Comparative assessment of ERA-40 ocean wave data

S. Caires and A. Sterl

Royal Netherlands Meteorological Institute
P.O. Box 201, NL-3730 AE De Bilt, Netherlands
email: caires@knmi.nl

Abstract

A 40 year reanalysis of atmospheric observations (including surface ocean wave observations) is presently underway. The computations are being performed at the European Centre for Medium-Range Weather Forecasts (ECMWF), and will cover the period from mid 1957 to 2001. This paper aims at giving an assessment of the first 7 years (1987-93) of produced ocean-wave and wind data.

We give here a detailed assessment of the quality of the data and its adequacy for ocean wave and wind climatology and extreme events studies.

1 Introduction

Computations are underway for a reanalysis of global meteorological wind, temperature and humidity fields, stratospheric ozone, deep water sea states and soil conditions from mid 1957 to 2001. The reanalysis is being performed at the ECMWF using its Integrated Forecasting System (IFS, a coupled atmosphere-wave model) with variational data assimilation. This is a state-of-the-art model that is very similar to (although with lower resolution than) the one used operationally. The aim of this reanalysis is to produce a data set with no inhomogeneities as far as the technique of analysis is concerned, by using the same numerical model throughout. However, since the availability of the observations to be assimilated varies in time and space, a certain amount of inhomogeneity will result. The assimilation of data also reduces the number of independent data sets available to validate the results. On the other hand, these two shortcomings are countervailed by the increase in the quality of the data provided by the assimilation—most of the reliable data sets of observations will be used in the assimilation, leading to the best reanalysis possible.

This is the fourth of such initiatives: Previously, the ECMWF (Gibson et al., 1997) produced a 15 year world climatology reanalysis, ERA-15. Contrary to the present reanalysis, there was no wave model coupled with the system used, but Sterl et al. (1998) computed the corresponding (off-line) ERA-15 ocean wave field using the ERA-15 surface winds to force the wave model WAM (WAMDI Group, 1988). The NCEP (Kalnay et al., 1996) also produced a reanalysis of data from 1958 to 1997. Again, in this reanalysis there was no wave model coupling, and the ocean-wave fields were obtained off-line, using the WAM model, by Günter et al. (1998) for the Northeast Atlantic, and by Cox and Swail (2001), using Ocean Data Gathering Program version 2 (ODGP2) spectral ocean wave model, for the whole globe. Recently, these global winds were also used off-line to force the Wavewatch III model (Tolman, 1999), but the results of this study are not published yet. Finally, there was the 15 year reanalysis at GSFC/DAO (Schubert et al., 1995), which produced no ocean-wave data.

In terms of the ocean-wave data, this will be the most complete – 40 years of data on a 1.5 by 1.5 degrees latitude/longitude grid covering the whole globe – and realistic – since the coupling of the atmosphere model with the wave model allows the atmosphere to react to the waves-data set available. If successfully validated, this data set can be used to study the climatology of ocean waves and to compute extreme wave statistics.

This would be a very positive outcome of the project, since studies of this kind are usually confined to the Northern Hemisphere (e.g. WASA Group (1998) and Graham and Diaz (2001)).

The Royal Netherlands Meteorological Institute (KNMI), as one of the partners of the ERA-40 project, is responsible for the validation of the ERA-40 ocean wave product. The objective of this paper is to give an assessment of the quality and potential of the ERA-40 waves and wind fields produced so far. All the comparative plots and statistics commented here, and more recent ones, are available on the ERA-40 Ocean wave product validation and analysis internet webpage[1], where an up to date monitoring of the ERA-40 ocean wave and wind product is presented. Apart from a few exceptions, these plots and tables will not be reproduced here.

The paper is organized as follows. In Section 2 we give an overview of the inhomogeneities that can be expected to occur in the data, and of the data sets available for validation. In Section 3 we present some preliminary validation results of the presently available ERA-40 wave data. In Section 4 we give some comments, based on the assessment of the previous section, on the adequacy of the data to infer patterns and trends of wave variability and extreme statistics. We finish in Section 5 by pinpointing the important conclusions of this initial assessment of the data.

2 Inhomogeneities; data sets available for validation

Most of the existing reliable sets of climate observations will be used in the assimilation procedure of ERA-40. This leaves out very few independent data sets for the validation of the data. As regards the reanalysis of wave data, the sets that will have a more direct effect in the results are the SSM/I 1D-Var winds, which are assimilated in the reanalysis data from July 1987 onwards, the buoy winds, which are assimilated from June 1990, the scatterometer winds over oceans, and the altimeter wave height fast delivery product data from the ERS 1/2 satellites. The scatterometer wind data covers the period from April 1992 onwards, and the altimeter wave heights have been used inappropriately in the production of data from December 1991 to May 1993, at which point the assimilation was halted; this period will be rerun with no assimilation. The assimilation will be resumed with data from 1994 onwards, a period for which good altimeter data is available. The preceding altimeter data is faulty due to a processing error, which had already been identified by Bauer and Staabs (1998). This error in the measurements is assumed to have no big impact in the other reanalysis fields and, in principle, only the wave fields will be recomputed for this period, forcing the wave model (off-line) with the archived winds. This may be another source of inhomogeneity in the wave data.

The problem with the altimeter wave heights makes the ERA-40 sea state reanalysis data presently available invalid from December 1991 to May 1993, and therefore no validation of that data is presented here. However, we shall use this data to illustrate the impact that the assimilation of the altimeter wave heights have in the results.

Having pointed out the inhomogeneities in the reanalysis wave and wind data that may result from changes in data practice, in the rest of this section we present an overview of the deep water wave data sets available, indicating those that will be used in the validation.

The coverage, availability and detail of wave measurements have varied a lot during the ERA-40 period. Before 1977 most of the measurements available were reported by moving ships, and are not very reliable. These ship observations are available in the COADS database. Wave heights have been reported since 1888, and swell height since 1922. The quality of these observations changed drastically in 1968 when the

[1] http://www.knmi.nl/onderzk/oceano/waves/era40/index.html

reporting code was changed. In terms of validation of the ERA-40 results, these data are not useful and will not be used unless we can somehow assess their quality.

In 1977 the American Buoy Network was started and an increasing number of buoys have been deployed since then. As time went by, there was not only an increase in the number of buoys but also an increase in the detail of the information they reported. Initially, buoys would measure only the significant wave height and mean wave period, whereas nowadays most of the buoys report the full directional wave spectrum. All these measurements are available in the NOAA Marine Environmental buoy database.

