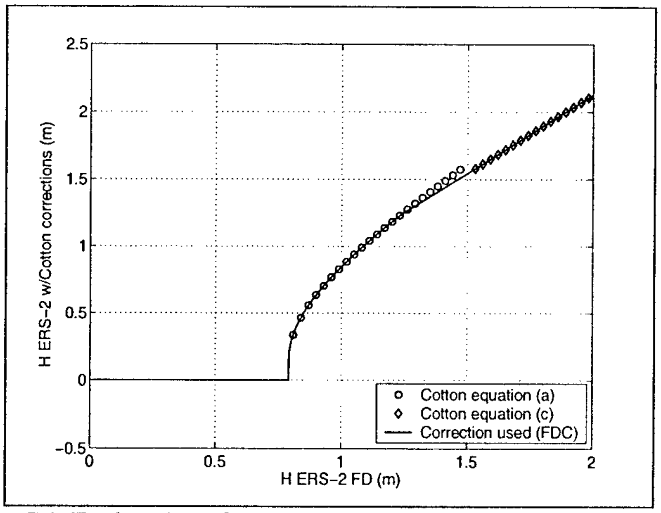
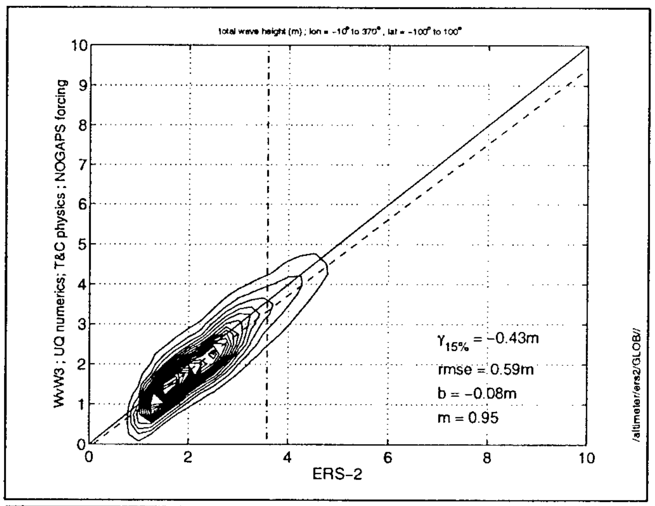


Fig. B1. Explanation of ERS-2 correction used in this study.

a)


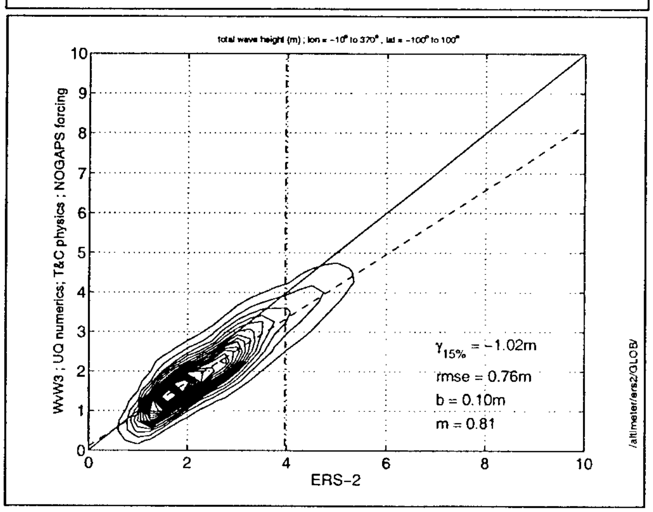
b)


Fig. B2. Wave height comparison of WvW3 model hindcasts (default physics, numerics, January/February 2002) with NOGAPS (analyses) forcing vs. ERS-2 for the globe. A) Fast Delivery ERS-2 (FD); B). FD ERS-2 Corrected using Cotton equations (FDC).

Table 1. Statistics for comparisons of WvW3 hindcasts (forced with different wind analyses) vs. data (FDC TOPEX, FDC ERS-2, and buoy 46006).

