MEMORANDUM
RESEARCH DEPARTMENT

To: HR, HO, HMD, HMOS, RD staff and consultants

From: J.-R. Bidlot and Peter Janssen

Date: 03 December 2003

Ref.: R60.9/JB/0400

Subject: **Unresolved bathymetry, neutral winds, and new stress tables in WAM.**

Abstract:

Three enhancements to the wave model are presented here. Firstly, a simple method for the treatment of unresolved islands and shallow submerged features is presented. The large systematic overestimation in low frequency wave energy that otherwise exists in the lee of small island chains is largely removed with the new scheme. The resulting wave scores are much improved, especially in the tropics. Secondly, as WAM should be forced by surface stress, neutral 10m-winds instead of regular 10m-winds are transferred from the atmospheric model to WAM. Impact on the scores is small yet beneficial. Finally, unrealistic large values of the Charnock parameter were removed following refinement in the stress tables used by the wave model.

1. Impact of unresolved bathymetry:

1.1 Introduction:

By looking at monthly mean analysis wave height increments, especially during the Northern Hemisphere summer (Figure 1), it appears that there are areas where the wave model first guess is systematically too high or too low. The underestimation in wave heights tends to be located in the active storm track areas or in areas affected by the Indian sub-continent monsoon. It is known that this underestimation is likely caused by too weak model winds. On the other hand, the overestimation for most of the tropical and northern Pacific cannot be explained in terms of local winds. After further scrutiny, it appears that these systematic overestimations are often present in areas where small island chains exist (French Polynesia and Micronesia in the Pacific Ocean, Maldives Islands and Andaman Islands in the Indian Ocean and Azores and Cape Verde Islands in the Atlantic Ocean, …).

Recently, we have compared the wave model analysis to buoy 1-D wave spectra downloaded from the American National Data Buoy Center (NDBC) and the Canadian Marine Environmental Data Services (MEDS) servers. These buoys are deployed some distance offshore on both the Atlantic and Pacific sides of the North American continent (including Hawaii and Alaska) and provide valuable information on the frequency distribution of wave energy. Figure 2 shows that the model has the tendency to have too much energy in the summer months for waves longer than 8 seconds. The problem is even more pronounced if we restrict the analysis to buoys located in the Pacific basin (not shown). This overestimation of low frequency energy can generally be traced to swell systems and not to local wind effects. Furthermore, it is known that, especially in summer, part of waves in the northeastern Pacific can have their origin in the southern ocean.

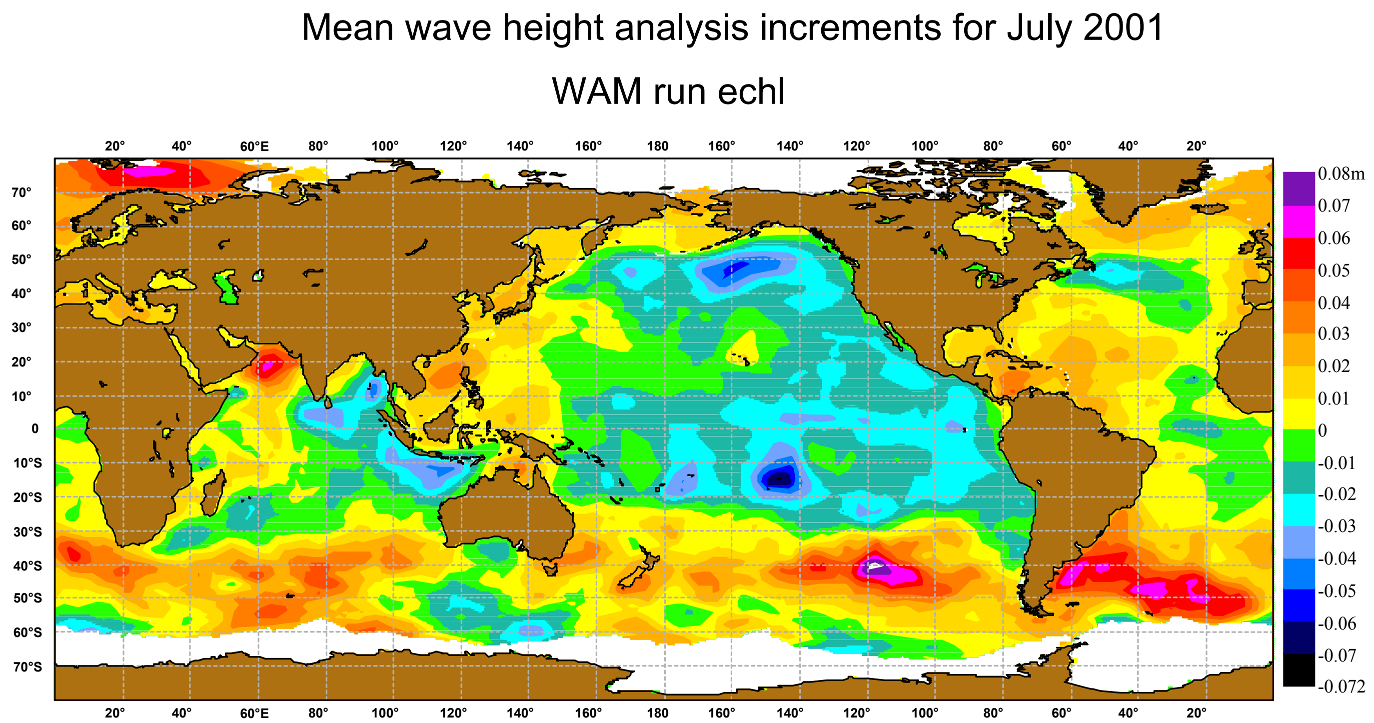

Figure 1: Mean wave height analysis increments for July 2001 (in meters). ERS-2 altimeter data were the only data used in the data assimilation. The stand alone WAM on a 55 km grid was used.

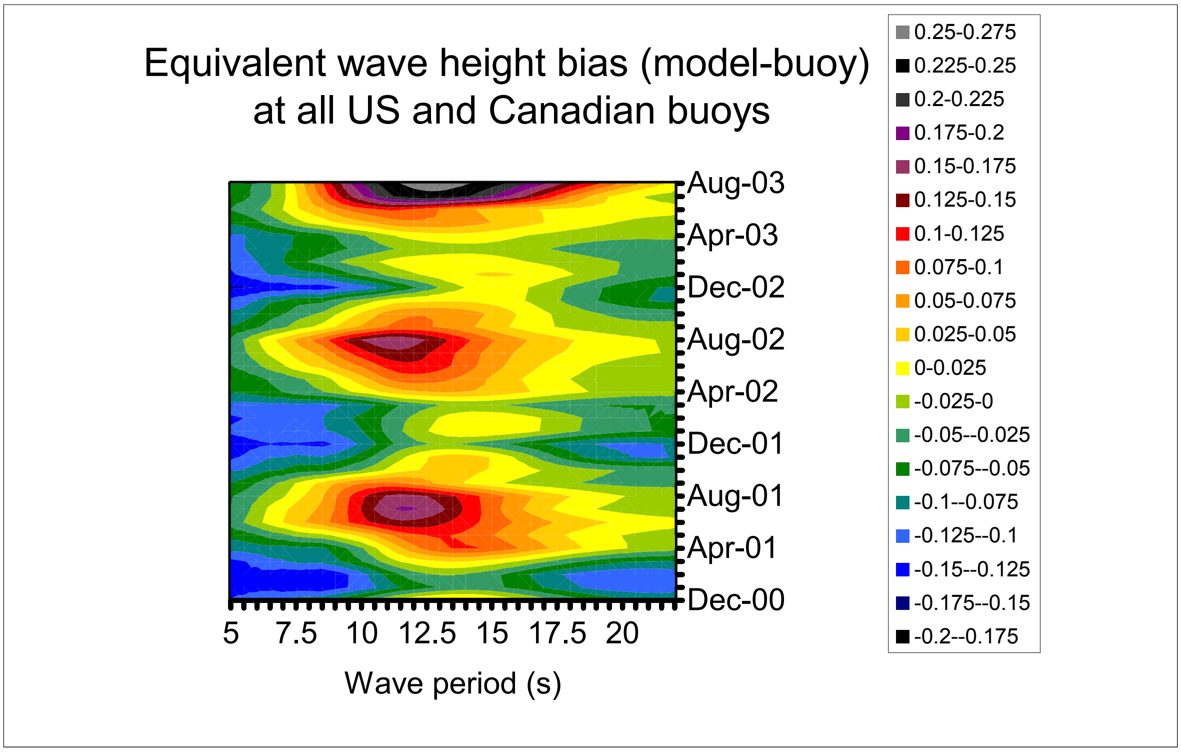

Figure 2: Comparison between 1-D frequency spectra from US and Canadian buoys and model operational analysis. The 1-D spectra were smoothed out by averaging over 3 consecutive frequency bins and by converting each average value into an equivalent wave height (m).

Hence, it appears that small islands and submerged bathymetric features that are not at all resolved by the coarse wave model grid (55 km) may have a larger impact on the wave climate than it is usually assumed. Although, in the current operational grid, representation of some islands were artificially enhanced to produce the necessary blocking to wave propagation, the results were not very satisfactory. A more appropriate and automatic procedure will be followed to deal with small and not so small islands and reefs.

