CLIMATOLOGICAL ASSESSMENT OF REANALYSIS OCEAN DATA

S. Caires, A. Sterl

Royal Netherlands Meteorological Institute, P.O. Box 201, NL-3730 AE De Bilt, Netherlands.

email: caires@knmi.nl

J.-R. Bidlot

European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

N. Graham

Scripps Institution of Oceanography, University of California, San Diego, USA.

V. Swail

Environment Canada, Toronto, Ontario, Canada

1 INTRODUCTION

The study of wave climatology and climate variability requires good quality data with a reasonable time and space resolution and extent. One way of obtaining such data would be to collect *analysed* wave data produced by one or more meteorological institutes over the years. By analysed data we mean, as usual, model output for a given date corrected by the observations available at that date. The quality of the data thereby obtained would, however, be quite inhomogeneous over time. The inhomogenity would be due to two major sources:

§ analysis technique—over the years, wave prediction techniques have evolved from hand made wave maps using empirical charts to the present third generation wave models using modern assimilation techniques, every time with finer grid resolutions;

§ quality, coverage and resolution of the observed data used—for example, the presently available altimeter measurements provide a lot of data in the southern hemisphere, where in the past there were hardly any observations.

Although nothing can be done to improve the past quality and coverage of observations, the past wave analysis can be redone by running the same numerical model throughout the period in question. This is the goal of ***reanalysis*** studies: to produce a dataset with no inhomogeneities as far as the technique of analysis is concerned, by using the same numerical model throughout.

Sterl et al. (1998) produced the first wave reanalysis fields by forcing the WAM model on a 1.5 by 1.5 degree latitude/longitude grid covering the whole globe with the ERA-15 (Gibson et al., 1997) reanalysis winds from 1979 to 1994. In their study they analysed the wave height climatology in terms of annual cycles and trends. The success of the ERA-15 reanalysis products led the European Centre for Medium-Range Weather Forecasts (ECMWF) to conduct a reanalysis for the longer period of 1957 to 2002, named ERA-40. This is a reanalysis of global meteorological wind, temperature and humidity fields, stratospheric ozone, deep water ocean waves and soil. It uses ECMWF's Integrated Forecasting System, a coupled atmosphere-wave model with variational data assimilation, which is a state-of-the-art model very similar to the one used operationally but with lower resolution. The wave model used is WAM (WAMDI, 1988); it is coupled to the atmospheric model through the Charnock parameter (see Janssen et al., 2002). ERS-1 and ERS-2 wave height altimeter measurements are also assimilated into the model for the period in which they are available (1994-2002).

The wave model grid resolution and coverage are the same as those in the ERA-15 study. Although the ERA-40 data available at the time of writing this article does not yet cover the whole ERA-15 period, the authors have compared the available ERA-40 and ERA-15 wind speed and wave data, and concluded that the ERA-40 data compare better with the observations than the corresponding ERA-15 data. The superiority of the ERA-40 data relative to the ERA-15 data can be attributed, among others, to local improvements in the wind fields due to the correction of errors identified in the ERA-15 reanalysis.

In parallel with the European reanalysis efforts, the American National Center for Atmospheric Research and the National Centers for Environmental Prediction (NCEP/NCAR) have also produced a global reanalysis of the surface winds from 1958-1997 which continues to be extended (Kalnay et al,1996). Cox and Swail (2001) used these winds to force the ODGP2 spectral ocean wave model (see Cox and Swail, 2001) on a 1.25 by 2.5 degree latitude/longitude grid to produce the first 40-year wave reanalysis covering the whole globe. These results were studied in terms of seasonal extremes of wave height by Wang and Swail (2001). Graham and Diaz (2002) used the same winds to force the Wavewatch III model (Tolman, 1999) on a 2.5 by 2.5 degree latitude/longitude grid covering the Pacific Ocean. Motivated by some deficiencies in the NCEP/NCAR reanalysis winds, Swail and Cox (2000) carried out an intensive kinematic reanalysis of the NCEP/NCAR surface wind fields in the North Atlantic; the resulting improved winds were used to force the OWI 3-G wave model (see Swail and Cox, 2000) on a 0.625 by 0.833 degree latitude/longitude grid. These results were studied in terms of seasonal extremes of wave height by Wang and Swail (2002).

Given the wealth of wave reanalysis data covering the last 4 decades, produced using different wave models and different quality wind fields, it is interesting to know which dataset is more adequate for which purpose. Without any assessment of the data, one may expect, for example, the dataset of Swail and Cox (2000), due to the high quality of the wind fields, to be the most appropriate for a study of the wind and wave conditions in the North Atlantic on a fine time scale, particularly for extremes, and the ERA-40 dataset to be the most adequate for a global study of the wave conditions in the late 1990's, as it is the only one benefiting from the assimilation of altimeter observations. However, it is not clear whether the datasets differ in terms of climatology, for instance in terms of monthly means, or in terms of large time scale features in the data, such as trends.

The goal of this article is to compare the different datasets of significant wave height (H_S) and wind speed (U_{10}) in terms of their quality and in their description of the wave and wind conditions at different time scales. In section 2 the different reanalyses of wind and wave 6 hourly fields for 1988 and 1997 are validated against buoy data in both years and Topex altimeter data for 1997. The buoy wind speed measurements do not provide an independent assessment of the wind data since they are available in the COADS dataset, which was assimilated into all the wind reanalysis. The buoy significant wave height measurements and the Topex altimeter measurements were not used in the production of the reanalysis data and provide an independent assessment of the quantities. In section 3 we compare the fields of monthly means of the different datasets. In Section 4 we compare the trends from 1990 to 1997 in the different datasets. We finish in section 5 with final comments and conclusions.

2 DATA VALIDATION

2.1 Description of the observations

In order to compare the reanalysis results with buoy and altimeter observations, time and space scales must be brought as close to each other as possible. The reanalysis results are available at synoptic times (every 6 hours) and each value is an estimate of the average condition in a grid cell; on the other hand, both the buoy and the altimeter measurements are local. Since the ERA-40 resolution is in-between the resolution of the other reanalysis products we will use the resolution of the ERA-40 data as a reference (the implications of which are discussed in section 5). In order to make the time and space scales of the data compatible, the reanalysis data will be compared with 4-hour averages of buoy observations (which is the approximate time a 10 s wave would take to cross the diagonal of a 1.5 by 1.5 degree grid cell) and with the average of the altimeter measurements within a 1.5 by 1.5 degree cell. The origin of the buoy and altimeter data and the treatment we have applied to its measurements are described below.