From 1987 onwards the UK network of buoys, located mainly around Great Britain, has also been providing wave measurements. As with the American Network, the number and degree of sophistication of the buoys have increased with time. These data have been distributed through the Global Telecommunication System (GTS), and are available from the ECMWF Mars storing system, which also includes observations from ships, drifters, moored buoys and fixed platforms. Although the collection of buoy observations begun in 1987, before July 1991 the recording format of the ECMWF Mars storing system did not identify precisely observations coming from buoys, and the information on the sea state was limited. For this reason, only the use of data after July 1991 is feasible.

A Canadian Network of buoys has been in operation since 1992; the data collected can be obtained from Environment Canada.

All the above mentioned buoy wave measurements are concentrated on the Northern Hemisphere, apart from two locations on the Southern Hemisphere, namely on the coast of Peru. There were a few other buoy experiments on the Southern Hemisphere, but they all seem to be confined to shallow waters.

A full world coverage of wave measurements, other than those obtained by reporting ships, became possible only after the advent of satellites.

From July to September 1978 altimeter measurements were performed onboard the Seasat satellite. However, Bauer and Staabs (1998) identified some problems in this data set (its histograms show an abnormal tri-modal shape), and therefore it will not be used here.

From March 1985 to September 1989, the Geodetic Mission of the U.S. Navy Geodetic Satellite (Geosat) was on orbit, and significant wave height and wind speed data can be inferred from its measurements.

From 1991 onwards, the ERS-1 and subsequently the ERS-2 have been orbiting the earth and recording altimeter wave heights and wind speeds, as well as Synthetic-Aperture-Radar (SAR) imagery, from which the directional wave spectrum can be computed. As mentioned above, the altimeter data will be used in the assimilation, and therefore no independent validations can be made with it.

From 23rd September 1992 altimeter measurements have been performed onboard the Topex satellite mission. The measurements have a time overlap with the assimilated ERS-1 altimeter measurements and will be used here as an independent data set in the validations.

From the above description it is clear that limited, if any at all, verification of the ERA-40 wave product can be made before 1978, and that the information is mainly limited to the Northern Hemisphere, with Geosat and Topex being the only reliable and independent altimeter data sets available. We still need to assess the availability and quality of the SAR wave observations.

In order to complement the validation of the ERA-40 waves and winds, we will compare it with the ERA-15 results. Several problems have been identified in the ERA-15 winds (Kållberg, 1997) and waves (Sterl et al., 1998); the comparison of ERA-40 results with ERA-15 will help determining whether the problems remain, and assessing the effect of changes from one system to another. For instance, in ERA-15 there was no assimilation of the SSM/I winds nor of the altimeter wave heights, and the most striking difference was that the wave model was not coupled with the atmospheric model.

The wave data will be further assessed by comparing the reanalysis ERA-40 sea state data for 1988 with the hindcasts of the ODGP2 wave model (the model used in the Cox and Swail (2001) reanalysis, referred to in the introduction) forced with the ERA-40 archived reanalysis winds for that period.

3 Preliminary validation results

The ERA-40 computations are divided into 3 streams: stream 1, from July 1957 to 1972; stream 2, from January 1972 to 1987; stream 3, from September 1986 to 2001. The production has started with stream 3, and so far results from September 1986 to mid 1993 have been obtained. These are the results that we will comment on here.

The ERA-40 stored results comprehend the full directional wave spectrum. However, this initial validation will be done only in terms of significant wave height (H_s), mean wave period from the second spectral moment (T_m), and wind speed (U_{10}). Also, the comparison statistics to be presented will be ordinary statistics such as the bias $(\overline{y}-\overline{x})$, the root-mean-square-error $\left(RMSE=\sqrt{n^{-1}\sum\left(y_i-x_i\right)^2}\right)$, the scatter index $\left(SI=RMSE/\overline{x}\right)$ and the correlation coefficient $\left(r=\sum\left(x_i-\overline{x}\right)\left(y_i-\overline{y}\right)/\sqrt{\sum\left(x_i-\overline{x}\right)^2\left(y_i-\overline{y}\right)^2}\right)$. In all these formulas y_i represents the ERA-40 results and the x_i the other data.

3.1 Buoy

For the 1987-91 period we have so far only been able to collect observations from the NOAA database. From the buoys available we have selected 22 to be used in the validation. The locations of the buoys are shown in Figure 1.

The selection of the locations took into account their distance from the coast and the water depth. Only deep water locations can be taken into account since no shallow water effects are accounted for in the wave model, and the buoy should be at enough distance from the coast so that the corresponding grid point is located at sea. This makes most of the buoys in the NOAA database inadequate for the validations, since most of them are close to the shore.

The buoy measurements are in most cases hourly. These measurements have gone through some quality control; we do, however, still process the timeseries further creating super observations from 4 hours averages in order to bring the temporal and spatial scales closer to each other; and when the anemometres of the buoys are not at a 10 metres height, the wind speed measurements are adjusted to that height using the neutrally stable logarithmic wind profile.

The 22 buoys selected for this study come from 7 separate basins: the Peru coast; the area around the Hawaiian Islands; the Gulf of Mexico; the Northwest Atlantic Ocean; the coast of Alaska; the Northeast Pacific Ocean; the coast of California (see Figure 1).

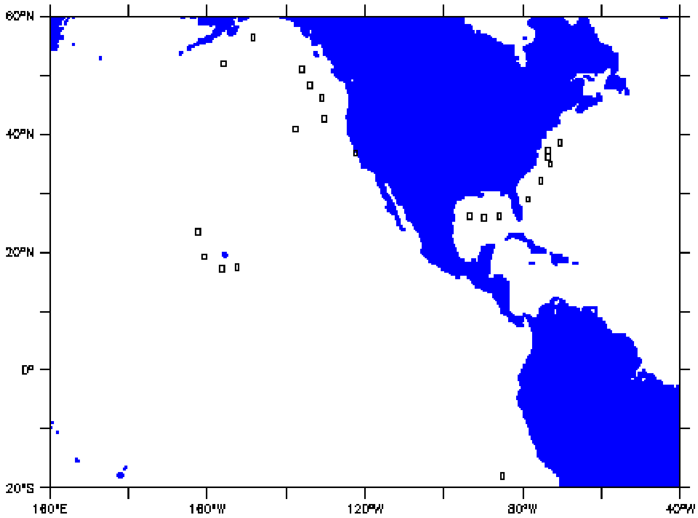

Figure 1: Area covered by the NOAA Marine Environmental Database with the locations of the buoys selected for this study indicated by squares.

