AN IMPLEMENTATION TEST
ON
SUPPORT TO WEATHER SAFETY IN THE NORTH WEST APPROACHES – THROUGH THE USE OF SATELLITE DATA IN ASSESSING WAVE ENERGY DYNAMICS

Phase 2 Report
Demonstration Product: Generation and Evaluation.
Recommendations for Implementation of
a NW Approaches Wave Conditions Monitoring and Analysis Service

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Phase 2 Report
Demonstration Product: Generation and Evaluation. Recommendations for Implementation of a NW Approaches Wave Conditions Monitoring and Analysis Service

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This report describes the generation and evaluation of a demonstration ocean wave data product, designed to represent key aspects of a proposed NW Approaches Wave Conditions Monitoring and Analysis Service. It then goes on to provide an assessment of the potential value of an EO based wave conditions monitoring service to the HSE /BNSC in terms of improvements on services that are presently available. Finally the report provides costed recommendations for implementation, and ongoing development, of an operational NW Approaches Wave Conditions Monitoring and Analysis Service.

Disclaimer:
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2.0	21/06/05	D. Cotton SOS	Modifications in response to sponsor comments

[1] *In May 2005 Southampton Oceanography Centre was renamed the National Oceanography Centre*

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EXECUTIVE SUMMARY

This test project has been conducted under the British National Space Centre (BNSC) Government Information From The Space Sector (GIFTSS) initiative in close collaboration with the Health and Safety Executive Offshore Division (HSE OSD).

The HSE OSD requirement is the safety of operations and equipment used for drilling and extraction of oil and gas in the North West Approaches to the UK, and covers the following:

- The need to assess the possible utilisation of all-weather information from ongoing spaceborne systems to measure offshore wave energy
- To add to the statistical and management base that is used to support offshore operations
- The potential for supporting safety in all weathers for operations in the NW Approaches

The project has carried out an in depth assessment of all aspects of wave products that can be derived from satellite measurements over the ocean, and which could form components of a North-Western Approaches wave conditions monitoring and analysis service.
A demonstration service was established to demonstrate and evaluate key aspects of a full service: A near real time data service which – through a web page updated hourly, every day, provides the client with easy and fast access to present and recent wave conditions in the NW approaches, and a wave climatology and analysis service which provides information on expected conditions as they vary throughout the year and across the region of interest.
Ocean wave data can be derived from two different satellite instruments, both of them microwave radar. The first is the radar altimeter which provides a measurement, directly beneath the satellite, of significant wave height, wind speed and mean (or zero upcrossing) wave period. This technology is mature, and altimeter wave data have been accepted by the operational offshore community as reliable ocean state measurements, although the sampling is limited. The second instrument is the synthetic aperture radar (SAR), which can provide estimates of the wavelength and direction of long waves (wavelength > 100m). Recent developments have also allowed an estimate of significant wave height (of long period waves) to be estimated, as well as a direction / energy spectrum (again for long period waves). However, because of the complex imaging mechanism these data are less reliable and SAR wave measurements are only possible under a limited range of surface wind speeds.

The report provides costed recommendations for phased implementation and development of an operational NW approaches wave conditions monitoring and analysis service. These recommendations are designed to meet the following key priorities:

- Satisfy the joint sponsor priorities of providing statistical analyses of archived wave data (including directional information) and a near real time wave monitoring service.
- Offer a useful capability in the short term (i.e. was based upon existing capability, and available operational data sets), but which will allow for future planned incorporation of additional data sets and analysis capabilities.

In addition, recommendations are also provided for capacity building by knowledge transfer between academic and commercial organisations.

1 INTRODUCTION

The main aim of this report is to provide costed recommendations for implementation, and ongoing development, of an operational NW Approaches Wave Conditions Monitoring and Analysis Service, based on satellite derived data. The basis for these recommendations is provided by a detailed analysis of available EO (Earth Observation) data sets and data services, carried out in phase 1 of this implementation test (Cotton *et al.*, 2005), followed by an assessment of the demonstration product reported here.

Section 2 of this report describes the generation of a demonstration ocean wave data product, designed to represent key aspects of a proposed NW Approaches Wave Conditions Monitoring and Analysis Service. This covers tasks 2.1 (Selection and acquisition of satellite data sets), 2.2 (Implement data processing chain), and 2.3 (Process satellite data) as defined in the original BNSC/HSE ITT.

Section 3 provides an evaluation of this data set, through a variety of techniques, including comparison against buoy data and wave models. This covers task 2.4 (Review the accuracy of the overall process for generating the derived wave parameters) as defined in the original BNSC/HSE ITT.

In Section 4 we assess the improvements offered by EO derived wave data products for the NW approaches region, relative to presently available data products. This covers task 2.5 (Assess the potential benefit of using new satellite data to provide wave statistics and nowcast support) as defined in the original BNSC/HSE ITT.

In Section 5, we review the benefits of using data products including EO data sets, and provide estimated costs of implementing all aspects of an operational wave monitoring system. This covers tasks 2.6 (Estimate the expected cost/benefit from the use of satellite data for HSE OSD) as defined in the original BNSC/HSE ITT.