The buoy data to be used in this study come from the NOAA database (http://seaboard.ndbc.noaa.gov/). From all the NOAA data buoy locations available during this period, we have selected a total of 19 locations for these comparisons: 1 off the coast of Peru (buoy 32302), 4 around the Hawaiian Islands (buoys 51001, 51002, 51003 and 51004), 3 in the Gulf of Mexico (buoys 42001, 42002 and 42003), 4 in the Northwest Atlantic (buoys 41001, 41002, 41010 and 44004), 3 off the coast of Alaska (46001, 46003 and 46004), 3 in the Northeast Pacific (46002, 46005 and 46006) and 1 off the coast of California (buoy 46059). 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 models, and the buoy should not be too close to the coast in order for the corresponding grid point to be located at sea. The locations of the buoys are shown in Figure 1.The buoy H_s and wind speed measurements are available hourly from 20-minute and 10-minute long records, respectively. These measurements have gone through some quality control; we do, however, still process the timeseries further. All the observations outside the range $0.15\,m < H_s < 25\,m$ are discarded. Observations that deviate more than 6 times the standard deviation of the monthly data from its mean, or more than 2 times the standard deviation of the monthly data from the previous observation, are identified as outliers and removed from the data. This procedure is executed 3 times. Sometimes buoys report every 2 or 3 hours rather than hourly. When such gaps occur they are filled in by linear interpolation. The hourly timeseries resulting from the application of the 3 above procedures are used to produce a new timeseries at synoptic times by averaging the data over 4 hours around synoptic times. The synoptic timeseries still goes through another quality control: the removal of measurements during the 24 hours immediately preceding a gap of 18 hours or more. Experience has shown that before these gaps occur there is usually a sudden and unrealistic increase in wave height. When the anemometers of the buoys are not at a height of 10 metres, the wind speed measurements are adjusted to that height using a logarithmic profile under neutral stability. The reanalysis data at the synoptic time around which the buoy measurements were averaged is interpolated bilinearly to the buoy location.

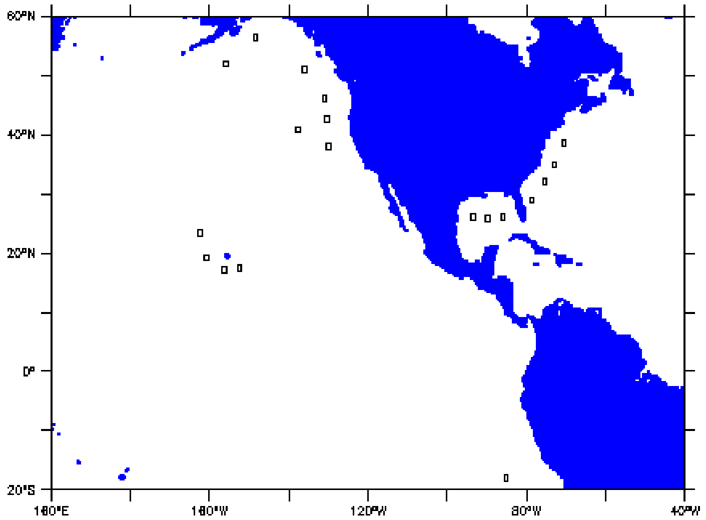

Figure 1 – Location of the NOAA buoys used in the data assessment.

The Topex along track quality checked deep water altimeter measurements of H_s and the normalized radar cross section (s_0) were obtained from the Southampton Oceanography Centre (SOC) GAPS interface at http://www.soc.soton.ac.uk/ALTIMETER/ (Snaith, 2000). Although altimeters do not measure wind speeds directly, the altimeter backscatter depends and correlates highly with the sea surface wind speed. There are several empirical algorithms available to compute the wind speeds up to 20 m/s from s_0. The most widely used algorithm is the one due to Witter and Chelton (1991), which is the operational altimeter wind speed algorithm for the Topex/Poseidon satellite altimeters and is the one used here. Caires and Sterl (2002) have compared the data produced using this algorithm and using a more recent algorithm of Gourrion et al. (2001) and the results were inconclusive as to if one of the algorithms should be preferred. For wind speed above 20 m/s the relation of Young (1993) is used. The satellite measurements are performed about every second with a spacing of about 5.8 km. From these we form altimeter ”observations” by grouping together the consecutive observations crossing a 1.5 by 1.5 degrees latitude-longitude region (observations at most 30 seconds or $1.5\sqrt{2}$ degrees apart). The altimeter observation is taken as the mean of these grouped data points after a quality control similar to the one applied to the buoy data. The reanalysis data at the synoptic times before and after the time of the altimeter observation are interpolated bilinearly to the mean observation location and these 2 data points are then linearly interpolated in time to the mean time of the observation.

We have assessed the different reanalysis data against the observations by looking at different plots such as scatter plots comparing the different reanalysis products with the buoy and altimeter observations, timeseries plots in the case of the buoy comparisons, histograms and quantile plots. Most of these plots are not shown here, but all are available at the ERA-40 ocean wave product validation and analysis webpage (http://www.knmi.nl/onderzk/oceano/waves/era40/index.html). The differences between the reanalysis products and the observations were also quantified by computing some standard statistics such as the bias ($\bar{y} - \bar{x}$), the root-mean-square error ($RMSE = \sqrt{n^{-1}\Sigma(y_i - x_i)^2}$), the scatter-index ($SI = \sqrt{n^{-1}\Sigma[(y_i - \bar{y}) - (x_i - \bar{x})]^2} / \bar{x}$), and the correlation coefficient ($r = \Sigma(x_i - \bar{x})(y_i - \bar{y}) \Big/ \sqrt{\Sigma(x_i - \bar{x})^2 \Sigma(y_i - \bar{y})^2}$). In all these formulae the x_i's represent the observations, the y_i's represent the reanalysis products, and n the number of observations. An overview of these results is presented in Tables 1 to 4 and will be commented separately in terms of wind speed and significant wave height in the following two subsections.

2.2 Wind speed

Based on the data assessment, the ERA-40 wind speeds compare better with the observations than the NCER/NCAR wind speeds. The kinematically improved wind speeds of Swail and Cox (2000) are clearly of superior quality.

