AN INTERCOMPARISON OF VOLUNTARY OBSERVING, SATELLITE DATA, AND MODELLING WAVE CLIMATOLOGIES

P. David Cotton[1]; Peter G. Challenor, Lisa Redbourn-Marsh[2]; Sergei K. Gulev, P. Shirshov[3]; Andreas Sterl[4]; Roman S. Bortkovskii[5]

1. INTRODUCTION

This paper presents early results from an INTAS sponsored programme, the aim of which is to evaluate global scale wave climatologies compiled from visual observations, remotely-sensed data and global wave model output. Three large scale wave climatologies are compared, namely a climatology derived from the most recent release of COADS data (1979-96), a satellite altimeter-derived climatology based on measurements from Geosat, ERS-1 and TOPEX/Poseidon (1985-97), and finally a climatology based on output from the ECMWF Reanalysis project (ERA), whose homogeneous wind fields were used to drive a global scale third generation WAM model (1979-94). The INTAS programme is investigating 'static' differences in the climatologies (e.g. through point-by-point comparisons of co-located grid cells), and 'dynamic differences' by comparing how the three climatologies represent interannual climate variability. Separate climatologies of wind sea (i.e. waves generated by the local wind field) and swell (waves not generated locally) are available in the COADS and ERA analyses, but not from the altimeter data.

2. THE 'INTAS' PROJECT
2.1 DESCRIPTION

This study is supported by the INTAS foundation (project 96/2089), which exists to develop the scientific potential of the Newly Independent States (NIS) of the former Soviet Union by encouraging scientific cooperation between the INTAS partners (the NIS, a number of western European countries, and the European Community).

This programme — The intercomparison of the world ocean wind and wave climatology from in situ, voluntary observing, satellite data and modelling — started in February 1998 and continues until February 2001.

The main goal of the scientific programme is to evaluate three global scale ocean surface wind and wave climatologies through comprehensive intercomparisons and to eventually publish a climatology atlas. To achieve this goal a number of intermediary objectives have been set:

- An update of global scale sea-state parameters for the period 1979-1996 from the historical collection of merchant ships' observations and evaluation of the basic characteristics of the wind and waves.
- Analysis of accuracy and reliability of the 13-year (1985-1997) remotely-sensed global wave and wind data from different research satellites.
- Analysis of accuracy and reliability of the homogeneous surface wave hindcast from the WAM model, driving by the ERA (ECMWF Reanalysis) project winds.
- Cross calibration of voluntary observing fields, satellite wave and wind data and model wave hindcast using high quality instrumental measurements.
- Evaluation of the reliability of long-term changes in winds and waves during the 1980s and 1990s and the study of the relationships between interannual variability of the wave and wind characteristics and atmospheric circulation patterns, such as the North Atlantic Oscillation.

1 Satellite Observing Systems, 15, Church St, Godalming, Surrey, GU7 1EL, UK
2 Southampton Oceanography Centre, Southampton, UK
3 Institute of Oceanology, Moscow, Russia
4 Royal Netherlands Meteorological Institute, De Bilt, The Netherlands
5 Main Geophysical Observatory, St. Petersburg, Russia

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**3.
DATA SETS**

The main characteristics of the three data sets compared in this paper are summarized in Table 1, and discussed in more detail below:

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Table 1

	period	grid size	parameters
COADS	1964–96	5° × 5° (na)	*U*, *hs*, *hw*,
ALT	1985–97	2° × 2° (g)	U, SWH
ERA/WAM	1979–94	1.5° × 1.5° (g)	*U*, wave spectra (12 dirs × 25 freqs)

The three data sets compared in this study are the following: COADS (visual observations), ALT (satellite altimeter data), and ERA/WAM (global wave model output). The COADS gridded data cover the North Atlantic (NA) only, ALT and ERA/WAM are global (g). Parameters in bold and italicised are available as vectors. U - ocean 10 m wind, SWH - significant wave height, hs - swell height, hw - wind sea height.

**3.1
COADS DATA**

The visual data used here were extracted from the Comprehensive Ocean-Atmosphere Data Set (COADS) for the 1964–1996 period. Data from Compressed Marine Reports (CMR-5) were used for the 1964–79 period, and from Long Marine Reports (LMR) for the 1980–96 period (Woodruff *et al.*, 1998). Maps of data density were produced and evaluated, so that ocean regions which provide high and low sampling could be identified. Data from areas of high sampling (North Atlantic, north-west Pacific, tropical Pacific) have been used for the cross-calibration of visual observations against instrumental measurements (Gulev, Proceedings of CLIMAR99).

These data have also been used to assess the algorithms used to combine the separate visual estimates of wind sea and swell into a single significant wave height (SWH) estimate (Gulev *et al.*, 1998). It was established that H30 (generated by taking the square root of the sum of squares of the wind sea and swell significant heights when their directions lay within 30° of each other, or otherwise by taking the higher of sea or swell height) provided the best fit to the instrumental data in regions where the wind sea and swell displayed directional steadiness. So this algorithm was selected for the comparisons presented in this paper.

To generate the gridded data (in this paper we consider only the North Atlantic) individual COADS reports were quality controlled (Gulev and Hasse, 1998) and then selected variables and derived products were extracted and averaged to provide monthly means on a 5° × 5° grid, for each month from 1964-1993.