Location	Forcing type	Measurement type	Bias (upper 15%) (m)	RMSE (m)	Intercept "b" (m)	Slope "m"
46006 (west of northern California) (altimeter comparisons are for 120°E to 290°E, 24°N to 68°N)	NOGAPS	TOPEX	-0.93	0.64	0.15	0.85
		ERS-2	-1.24	0.77	0.47	0.77
		buoy	-0.88	0.66	0.15	0.86
	NCEP	TOPEX	0.39	0.48	-0.06	1.09
		ERS-2	0.22	0.53	0.27	0.99
		buoy	0.28	0.45	0.20	0.99
	L2W6	TOPEX	0.50	0.60	-0.19	1.14
		ERS-2	0.45	0.62	0.14	1.04
		buoy	0.58	0.58	-0.06	1.08
North Pacific (120°E to 290°E, 24°N to 68°N)	NOGAPS	TOPEX	-0.93	0.69	0.17	0.84
		ERS-2	-1.10	0.79	0.23	0.81
	NCEP	TOPEX	-0.11	0.56	0.06	1.00
		ERS-2	-0.25	0.63	0.11	0.97
	L2W6	TOPEX	0.11	0.65	0.22	1.01
		ERS-2	-0.01	0.72	0.29	0.98
Equatorial Pacific (120°E to 290°E, 24°S to 24°N)	NOGAPS	TOPEX	-0.61	0.48	0.09	0.80
		ERS-2	-0.68	0.55	0.14	0.76
	NCEP	TOPEX	-0.01	0.32	0.16	0.95
		ERS-2	-0.09	0.39	0.24	0.90
	L2W6	TOPEX	0.35	0.54	0.36	1.00
		ERS-2	0.29	0.57	0.43	0.96
South Pacific (120°E to 290°E, 74°S to 24°S)	NOGAPS	TOPEX	-0.94	0.71	0.33	0.77
		ERS-2	-1.09	0.80	0.38	0.74
	NCEP	TOPEX	-0.46	0.55	0.48	0.83
		ERS-2	-0.59	0.62	0.54	0.80
	L2W6	TOPEX	0.13	0.72	0.40	0.95
		ERS-2	0.00	0.79	0.50	0.91
Pacific Ocean (120°E to 290°E, 74°S to 68°N)	NOGAPS	TOPEX	-0.79	0.64	0.08	0.84
		ERS-2	-0.91	0.71	0.12	0.81
	NCEP	TOPEX	-0.23	0.48	0.24	0.92
		ERS-2	-0.33	0.54	0.29	0.89
	L2W6	TOPEX	0.18	0.64	0.38	0.97
		ERS-2	0.09	0.69	0.45	0.94
North Atlantic (308°E to 349°E, 30°N to 59°N)	NOGAPS	TOPEX	-2.24	1.31	0.67	0.71
		ERS-2	-2.38	1.34	0.65	0.71
	NCEP	TOPEX	-0.99	0.86	0.63	0.86
		ERS-2	-1.12	0.91	0.61	0.85
	L2W6	TOPEX	-0.34	0.79	0.46	0.95
		ERS-2	-0.43	0.82	0.49	0.93
Global	NOGAPS	TOPEX	-0.91	0.69	0.09	0.83
		ERS-2	-1.02	0.76	0.10	0.81
	NCEP	TOPEX	-0.32	0.50	0.19	0.92
		ERS-2	-0.42	0.56	0.22	0.90
	L2W6	TOPEX	0.12	0.63	0.29	0.98
		ERS-2	0.01	0.67	0.35	0.95

Table 2. Statistics for comparisons of WvW3 hindcasts (forced with different wind analyses) vs. data (FD TOPEX, FD ERS-2, and buoy 46006). Since the altimeter data has not been calibrated using the Cotton corrections (as was done in Table 1), results for different measurement types are not consistent. THESE RESULTS PREDATE AND ARE SUPERCEDED BY THOSE OF TABLE 1.

Location	Forcing type	Measurement type	Bias (upper 15%) (m)	RMSE (m)	Intercept "b" (m)	Slope "m"
46006 (west of northern California) (altimeter comparisons are for 120°E to 290°E, 24°N to 68°N)	NOGAPS	TOPEX	-0.77	0.58	0.09	0.89
		ERS2	-0.48	0.54	0.32	0.89
		buoy	-0.88	0.66	0.15	0.86
	NCEP	TOPEX	0.55	0.52	-0.14	1.13
		ERS2	0.97	0.78	0.07	1.15
		buoy	0.28	0.45	0.20	0.99
	L2W6	TOPEX	0.66	0.65	-0.27	1.19
		ERS2	1.24	0.89	-0.12	1.23
		buoy	0.58	0.58	-0.06	1.08
North Pacific (120°E to 290°E, 24°N to 68°N)	NOGAPS	TOPEX	-1.98	1.19	0.63	0.74
		ERS2	-1.24	0.87	0.51	0.83
	NCEP	TOPEX	-0.73	0.81	0.57	0.89
		ERS2	0.01	0.86	0.44	0.99
Global	NOGAPS	TOPEX	-0.78	0.65	0.03	0.86
		ERS2	-0.43	0.59	-0.08	0.95
	NCEP	TOPEX	-0.19	0.48	0.13	0.96
		ERS2	0.17	0.54	0.02	1.05
	L2W6	TOPEX	0.25	0.65	0.23	1.02
		ERS2	0.60	0.76	0.13	1.11