We have compared the H_s, T_m and U_{10} buoy measurements and the corresponding ERA-40 results by observing monthly timeseries, scatter, histogram, and Q-Q (or quantile) plots, and the above mentioned statistics for the monthly data. As mentioned above, U_{10} buoy measurements are assimilated into the atmospheric model (not all the buoy measurements are used in the assimilation, and data only started being assimilated in June 1990), and the differences between the observations and the hindcasts are expected to be small. It is important, however, to assess the quality of the U_{10} hindcasts at the buoy locations, since errors in the predicted wind speeds translate into errors in the predicted wave heights. In these comparisons we will not be analysing the period between December 1991 and May 1993 for the reasons pointed out in Section 2.

The main results of the comparisons are the following:

- Low wave heights are overestimated. This occurs for observed wave heights of up to 2 metres, with timeseries features below 1 metre being missed. The high wave height peaks are underestimated, with most of the peaks above 4 metres being missed. These characteristics make the quality of the wave height data dependent of the season and the region. In locations close to the Tropics, which are characterized by low sea states, there is a lot of overestimation of the low wave events, and in locations at high latitudes, which are characterized by high sea states, there is a lot of underestimation. Biases are negative in the Winter months and higher in the Summer months. The monthly bias take values between –1 m to 0.5 m. The best results occur at the Alaska locations where the scatter is also lower.

- There is a better agreement between observations and reanalysis data in terms of wind speeds than in terms of wave heights, the underestimated high wave height peaks not always corresponding to underestimated high winds. The worse comparisons occur in the Peruvian Coast, where the monthly bias is mostly positive.

- The mean wave period comparisons depend on whether the buoy is located in the Atlantic Ocean, the Gulf of Mexico or the Pacific Ocean. The Pacific Ocean is characterized by overestimation (monthly biases as high as 2 seconds at the lower latitudes), and the Atlantic Ocean and the Gulf of Mexico by underestimation (monthly biases of about -0.5 seconds). The overestimation of the mean wave period is particularly serious in low sea states, and consequently more critical in the Peruvian Coast.

3.2 Satellite

3.2.1 Geosat

The Geosat data is available in terms of monthly means on a 3° by 3° longitude/latitude grid from 63°S to 72°N. This data was provided by the Southampton Oceanographic Centre (SOC). The original values of significant wave height are increased by 6.5% according to Cotton and Carter (1996). Although the period of observations overlapping the ERA-40 results goes from January 1987 to September 1989, we will only be comparing H_s data from 1987 and 1988, because the measurements of the last months have many gaps and the quality of the data around the gaps seems dubious. The comparisons of U_{10} are performed only for 1988 because the Geosat wind measurements for 1987, available to us, are corrupted. The remaining monthly means compare well with the buoy monthly means, with no bias, quite a low scatter in the H_s comparisons, and a slightly higher scatter in the wind comparisons. We have also collocated GEOSAT 1988 along track measurements with the ERA-40 data. However, we had problems in correctly identifying erroneous U_{10} values and were therefore unable to produce a good U_{10} data set. The comparisons of H_s collocated data support the conclusions we present here for the monthly means.

The ERA-40 grid results were interpolated to the same grid as that of the Geosat data. We have compared the Geosat data in terms of surface plots of the difference between the ERA-40 monthly means, the corresponding scatter plots, and surface plots of the comparison statistics.

The comparisons with Geosat data are consistent with the buoy comparisons. The surface plots of the H_s bias between Geosat and ERA-40 monthly means show biases mainly between -1 and 1 metre. The overestimation occurs mainly in the South-eastern Pacific Ocean (this is in line with the comparison in the location at the coast of Peru). Spotlights of underestimation occur in the storm tracks of the Southern and the Northern hemispheres, in the respective winter periods. The underestimation is more pronounced between May and August, the stormy period in the southern mid-latitudes. The scatter plots show small scatter and good correspondence between the monthly means for values of H_s between 1 and 3 metres; higher values are consistently underestimated, and lower waves sometimes overestimated.

Figure 2 shows the H_s comparison statistics between Geosat and ERA-40 data for 1988.

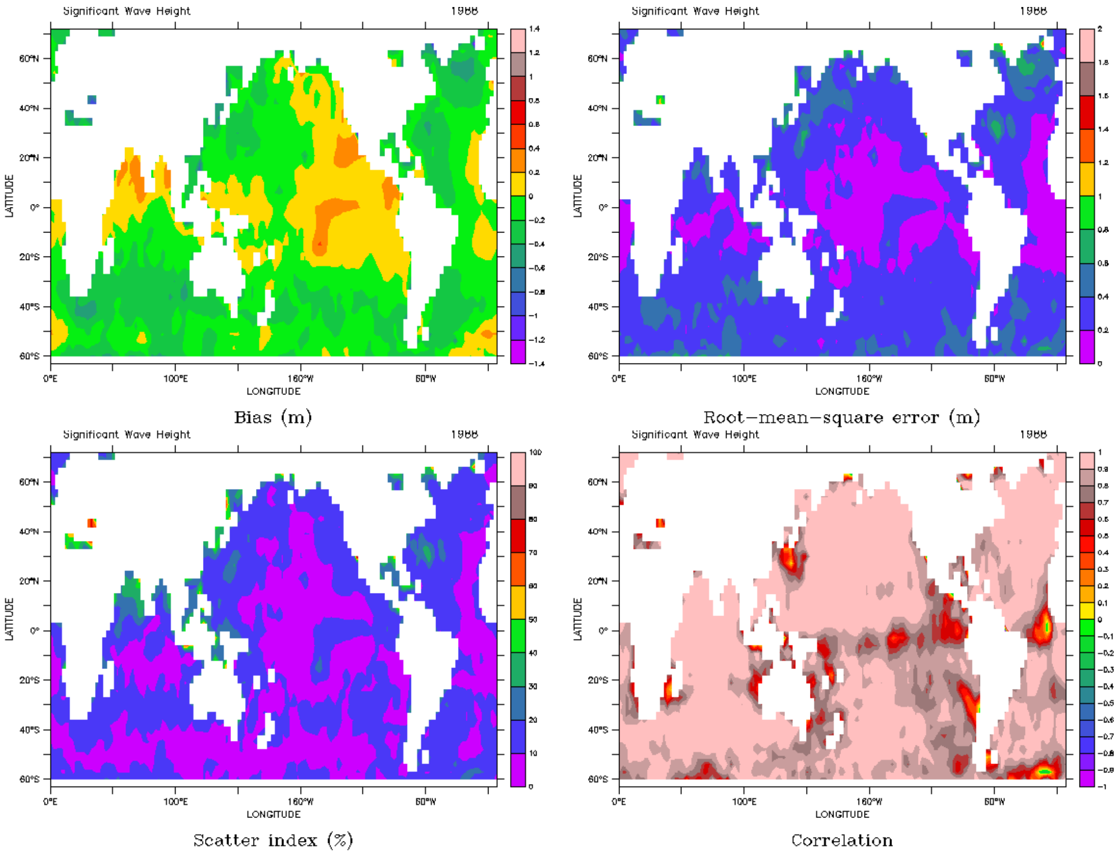

Figure 2: Bias, root-mean-square-error, scatter-index and correlation between ERA-40 and Geosat 1988 H_s monthly means.