Features

The major advantage of COADS data is their long term coverage (1964 onwards). Also, the availability of separate estimates of wind sea and swell with directions is a useful feature. To balance this however, the COADS data have the disadvantage of being based upon a subjective estimate and so their reliability may suffer. The COADS data are assessed against in situ data elsewhere in this publication (Gulev, Proceedings of CLIMAR99). There is also a possibility that the sampling of conditions may be self selective (few commercial vessels will choose to endure severe conditions unnecessarily) which could bias statistics. Whilst shipping lanes are well sampled, limited spatial coverage may also cause problems, if global fields are required.

**3.2
SATELLITE ALTIMETER DATA
(ALT)**

The altimeter 2° × 2° monthly mean SWH climatology was generated at Southampton Oceanography Centre (SOC) from three Ku-band altimeters: on GEOSAT (1985-89), TOPEX/POSEIDON (1992-97) and ERS-1 (1991-96). There are some gaps in this altimeter data set, in 1986 and 1990-1991. Cotton and Carter (1994) compared altimeter monthly mean values on a 2° × 2° grid with data from 24 NDBC buoys. The linear regressions thus obtained were then applied to the data from each satellite to produce consistent and corrected SWH values. The 1 Hz altimeter geophysical data records provided by NOAA (Geosat), AVISO (TOPEX/Poseidon) and CERSAT (ERS-1) were quality controlled, calibrated and then averaged onto a 2° × 2° monthly mean grid. The gridding procedure at SOC took the average of the medians of each pass through a grid square in each month

(Cotton and Carter, 1994). For the comparison presented in Figure 1, the data were averaged onto a 5° × 5° monthly mean grid.

Challenor and Cotton (this publication) have provided more recent calibrations which represent an improvement on previous work. Whilst these new calibrations have not been applied to the data set studied in this paper, it is not believed that they would materially effect the conclusions.

Features

The companion paper by Challenor and Cotton contained in this publication, confirms the view of previous work (e.g. Gower, 1996; Cotton *et al.*, 1997), that individual altimeter measurements of significant wave height are highly accurate. Comparisons with co-located in situ buoy data show residual root mean square values of less than 0.5 m (0.3 m for TOPEX and Poseidon). Thus, the altimeter data can be regarded as being at least as accurate as the buoy measurements. However, whilst work is proceeding on the development and testing of a wave period algorithm (Davies *et al.*, 1998), the altimeter is not currently able to provide any directional or spectral information. A further problem is that global altimeter data are only available since 1985. The future is encouraging, though, with the launch of Geosat follow-on in 1998 (it became operational in November 2000) and the planned launches of two further altimeter satellites in 2001 (JASON and ENVISAT).

**3.3
GLOBAL WAM/ERA MODEL
OUTPUT (ERA)**

The model output employed in this study were generated by the third generation WAM at the Royal Netherlands Meteorological Office (KNMI) which was forced by wind fields produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) under its ERA Reanalysis project. The ERA project ran a consistent version of the ECMWF atmospheric model for a 15-year period from
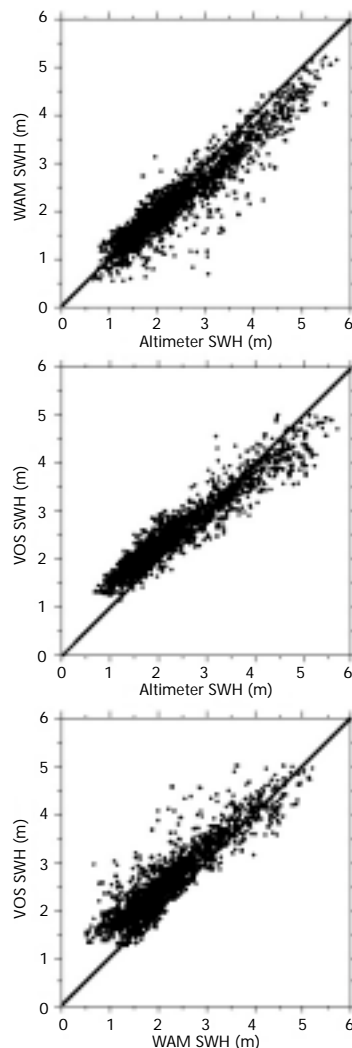

Figure 1—Scatter plots of monthly means on a 5° × 5° North Atlantic grid, from the ALT, ERA/WAM and VOS data sets (see text), (top) WAM vs. ALT, (middle) VOS vs. ALT, (bottom) VOS vs. WAM. Copyright Physics and Chemisty of the Earth (Pergamon).

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January 1979 to February 1994. The WAM model was run as part of an evaluation study for the ERA project (Sterl *et al.*, 1998). For the ERA study, the WAM model was run in both low resolution (LR, 3° × 3° grid) and high resolution (HR, 1.5° × 1.5° grid) versions. We only consider results from the HR version here, because these data showed less scatter and smaller biases than those from the LR version when compared with instrumental data. The HR version covers the globe from 81°S to 81°N and computes wave spectra in 12 directions and at 25 frequencies. Results are output every six hours, giving, among other quantities, heights and periods of sea, swell, and SWH. Again, for the comparison presented in Figure 2, the data were further averaged onto a 5° × 5° monthly mean grid.

Note that ECMWF has recently commenced the ERA40 project, in which it will run a consistent version of its atmospheric model, coupled with the WAM wave model, over a period of 40 years.