		1988						**1997**					
Region	Reanalysis	n	$\bar{x}$	Bias	RMSE	SI	ρ	n	$\bar{x}$	Bias	RMSE	SI	ρ
Peru Coast	ERA-40	1460	6.84	0.28	1.23	0.18	0.81						
	NCEP/NCAR	1460	6.84	0.28	1.43	0.20	0.76						
Hawaiian Islands	ERA-40	3396	7.07	-0.36	1.41	0.19	0.81	5456	7.31	-0.33	1.37	0.18	0.85
	NCEP/NCAR	3396	7.07	-0.75	1.74	0.22	0.74	5456	7.31	-0.63	1.66	0.21	0.79
Gulf of Mexico	ERA-40	3032	5.82	-0.17	1.56	0.27	0.86	3664	6.03	-0.62	1.71	0.26	0.85
	NCEP/NCAR	3032	5.82	0.59	1.86	0.30	0.81	3664	6.03	-0.07	1.82	0.30	0.80
Northwest Atlantic	ERA-40	3219	7.30	-0.26	1.92	0.26	0.82	4463	6.91	-0.23	1.89	0.27	0.84
	NCEP/NCAR	3219	7.30	0.42	2.14	0.29	0.79	4463	6.91	0.05	2.10	0.30	0.80
	Swail&Cox	3046	7.39	0.27	1.17	0.15	0.94	3157	7.16	0.30	1.19	0.16	0.95
Alaska	ERA-40	4051	8.18	0.22	1.92	0.23	0.87	3787	7.56	0.05	1.86	0.25	0.86
	NCEP/NCAR	4051	8.18	0.63	2.26	0.26	0.84	3787	7.56	0.40	2.16	0.28	0.83
Northeast Pacific	ERA-40	1942	7.42	0.03	1.65	0.22	0.88	1557	7.78	-0.01	1.68	0.22	0.88
	NCEP/NCAR	1942	7.42	0.40	1.87	0.25	0.86	1557	7.78	0.27	1.99	0.25	0.83
California	ERA-40							1408	7.19	-0.24	1.49	0.20	0.88
	NCEP/NCAR							1408	7.19	0.04	1.60	0.22	0.86

Table 1 – Wind speed (m/s) statistics of different reanalysis products versus buoy measurements at different ocean basins and Topex measurements.

The analysis of the buoy assessments according to the basin is as follows. On the Peru Coast there are only buoy measurements from one location available in 1988, and none in 1997. Throughout 1988 the NCEP/NCAR winds overestimated the buoy measurements at this location. As can be observed in Table 1, the comparative statistics of both reanalyses are very similar. The ERA-40 winds underestimate the observations in March and April, and overestimate them throughout the rest of the year. At the buoy locations around the Hawaiian Islands both ERA-40 and NCEP/NCAR underestimate the measurements all year through, both in 1988 and 1997. In the Gulf of Mexico the wind conditions are underestimated by ERA-40 and overestimated all through 1988 by NCEP/NCAR; for 1997 the behaviour differs with some months being overestimated and others underestimated. The buoy observations located off the East Coast of the United States can also be used to assess the Swail and Cox (2000) wind fields. As the results presented in Table 1 testify, their wind speed fields compare much better with the observations than the ERA-40 and the NCEP/NCAR wind speeds; scatter-index values of about 15%

compared with above 25% for the other products. Here, as in the rest of the locations, the ERA-40 wind speeds compare slightly better with the observations than the NCEP/NCAR winds. In the buoy locations off the Alaska Coast both ERA-40 and NCEP/NCAR wind speed overestimate the observations except in July and August, when both underestimate them. In the Northeast Pacific locations the total year bias of the ERA-40 data is very close to zero; in terms of monthly bias the data is underestimated from June to September and overestimated in the rest of the year. The NCEP/NCAR data overestimates the observations in most of the months. On the coast of California there are only observations available in 1997, where the ERA-40 data has a higher bias but less dispersion than the NCEP/NCAR wind speeds.

Region	Reanalysis	n	$\bar{x}$	Bias	RMSE	SI	ρ
20ºN-80ºN	ERA-40	4769	8.12	-0.72	1.64	0.18	0.92
	NCEP/NCAR	4707	8.12	-0.40	1.73	0.21	0.89
	Swail&Cox	1810	8.07	-0.37	1.50	0.18	0.92
20ºS-20ºN	ERA-40	7326	6.60	-0.39	1.35	0.20	0.86
	NCEP/NCAR	7142	6.62	-0.45	1.77	0.26	0.76
	Swail&Cox	767	6.42	-0.29	1.51	0.23	0.80
80ºS-20ºS	ERA-40	11468	9.66	-0.89	1.79	0.16	0.91
	NCEP/NCAR	11427	9.69	-0.86	2.33	0.22	0.82

Table 2 – Wind speed (m/s) 1997 statistics of different reanalysis products versus Topex measurements at different ocean latitude bands.

A global view of the wind quality can be obtained by comparing the reanalysis data with the Topex altimeter observations. We have considered three latitude bands in our comparisons: north of 20ºN, south of 20ºS and the region between 20ºS and 20ºN. The statistics of the different reanalysis comparisons with the Topex measurements are presented in Table 2. Note that the dataset of Swail and Cox (2000) does not cover the whole longitude range of the other 2 products, and therefore the comparisons are for a much smaller dataset; the statistics are representative of the quality of the dataset but should not be compared with the statistics of the other two reanalysis products. The ERA-40 winds compare better with the observations than the NCEP/NCAR data, especially in the southern region where the RMSE of NCEP/NCAR data is 0.5 m/s higher the one of the ERA-40 data. Both reanalyses compare better with observations in the northern region than in the southern, but in the case of ERA-40 only marginally. The Swail and Cox (2000) dataset compares better with the observations in the northern region than in the Tropics.

It should be noted that there is more than one 10 metre wind speed parameter available from the ERA-40 reanalysis, namely the *10 m atmospheric wind speed* and the *10 m wave model wind speed*—the one used in this study. The differences between these two U_{10} products have to do with way the coupling of the wave model with the atmosphere is done and with the 3D-var assimilation scheme used in ERA-40. Roughly speaking, the wave model is forced by hourly winds from the latest 6-h forecast instead of by the analysed winds (see Janssen et al., 2002).