1.2 Treatment of unresolved bathymetry:

The current operational 55 km wave model grid is based on the ETOPO5 data set that represents the land and sea-bottom elevation on a 5-minute latitude/longitude grid. This data set is available from the National Geophysical Data Center. Recently, NGDC produced a finer data set, namely ETOPO2 that has a 2-minute resolution. Figure 3 shows the bathymetry for an area centred on the Tuamotu Archipelago in the South Pacific as derived from the ETOPO2 data (only sea points with water depth less than 300m are shown). The complexity of the bathymetry is clearly visible. This data set can be used to produce the wave model grid by averaging the depths of all ETOPO2 sea points within a model grid box and vice-versa for land points. A model grid box is considered to be over sea if 50% or more ETOPO2 points are sea points. Figure 4 shows the resulting mean depth for the 55 km grid. Much of the shallow features of the archipelago are gone. It is therefore not surprising that when model swell propagates across this area, very little attenuation is experienced (even with the model shallow water physics switched on).

Based on a similar idea as in Tolman (2003), we have modified the wave propagation scheme to limit the amount of wave energy that can be advected through these sub grid bathymetric features. The WAM model uses a simple first order upwind scheme that requires the knowledge of the wave spectral flux entering a given grid box in the upwind direction. These incoming fluxes are specified by the product of the wave spectral component and the corresponding mean group velocity perpendicular to the upwind grid box facet. However, in reality, if small islands or shallow water features are present, only part of incoming energy will reach the central grid point. With the availability of a finer resolution topographic data set such as ETOPO2, it is possible to estimate how much obstruction these features would produce. For each model grid point, the 2-minute data are analysed line by line in all four cardinal directions up to the neighbouring grid points. If land or shallow water features are present, then the proportion of how much energy would have propagated along each line is reduced accordingly. Land and very shallow features are fully blocking the flux along the respective line, provided deeper data points on both sides surround them. Points, which are shallow enough to affect the incoming waves but deep enough that they do not block the waves, are only reducing the flux in proportion to the total number of points in a line. How relatively shallow the water is depends on the frequency (wavelength) of the spectral component under consideration. The total obstruction for each upwind flux is then obtained by summing over all lines that are intersecting the corresponding grid box facet. High frequency waves are less affected by the bathymetry than low frequency components. Thus, at each grid point there is a transmission factor for each discretised frequency bin corresponding to all four cardinal directions. Figure 5 shows how much energy is allowed to propagate towards the north for the first frequency bin of the model (wavelength ~ 1360m) for the same area as in Figure 4. These long waves will indeed be quite attenuated as they cross the Archipelago. On the other hands, the short waves should be a lot less affected by the unresolved bathymetry. Figure 6 displays the corresponding transmission coefficient for the very short waves in the model (wavelength ~ 6 m). The impact of the unresolved bathymetry is indeed much reduced.

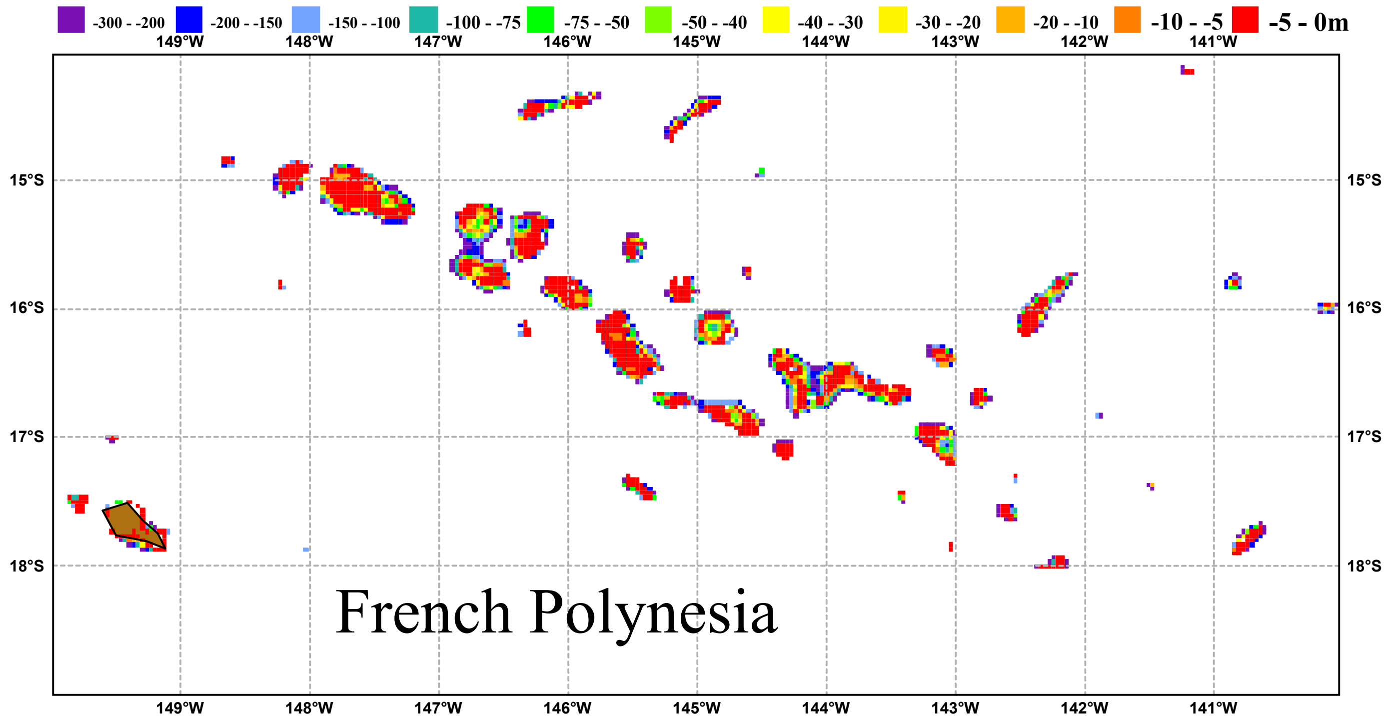

Figure 3: ETOPO2 bathymetry obtained from the National Geophysical data Center (only sea points shallower than 300 m are shown).

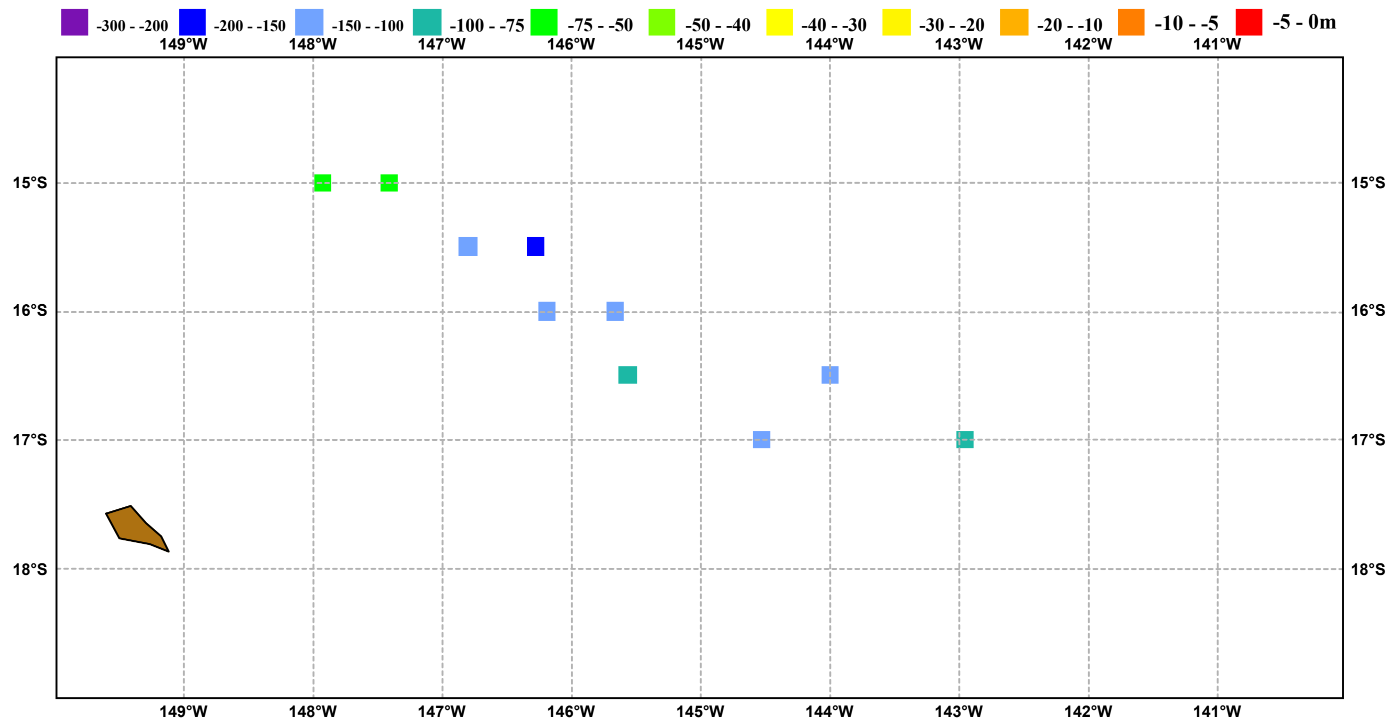

Figure 4: WAM bathymetry (only sea points shallower than 300 m are shown) for the 55 km grid.