4. 'STATIC' COMPARISON OF ALT, WAM AND VOS CLIMATOLOGIES

In this section we present results from two studies. In the first study (Sterl *et al.*, 1998), the ERA/WAM data were assessed through comparisons against the ALT data and in situ measurements. The ERA/WAM data were then studied for evidence of significant change in wave climate over the 15-year ERA period (1979-94). We subsequently refer to this paper as S98. In the second study (Gulev *et al.*, 1998), the VOS, ERA/WAM and ALT data were intercompared, and preliminary studies were carried out into representation of climate variability in the ERA/WAM and VOS data. This paper is subsequently referred to as G98.

4.1 WAM Vs. ALT

S98 compared ERA/WAM gridded wave fields with ALT data and in situ data. The altimeter data were co-located within 30 minutes and 50 km of the buoy measurements. The model parameters were extracted at the buoy location. In the comparison it was established that, even with the high resolution data (HR - 1.5° × 1.5° grid), the ERA/WAM estimates of significant wave height were consistently lower than the ALT data for higher waves, but were higher for low waves. This tendency was seen in comparisons of climatological charts, and in time series of averaged data. Following further comparisons with in situ buoy data, S98 concluded that the WAM output appeared to be in error since the WAM significant wave height displayed the same tendencies when compared to buoy measurements (Figure 2). The consequence of these WAM underestimates of high waves and overestimates of low waves is that, although the averaged model and buoy values compare well, and the WAM estimates display little overall bias, the full extent of true short-term variability in wave height may not be recreated in the model. This in turn may have consequences in how well climate variability is represented in the model output.

S98 considers a number of possible sources for the mismatch between model output and altimeter and buoy data. It concludes the two most likely sources lie within WAM; namely model resolution and model error. A comparison between the results from the low and high resolution versions of WAM showed that increasing the resolution had a beneficial effect in situations of high SWH and highly variable SWH, while at low wave heights the model results actually became worse (i.e. the WAM SWH overestimated to a greater extent). This suggests that the higher resolution model runs improve the representation of variability, but then reveal an underlying tendency in WAM to overestimate the magnitude of the background wave height field. Maps of the relative strengths of swell and significant wave height revealed that the areas of overestimation of SWH coincided with areas of high swell to SWH ratio. This raised the possibility that WAM contains too high swell, and there has been some discussion as to whether the swell propagation within WAM could be improved. S98 concluded, therefore, that the WAM underestimation of high waves was due to limited resolution in the wind fields (meaning that the highest wind peaks are missed), whereas the overestimation of low waves may be due to internal WAM errors, possibly in the swell propagation terms.

4.2 VOS Vs. WAM Vs. ALT

G98 intercompared 5° × 5° climatologies for the North Atlantic produced from the VOS, ALT and ERA/WAM North Atlantic data sets, and demonstrated that all three products have their strengths and weaknesses.

Figure 2—Time series of WAM HR (solid line), WAM LR (dashed line) and Buoy (NDBC buoy 46006 -dotted line) significant wave heights, with co-located, calibrated, Geosat altimeter data (asterisks) for January-March 1987 (a) and July-August 1987 (b). Copyright J. Geophys. Res. (AGU).
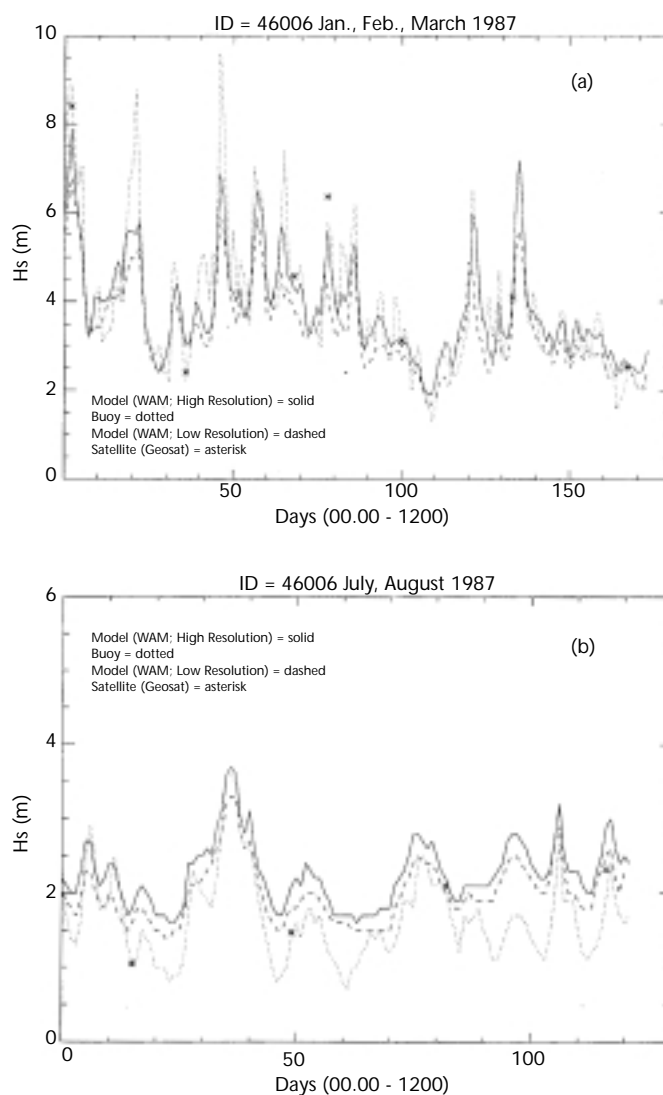