In section 6, the report provides recommendations for implementation, and ongoing development, of an operational NW Approaches Wave Conditions Monitoring and a NW Approaches Wave Statistics Information System. This covers tasks 2.7 (Provide recommendations for implementation of a possible operational system) as defined in the original BNSC/HSE ITT.

2 PHASE 2 DATA PRODUCT

2.1 INTRODUCTION

The demonstration product generated in Phase 2 of this GIFTSS-supported implementation test aimed to demonstrate and test key components of the proposed NW Approaches Wave Conditions Monitoring and the NW Approaches Wave Statistics Information System.

The specification of this demonstration data product was built upon the following assumptions and observations:

- A priority is to provide costed and evaluated recommendations for a NW Approaches Wave Conditions Monitoring and Analysis Service, to cover both Near Real Time monitoring of wave conditions, and statistical analyses.
- The status and capabilities of altimeter derived wave products were well understood by the sponsors, therefore HSE/BNSC did not require further demonstration of wave statistics products derived from altimeter data within this project.
- Because of a request by the sponsors to carry out an extra review on the use of SAR within Phase 1 of the project, reduced time and resources were available to the project team in Phase 2. It was therefore necessary to scale down the original plans for the phase 2 product, and to concentrate on key issues for HSE/BNSC.

Therefore the focus of the Phase 2 demonstration product was:

- To provide a demonstration and evaluation of swell wave statistics (direction and period) derived from SAR *image mode* products.
- To demonstrate a joint presentation of SAR and altimeter derived wave products for Near Real Time monitoring.

2.2 DATA PRODUCT PRESENTATION AND PROCESSING CHAIN OVERVIEW

Remote access to the demonstration data products was enabled through a web portal established by Satellite Observing Systems, at http://www.satobsys.co.uk/hse (Figure 1). This front page provided separate links to wave climate statistics, and Near Real Time information.

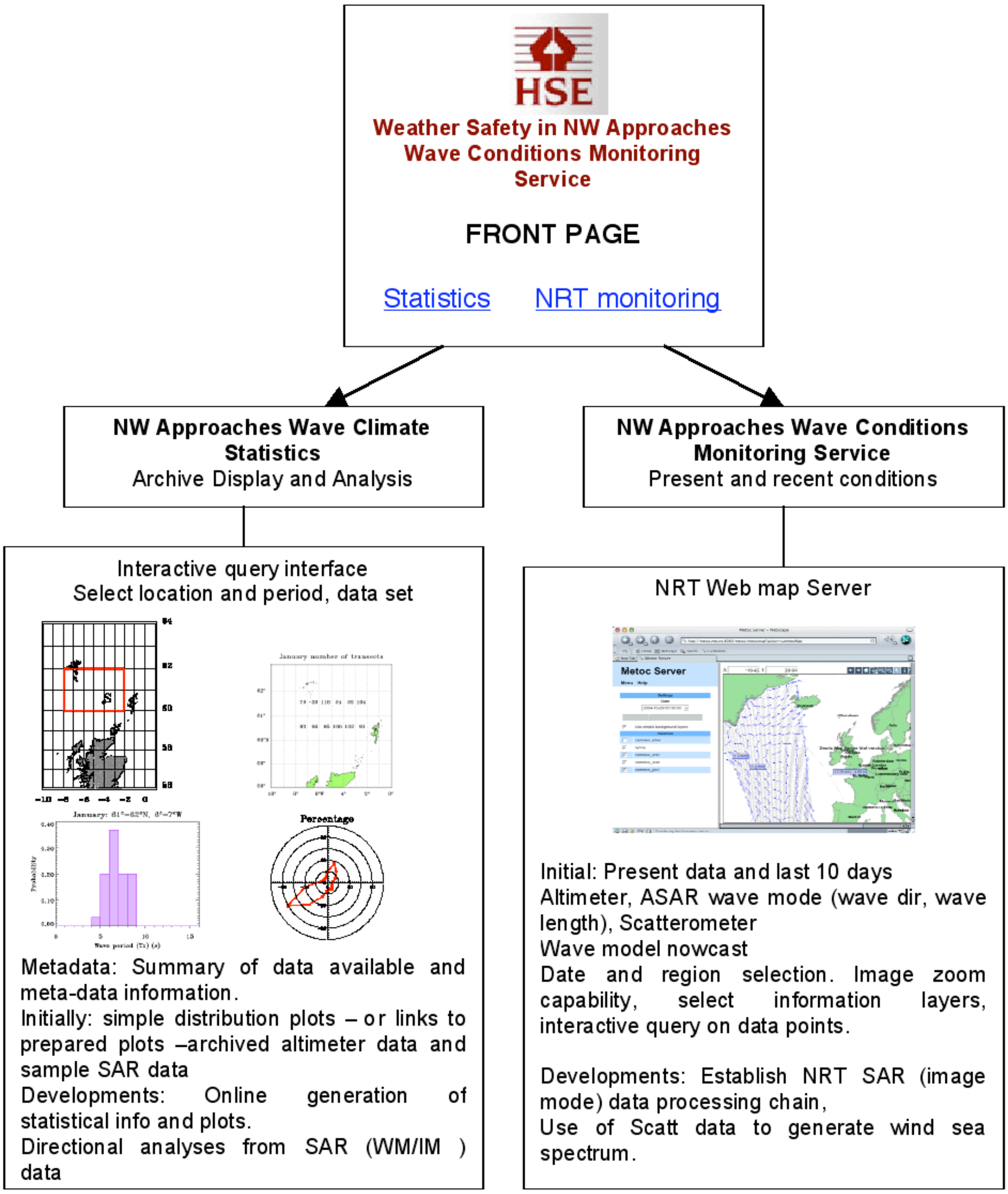
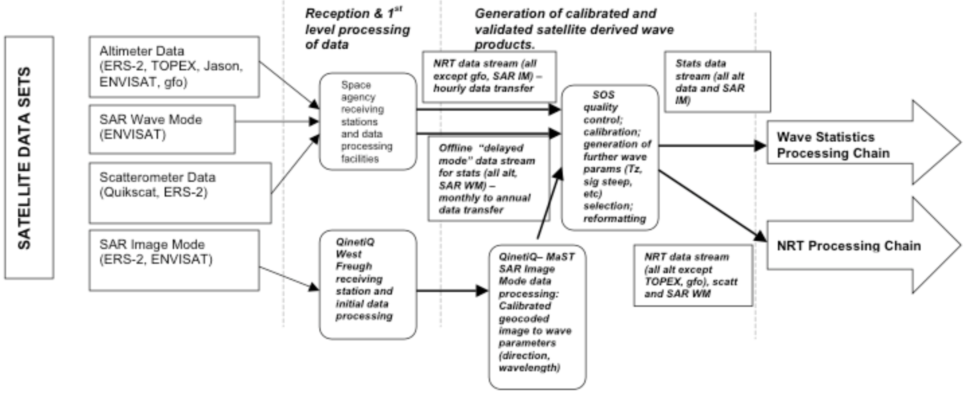