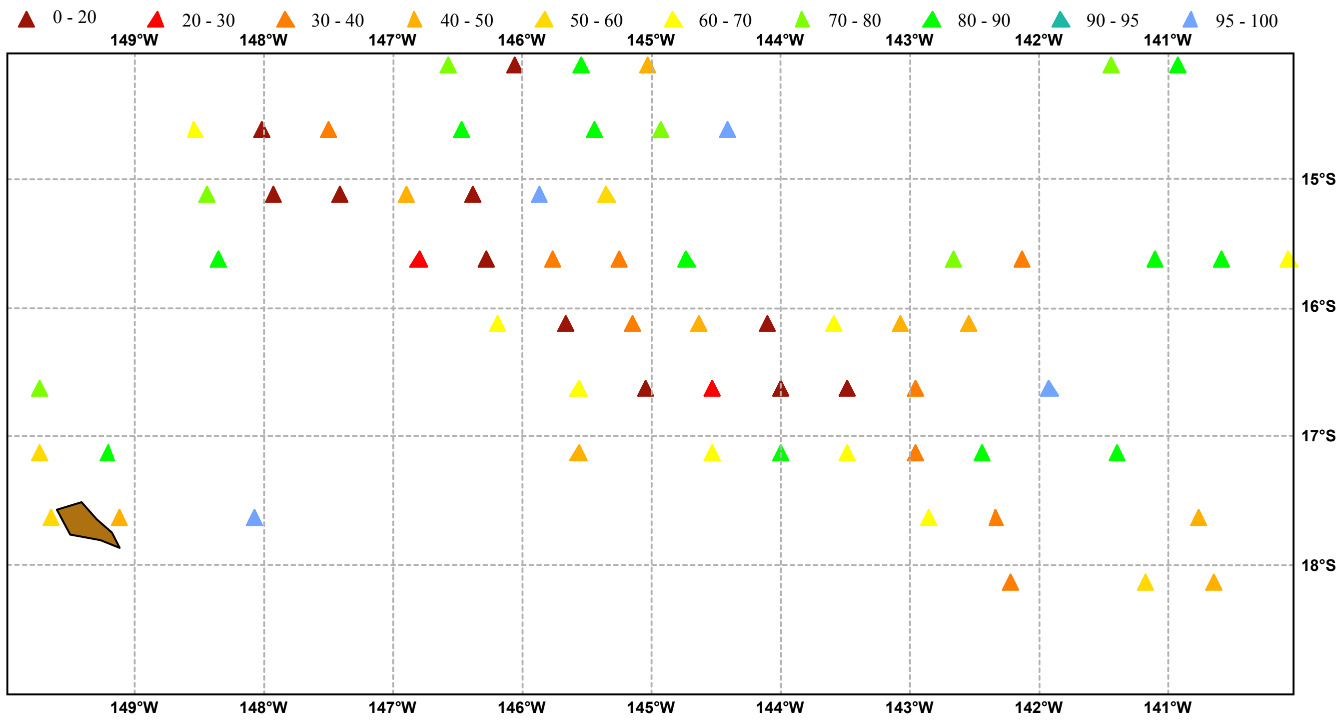

Figure 5: Percentage of the wave energy that is allowed propagates northwards for the lowest frequency bin (~ 0.035 Hz).

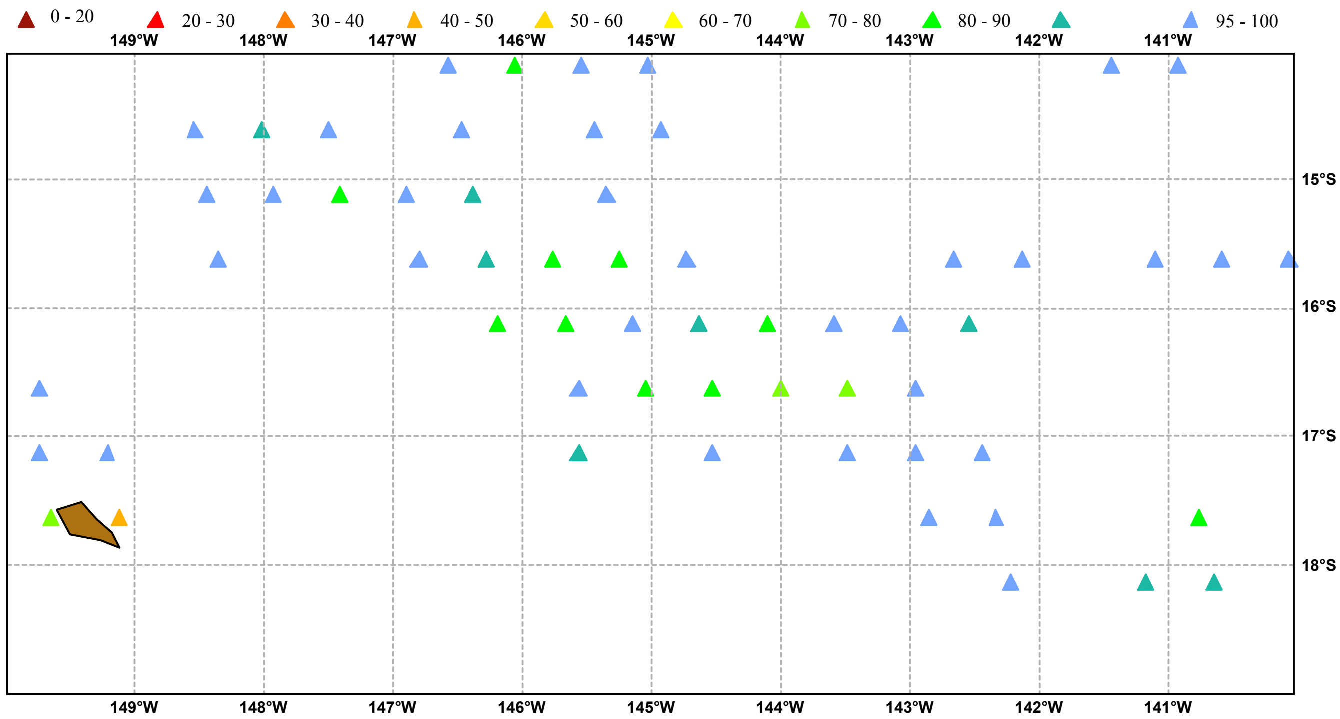

Figure 6: Percentage of the wave energy that is allowed propagates northwards for the highest frequency bin (~ 0.55 Hz).

1.3 Impact of unresolved bathymetry:

As we have seen, the largest impact of the unresolved bathymetry is expected for the long waves. These waves interact the least with the atmosphere. The stand-alone version of the wave model can therefore be used to study the effect that sub grid bathymetric features have on wave hindcasts. These runs were performed with WAM on a 55 km grid forced by 6-hourly operational analysis winds and at first without any data assimilation in order to clearly see the impact of the change. The reference runs were carried out with the current operational bathymetry as derived from the older ETOPO5 data set.

Mean wave height differences between runs with the new bathymetry including the unresolved bathymetry treatment and the reference runs for July 2001 and December 2002 are presented in Figure 7. As expected, there is a substantial reduction in the Pacific mean wave height in the lee of the main chains of islands. As dictated by climatology, the main propagation direction is out of the winter hemisphere and/or the direction of the trade winds. Other areas where wave height is reduced are also noticeable, in particular in the Indian Ocean. There are also places with increased wave heights for both months. This can be attributed to the new finer bathymetry and how it was used to derive the mean model water depth. Notably, wave heights are much increased on the Argentinean continental shelf and on the South African shelf. There are also many other small-scale topographic features that are nicely visible. Note however that one would have expected wave heights to be lower in the lee of the Aleutian Islands and in the lee of the Lesser Antilles but at these locations, the old grid was manually adjusted to artificially include these islands as land. The same is true for many other locations that are too small to appear on a global plot. As it turns out the islands are too small to be represented in the grid, nevertheless they are sufficiently large to have an impact on the waves. The new method proves to be a lot more robust in automatically generating the model grid and the attenuation associated with small scales features.

In Figure 8, a comparison between the different model hindcasts and the ERS-2 altimeter wave height data is given in term of scatter index (normalised standard deviation of the difference) and bias (model-ers2) for July 2001. For each set of four bars, the two bars on the left were obtained without assimilation, whereas the two bars on the right were derived from assimilation runs with ERS-2 altimeter wave height data (first guess wave heights were used for the comparison). The four runs were made with the stand alone WAM. The beneficial impact of the change is clearly visible, especially in term of scatter index, in all areas that were mentioned when describing Figure 7. The inclusion of the sub-grid bathymetry has a tendency to reduce wave heights, resulting in a more negative bias. The beneficial impact is not only limited to the extra tropics but also around the areas where the largest sub-grid attenuation is taking place. This indicates that the method used here does work well in the far field as well in the close field. Note also that, in agreement with Figure 1, the assimilation of altimeter wave heights generally has a marked impact on the wave height statistics. Combining both sub-grid treatment and assimilation yields the best fit to the data. Note however, that the assimilation of wave height data has some drawbacks, as we will show next.