Figure 1 shows scatter plots of the monthly mean SWH on a 5° × 5° grid over the North Atlantic from the ALT, WAM and VOS data. These data cover the 80 months during which the three data sets overlap. Note that the large spatial scale and monthly averaging in this comparison may mask some of the WAM tendencies to underestimate variability. Bearing this in mind, we see that the WAM data agree fairly well with the ALT data, but display a tendency to underestimate higher values (by about 0.5 m for Mean SWH > 2.5 m). The orthogonal regression slope of WAM against ALT SWH is 0.86.

When compared against ALT and WAM monthly means, the VOS data are seen to overestimate low waves, and also to underestimate high waves with respect to ALT. The orthogonal regression slopes of VOS against WAM and ALT were 0.89 and 0.77 respectively. The overall biases in VOS data were 0.32 m and 0.14 m, respectively, against WAM and ALT.

The major climatological spatial patterns and the seasonal cycle in all three products are at first glance comparable, and appear to depict the North Atlantic wave climatology quite realistically. In fact, previous comparisons of different VOS-based atlases have shown even higher biases with respect to each other than the biases which have been found between the three independent climatologies considered in this paper. At the same time, the differences between the VOS wave data, altimeter measurements and the model hindcast are not negligible, and the nature of biases must be carefully studied. Figure 3(a) presents a mean VOS SWH climatology for the 80 months of contemporaneous data. The general pattern of this figure is repeated in the ALT and WAM data sets, with the mid-latitude maxima occurring in the same location, as are the subtropical and equatorial
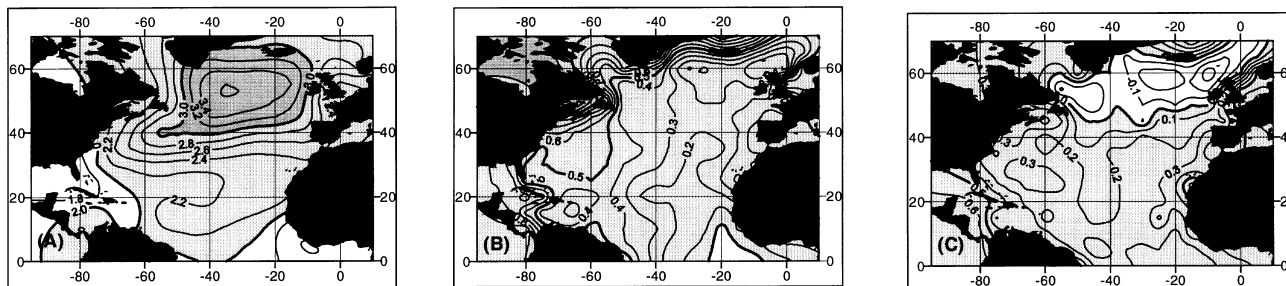
Figure 3—(a) Mean VOS significant wave height climatology (1985-94), and difference plots against WAM (b) and ALT (c). Contours in m. Copyright Physics and Chemisty of the Earth (Pergamon).

minima. Figures 3(b) and 3(c) illustrate the differences between this mean climatology and those from WAM and ALT. Note that the largest differences between the climatologies are seen at high latitudes, which may be a consequence of ice cover being dealt with in different ways by the three data sets. Thus, the reader is advised to focus on areas which remain ice-free throughout the year. From Figures 3(b) and 3(c) we see that VOS SWH is systematically higher than the WAM SWH over the whole North Atlantic, by 0.2-0.6 m. The largest differences between the VOS and WAM fields are found in the western subtropics, in regions close to the North American coast, and at high latitudes (possibly due to ice cover). The best agreement occurs in the north-east Atlantic, where differences are less than 0.2 m.

Differences between VOS and ALT are generally of lower magnitude, and VOS SWH are again higher than ALT SWH, except at mid- to high-latitudes (50°-70°). Note that in this region WAM gives 0.3-0.5 m lower waves than ALT.

Of the three sets of comparisons, the VOS and altimeter SWH show least scatter, whilst the largest scatter is obtained for the VOS-WAM comparison.

4.3 VOS Vs. WAM: WIND SEA AND SWELL

G98 also compared the separate wind sea and swell fields from VOS and WAM. Figure 4 shows the mean VOS climatology, and the VOS minus WAM difference fields. Again the spatial patterns are similar in nature, but some important differences can be identified.

Considering first the wind sea (Figures 4(a) and 4(c)), it is apparent that the VOS climatology is systematically higher than WAM apart from a small region centred on 60°N 30°W. The difference becomes largest at subtropical and equatorial latitudes. This may be a consequence of the use of the lowest COADS code '1', which in theory corresponds to a height of 0.5 m, though in practice is also used to represent all heights below this. Thus, very low wave height values may be over-represented in COADS, perhaps by tens of centimetres. In fact, a study of seasonal values demonstrated that the VOS overestimate was greatest during the summer months in the tropics and subtropics, and was 0.6-0.7 m. In the winter at mid-latitudes, the WAM wind sea was greater than the VOS wind sea.