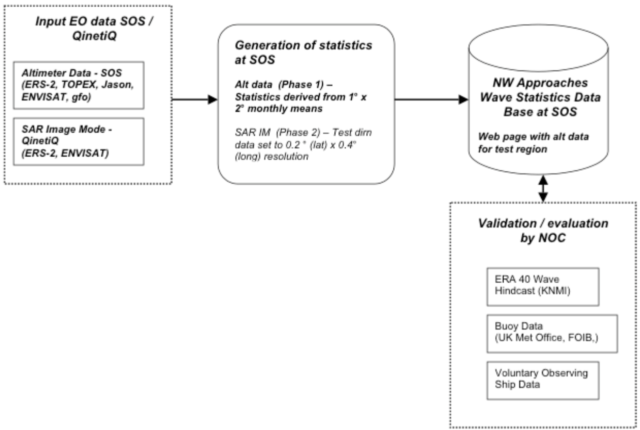
Figure 1 Front page and link for the NW Approaches Wave Monitoring Service Demonstration Products

Figure 2 provides some more detail on the data flow through the processing chain. The top panel giving common aspects, the central panel the processing chain specific to the generation of wave statistics, and the lower panel detail for the Near Real Time data processing chain. We describe the two parts of the service separately below, first considering wave statistics.

Initial and Common Processing Chain



Wave Statistics Processing Chain (Section 2.3)



Near Real Time Processing Chain (Section 2.4)

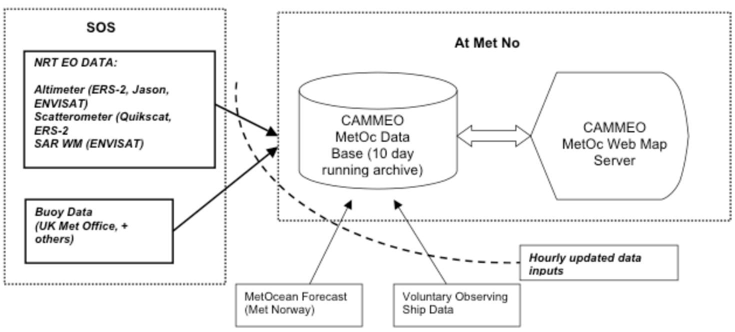


Figure 2 The Data Processing chains for the wave data sets. Top: Common aspects, Middle: The wave statistics data processing chain (altimeter data chain described in Phase 1 report, SAR *image mode* chain is discussed below in Section 2.3, Bottom: The Near Real Time Data Processing Chain (see Section 2.4)

2.3 WAVE CLIMATE STATISTICS

The wave climate statistics section of the demonstration product comprised:

- altimeter derived monthly wave climate statistics, for 12 1° x 1° grid squares, within 60°-62°N, 2°-8°W.
- wave direction and wave length statistics from SAR *image mode* data (processed through MaST)– for the winter season (November-March) in a single area: 60°-61°N, 4°-8°W

The processing chain for generating wave statistics is outlined in the central panel of figure 2. Input EO data are received and initially processed by QinetiQ (for SAR *image mode* data) and SOS (for altimeter data) The statistical analyses for both data sets were carried out at SOS, and the statistical data thus produced were assessed by NOC. The altimeter data set was discussed and assessed in phase 1 (Cotton *et al.*, 2005 and refs therein), we shall therefore only consider the SAR derived statistics in this report.