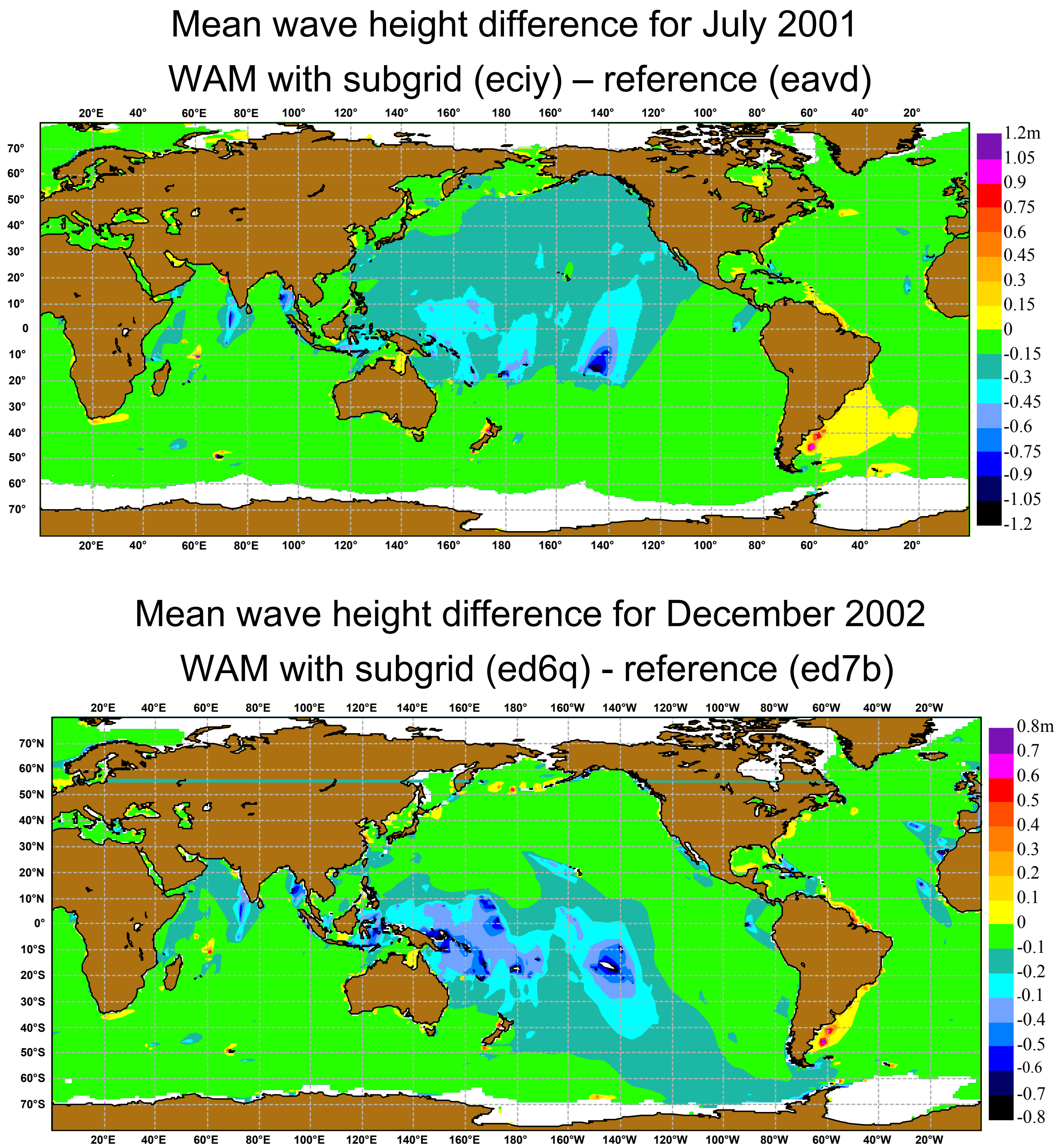

Figure 7: Mean wave height difference for the 55 km stand alone WAM between the new sub-grid bathymetry model and a reference. The new model used the mean bathymetry based on ETOPO2 whereas the reference employed the old bathymetry based on ETOPO5.

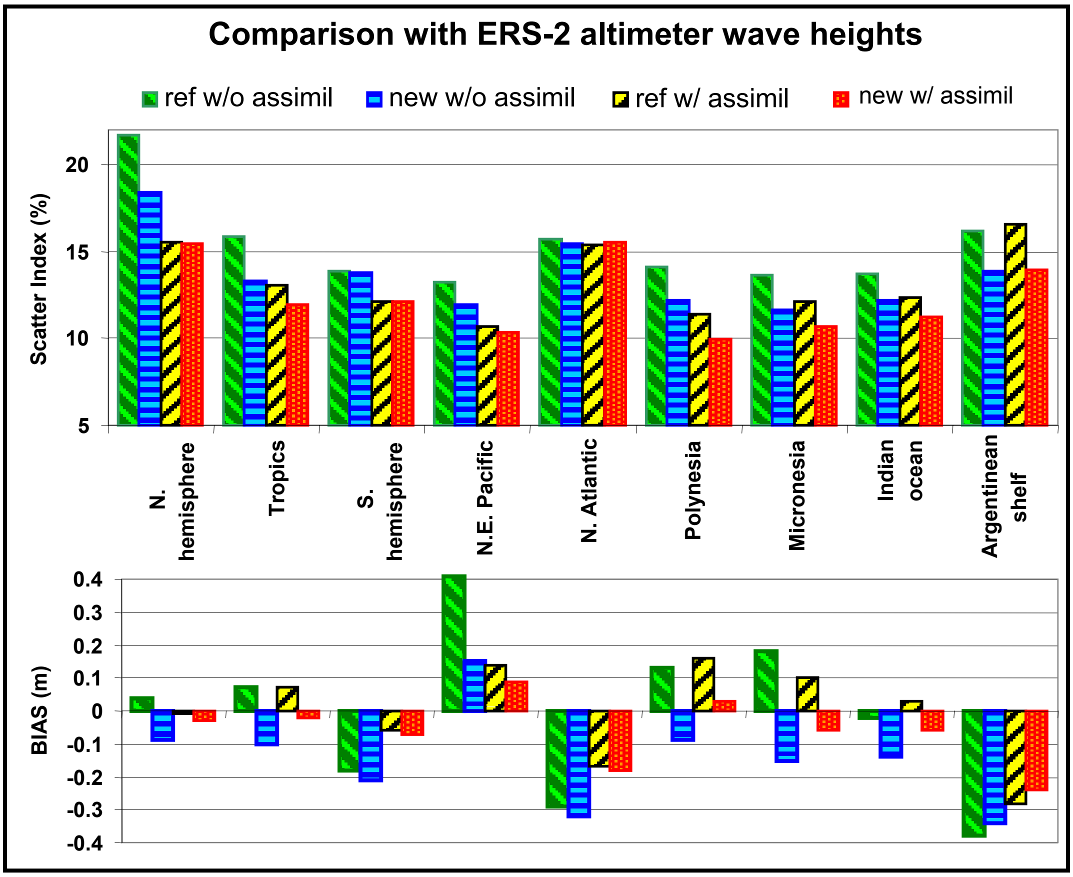

Figure 8: Statistical comparison between model first guess wave heights and ERS-2 altimeter values for different sub-areas in July 2001. The ERS-2 data are those presented to the data assimilation, namely, all individual quality controlled values that have been averaged over all corresponding model grid boxes. The grid averaged satellite data were also corrected for the non-gaussian distribution of the sea surface elevation. Reference runs (ref.) were obtained with the current mean bathymetry whereas the new runs (new) employed the mean bathymetry and the transmission coefficients derived from ETOPO2. Both configurations were run with and without data assimilation.

Buoy and platform wave data can be used as an independent validation tool. Such data set is obtained at ECMWF via the GTS and is therefore labelled here as GTS buoy data. Figure 9 illustrates the comparison between model and GTS buoy wave height and wave period data for areas around the North American continent and the British Isles for July 2001. The results for wave heights confirm that using both satellite data and a proper treatment of the unresolved bathymetry has a positive impact on the wave statistics. However, strictly speaking this is not entirely true for the assimilation hindcasts for wave periods. This problem is thought to be related to the inability of the simple O.I. assimilation scheme used by the wave model to properly update wave spectra following the assimilation of wave height observations alone.

An even more detailed analysis of how the new model affects the distribution of wave energy in term of frequency is obtained by comparing the different runs with US and Canadian buoy 1-D frequency spectra as was done in Figure 2. As expected, the impact of the inclusion of unresolved bathymetry in the wave model advection is the largest for the runs without any data assimilation (upper panel in Figure 10). Using ERS-2 altimeter data has a similar effect on the wave energy distribution around 10-12 seconds as was obtained when sub-grid effects were included. However, there is a small degradation for periods larger than 16 seconds (lost of correlation and increase in standard deviation). As already noted in the comparison with GTS data, the assimilation of altimeter data seems the have a detrimental effect on the low frequency wave energy distribution.