As regards the swell fields (Figures 4(b) and 4(d), one can see that the VOS swell climatology is higher than the WAM swell over the entire North Atlantic, apart from a small region off West Africa (0°-10°N, 0°-40°W). If the WAM climatology does indeed contain an overestimate of swell, then this would indicate an even greater error in the VOS swell climatology. This overestimation gets progressively higher towards the North West. Clearly, WAM generates much less swell than the VOS data show in the Labrador Sea.

5. 'DYNAMIC' COMPARISON OF ALT, WAM AND VOS CLIMATOLOGIES

5.1 INTRODUCTION

A significant aim of this scientific study was to develop a better understanding of the nature of wave climate variability, by taking advantage of the individual merits of the three separate data sets. However, before this could be achieved it was clearly important to establish the major characteristics and differences in climate variability as represented in the different WAM, ALT and VOS climatologies.

Given the widely different characteristics of the three data sets, the definition of a suitable methodology for comparing the climate variability within them is not a trivial task, and a significant part of the INTAS project is given over to this problem. At a simple level one can compare trends over specified ocean regions, but it is now widely accepted that the true nature of climate variability is complex,

Figure 4—VOS wind sea (a) and swell (b) long-term mean and difference plots against WAM wind sea (c) and swell (d) (contours in m), for the period 1979-93. Copyright Physics and Chemisty of the Earth (Pergamon). Grey shading indicates where VOS > WAM.
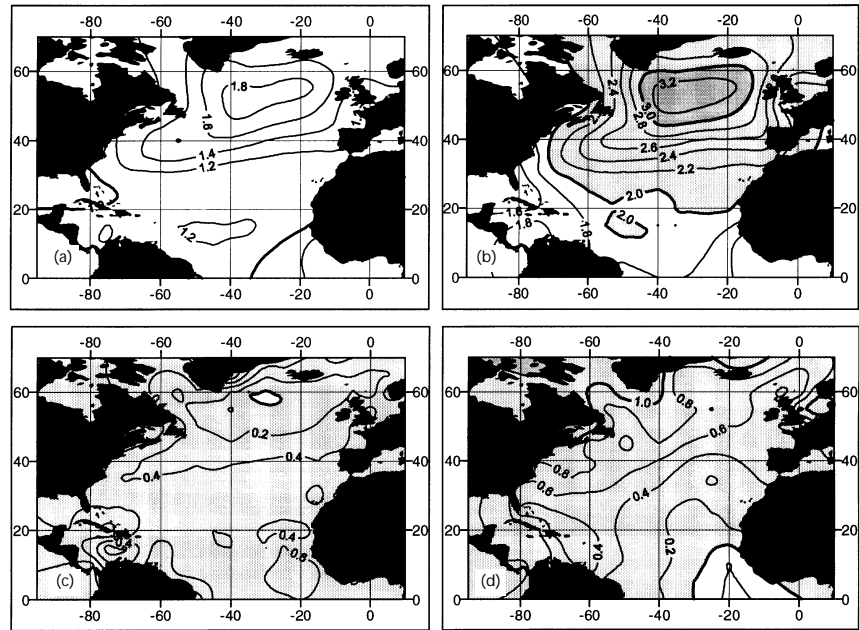
since it occurs on a range of temporal and spatial scales. Therefore, early work has concentrated on evaluating potentially useful statistical procedures which could be employed in a global scale study of wind and wave climate variability in different data sets (e.g. EOF analysis, SVD methods).

Because we are at the early stages of this part of the scientific programme, the following section will mostly present independent studies of patterns of variability within the three data sets. However, some early results from a comparison between trends in the ERA/WAM and VOS data from G98 are also discussed.

5.2 ALT

Initial work on the ALT data investigated the increasing trend of mean winter wave heights in the north-east Atlantic, as observed by Bacon and Carter (1991), inter alia. Figure 5 presents mean wintertime (December, January, February, March) ALT SWH from the 2° × 2° square covering Ocean Weather Station Lima (57°N, 20°W), appended to the ship-borne wave recorder data taken at this location. A linear trend fitted to these data gives an increase of 0.33 m per decade between 1975 and 1996. It is clear that the winter of 1995-96 was unusually calm (in the context of recent years), and that up until that year a steeper trend of about 0.75 m per decade was in evidence (achieved from fitting a trend to 1975-94 data). It is too early to say whether the winter of 1995/96 represents a turning point in the long-term trend, or is merely a short-term anomaly.

To investigate the spatial nature of this trend, the altimeter data were divided into two sets, the first containing data from Geosat (1985-89), and the second
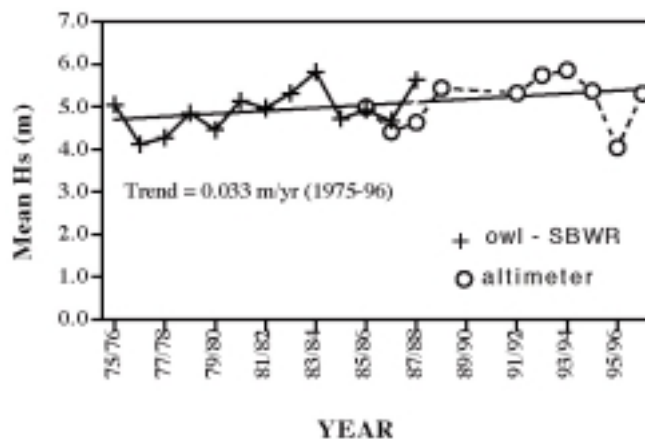

Figure 5—Mean winter significant wave heights at Ocean Weather Station Lima from ship-borne wave recorder (crosses) and altimeter (zeros) data.