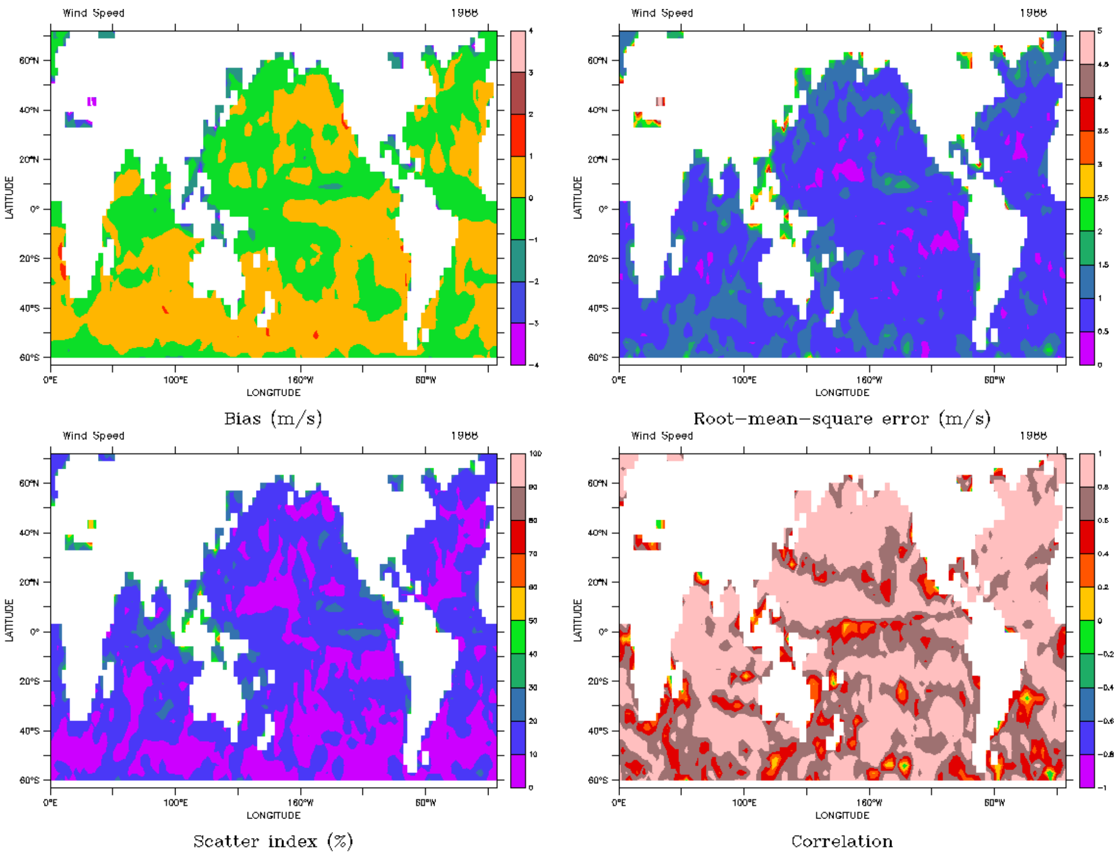

Figure 3: Bias, root-mean-square-error, scatter-index and correlation between ERA-40 and Geosat 1988 U_{10} monthly means.

The H_s bias patterns are similar for different years and show quite a good correspondence between the model and observations, especially in regions where the wave conditions are not so severe. Model overestimation occurs mainly in the eastern Pacific Ocean, the Arabian Sea and the Bay of Bengal, and underestimation along the South Hemisphere storm track and in the Northeast Atlantic Ocean. The tendency is for the underestimation to occur in the regions of high waves and overestimation in the regions of low waves, the exception being the North Pacific where the summer overestimation and winter underestimation seem to cancel each other out. In terms of root-mean-square-error, the comparisons are quite good, values being for most locations below 0.4 m. The comparisons are better in 1987 than in 1988. The difference are, however, small. The correlations are in most of the world above 80%, apart from some regions mainly around South America and Australia; the values are particularly low for 1987 in the Southeast Pacific. The scatter-indices are below 20% for most of the world.

The correspondence between wind fields is even better than between waves; see Figure 3. The monthly bias varies from -3 to 3 m/s, with typical values between -2 and -1 m/s. The scatter plots show a very good correspondence between the model and the observations.

As to the statistics presented in Figure 3, we can observe that the bias varies mainly between -1 and 1 m/s, the root-mean-square-errors are mainly below 1 m/s, the scatter-indices are lower than 20%, and the correlations between 0.8 and 1 almost everywhere, the exception being some trouble spots in the Southern Hemisphere, where values can be as low as 20%.

3.2.2 *Topex*

Topex along track quality checked deep water altimeter measurements of significant wave height and radar backscatter (which is transformed into wind speed using the Witter and Chelton (1991) wind speed tabular model) were obtained from SOC (GAPS interface). We have created collocated data sets of Topex and ERA-40 data. The resulting significant wave height Topex collocated data set seems to be quite good, but we found some problems with the U_{10} data and need to validate it further before comparisons can be made.

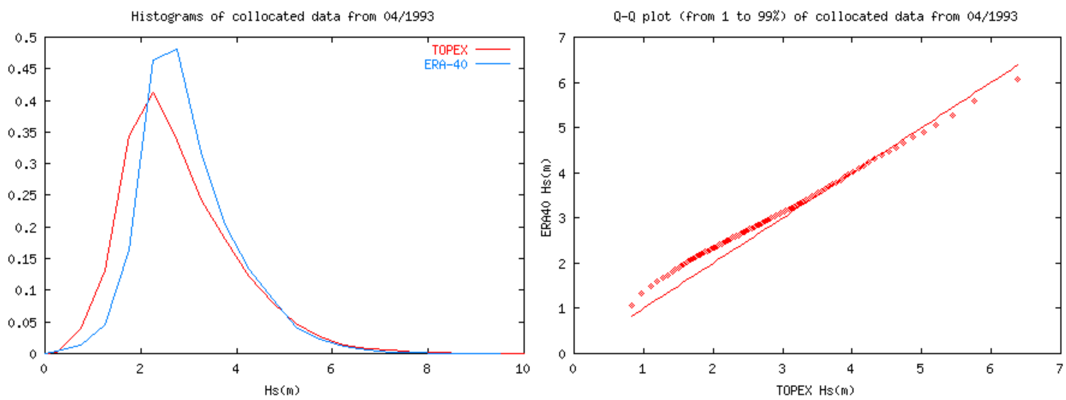

Figure 4: Comparisons between the histograms and Q-Q plots of Topex and ERA-40 H_s collocated data for April 1993.