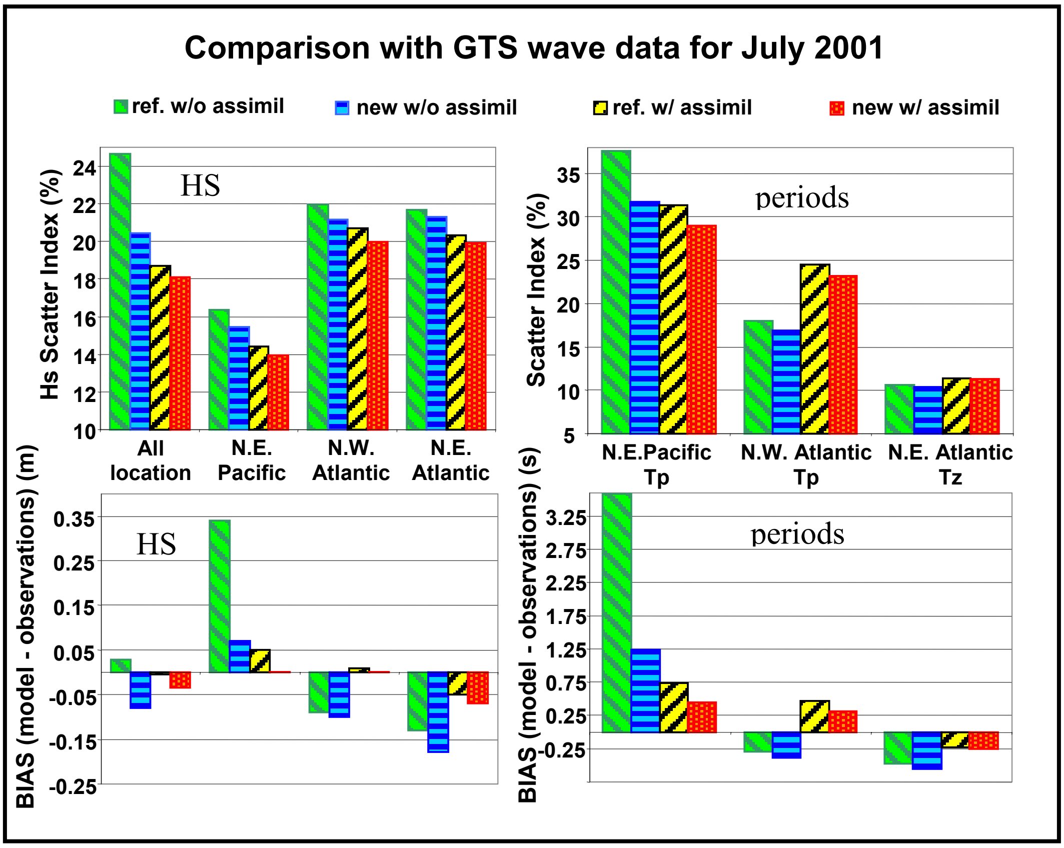

Figure 9: Comparison between model hindcasts and GTS buoy and platform wave heights (Hs) and periods (Tp: peak period, Tz: zero mean crossing). Reference runs (ref.) were obtained with the current operational mean bathymetry whereas the new runs (new) employed the mean bathymetry and the transmission coefficients derived from ETOPO2. Both configurations were run with and without data assimilation.

We have shown that there is an overall benefit of the new scheme for summer cases. Winter hindcasts tend to be less sensitive to unresolved bathymetry. Figure 11 shows the comparison against ERS-2 and GTS wave data for December 2002. Generally, the impact is small yet beneficial. The main consequence of removing spurious low frequency wave energy is an increase in the negative wave height bias. This negative bias is not necessarily a bad feature since it is known that with the present surface wind quality, the model wave heights in stormy events have a tendency to be underestimated. By not treating the unresolved islands and atolls, we are just masking this general tendency when we only focus on wave height statistics. Looking at 1-D spectra confirms that the new approach only impacts the bias and not the other statistics (Figure 10 lower panel).

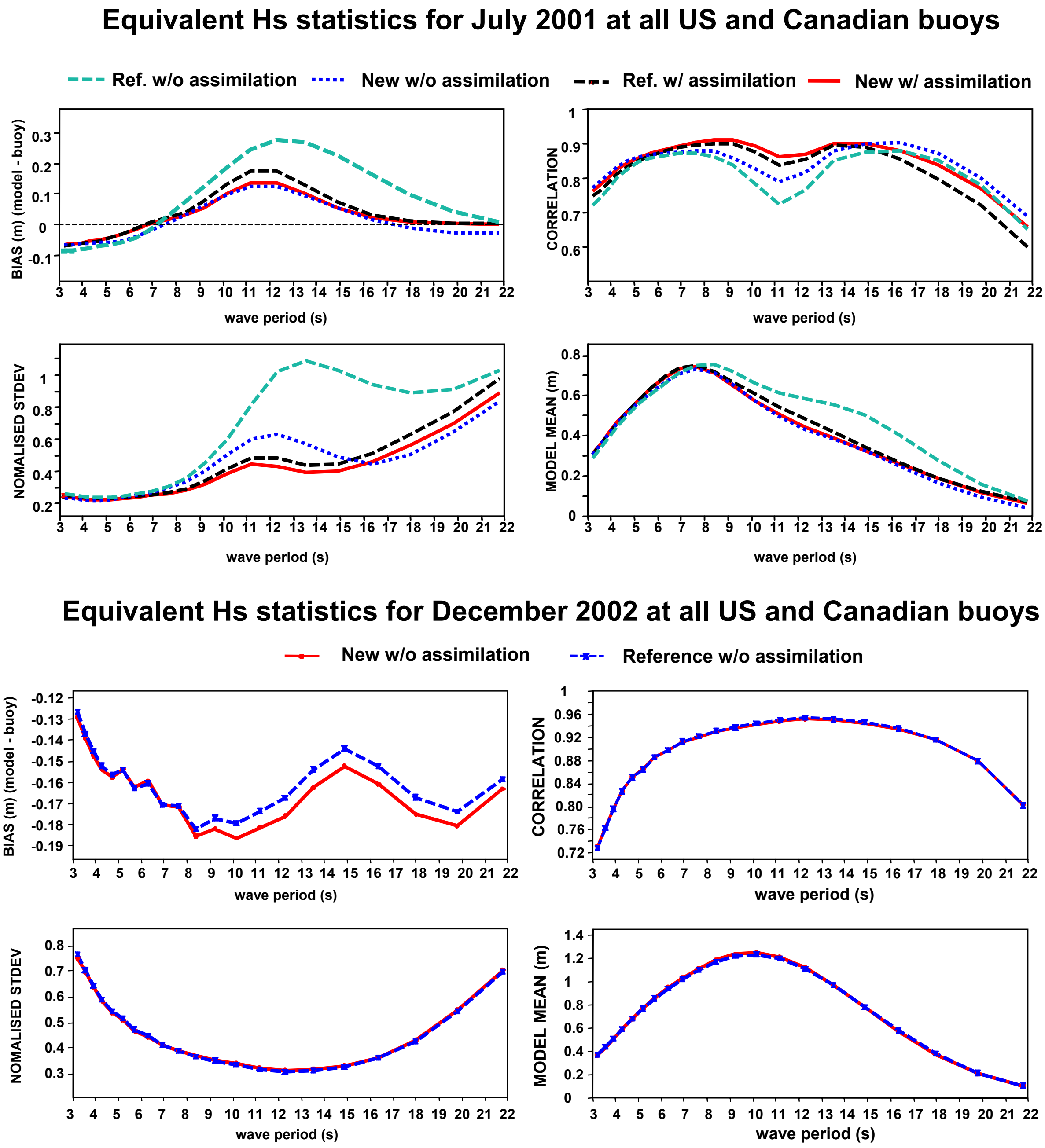

Figure 10: Comparison between wave model hindcasts and 1-D wave spectra for locations along the American and Canadian coasts. The spectral data were smoothed by averaging over 3 consecutive wave model frequency bins and converting the average energy density to equivalent wave heights. All runs used the stand alone 55 km WAM. Reference runs (Ref.) were obtained with the current operational mean bathymetry whereas the new runs (new) employed the mean bathymetry and the transmission coefficients derived from ETOPO2. The normalised standard deviation of the difference (STDEV) is computed by normalising with the standard deviation of the observations for each bin. Results for July 2001 are given in the upper panel and those for December 2002 in the lower panel.