2.3 Wave height

In terms of significant wave height we are able not only to assess the 4 different reanalysis products but also the effect of forcing different wave models using the same wind field. The NCEP/NCAR winds fields were used to produce the Cox and Swail (2001) data as well as the Graham and Diaz (2002) data. In an independent study the ERA-40 wind fields for 1988 were also used to force the ODGP2 spectral ocean wave model, used to produce also the Cox and Swail (2001) data, on a 1.25 by 2.5 degree latitude/longitude grid covering the whole globe. We shall refer to this dataset as ERA40/ODGP2.

In general terms the dataset of Swail and Cox (2000) is the one that compares better with observations in the North Atlantic. The two wave datasets produced with the NCEP/NCAR winds in the Pacific seem to be of similar quality, but the timeseries compare quite differently: there are periods of overestimation, for instance, in the data of Cox and Swail (2001) corresponding to periods of underestimation in the Graham and Diaz (2002) dataset. The ERA-40 data quality is much better for 1997 than for 1988, which seems to be a direct result of the assimilation of the ERS-2 significant wave height altimeter measurements in 1997. The quality of the Cox and

Swail (2001) data is similar to the ERA-40 data for 1988, and remains essentially the same for 1997, whereas the ERA-40 quality is close to that of the Swail and Cox (2000) dataset for 1997. The data produced by forcing the ODGP2 spectral wave model with the ERA-40 wind compares generally better with the buoy observations than the ERA-40 data. A close look at the timeseries shows that the ERA40/ODGP2 data captures high significant wave height peaks better than does the ERA-40 data.

		1988						**1997**					
Region	Reanalysis	n	$\bar{x}$	Bias	RMSE	SI	ρ	n	$\bar{x}$	Bias	RMSE	SI	ρ
Peru Coast	ERA-40	1461	2.21	-0.02	0.35	0.16	0.82						
	ERA-40/ODGP2	1461	2.21	-0.30	0.42	0.14	0.86						
	Cox&Swail	1461	2.21	-0.24	0.41	0.15	0.82						
	Graham&Diaz	1337	2.25	-0.14	0.39	0.16	0.83						
Hawaiian Islands	ERA-40	3399	2.20	-0.23	0.44	0.17	0.85	5569	2.37	-0.16	0.36	0.13	0.89
	ERA-40/ODGP2	3399	2.20	-0.31	0.47	0.16	0.86						
	Cox&Swail	3399	2.20	-0.16	0.41	0.17	0.82	5569	2.37	-0.31	0.48	0.16	0.84
	Graham&Diaz	3261	2.18	-0.45	0.62	0.20	0.80	5076	2.34	-0.37	0.58	0.19	0.84
Gulf of Mexico	ERA-40	3452	1.14	-0.29	0.46	0.32	0.93	3672	1.09	-0.10	0.31	0.31	0.92
	ERA-40/ODGP2	3452	1.14	0.15	0.34	0.34	0.93						
	Cox&Swail	3452	1.14	0.33	0.49	0.32	0.90	3672	1.09	0.27	0.42	0.29	0.90
Northwest Atlantic	ERA-40	3604	1.94	-0.44	0.63	0.23	0.91	4785	1.74	-0.15	0.44	0.24	0.93
	ERA-40/ODGP2	3604	1.94	-0.21	0.48	0.22	0.90						
	Cox&Swail	3604	1.94	0.00	0.51	0.26	0.86	4785	1.74	-0.02	0.48	0.27	0.88
	Swail&Cox	3431	1.97	0.01	0.40	0.20	0.91	3479	1.87	0.03	0.41	0.22	0.92
Alaska	ERA-40	4054	3.17	-0.34	0.71	0.20	0.94	3789	2.87	-0.20	0.51	0.16	0.95
	ERA-40/ODGP2	4054	3.17	-0.10	0.59	0.18	0.93						
	Cox&Swail	4054	3.17	0.30	0.73	0.21	0.92	3789	2.87	0.20	0.66	0.22	0.92
	Graham&Diaz	3641	3.11	-0.14	0.81	0.26	0.91	3436	2.80	-0.21	0.76	0.26	0.91
Northeast Pacific	ERA-40	2179	2.83	-0.16	0.63	0.22	0.93	1916	2.90	-0.14	0.47	0.15	0.94
	ERA-40/ODGP2	2179	2.83	-0.08	0.51	0.18	0.93						
	Cox&Swail	2179	2.83	0.14	0.58	0.20	0.93	1916	2.90	0.19	0.61	0.20	0.91
	Graham&Diaz	1931	2.68	-0.01	0.63	0.23	0.93	1699	2.80	-0.02	0.64	0.23	0.92
California	ERA-40							1460	2.59	-0.13	0.43	0.16	0.95
	Cox&Swail							1460	2.59	0.01	0.47	0.18	0.92
	Graham&Diaz							1336	2.54	-0.08	0.53	0.21	0.92

Table 3 – Significant wave height (m) statistics of different reanalysis products versus buoy measurements at different ocean basins.

Region	Reanalysis	n	$\bar{x}$	Bias	RMSE	SI	ρ
20ºN-80ºN	ERA-40	4769	2.66	-0.22	0.45	0.15	0.96
	Cox&Swail	4707	2.66	-0.01	0.59	0.22	0.91
	Swail&Cox	1810	2.54	-0.04	0.40	0.16	0.95
	Graham&Diaz	2517	2.78	-0.23	0.76	0.26	0.89
20ºS-20ºN	ERA-40	7326	2.06	-0.06	0.24	0.11	0.93
	Cox&Swail	7142	2.07	-0.12	0.40	0.18	0.80
	Swail&Cox	767	1.81	0.09	0.29	0.15	0.85
	Graham&Diaz	4041	2.17	-0.26	0.50	0.20	0.82
80ºS-20ºS	ERA-40	11468	3.41	-0.25	0.47	0.12	0.95
	Cox&Swail	11427	3.42	0.00	0.72	0.21	0.86
	Graham&Diaz	6116	3.40	-0.24	0.93	0.26	0.79

Table 4 – Significant wave height (m) 1997 statistics of different reanalysis products versus Topex measurements at different latitude bands.