Comparisons between ERA-40 and Topex collocated data for the period when erroneous ERS-1 significant wave height data was assimilated clearly show the problem in the assimilated data. Figure 4 is an example of such a comparison. The figure shows histogram and 1 to 99% quantile plot comparisons between the two data sets for April 1993. The ERA-40 data lack low wave heights and most of the data is concentrated between 2 and 3 m. On the other hand, for wave heights above 3m the comparisons seem to be quite good.

This is a clear indication that the future assimilation of altimeter data will have a positive effect in the reanalysis, reducing much of the high sea state underestimation.

Figure 5 shows comparisons between the ERA-40 and the Topex data after the assimilation was halted; the comparisons are consistent with those between buoy and Geosat measurements—ERA-40 wave heights above 3 metres are underestimated.

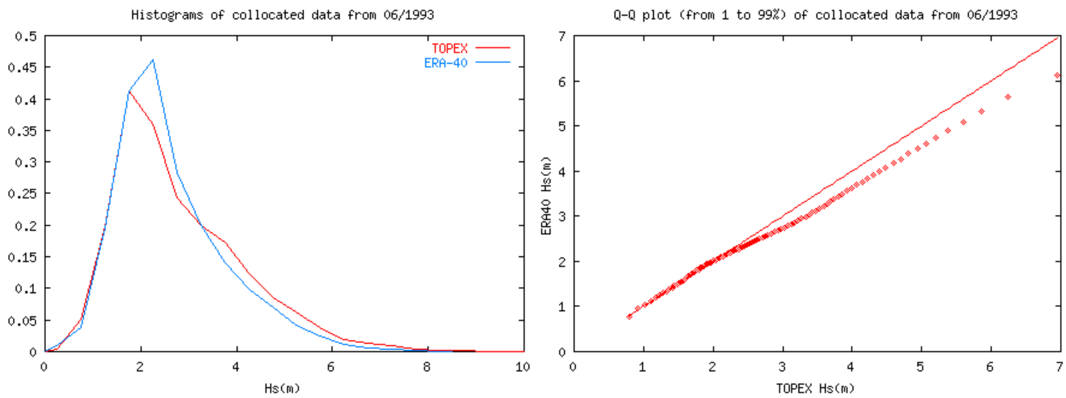

Figure 5: Histogram and Q-Q plot comparisons between Topex and ERA-40 H_s collocated data for June 1993.

3.3 ERA-15

The ERA-40 waves are overall lower than those of ERA-15 (up to 1.5 metres, and 0.5 metres on average), higher differences occurring with higher wave height conditions. There are, however, a limited number of locations where the ERA-40 waves are higher than those of ERA-15. These locations are close to the ice covered areas and the discrepancies occur because ERA-40 uses an ice limit data set different from that used in ERA-15, and some regions that were identified as ice covered are now ice free. In locations around small islands, mainly in the Southwest Pacific (Polynesia, Fiji, Solomon islands, etc), there are some discrepancies between the ERA-40 and ERA-15 hindcasts, but these are only visible in the yearly statistics. These discrepancies come from the correction of a problem, identified by Kållberg (1997), in the ERA-15 wind fields, caused by the assimilation of wind observations on small islands which were taken as observations at sea without any increasing factor.

In terms of U_{10} the correspondence between ERA-40 and ERA-15 is quite good apart from the locations close to the ice-covered areas and around small islands. In the latter locations there were also discrepancies between the values, but in the wind comparisons the differences are more visible.

The comparisons show that there are some global and some local differences between the ERA-40 and the ERA-15 results. The local differences (icy region and small islands) are a direct effect of changes (corrections) in the wind fields. The global differences seem to come from the fact that the wave model is now coupled with the atmospheric model, and from some differences in the model formulation.

The question is now whether these differences are for the better, i.e., it would be good to known whether the differences correspond to improvements in ERA-40 compared with ERA-15. In order to analyse this we have compared the ERA-15 fields with the Geosat observations, in the same way we had compared the latter with the ERA-40 results. The conclusions of the comparisons are the following:

- The ice limit data set used in ERA-40 is better than the one used in ERA-15, the improvements being visible in the comparisons.
- The small islands spurious effect identified by Kållberg (1997) has been corrected.
- The ERA-40 waves compare better with the GEOSAT observations than those from ERA-15 did. The ERA-15 fields tend to overestimate most of the heights, the only exceptions being the really extreme ones, and all statistics perform worse.
- In terms of winds there are no major differences between the two reanalysis, apart from the local ones identified above. This is surprising since ERA-40 benefits from the assimilation of the SSM/I winds, which were not used in ERA-15; thus the assimilation seems to produce no big impact in the wind speed. We should, however, note that the quality of the ERA-15 wind speed fields was already quite good, and therefore improvements would be difficult to obtain.

We have also computed timeseries of the bias between ERA-40 and ERA-15 for different latitude strips (figures 6 and 7) for H_s and U_{10}, respectively.

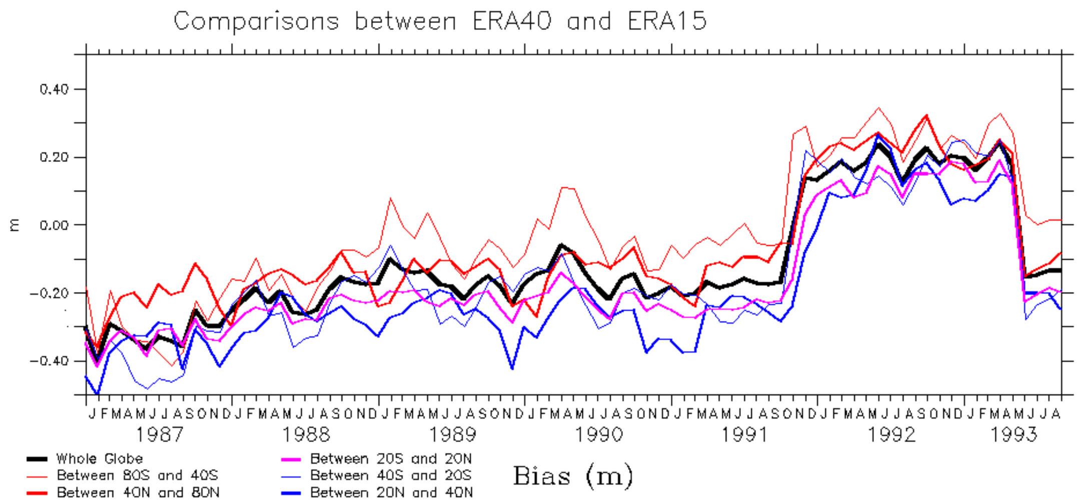

Figure 6: Timeseries of the bias between ERA-40 and ERA-15 H_s monthly means at different latitude strips.