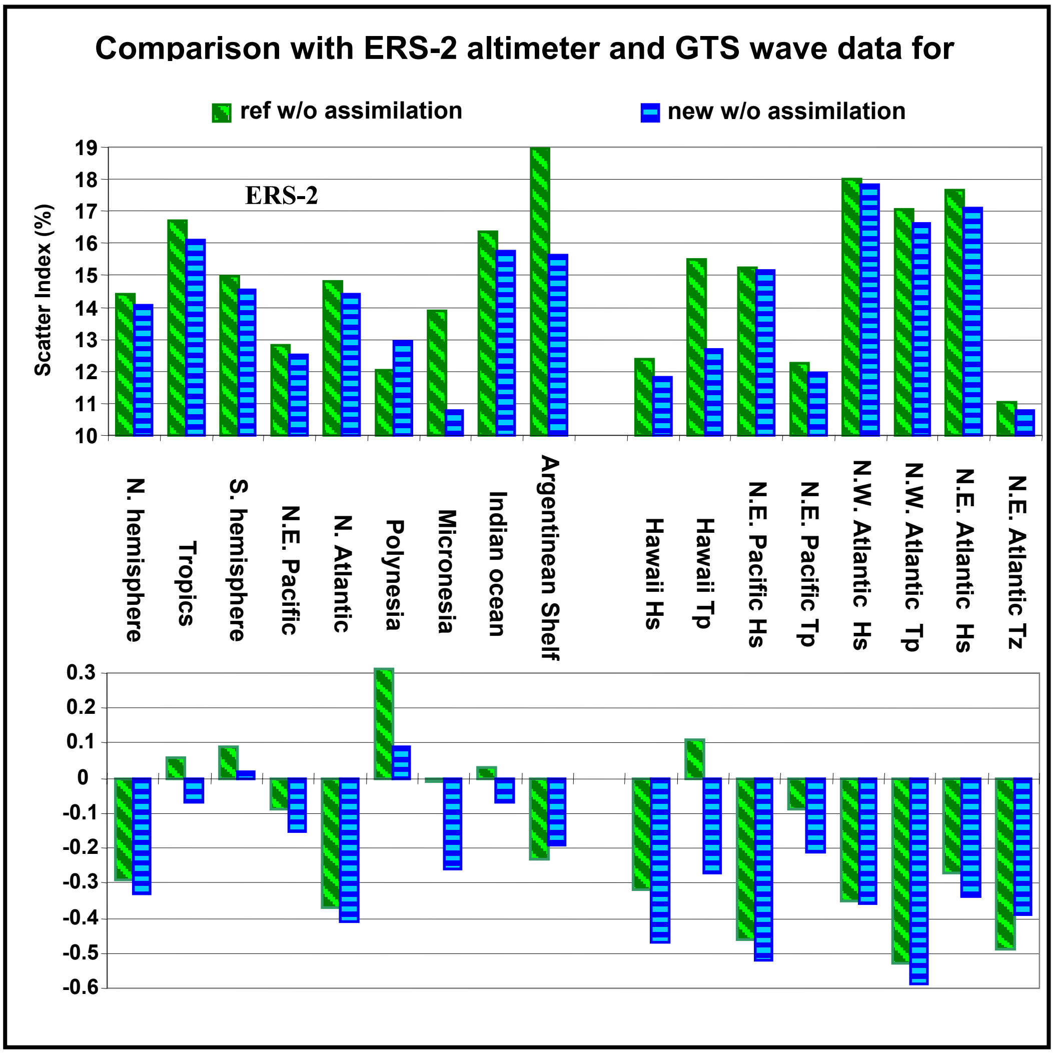

Figure 11: Same as Figure 8 and 9 combined for December 2002. Only runs without data assimilation are compared.

2. Use of neutral winds:

The WAM model was developed in term of surface stress as expressed by the friction velocity u_*. The relation between u_* and the wind speed at a given height (currently 10m) is assumed to be given by the logarithmic profile corresponding to neutral stability condition. The wave model should therefore be forced by surface stresses. However it is usually forced by wind speeds because they are readily available. Hence, these winds should be transformed into their neutral wind counterparts. In the coupled IFS/WAM system, this transformation can easily be achieved on the IFS side by using the atmospheric surface stress and the logarithmic wind profile with the roughness length based on the Charnock parameter. This conversion has been successfully tested.

In Figure 12, the mean difference over 32 days between a coupled run in which the wave model was forced by neutral winds and a reference run forced by the usual 10m-winds is displayed with the colour shading for the Gulf Stream area. The black contour lines correspond to the mean sea surface temperature (SST) for the same period. As expected the impact of the SST is clearly visible. The airflow over colder water north of the Gulf Stream should be more stable than the flow over the warm water of the Gulf Stream resulting in lower neutral winds and vice-versa.

Since the global mean impact of using neutral winds was an increase in mean wave height, this change was further tested in combination with the previous change for the unresolved bathymetry because it had the opposite effect on wave height model bias (see Section 4).

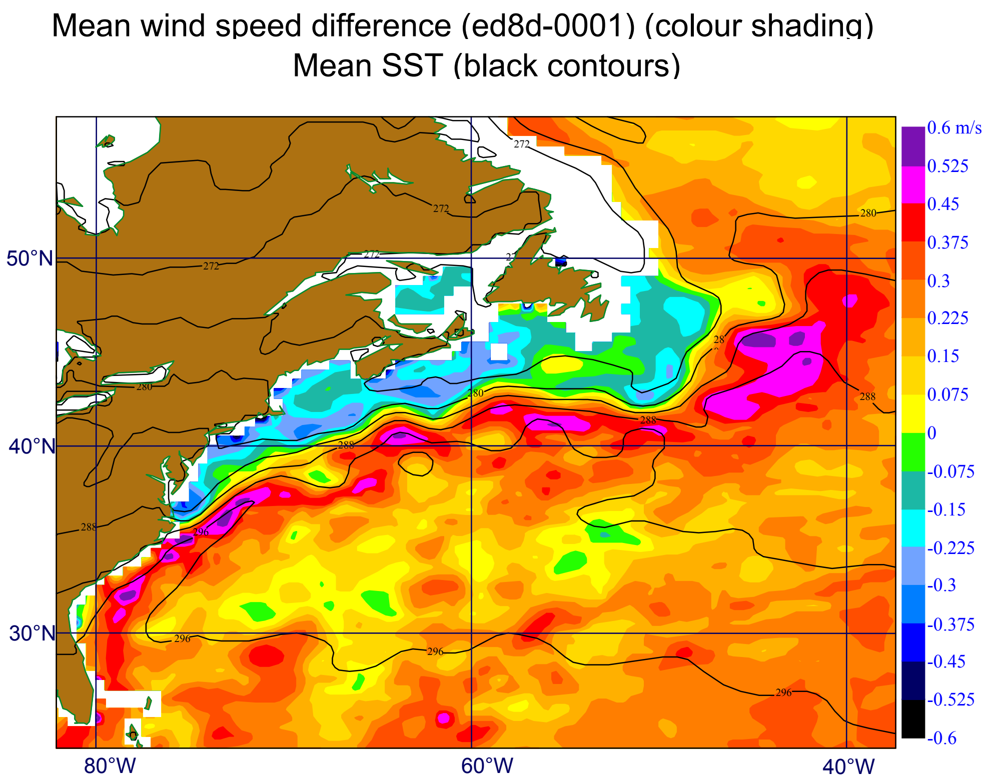

Figure 12: Mean difference in wind speed used to force WAM in coupled high-resolution analysis runs (T511/55km) between the new version with neutral wind (ed8d) and operation. The black contour lines are the corresponding mean SST.

3. More accurate total stress and wave induced stress tables in WAM:

It was found that the numerical evaluation of the integral for the high frequency contribution in the wave induced stress table was too coarse. A more accurate procedure can be used for the evaluation of the integral. Similarly, the maximum value for the Charnock parameter was modified to 0.2 in the table range and the number of values in the table was doubled. The accuracy of the total stress table was also increased by doubling the number of values in both directions (10m wind and wave induced stress).

The net impact of using more accurate tables is clearly visible in Figure 13. It shows the evolution of the maximum Charnock parameter as determined from the norm in the log files of coupled 10-day forecast runs. Both operation and a run with neutral winds show unrealistic large values of the Charnock parameter. If the new tables are used then the maximum values are reduced by as much as an order of magnitude, in accordance with what is physically expected. Similarly, the relationship between the mean Charnock parameter and the 10m winds as found by binning the Charnock values (including its viscous contribution) in terms of the 10m wind speeds and taking the average for each bin is not longer displaying the unrealistic local maximum around 5 m/s (Figure 14).

Moreover, the mean value is slightly reduced. The largest differences between a run with the new tables and another one with the old tables are mostly confined to enclosed basins and areas along the coastlines (Figure 15).

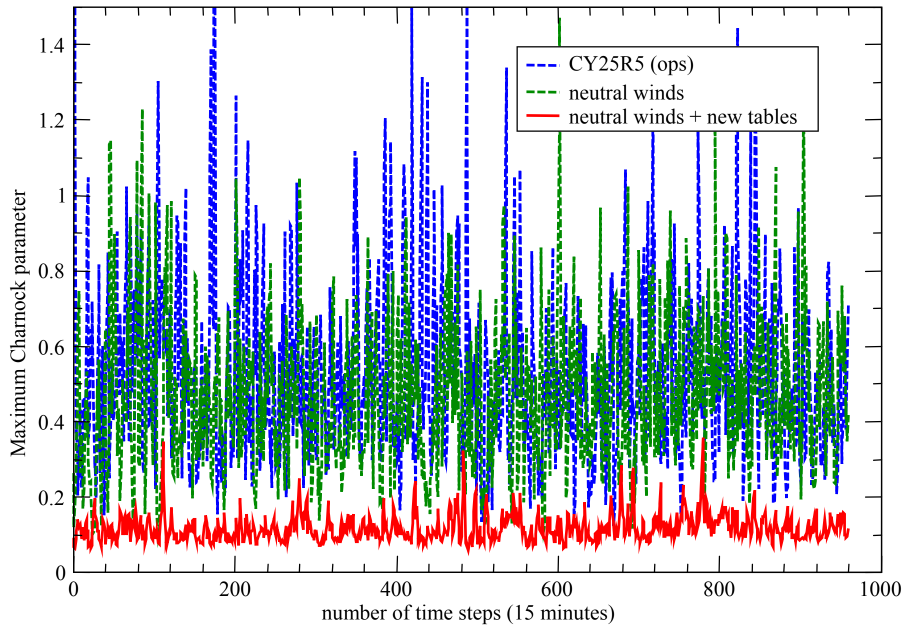

Figure 13: Maximum Charnock parameter norm as found in 10-day coupled forecast log files.