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containing data from ERS-1 and TOPEX/Poseidon (1991-95). Figure 6 shows the mean winter wave height over the north-eastern Atlantic for these two periods. An increase to north-east in the extent of the 5 m contour can be seen, as can a new region of 5.5 m mean winter wave height, centred on 55° 25°W.

However, this analysis does not provide any information on the variability of wave climate at different time scales. To investigate this, Cotton and Challenor (1999) used the technique of empirical orthogonal functions, employed by a number of other researchers in climate related studies (see e.g. Preisendorfer, 1988). They first fitted a simple sinusoidal model for the annual cycle from the ALT data set, then smoothed the residuals from the fit in time (five-month running mean) and in space (nine point, nearest neighbour, Gaussian filter), before extracting the highest orthogonal modes of variability (those which explain the most variance in the data) from the SWH residuals variance-covariance matrix. Whilst their study found interesting evidence of connections between the wave climates of the North Atlantic and North Pacific, we shall only consider their North Atlantic results here.

Figure 7 shows the most significant eigen mode, which accounted for over 42 per cent of the variance in the residual SWH ALT data. The North Atlantic Oscillation Index (smoothed with a five-month running mean) is also given. This figure clearly shows a bipolar structure in which the south-western North Atlantic is anti-correlated with the north-eastern North Atlantic, the dividing line running south-east from the southern tip of Greenland toward the west coast of the Iberian peninsula. This pattern matches well with the pattern identified by Kushnir *et al.* (1997) in a model wave height climatology. Through a canonical correlation analysis, coupled with sea level pressure fields, they connected this pattern to the two main phases of the NAO. When the NAO is in its negative phase (i.e. the pressure gradient across the North Atlantic is lower than normal), westerly winds over the Atlantic are weaker than usual and wave heights are lower than normal in the north-east Atlantic. In the converse case (the positive NAO phase, more common in recent years), westerly winds are stronger and hence wave heights are greater in the north-eastern Atlantic. The time series of the first

Figure 6—Mean winter significant wave heights in the north-eastern Atlantic from ALT data for the two periods 1985-89 (left) and 1991-95 (right). Contours in m.
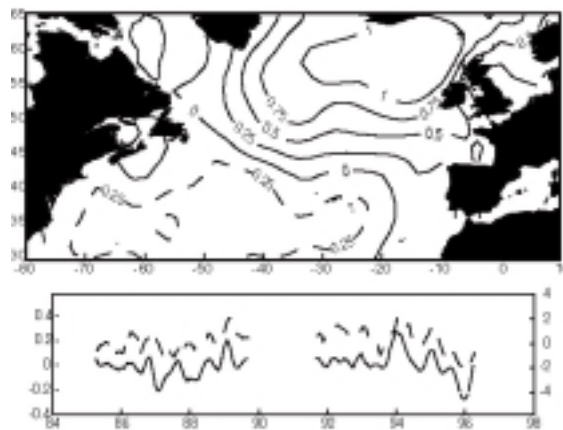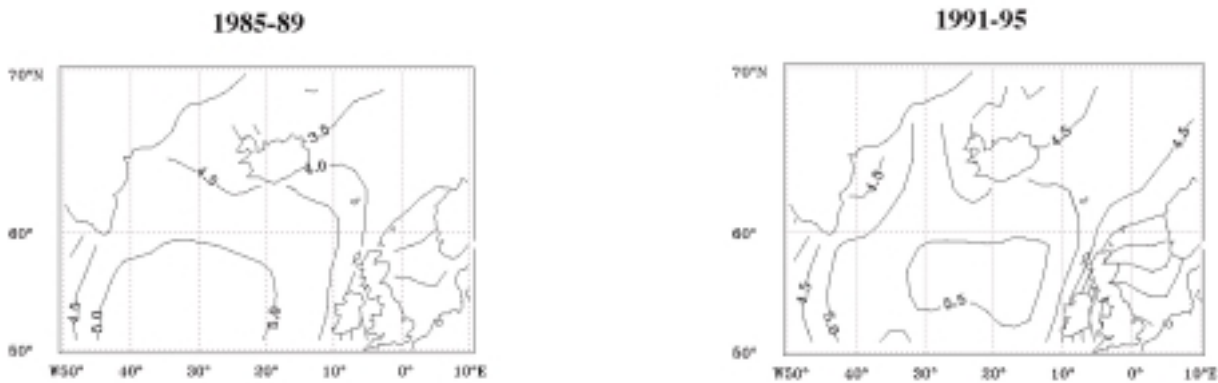

1985-89

1991-95

Figure 7—First EOF mode from ALT data (annual cycle removed), time series in bottom panel (solid line - LH scale), with North Atlantic Oscillation Index (dotted line - RH scale). Copyright ISOPE.

eigen mode of the altimeter data (bottom panel of Figure 7) shows the pattern was negative (i.e. lower than average wave heights in the north-east Atlantic) in the winters of 1986–87, 1987–88, and 1995–96, but positive (higher than average waves) in 1988–89, 1993–94 and 1994–95. The correlation between this time series of the first eigen and the smoothed NAO index is 0.78, confirming the strength of the connection.