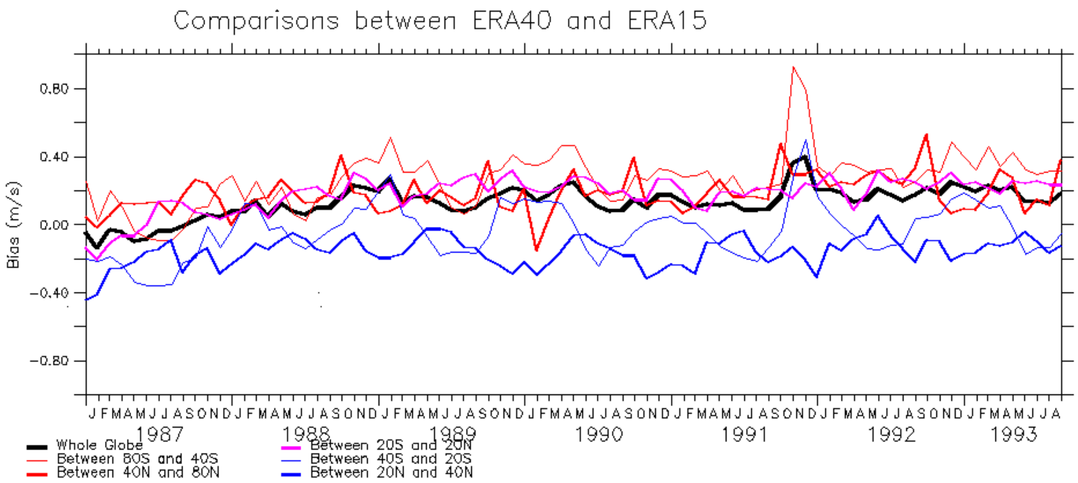

Figure 7: Timeseries of the bias between ERA-40 and ERA-15 U_{10} monthly means at different latitude strips.

Figure 6 shows that from January 1987 to June 1988 there was a small but steady increase of the monthly bias between ERA-40 and ERA-15, which, by looking at Figure 7 we can see is caused by an increase in the bias in the wind speed. A more detailed analysis of the data shows that this is a result of an increase in the mean of ERA-40 wind speed in the Tropics and southern high latitudes. This increase is probably due to the assimilation of the SSM/I winds, but we still have to look into the problem in more detail. Figure 6 also reveals the impact the assimilation of the altimeter measurements had in the ERA-40 H_s monthly means, since it shows a big increase in all the monthly means. When good altimeter data is assimilated we expect to see also an increase in the monthly mean in all regions except for the Tropics (where the results are mainly overestimated rather than underestimated). Although the assimilated data is not correct, it demonstrates the beneficial effect the assimilation will have in the data after 1994 (correction of the overestimation and underestimation of H_s) and the scale of the inhomogeneity it will create.

3.4 ODGP2 forced with ERA-40 winds

The wave data for 1988 was computed off-line using a deep water version of its Ocean Data Gathering Program version 2 (ODGP2) spectral ocean wave model (see Cardone et al. (1996) for a comparison between this model and WAM). The wind fields used in the generation of the wave hindcast were the ERA-40 archived 6 hourly 10 m wind fields adjusted to neutral stability, using the ERA-40 mean sea level pressure, the 2 m air temperature, and the sea surface temperature fields. ODGP2 is a second generation ocean wave model run in a global grid (from 70S to 75N) of 1.25° degrees spacing in latitude and 2.5° spacing in longitude, and with a spectral resolution of 23 frequency bins ($df/f = 0.01$) and 24 directional bins (15°).

The comparisons between the ODGP2 hindcasts and the ERA-40 reanalysis data show that the significant wave height of ODGP2 data is lower in the Tropics (area where the ERA-40 data overestimates the observations) and higher in the storm tracks (areas where ERA-40 underestimates the observations). However, the comparisons with the Geosat data indicate some overestimation of the ODGP2 in the storm tracks, mainly in the South Hemisphere (a bias of about 0.6 m), although such overestimation is not observed in the comparisons with the buoy data. The ODGP2 hindcasts in general compare better with the observations, without so much underestimation of the high peaks.

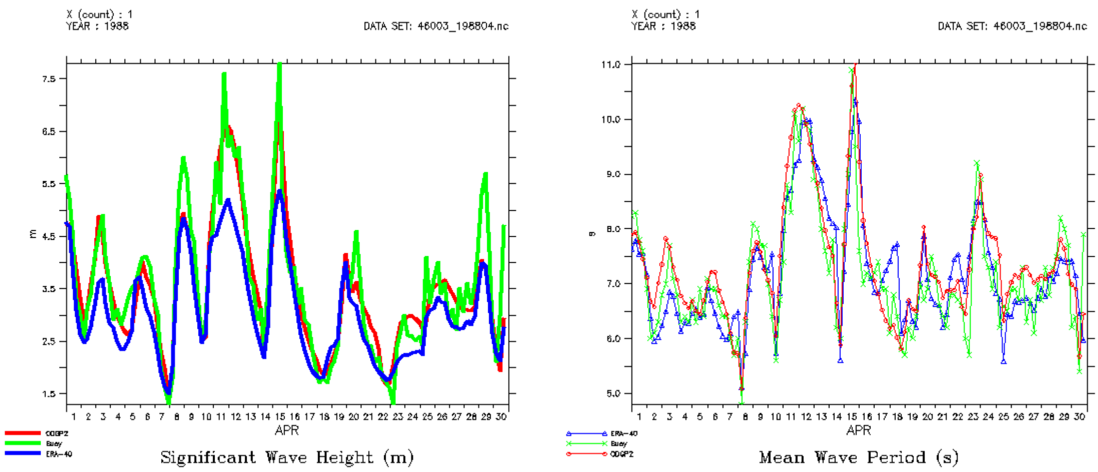

Figure 8: Timeseries comparisons of ERA-40 reanalysis (blue), ODGP2 hindcasts (red) and buoy 46003 measurements (green) of H_s and T_m for April 1988.