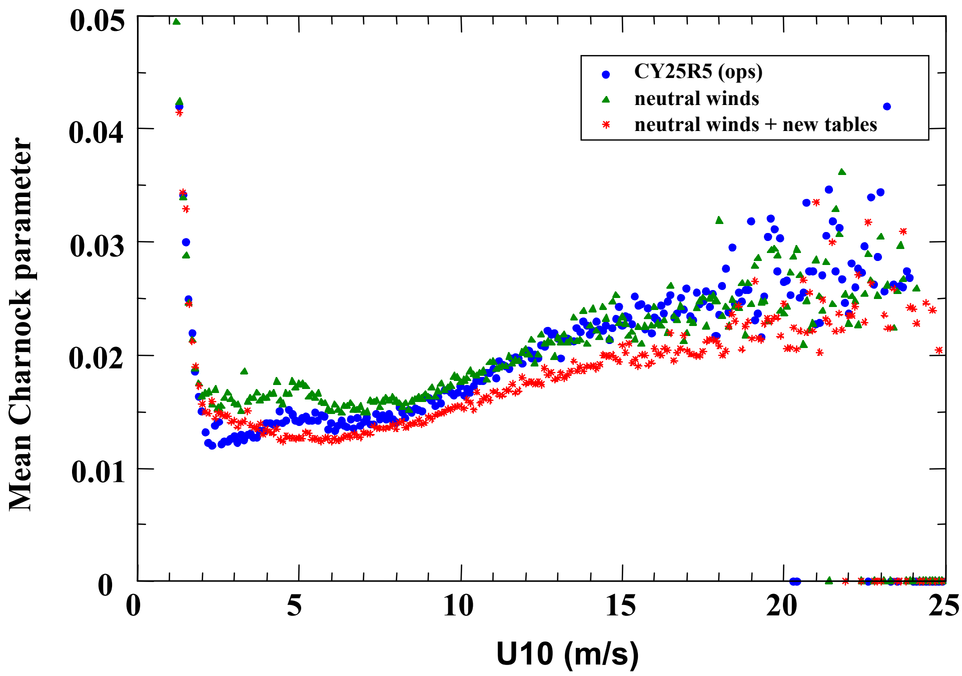

Figure 14: Mean Charnock parameter as obtained by averaging the day 4 forecasts field for each wind speed bin. The viscous contribution to Charnock has been added.

Charnock parameter difference (ed8d - ed4c)
April 1 2003, 0UTC analysis

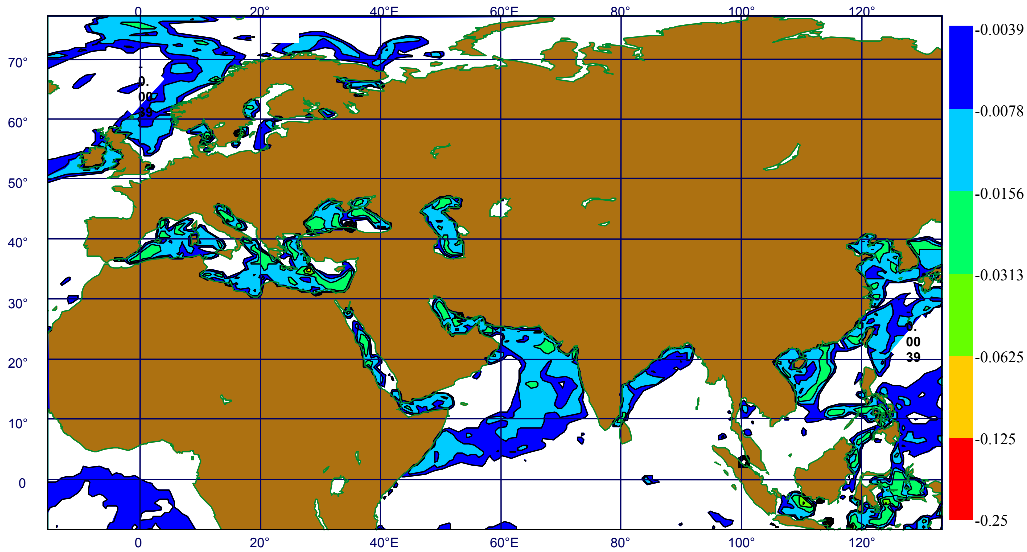

Figure 15: Difference in Charnock parameter between a run with the new stress tables in WAM (ed8d) and a reference with the old less accurate tables. Only difference below -0.0039 are shown.

4. Combined impact of the three changes:

The three changes described above were combined into a single coupled analysis experiment and compared to operation.

Figure 16 shows the small beneficial impact the new system (mostly the use of neutral winds) has on the analysed 10m-wind speed when compared to both ERS-2 and ENVISAT wind speeds. Likewise, comparisons against 1D-spectra (Figure 17) and GTS data (not shown) confirm the positive impact of the changes on the wave analysis.

Wave forecast scores can be obtained by either comparing the forecasts with ERS-2 data or with the verifying analysis. Figure 18 shows that the new system performs remarkably better in the tropics without any detrimental effect on the Northern hemisphere when compared to ERS-2 data. A similar conclusion can be reached when the results are assessed against their own analysis (Figure 19). The usual atmospheric scores are mostly neutral.

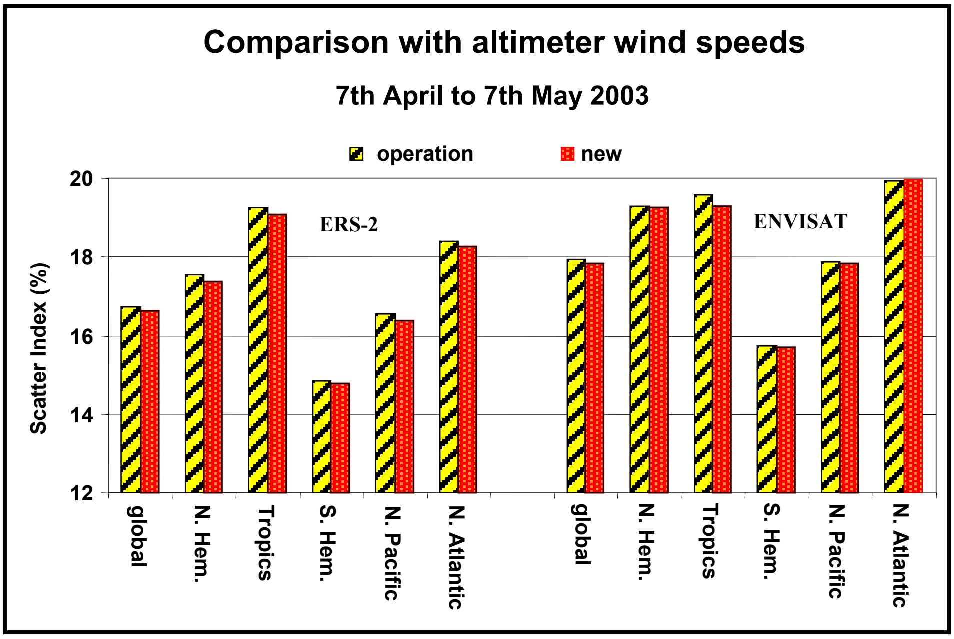

Figure 16: Scatter index for the comparison of analysed 10m winds with altimeter wind speeds. Both ERS-2 and Envisat were used for the comparison. The reference is the operational analysis (0001) and the new model uses neutral winds, unresolved bathymetry and new stress tables.

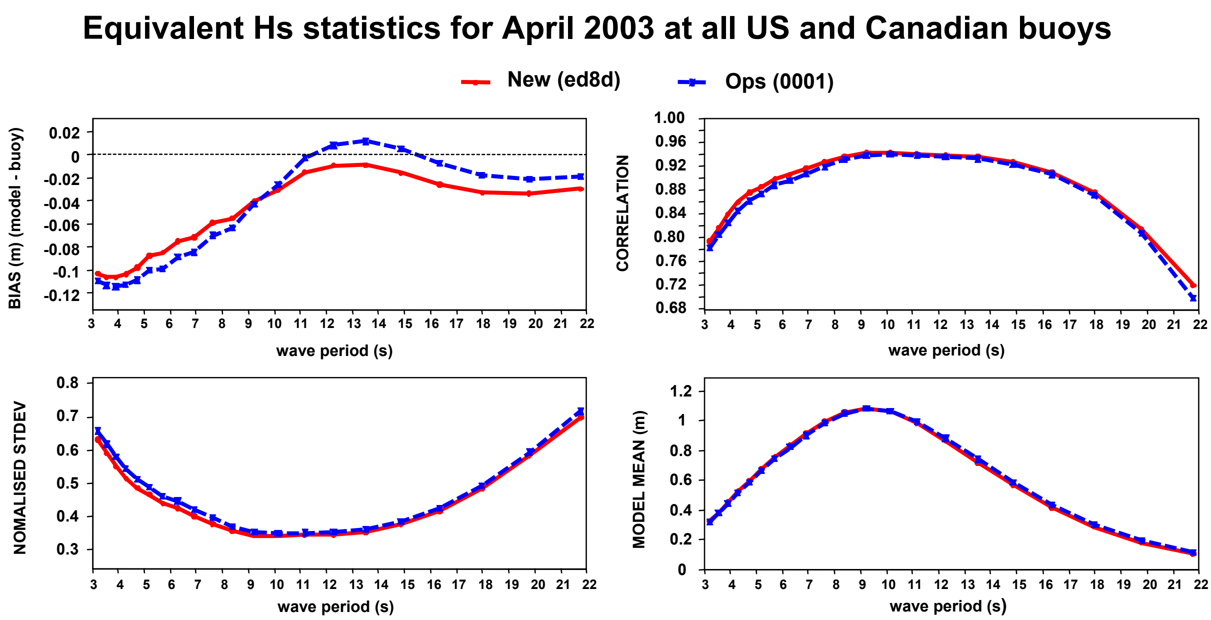

Figure 17: Same as Figure 10 but for coupled T511/55km runs. The reference is the operational analysis (0001) and the new model uses neutral winds, unresolved bathymetry and new stress tables.