The aims of the SAR *image mode* data product, based on SAR images processed through MaST by QinetiQ and with subsequent analysis by SOS, were:

- To generate a representative swell direction and wavelength database, for a selected region and season.
- To provide a demonstration display of direction and wavelength statistics.
- To assess the impact of high wind speed conditions on the sampling of the region by SAR.
- To establish if there is any difference in wave statistics derived from ascending and descending passes and, if there is, develop a strategy to overcome it.

The analysis focussed on an area to the South of the Faroe Islands, an area in which the offshore oil and gas exploration industry are active, and for which representative *in situ* buoy data are available (Figure 3).

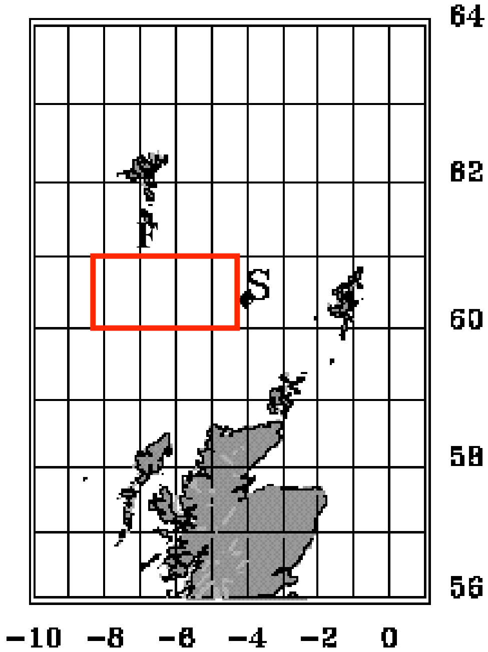


Figure 3 The GIFTSS Area of Interest. The Red square indicates the region for which SAR *image mode* data has been extracted. The location of the Schiehallion FPSO (“S”) and the Faroes waverider buoy (“F”) are also indicated.

2.3.1 SAR Image Data Selection

Through cost limitations this project was limited to the analysis of 35 SAR scenes from QinetiQ, 27 for this part of it. So it was decided to examine 27 scenes processed through the QinetiQ MaST application, initially from a 2° latitude by 1° longitude area North of Scotland (60°-61°, 4°-6°W) during the winter months of January and February. The aim was to provide sampling of winter conditions representative of the Shetland-Faroes channel, and in wave climate found to be similar to that experienced by the Faroes wave rider buoy. An initial search in the QinetiQ West Freugh, SAR archive for (ERS-1 and ERS-2) SAR Images could not find sufficient scenes available within the specified area and months when surface wind speed was in a suitable range, partly because of a temporary difficulty in accessing post-2000 records[2]. So the area was expanded (to 60°-61°, 4°-8°W) and the period extended to include data from November to March. Table 1 lists the scenes acquired for the project and processed. It also identifies whether the scene was from an ascending or descending track of the satellite; all 27 were from descending passes - while the previously analysed 8 scenes, from summer months, were all from ascending tracks.

Table 1 Initial list of SAR ERS-1 and ERS-2 Images selected by QinetiQ

Image #	*GIFTSS*	*ERS*	*Orbit*	*Track*	*Frame*	*Day*	*Mon*	*Year*	*Time*	*A/D*	*Wind (ms^{-1})*
1	9	E1	06781	123	2385	01	11	1992	11:35:50	D	None
2	10	E1	07239	080	2385	03	12	1992	11:29:57	D	5-10
3	11	E1	08241	080	2385	11	02	1993	11:30:02	D	8-11
4	12	E1	08284	123	2385	14	02	1993	11:35:47	D	9-12
5	13	E1	17283	482	2385	04	11	1994	11:26:24	D	6-8
6	14	E1	17484	683	2385	18	11	1994	11:34:41	D	3-6
7	15	E1	17728	927	2385	05	12	1994	11:37:36	D	7-11
8	16	E1	17771	970	2385	08	12	1994	11:32:14	D	9-11
9	17	E1	19163	2362	2385	15	03	1995	11:20:36	D	1-4
10	18	E1	17240	439	2385	01	11	1994	11:31:48	D	None
11	19	E1	19378	352	2385	30	03	1995	11:32:50	D	8-11
12	20	E1	22885	352	2385	30	11	1995	11:33:00	D	8-11
13	21	E2	03212	352	2385	01	12	1995	11:33:04	D	8-11
14	22	E2	03255	395	2385	04	12	1995	11:38:49	D	0-5
15	23	E1	23114	080	2385	16	12	1995	11:30:11	D	2-5
16	24	E2	03441	080	2385	17	12	1995	11:30:11	D	0-5
17	25	E1	23386	352	2385	04	01	1996	11:33:01	D	11-15
18	26	E2	08179	309	2385	12	11	1996	11:27:14	D	8-10
19	27	E2	13504	123	2385	19	11	1997	11:35:47	D	7-10
20	28	E2	13776	395	2385	08	12	1997	11:38:36	D	8-10
21	29	E2	19015	123	2385	09	02	1998	11:35:41	D	11-15
22	30	E2	18972	080	2385	06	12	1998	11:29:56	D	2-6
23	31	E2	19287	395	2385	28	12	1998	11:38:37	D	7-11
24	32	E1	18015	1214	2385	25	12	1994	11:35:14	D	13-15
25	33	E2	13275	395	2385	03	11	1997	11:38:38	D	10-13
26	34	E2	18514	123	2385	04	11	1998	11:35:44	D	12-15
27	35	E2	18743	352	2385	20	11	1998	11:32:46	D	15+