The next three modes of variability (not illustrated) together explain a further 29 per cent of the variability in the data. Thus, the first four modes account for over 70 per cent of the interannual variance in the monthly mean SWH.

5.3.
WAM

The 15-year WAM global wave climatology has been analysed in terms of annual cycle and trends. The largest trends in SWH were seen to occur in the North Atlantic with an increase of more than 12 cm/yr in January and south of Africa where the increasing trend exceeds 7 cm/yr in July. These trends, however, are only marginally significant. Furthermore, they exhibit a large month-to-month variability, so that on a seasonal basis the trends are significant only in small areas.

Figure 8 shows the trends in SWH and U for each calendar month averaged over the North Atlantic (40°-60°N, 10°-40°W). At the 95 per cent level, the SWH trends are only significant in April, September and October, and at the 90 per cent level also in January. The trend in SWH for the winter season (DJF) in this area reaches a maximum of 0.4 m per decade, which is not significant (but is close to the trend found in the measurements at the Ocean Weather Station Lima, 59°N 20°W). When one looks for long-term trends in the annual mean SWH (not shown here, but in S98), there remains little convincing evidence of any large-scale long-term increase. The increase in mean annual SWH in the north-east Atlantic rarely exceeds 0.1 m/decade and is significant (at the 95 per cent level) only in a very small region in the direct vicinity of Iceland. There is, however, a large area of significant negative trend in the western North Atlantic, of more than -0.15 m per decade.

Changes in wave statistics were also investigated. To this end, the 10 per cent and 90 per cent exceedance wave heights and their trends were computed for a number of regions (North Atlantic, 40°-60°N and 10°-40°W, North Pacific, 30°-60°N and 140°E-120°W, northern hemisphere, southern hemisphere, and tropics with latitudinal boundaries at 20° N and 20° S, respectively). These trends form a similar picture to those of annual mean SWH. Significant trends are only found for some months over the North Atlantic, while in the other regions the distribution of wave heights remained more or less the same over the ERA period. In the North Atlantic, the 10 per cent and 90 per cent exceedence wave heights are increasing in parallel to the annual mean SWH, the increase of which is thus accomplished by a shift of the whole wave height distribution towards higher waves.

Readers should also note the results of the WASA (1998) study, discussed in section 4.6 below.

5.4.
VOS

Gulev and Hasse (1999*a* and 1999*b*) report on a study of changes in the North Atlantic VOS wave climatology between 1963 and 1993. Whilst they found signif-

Figure 8—Linear trend of ERA/WAM SWH (solid line, m/yr) and U (dashed line, ms-1/yr) averaged over a region of the North Atlantic (40°-60°N, 10°-40°W). Copyright J. Geophys Res. (AGU).

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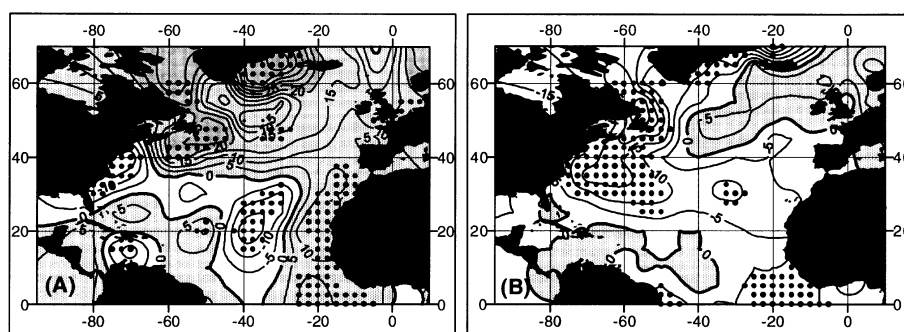
icant positive linear trends in the wind sea in the north-western Atlantic, and at mid-latitudes (0.1-0.18 m/decade), they did not find any significant trends in the north-eastern Atlantic. However, they did see strong increasing trends in swell height at mid-latitudes in the central and eastern Atlantic of 0.2-0.3 m /decade. They were able to use the directional information available from COADS data to further investigate the possible source of this increased swell, and establish its directional characteristics. When they studied these data for the region 10°-20°W and 50°-60°N, they found a negative trend in wind seas coming from the westerly directional sectors, but a positive trend in other directions. They also showed that the swell entering from the north had the largest and most significant increase.

5.5
VOS Vs. WAM

G98 compared the interannual variability in the WAM and VOS data. They separated out variability into the seasonal cycle, intraannual variability and long-term interannual variability, and then used the latter to derive estimates of long-term trends. Figure 9 compares the long-term trends from VOS and WAM. The two data sets clearly present quite different patterns. The VOS data show significant positive trends in the mid-latitude north-western Atlantic and at high-latitudes to the west of Iceland. They show a significant negative trend in the central subtropical North Atlantic. In contrast, the WAM data show a significant decreasing trend over a large part of the mid-latitude western Atlantic, but no significant positive trends anywhere. WAM and VOS show significant trends of opposite sign in the area to the south and south-west of Newfoundland. Furthermore, the long-term trend in swell is increasing in the VOS data, but decreasing in the WAM data.