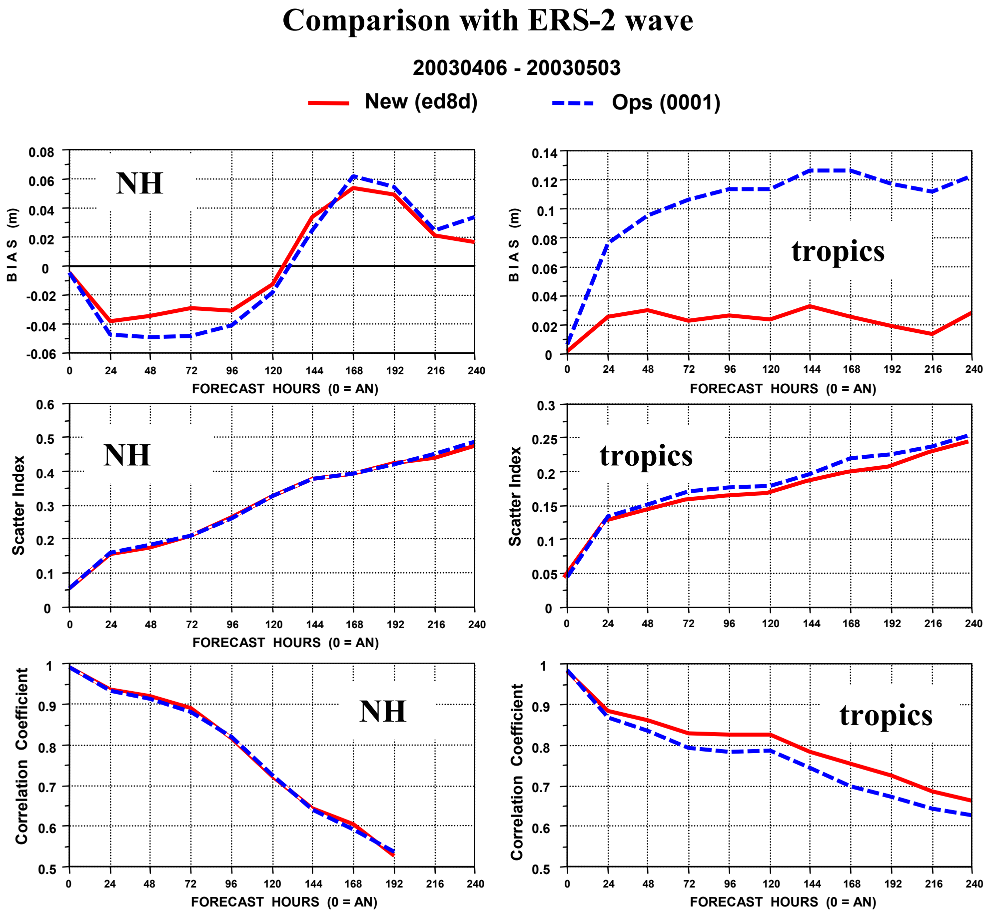

Figure 18: Wave height scores against ERS-2 altimeter wave heights for the Northern hemisphere (NH) and the tropics. The reference is operation (0001) and the new model uses neutral winds, unresolved bathymetry and new stress tables.

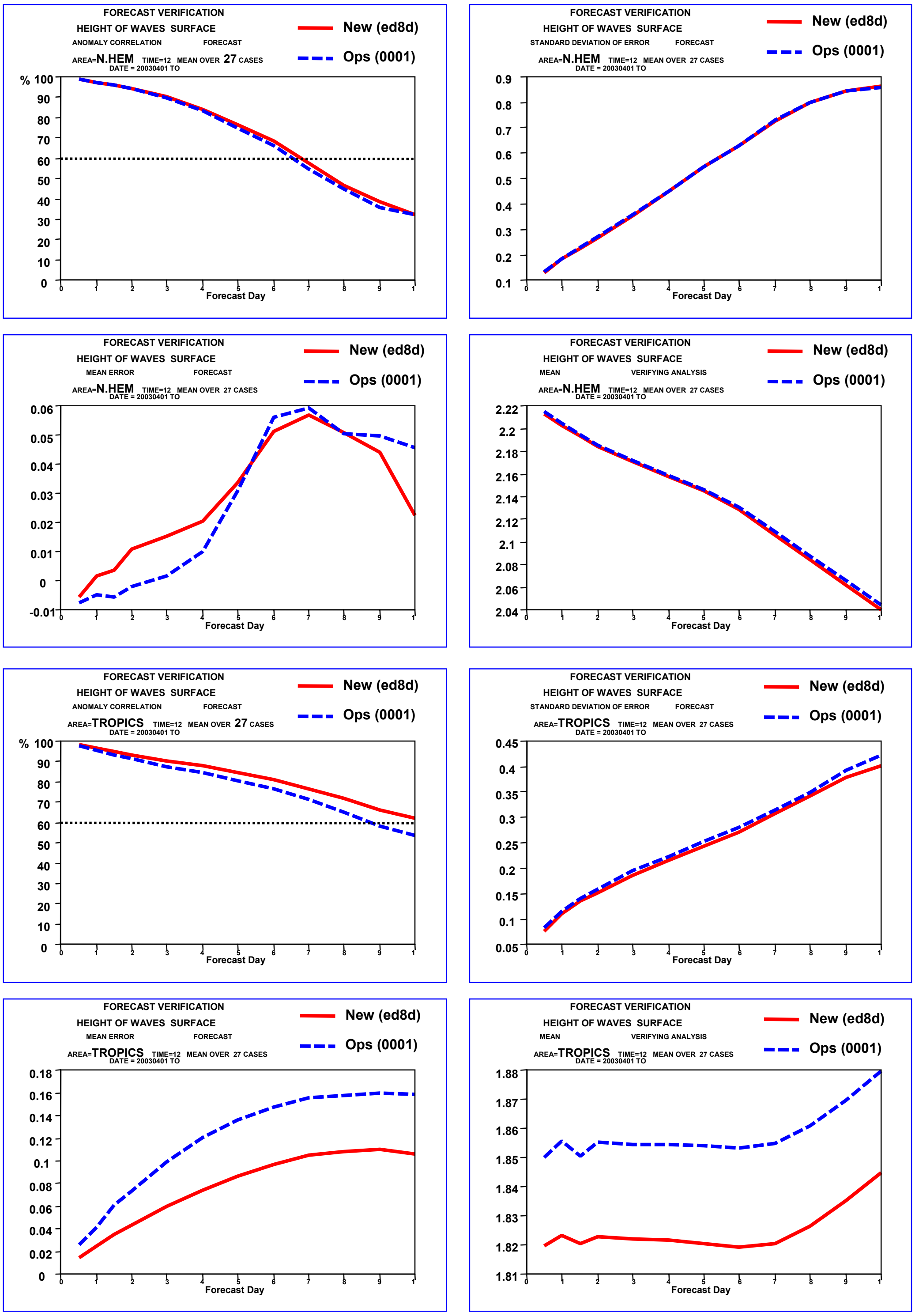

Figure 19: Wave height scores against own analysis for the Northern hemisphere and the tropics. The reference is operation (0001) and the new model uses neutral winds, unresolved bathymetry and new stress tables.

5. Conclusions:

We have shown that a systematic overestimation in the wave model low frequency spectral distribution can be removed by introducing a simple scheme to account for the attenuation of the global wave field due to unresolved islands and shallow submerged bathymetric features. A small yet positive impact of using 10m neutral winds to force WAM has also been found. Unrealistic large value of the Charnock parameter can be alleviated if more accurate stress tables are used in WAM.

These modifications are to be included in CY28R1 along with a bug fix for the EPS configuration (Bidlot, 2003).

Acknowledgements:

Careful reading by Saleh Abdalla is gratefully acknowledged.

References:

Bidlot J.-R., 2003: Corrupted Charnock parameter in the EPS configuration. Memorandum of the Research Department R60.9/JB/0399.

Tolman, H. L., 2003: Treatment of unresolved islands and ice in wind wave models. Ocean Modelling, 5, 219-231.