In the different ocean basins the reanalysis products compare with the buoy observations as follows. As for the wind speed assessment, comparisons in the Peru Coast buoy location are available only for 1988. The ERA-40, the Cox and Swail (2001) and the Graham and Diaz (2002) datasets all cover this location. The datasets show comparable quality. The bias of ERA-40 data is closer to zero than that of the other two products, but this is because the monthly biases oscillate between months of underestimation and overestimation. In the locations around the Hawaiian Islands the quality of the ERA-40 and Cox and Swail (2001) data is quite similar. The Graham and Diaz (2002) dataset compares worse with the observations, maybe because the grid used to run the wave model is too coarse and misses most of the topographic features in that region. The ERA-40 data persistently underestimates the wave conditions in the Atlantic locations for 1988, the dataset of Swail and Cox (2000) comparing better with the observations. For 1997 all 3 datasets compare well with the observations. In the comparisons with the buoy observations off the Alaska Coast and off the coast of the Northeast Pacific the quality of the ERA-40 and the Cox and Swail (2001) datasets is comparable for 1988, but the quality of the ERA-40 data is superior for 1997. In the location off the coast of California, where observations are available for 1997, the ERA-40 dataset compares slightly better with the observations than the other two products available.

For the Topex comparisons, the Swail and Cox (2000) results are the closest to the observations; however, the ERA-40 data shows also low scatter-index and root-mean-square error, but consistently underestimates the data. The Graham and Diaz (2002) data shows the worst correspondence with the measurements.

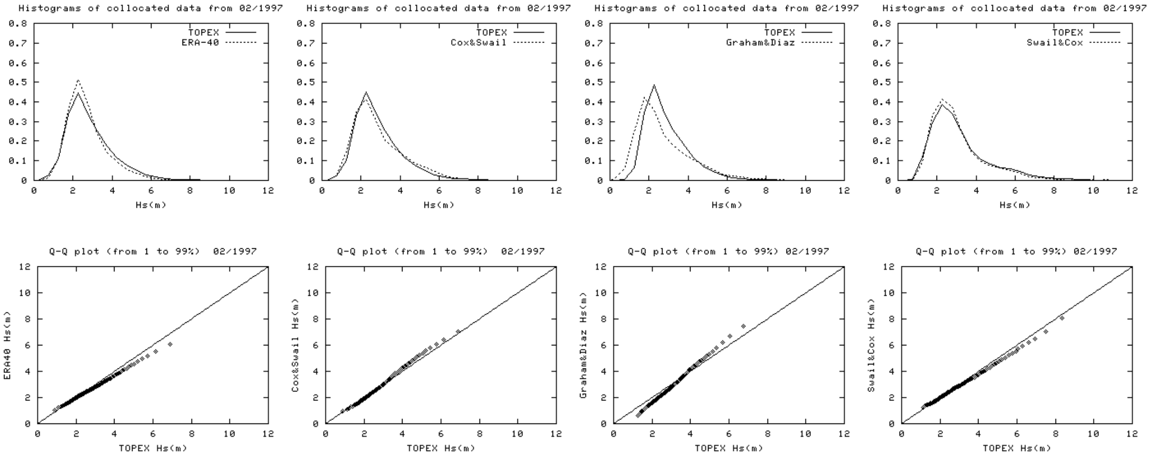

Figure 2 – Graphs comparing histograms of Topex significant wave height observations (full lines) and the histograms of the corresponding reanalysis products (dashed lines), and corresponding quantile plots; data from February 1997. From left to right: ERA-40 data; Cox and Swail (2001) data; Graham and Diaz (2002) data; Swail and Cox (2000) data.

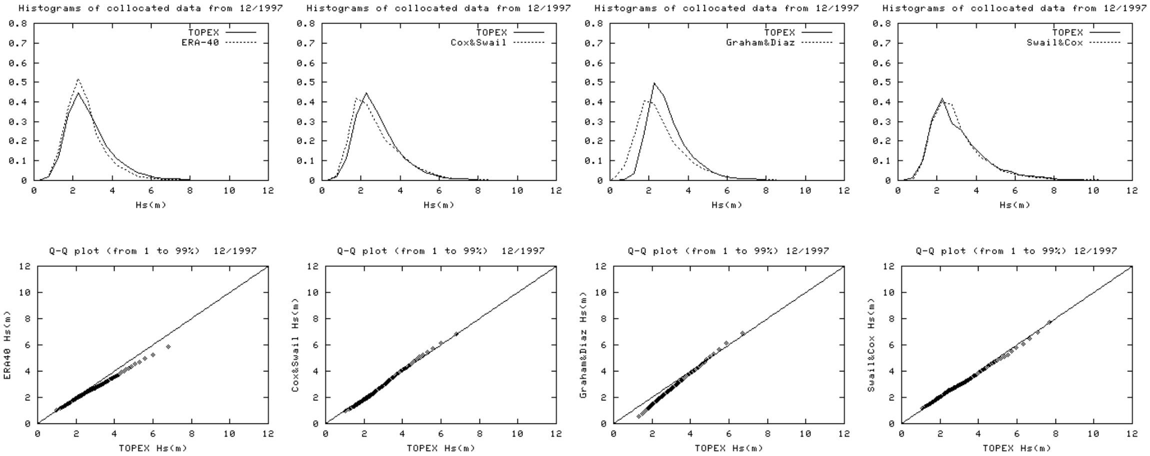

Figure 3 – The same as Figure 2 but for data from December 1997.

The histograms comparing the reanalysis data with the Topex observations help visualising the differences and deficiencies of the datasets. Figure 2 and 3 show the histograms and quantile plots of the Topex significant wave height observations and the corresponding reanalysis data for February and December 1997, respectively. The ERA-40 underestimates most of the high peaks of significant wave height and shows good correspondence with the observations at low sea states. On the other hand, the Cox and Swail data tend to overestimate high sea states. The Swail and Cox (2000) data shows quite a good correspondence with the observations, apart from some underestimation of the severe seas. The data of Graham and Diaz (2002) has negative bias for sea states with significant wave height below 6 m and positive above this value.

It should be noted that the dataset of Graham and Diaz (2002) was tuned in order to give the best results for major winter swell events from 1981 to 1998. This tuning produced a good agreement between the data and high wave observations, but made the agreement worse for smaller waves.

3 COMPARISON OF MONTHLY MEANS

We have produced and analysed surface plots with the relative differences between the significant wave height and wind speed data of different reanalyses. For the years of 1988 and 1997, where we had not only the monthly means available but also the synoptic data, we have applied the Mann-Whitney non-parametric test (see e.g. Mood et al., 1974, pp. 522-4) to find where the differences were significant at a 5% level.