[2] *The problem with processing post-2000 ERS scenes has since been resolved, and would not have effected the NRT processing of Envisat data. Should such an incident occur during an operational phase the failure would be deemed high priority and expected to be resolved expeditiously with no/minimum impact on the Service. The NRT service would be contracted to provide a set number of images with alternative options should the provision of data not be met.*

2.3.2 SAR Data

After pre-processing to .PRI format each SAR image was processed at QinetiQ Farnborough, with the MaST package to produce a file of wave field solutions with location, wave period and wave direction (see phase 1 report, Cotton *et al.*, 2005 for more details). Each scene covers an area of 100 km by 100 km[3], with pixel size of 12.5 m by 12.5 m. Data from every 200 by 200 pixel sub-scenes (i.e. 2.5 km by 2.5 km areas) were processed to extract dominant wave directions and wavelengths. All 27 winter scenes were processed without any smoothing of the pixel values, suggesting a minimum detectable wavelength of 25 - 30 m, but the resolution of the ERS/ENVISAT SAR imposes a higher minimum of 50 - 60 m. These data, from November 1992 to November 1998 extend from 59.5° - 60.9°N and from 3.4° - 8.6°W. A plot of all the sub-scenes from which wave data could be extracted is shown in Figure 4.

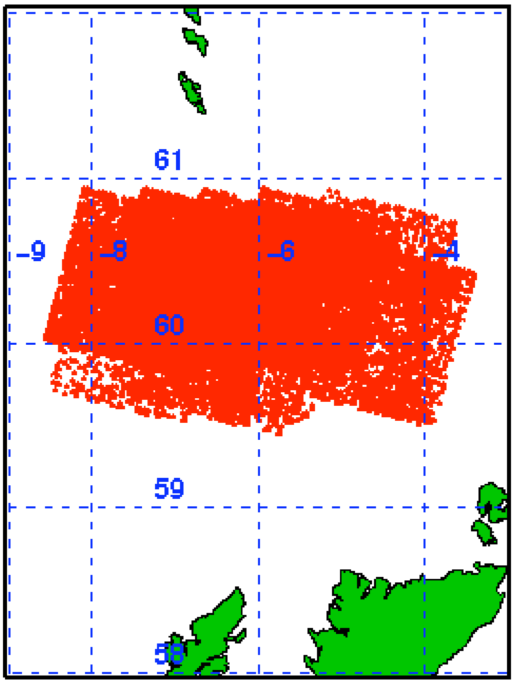


Figure 4 Locations of the 2.5 km by 2.5 km areas with estimates of wave direction and length

2.3.3 Data Issues

Generic SAR Issues

The limitations of SAR and the complex problems of deriving estimates of ocean wave parameters from SAR data are well known, and have been explained in a previous report from this project. One limitation, on extracting shorter waves, is the resolution of the SAR; another is the range of wind speed for which useful images are obtained (roughly 3 to 13 ms^{-1}); whilst a source of major limitations is the movement of the SAR which introduces complex, non-linear problems into the processing from what the SAR 'sees' to the true ocean wave picture. (E.g. Hasselmann & Hasselmann, 1991; Aage *et al.*, 1998; Woolf 2004b)

A further problem is that, unless produced by the most recent processing schemes, wave directions from SAR have a 180° ambiguity.

Recently, a processing technique has been introduced elsewhere in Europe which resolves the 180° ambiguity, and which also provides an estimate of energy in each wavelength/direction bin; Engen & Johnson (1995). It is currently being applied by ESA to Envisat SAR *wave mode*

[3] *Except for Scene 10 which was about 50 km by 100 km.*

data, but there remain some questions regarding automatic applications of recommended quality control criteria (we shall revisit this issue in Section 2.4).

SAR Issues Related to Use of MaST

The algorithm in the current MaST application gives the wave direction and wavelength (and the wave period and speed, derived from wavelength using the deep water dispersion relationship). It does not, at present, provide any assessment of the energy; so if - as is sometimes the case - two or three wave direction/wavelength solutions are obtained from one sub-scene, there is no way of telling which is the dominant one.

QinetiQ's processor resolves the 180° ambiguity problem by assuming that the waves are approaching land (since they are relatively long, 'swell' waves). Such waves are not related to the local wind, and this seems the most satisfactory resolution possible from this processor. For the area examined here, with longer waves generally from the west and with the Shetlands nearer than North America, it appears to produce generally sensible results.