In terms of mean wave period the comparisons with the buoy measurements show that the mean wave periods are in most of the buoy locations underestimated, except in the Alaska locations, where there is a slight overestimation.

Figure 8 shows timeseries comparisons between the ERA-40 reanalysis, ODGP2 hindcasts and buoy 46003 measurements of H_s and T_m for April 1988. The comparisons show that the ODGP2 model depicts better the high H_s peaks, and that both models behave reasonably in terms of T_m. This is further confirmed by the 1 to 99% quantiles at this buoy location presented in Figure 9.

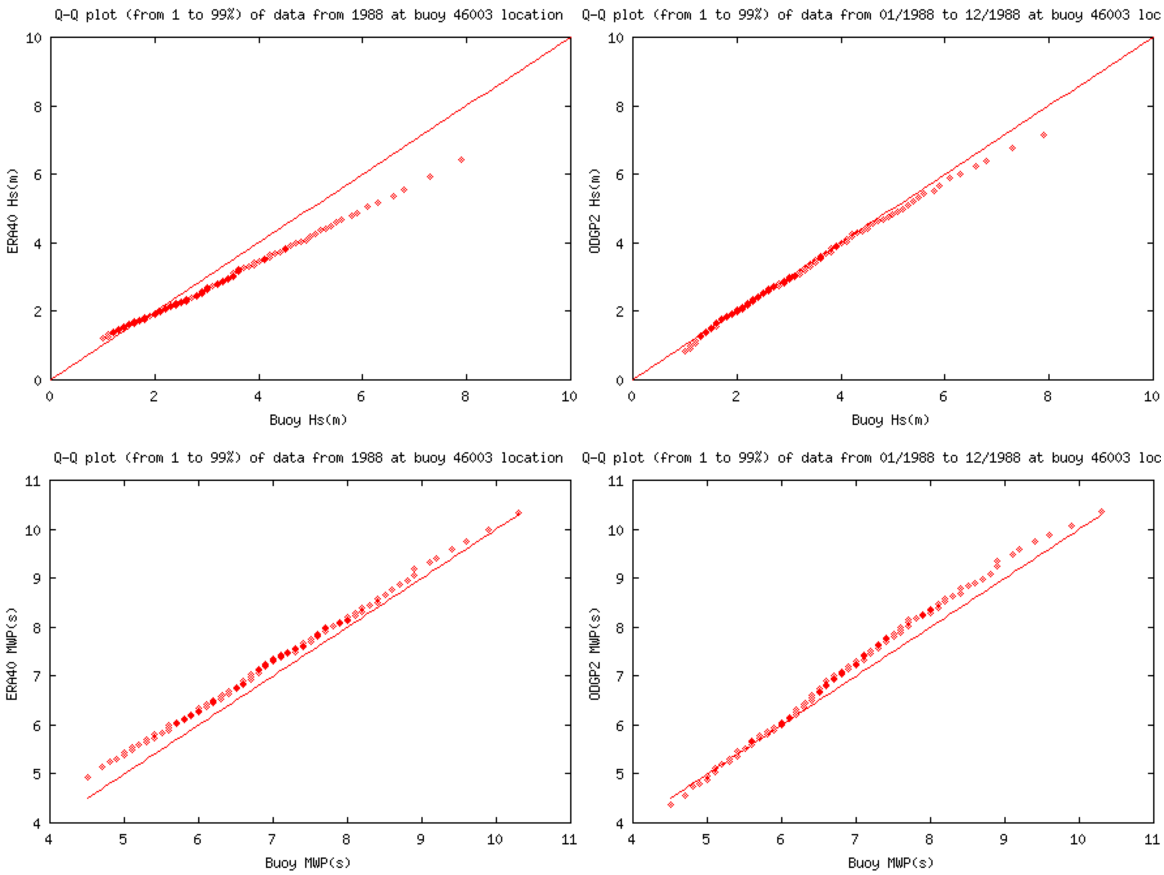

Figure 9: Q-Q of ERA-40 reanalysis and ODGP2 hindcasts of H_s (top panels) and T_m (bottom panels).

Since both WAM in the ERA-40 system and the ODGP2 model are forced with mainly the same wind speeds, these results seem to indicate that the underestimation of some of the ERA-40 high wave height peaks is due to the wave model.

We have looked into the reasons why the ODGP2 model depicts better the high wave peaks. One of the reasons found so far is that the wind forcing in ODGP2 is higher than in the ERA-40 system. Figure 10 shows contour plots of the ERA-40 reanalysis and ODGP hindcasts of U_{10} versus wind sea wave height (the part of the wave spectrum created directly by the wind forcing) for January 1988. The figure is representative of happens in the other months and shows that equally high wind speeds produce higher wind sea in ODPG2 as compared to the ERA-40 system.

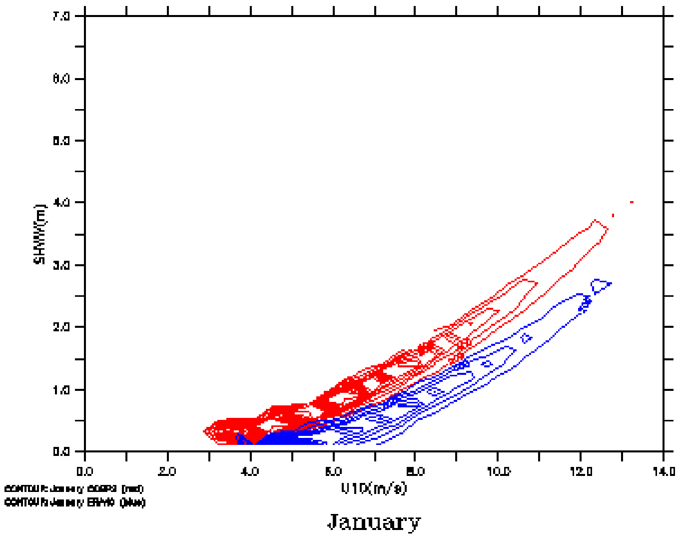

Figure 10: Contour plots of ERA-40 reanalysis (blue) and ODGP hindcasts (red) of U_{10} versus wind sea wave height for January 1988.

4 Comments on the quality and usefulness of the reanalysis data

The above results show that in terms of monthly averages the ERA-40 data compares well with the observations. This is a clear indication that the ERA-40 H_s and U_{10} data may be used reliably in studies of wave and wind climatology.

In general, both in terms of monthly means and of data at synoptic times, the H_s data and observations compare well for values between 2 and 4 metres. There are, however, some discrepancies between them, mainly at synoptic times, the ERA-40 hindcasts underestimating high waves and overestimating the very low events. On average there is an underestimation of about 0.5 metres. There are some differences between basins, but these are closely related to the typical wave conditions in each basin.