The source of these major inconsistencies is not known. They may result from inconsistent partitions of the wave field into wind sea and swell in the VOS and WAM data, or may possibly be related to sampling within the VOS data (more important at high-latitudes). An equivalent analysis of altimeter data is hoped to shed some light on this.

5.6
OTHER STUDIES

Within the WASA study (WASA, 1998), a number of different analyses of past wave North Atlantic wave climate were carried out.

Buows *et al.* (1996) studied operational analyses based on ship routing charts from KNMI. In particular, they considered a box to the west of Ireland (50°-55°N, 10°-20°W), and estimated the trend between the years 1961-87. In this area they found an increasing trend of 3.8 cm per year in both the annual maximum and annual 90 per cent quantile (increases of 0.3 and 0.7 per cent respectively). Whilst it is not possible to compare these trends with those found above, we can note that this region showed an increasing trend in both the VOS and ERA/WAM climatologies.
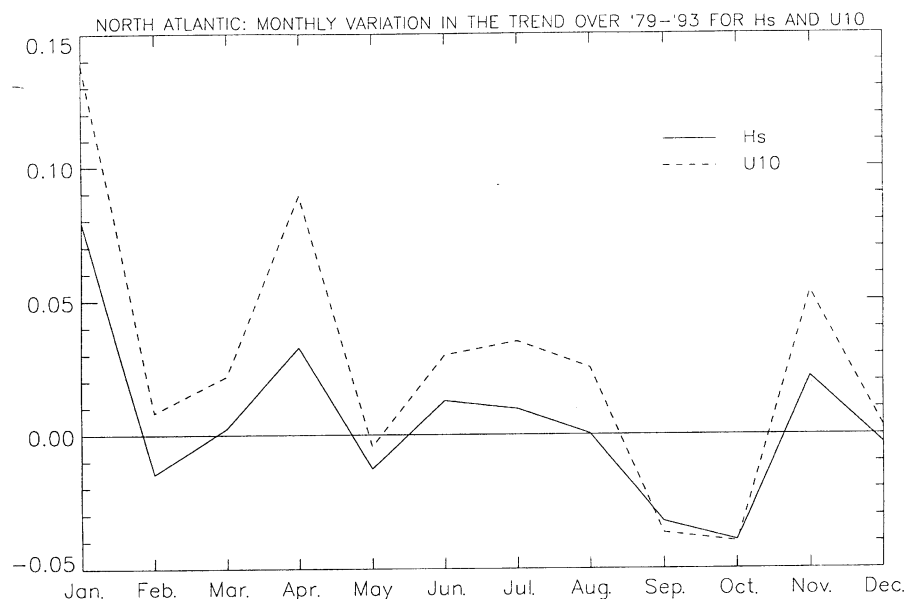

Figure 9—Estimates of the interannual linear trends (cm per decade) in VOS (a) and WAM (b) SWH climatologies in the North Atlantic. Areas marked with black dots indicate 95 per cent significance. Copyright Physics and Chemistry of the Earth (Pergamon).

In a modelling study, a regional version of fourth generation WAM (north-eastern North Atlantic, 0.5° lat. × 0.75° long resolution) was forced by winds derived from operational pressure fields from the Norwegian Meteorological Office (DNMI), and boundary conditions provided from a coarse run with FNOC winds. This model was run for the 1955-94 period (Gunther *et al.*, 1998). The resultant chart of trends in the interannual 90 per cent quantile showed mostly negative trends in the region considered by Buows *et al.* (1996), but positive trends in the North Sea and Norwegian Sea.

6. CONCLUSIONS

6.1 'STATIC' COMPARISONS WAM/ERA

The comparisons completed thus far indicate that the WAM/ERA data systematically overestimate low waves and underestimate high waves. This suggests an inability of the model to fully match the variability in the actual wave fields, due to resolution limitations, and a possible overestimate of swell.

ALT

The ALT data have been carefully calibrated against buoy data, and no dependency of accuracy on sea state has been identified. Work continues to investigate this possibility.

VOS

The VOS data are seen to overestimate low waves, possibly partly as a result of the problem with the COADS code '1'.

WIND SEA/SWELL

In a comparison of these fields from ERA/WAM and VOS, there was no spatially consistent pattern of differences. VOS appeared to increasingly overestimate (with respect to ERA/WAM) towards the north-western North Atlantic. It is possible that the separation of the wave field into wind sea and swell is not consistent in the WAM and VOS climatologies.

6.2 'DYNAMIC' COMPARISONS

The patterns of climate variability are different in each data set. Interannual trends are of different magnitudes and sign. The ERA/WAM climatology shows a significant trend only in the western mid-latitude Atlantic (decreasing), whereas the VOS climatology shows significant increasing trends to the west of Iceland, and the south and south-west of Newfoundland. VOS also showed a significant decreasing trend in the central subtropical North Atlantic. ALT data indicate an increase (in the years 1985-95) centred on 55°N, 25°W.

6.3 FUTURE WORK

Future work will need to consider a number of problems highlighted in this paper:
- The consistent partition of wave fields into wind sea and swell within the VOS and WAM data.
- The carrying out of an equivalent analysis of interannual variability on the ALT data, and widening of the methodology to look at other time scales.
- Investigations into how VOS sampling may effect these comparisons.
- Consideration of whether satellite instrumentation could provide a wider range of wave parameters. e.g. synthetic aperture radar data, or the use of an altimeter-derived wave period parameter.

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