Some questions concerning the wave data generated by the QinetiQ MaST application have arisen during this study. In particular, the lack of any waves travelling perpendicular to satellite track. (More accurately, wave travelling with an 'image angle' of zero, that is at right angles to the track). This is clearly seen in Figure 5 (left panel) which shows a histogram of image angles from all 27 scenes, with bin sizes of 1°. This peak-splitting effect in the range direction (at right angles to the satellite track) was noted in simulated data by Brüning *et al*. (1990).

The right panel of Figure 5 is a similar histogram for the 8 ascending scenes, showing a similar gap around an image angle of zero; but some of these scenes were from further north, and included the Faroe Islands, so the 180 ambiguity resolution introduced image angles around 180°.

Figure 5 strongly suggests that the SAR registers waves from around its image angle of 0°, which ever way it is travelling (but never exactly at 0°).

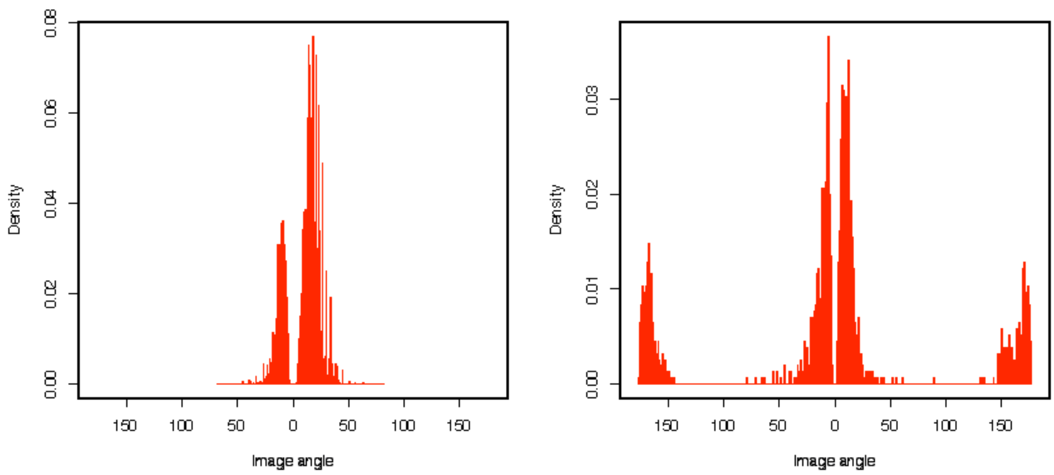


Figure 5 Distribution of image angle. Left: from 27 images on descending passes. Right from 8 images on ascending passes.

2.3.4 Individual Scenes Processed through MaST

Figure 6 shows an example of the wave data from the MaST package from Scene 17 obtained by ERS-1 on 15 March 1995. The number of grid points with data is 849 - greater than the average value of 686 for the 27 scenes. The lines show the direction of the waves - travelling up to the grid points - and the line lengths are proportional to the wavelength, which here ranged from 112 m to 439 m with a mean of 275 m. The angle from which the waves are coming ranged from 238° to 307°, with a mean of 268° and quartiles of 262° and 271°.

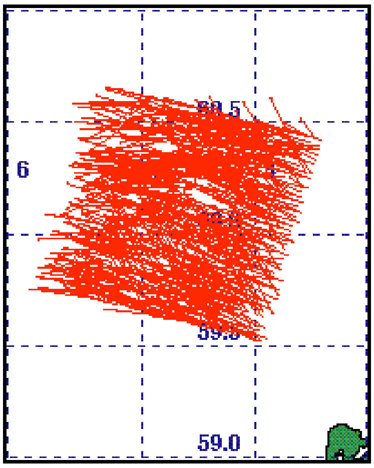


Figure 6 SAR Scene 17, from ERS-1 on 15 March 1995, showing wave directions and wavelengths for individual grid points.

The scene contains a grid of 43 by 38 points (roughly N-S and E-W respectively) and covers 106 km by 94 km; which gives a grid spacing of 2.5 km in both directions. Estimating spectra from such a small area must give noisy results, particularly for the longer waves, akin to estimating non-directional wave statistics from a couple of minutes of a waverider record.

The distributions of wavelength and direction of the waves are given in Figure 7. A plot of direction against wavelength is shown in Figure 8.

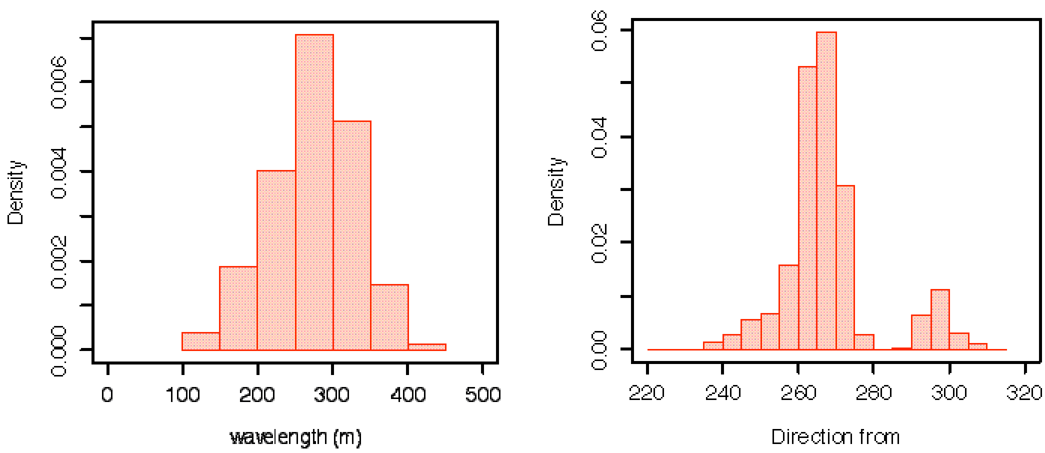


Figure 7 Distributions of wavelength (left) and direction (right) from SAR scene 17, from ERS–1 on 15 March 1995