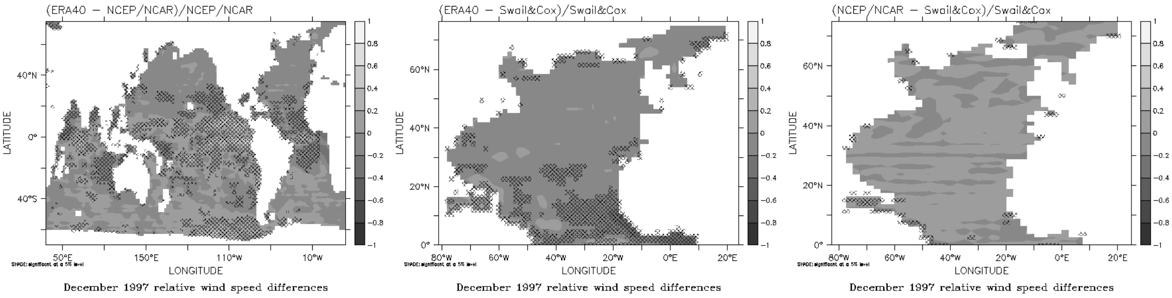

Figure 4 – Surface plots of the relative differences between the December 1997 monthly means of the wind speeds from the different reanalysis, with the regions where the differences are significant at a 5% level shaded. From left to right: ERA-40 versus NCEP/NCAR data; ERA-40 versus Swail and Cox (2000) data; NCEP/NCAR versus Swail and Cox (2000) data.

In the wind speed comparisons the ERA-40 and the NCEP/NCAR data differ mainly in the tropics, in the Southern Hemisphere, and in coastal regions. There are no significant differences in the northern storm tracks. In the comparisons between ERA-40 and Swail and Cox (2000) data the differences are mainly south of 30° N and in the coastal regions. Between NCEP/NCAR and the Swail and Cox (2000) data no pattern can de identified in the differences; they are significant only in the coastal locations, probably because errors in the incorporation of the surface wind data from COADS in the production of the NCEP/NCAR dataset were corrected in the study of Swail and Cox (2000) (regardless of the location of the anemometers, the assimilation scheme treated all observations at a 10-m reference level). Figure 4 presents surface plots of the relative differences between the various wind reanalyses for February 1997: the plots are representative of the extent of the significant differences throughout the studied period.

Figure 5 shows the surface plots of the relative differences between the significant wave height of the different reanalyses for December 1997.

In spite of the fact that the differences between the ERA-40 winds and the NCEP/NCAR winds are only significant south of 20º N, the ERA-40 and Cox and Swail (2001) significant wave height fields are significantly different almost everywhere. Even the Cox and Swail (2001) and the Graham and Diaz (2002) significant wave height fields, which were produced from the same wind fields, are significantly different everywhere. The only fields that show some agreement are those of Cox and Swail (2001) and the Swail and Cox (2000), most of the differences being south of 30º N. These differences are due, at least in part, to the explicit treatment of tropical storms wind fields in Swail and Cox (2000), whereby the tropical storm wind fields are rigorously reanalyzed using National Hurricane Center high quality, high resolution reconnaissance data, and incorporated into the kinematic analysis.

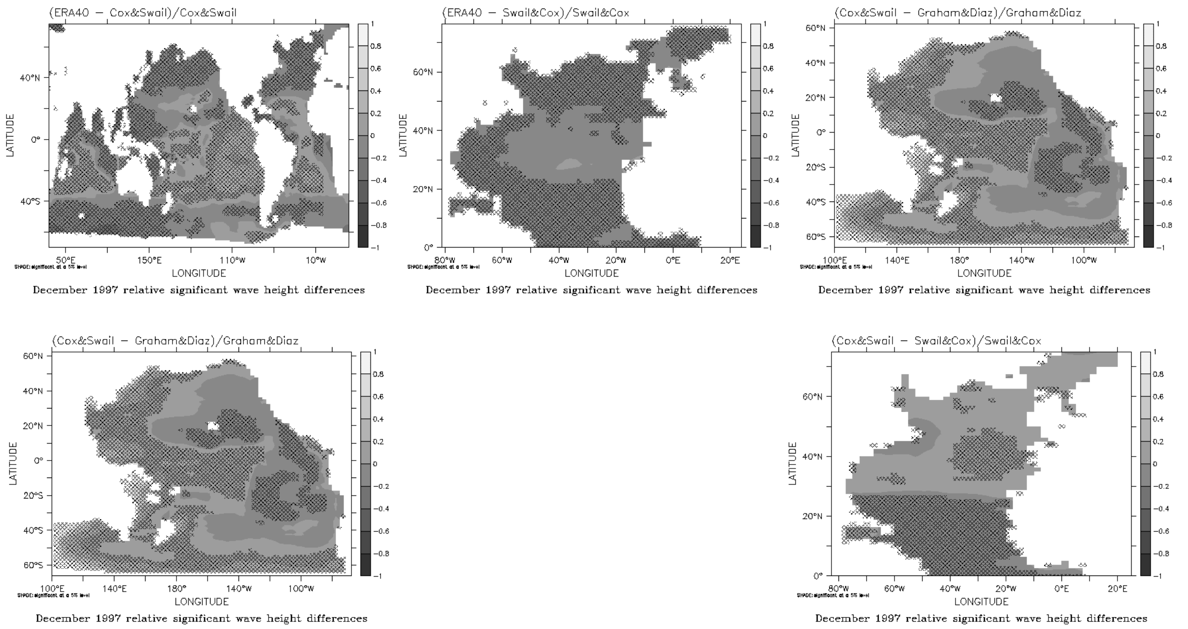

Figure 5 - Surface plots of the relative differences between the December 1997 monthly means of the significant wave height from the different reanalysis, with the regions where the differences are significant at a 5% level shaded. Top left panel: ERA-40 versus Cox and Swail (2001) data; top central panel: ERA-40 versus Swail and Cox (2000) data; top right panel: ERA-40 versus Graham and Diaz (2002) data; bottom left panel: Cox and Swail (2001) versus Graham and Diaz (2002) data; bottom right panel: Cox and Swail (2001) versus Swail and Cox (2000) data.