The overestimation of some of the low wave events seems to be a consequence of errors in the wave model; further investigation is still needed to determine its exact causes.

There are a number of reasons that can be given for the underestimation of extreme wave events: the coarse resolution of the atmospheric model (poor wind fields), the fact that the model has a fixed value of air density in all basins, and the gustiness of the wind not being modelled. Of these, the resolution of the model produces the biggest impact. Such a coarse resolution atmospheric model implies that the wind fields are not represented with enough detail for the wind epicentres to be well (if at all) defined. This can lead to errors as high as 100% in the H_s for extreme events such as hurricanes. The other two causes of underestimation are less important, the incorporation of fluctuations in the air/sea density ratio having at most an effect of 10%, the same obtained by accounting for the gustiness of the wind in the wave model.

Although it would be good to run the atmospheric model with higher resolution, this is not affordable for this 40-year reanalysis. And, although this would improve the wave product, it still looks like some underestimation of extreme wave events would remain. What our comparisons show is that even for well modelled high wind speeds (speeds that compare well with the observations; see Figure 8), the corresponding wave height hindcasts underestimate the observations, a behaviour that is not seen in the ODGP2 model. Our comparisons show clear indications that the ERA-40 system underestimates the observed relationship between the high significant wave height and wind speeds, and this implies that there are some physics occurring at high wind speeds that are either not being taken into account or not well accounted for by the model in this set-up.

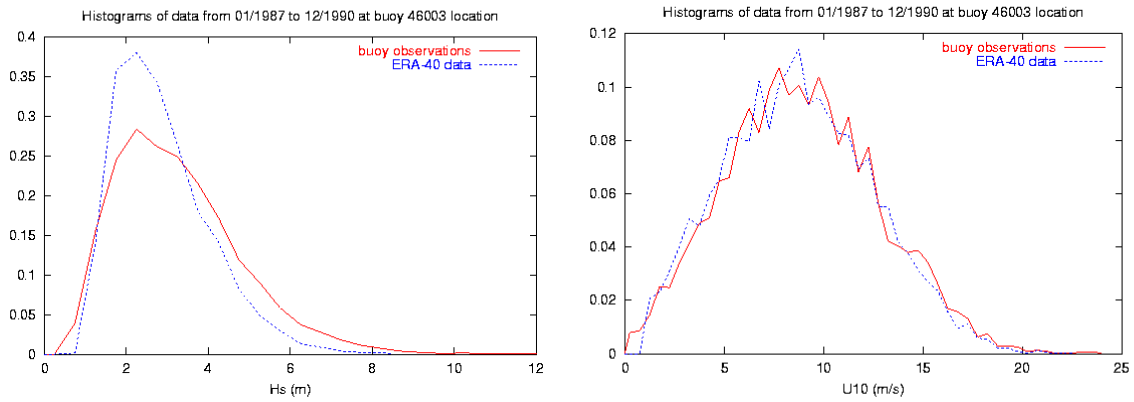

Figure 11 - Histograms of observations from buoy 46003 (red) and of the corresponding ERA-40 reanalysis (blue) from 1987 to 1990. Left Panel: H_s *data. Right Panel:* U_{10} *data.*

From what was said above, it seems obvious that the ERA-40 wave product without altimeter assimilation can not be used directly for the study of extreme wave events. We can support this further by looking, for instance, at the histograms of the observations at the location of Buoy 46003 and of the corresponding reanalysis data from 1987 to 1990, given in Figure 11. An inspection of the figure reveals that the (right) tails of the two H_s histograms are completely different. The histogram of the observations has a relatively long or heavy tail (decreasing roughly exponentially), while that of the model data has a lighter or shorter one (ending more abruptly). If we were to produce these histograms for data from longer periods and other locations, this discrepancy would be even more noticeable. Since the good definition of the tail is of utmost importance in the estimation of extreme wave events, no meaningful results can be obtained if the tail underlying the produced data differs from the tail underlying the observations.

These comparisons, however, do not exclude the use of the wind speed ERA-40 data to compute extreme statistics. Figure 11 reveals a good correspondence between the histograms of the observations at the location of Buoy 46003 and of the corresponding reanalysis wind data.

For the study of patterns of inter-annual and decadal variability it is not so important that particular short-term events are so well defined. In principle it suffices that on average the quality of the data is good. Our results show that the monthly averages of the ERA-40 H_s hindcasts compare well with the observations and seem to account for the main features. One should, however, be aware of the spatially inhomogeneous behaviour of the model – the overestimation at the eastern coast of South America as opposed to the underestimation at high latitude – since this may disguise some patterns, and of the impact that the assimilation satellite altimeter observations may have in the monthly means – all the indications are that it will produce a big inhomogeneity in the data set.

5 Conclusions

The production of roughly 7 years of ERA-40 data has been finalized. We have presented here an extensive assessment of its wave and wind product, based on comparisons with buoy and satellite observations as well as with data from the previous ECMWF reanalysis (ERA-15). The wave fields were further assessed by comparing them with the results of a second generation wave model forced with the archived ERA-40 winds.

Although this is a short period (compared to the 40 years that will be reanalysed), this is probably the period for which the reanalyses can be better assessed (it corresponds to a limited period of time where both independent buoy and satellite observations are available), and therefore the results of the present comparison give a good assessment of the reanalysed wave and wind fields. We may synthesize the results of this study in the following points:

- The produced ERA-40 data represents well the mean wave and wind characteristics.
- The ERA-40 significant wave height data before 1994 in some cases overestimate low wave events and generally underestimate the peaks of high wave events. The wind fields compare well with the observations.
- The ERA-40 wind speed and wave heights compare better with the observations than the corresponding ERA-15 data. There are local improvements in the wind fields due to the correction of the small islands effect and the use of a better ice limit data set. In the H_s data, apart from these local improvements we can also identify global improvements probably due to the coupling of the wave model with the atmospheric model.
- The underestimation of high wave heights by ERA-40 is not always a direct result of the underestimation of the corresponding wind speeds. Equally high wind speeds result in modelled waves that are lower than the corresponding observations and also lower than the hindcasts of another model forced with the same winds. Thus, there seem to be wave model inadequacies in the estimation of waves with high wind speed forcing.
- The ERA-40 data, preceding the assimilation of altimeter measurements, does not seem suitable for direct studies of extreme wave height events, due to their misrepresentation of the peaks of high significant wave height.
- The assimilation of ERS-1 significant wave height altimeter measurements is expected to have a very positive impact in the wave data. The resulting inhomogeneity, however, creates obstacles to the use of the whole data set, as it is produced, for studies of wave climate variability.

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