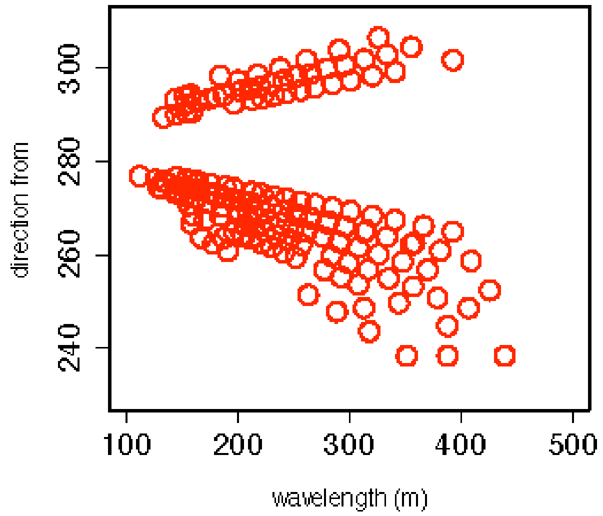


Figure 8 Distribution of wave direction against wavelength from SAR scene 17

It is not easy to see how to summarise the wavelength and direction over this scene, to incorporate into climate statistics. The histograms (Figure 7) suggest that the means of 275 m and 268° might be suitable parameters; but Figure 8 shows a more complex picture. The gap around a direction of 283° corresponds to an image angle of zero, so this gap is probably spurious; whether the increasing width of the gap with increasing wavelength is also a product of the processing algorithm remains to be seen. (This widening was found in all other scenes., see the MaST annex for further discussion) Does the histogram of directions, in Figure 7, indicate one wave train from about 270° with some random spread about 270° due to sampling variability; or is there a separate wave train from 295°? Or, because of the 180° ambiguity, does Figure 8 represent two wave trains, one from around 270° and the other from 115° (295°-180°)? In fact it is not possible to resolve this question without further information. All 27 scenes had this "double fan" shape, reflected about 283°, usually - but not always - with more data in the 270° "fan". See Figure□5 for a scatterplot of direction: wavelength from all the scenes. This strongly suggests that the gap is an artifice of the processing and that the waves are basically from one direction with considerable scatter about that direction.

Figure 8 also shows a discretisation of wave direction and wavelength. This results from limiting the cell size on the image input to a Fourier Transform procedure within MaST. The MaST annex discusses the effect and proposes a modification to the implementation of MaST to reduce its impact on the output wave parameters.

A strikingly similar picture to Figure☒ - and to Figure□5 - is seen in Figure☒ from Kerbaol *et al.* (1998), although this figure is a composite of some 2000 *wave mode* imagettes (each 10☒m by 5☒m) obtained from the Indian Ocean and North Pacific by ERS-1 and ERS-2. Clearly, this distortion away from the range axis, also found by Brüning *et al.* (1990) in simulated data, is a general problem of SAR, and was not introduced by QinetiQ's processing.

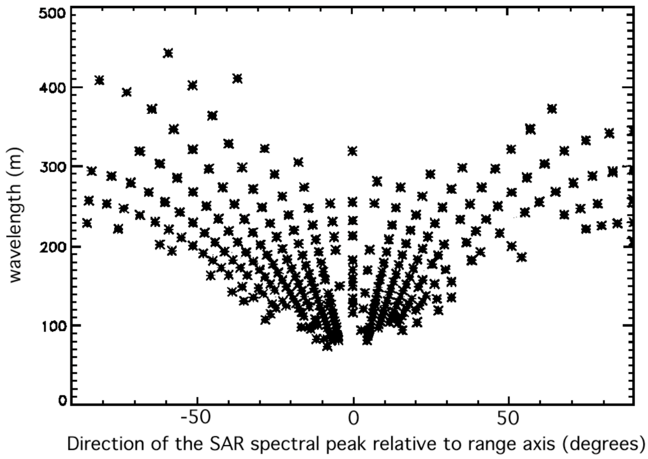


Figure 9 Wavelengths of spectral peaks against direction relative to the range axis from ERS-1 & ERS-2 SAR *wave mode* data. (From Kerbaol *et al.*;1998.)

It might seem better to use all the data for the climate analysis. But this does have drawbacks:

- The data from one scene are clearly correlated, making it difficult to assess the accuracy of climate statistics.

- It does not differentiate between two different directions at one or at different grid points. Because swells from markedly different directions are probably from independent events, this is not likely to be serious, except that it obscures statistics of the prevalence of cross-seas.