4 TRENDS

We have used the monthly mean fields of the different products to compute the trends from 1990 to 1997 for the various months. There is no physical meaning in these trends, since it is a small period and therefore only representative of an oscillation within a multi-decadal trend. We do, however, compute the trends with the objective of having a synthesised evaluation of the differences in the datasets at this time scale.

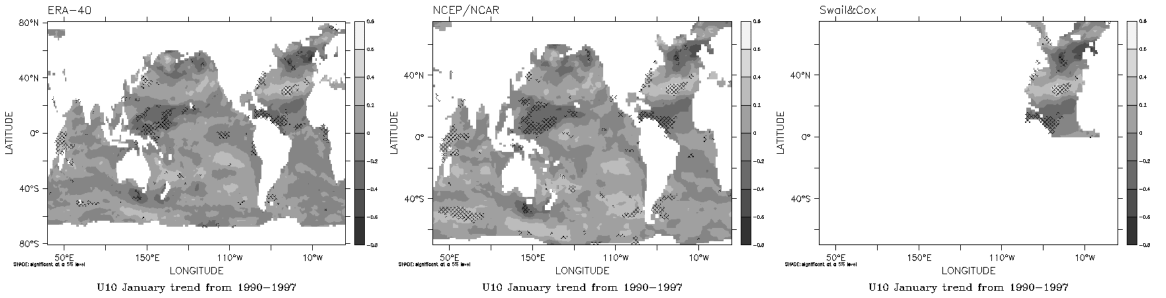

Figure 6 – Surface plots of the trend in the January monthly mean wind speed data of the different reanalyses from 1990 to 1997, with the areas where the trend is significant at a 5% level shaded. From left to right: ERA-40 data; NCEP/NCAR data; Swail and Cox (2000) data.

The trend analysis was done in the same way as described in Wang and Swail (2001). The Mann-Kendall non-parametric test was used to identify the significant trends at a 5% level and the trend estimator is based on Kendall's rank correlation.

Figure 6 presents the trends of the wind fields from the different reanalyses for the month of January. As for the other months, the regions with significant trends in the NCEP/NCAR and Swail and Cox (2000) wind fields are essentially the same. The trend patterns and significant regions in the ERA-40 and NCEP/NCAR wind fields are also similar.

The ERA-40 trends in significant wave height are corrupted because erroneous Fast Delivery Product (FDP) ERS-1 significant wave height measurements were assimilated into ERA-40 from January 1992 until May 1993. This period will be rerun with no data assimilation, but the data was not yet available for this study. The data trends are presented here with this caveat.

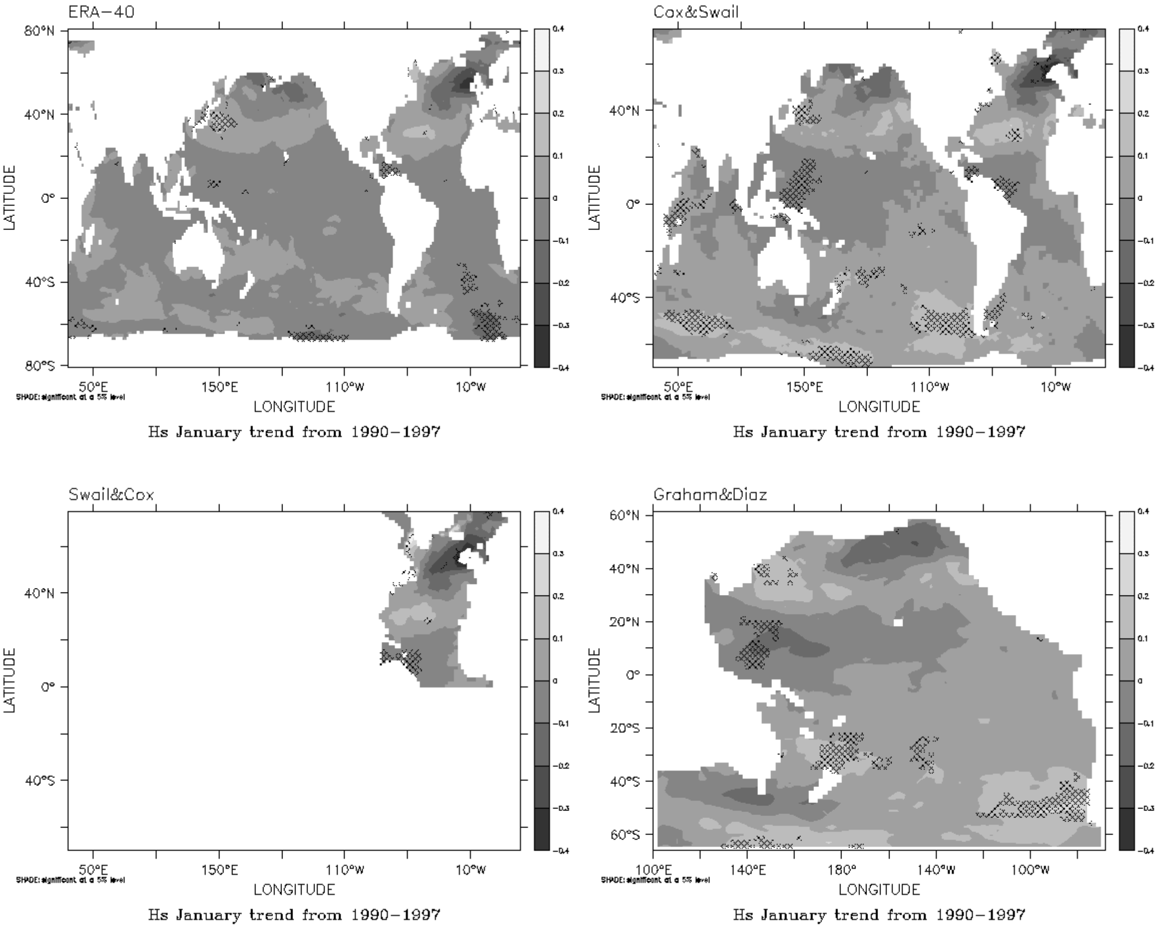

Figure 7 - Surface plots of the trend in the January monthly mean significant wave height data of the different reanalyses from 1990 to 1997, with the areas where the trend is significant at a 5% level shaded. Top left panel: ERA-40 data; top right panel: Cox and Swail (2001) data; bottom left panel: Swail and Cox (2000) data; bottom right panel: Graham and Diaz (2002) data.

For all calendar months, the trends in the Graham and Diaz (2002), Cox and Swail (2001) and Swail and Cox (2000) data have a similar pattern, although the trends of the latter are somewhat more pronounced. The ERA-40 trends have a different pattern from that of the other products, but the areas of significance tend to be the same. Figure 7 presents the trends of the significant wave height fields of the various reanalyses for the month of January.

5 CONCLUSIONS

We have collected, assessed and compared the wind speed and significant wave height data from several reanalyses.

The data were assessed against time averaged altimeter and buoy measurements. In a very crude way, the ERA-40 grid resolution was used as a reference for the averaging of the measurements. Since most problems with the data are at the high peaks, this would explain to a very small extent any possible underestimation of the high peaks by the Graham and Diaz (2002) and Cox and Swail (2001) waves and the NCEP/NCAR winds, and some overestimation by the Swail and Cox (2000) waves and winds.

Our assessment indicates that the Swail and Cox (2000) data, which is restricted to the North Atlantic, is the one which best represents the measurements within that basin. The ERA-40 results also compare well with the observations, and have in general better statistics than the other reanalyses results, especially as regards the significant wave height for 1997, a period where ERS-2 altimeter measurements are assimilated and in which the statistics are comparable with the ones obtained for the Swail and Cox (2000) data. Results of forcing the ODGP2 spectral wave model with the ERA-40 winds show that the use of another wave model forced with the ERA-40 winds can produce waves that compare better with observations. The same conclusion is drawn from the comparisons between the Cox and Swail (2001) and Graham and Diaz (2002) data, where the same wind fields were used to force the wave models and the results are quite distinct, not only at synoptic scales but also in terms of monthly means.

An interesting feature in the wind speed comparisons of the reanalyses results is their large differences in the tropics and the fact that differences are usually larger in the Southern than in the Northern Hemisphere, testifying to the present limitations of modelling those regions. This is a problem that is not only due to the lack of measurements in those regions, but also due to some deficiencies in the physical description of the processes, since the results also differ in the data for 1997 when both reanalysis models benefit from the assimilation of satellite measurements in those regions.

At a synoptic time scale the differences between the various reanalysis winds and waves are large. In terms of monthly mean the differences in wind fields of Swail and Cox (2000) and Cox and Swail (2001) are almost nowhere significant and the ERA-40 monthly means differ from those datasets mainly south of 30° N. The various significant wave height datasets differ both in synoptic and at monthly mean time scales. The longer term behaviour of both winds and waves in the various datasets analysed is however quite similar, an indication that the large time scale features are equally present in all datasets.

6 ACKNOWLEDGEMENTS

We are thankful to Helen Snaith of the Southampton Oceanography Centre for the altimeter data, to the American National Oceanographic Data Center for the available buoy data, and to Camiel Severijns for the Field library and technical support. This work was funded by the EU-funded ERA-40 Project (no. EVK2-CT-1999-00027).

7 REFERENCES

Caires, S. and A. Sterl. Validation of the ERA-40 ocean wave dataset using triple collocation. Submitted to *Journal of Geophysical Research*. Also available as KNMI Preprint 2002-14.

Cox, A. T. and V. R. Swail, 2001: A global wave hindcast over the period 1958-1997: Validation and climate assessment. *J. Geophysical Research*, **106(C2)**, 2313-2329.

Gibson, J. K., and Coauthors, 1997: ERA description. (*Re-Analysis Final Report Series 1*). ECMWF. (71 pp.)

Gourrion, J. and Coauthors, 2002: A two parameter wind speed algorithm for Ku-band altimeters. Submitted to *J. Atm. And Oceanic Tech*.

Graham, N. E. and H. F. Diaz, 2002: Evidence of Intensification of North Pacific Winter Cyclones since 1948. *Bull. American Meteorological Society*, **82**, 1869-1893.

Kalnay, E. and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteorol. Soc*., **77**, 437-471.

Mood, A. M., F. A. Graybill and D. C. Boes, 1974: *Introduction to the theory of statistics*. McGraw-Hill, **3**, 564 pp.

Janssen, P.A.E.M. and Coauthors, 2002: Impact and feedback of ocean waves on the atmosphere. *Advances in Fluid Mechanics*, *Atmosphere-Ocean Interactions*, **I**,WIT press, Ed. W.Perrie. 155-197.

Snaith, H. M., 2000: *Global Altimeter Processing Scheme User Manual: v1*, Southampton Oceanography Centre, Southampton, pp. 44.

Sterl, A., G. J. Komen and P. D. Cotton, 1998: Fifteen years of global wave hindcasts using winds from the European Centre for Medium-Range Weather Forecast reanalysis: Validating the reanalyzed winds and assessing the wave climate. *J. Geophysical Research*, **103**(3), 5477-5494.

Swail, V. R. and A. T. Cox, 2000: On the use of NCEP-NCAR reanalysis surface marine wind fields for a long-term North Atlantic wave hindcast. *J. Atmospheric Oceanic Technology*, **17**, 532-545.

Tolman, H. L., 1999: User manual and system documentation of WAVEWATCH III version 1.18, *Ocean Modeling Branch Contribution 166*, NOAA/NWS/NCEP,112 pp.

WAMDI Group, 1988: The WAM model—A third generation ocean wave prediction model. *J. Phys. Ocean. Research*, **18**, 1775—1810.

Wang, X. L. and V. R. Swail, 2001: Changes of Extreme Wave Heights in Northern Hemisphere Oceans and Related Atmospheric Circulation Regimes. *J. of Climate*, **14**, 2204-2221.

Wang, X. L. and V. R. Swail, 2002: Trends of Atlantic Wave Extremes as Simulated in a 40-Yr Wave Hindcast Using Kinematically Reanalyzed Wind Fields. *J. of Climate*, **15**, 1020-1035.

Witter, D. L. and D. B. Chelton, 1991: A Geosat altimeter wind speed algorithm and a method for wind speed algorithm development, *J. Geophysical Research*, **96** (5), 8853—18860.

Young, I. R., 1993: An estimate of the Geosat Altimeter Wind Speed Algorithm at High Wind Speeds, *J. Geophysical Research*, **98** (11), 20275—20285.