- There is a large range in the number of data in the 27 scenes, varying from 162 (Scene 18) to 1379 (Scene 20), with a mean of 686 (and poorly correlated positively with wind speed). But bias introduced by this uneven weighting of scenes could be avoided by extracting and analysing 162 data from each scene.

Figure 6 does not suggest any obvious spatial trends in either wavelength or direction across the scene; but, to check this, the scene was divided along latitude 60°N. Figure 10 shows the joint distribution of wavelength and direction for the two areas, with 458 in the North and 391 in the South. Now some differences become apparent. There is a higher proportion of waves from around 300° in the Northern part than in the Southern, and a higher proportion from around 260° in the South than in the North. The water is slightly shallower in the South - with the 100 fathom (182 m) contour running roughly SW to NE through 60°N 5°W so the longer waves would be expected to be refracting towards the SE more noticeably in the South; but detailed analysis needs to await an understanding of the gap in observation about the radar's image angle, separating these apparent wave trains.

One way of obtaining the dominant wavelength and direction from a scene is to generate a 'scatterplot', counting the number of data within specified wavelength and direction bins, and choosing the bin with the maximum count as representative of the scene. Figure 11 (left) shows a 'sunflower' plot of Scene 17, with data put into 25 m by 10° bins, and the count in each bin given by the number of 'petals'. For example, from this figure, the bin at (6,28) - i.e. wavelengths from 150 m ±12.5 m, direction from 280° ± 5°, there are 5 data pairs (out of a total of 849 pairs). The maximum count is 104 (12%) at (13,26) or (325 m, 260°), so 325 m and 260° were taken as representative of this scene. This selection depends to some extent on the chosen bin sizes. The second highest is 10% at (250 m, 260°); which might be a separate 'peak' - or perhaps they should be combined specifying 275 m and 270°. A proper solution to this problem would require a detailed analysis of sampling and processing errors.

The right hand panel of Figure 11 illustrates the problem of interpretation. It shows the sunflower plot of Scene 25. The highest count, of 21%, is at (4,29), or 100 m and from 290°. But was there also a separate swell train with wavelength 240-250 m from 270°, which combined had 11% of the count? Again we cannot tell without additional, external, information.

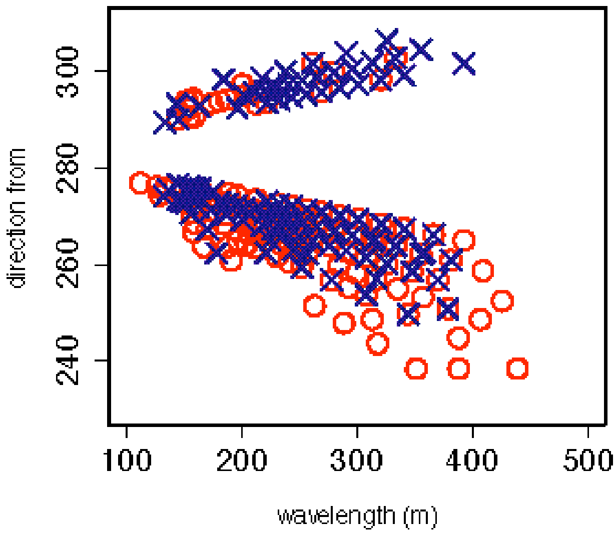


Figure 10 Distribution of wave direction against wavelength from SAR scene 17; red O:North of 60°N, blue X: South of 60°N.

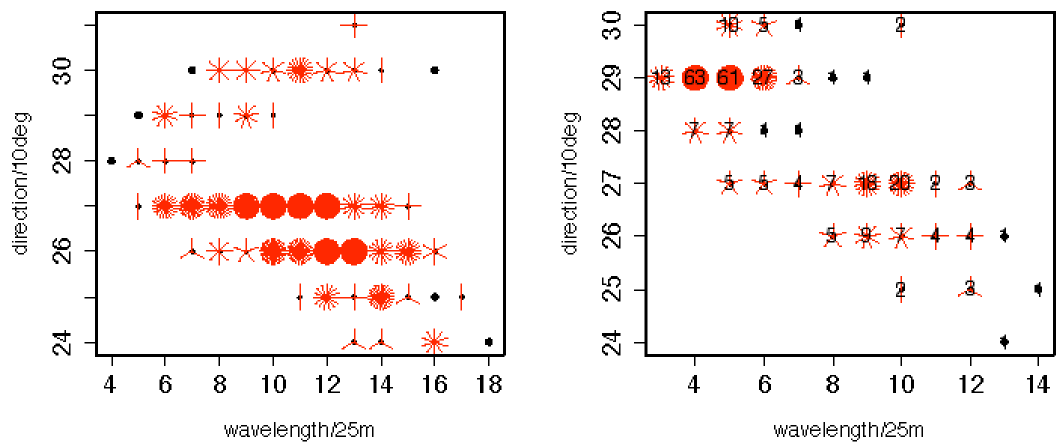


Figure 11 'Sunflower' plots of the joint distribution of wavelength and direction from Scene 17 (left), and Scene 25 (right) - with numbers of values superimposed.

2.3.5 Derivation of Climate Statistics from SAR Data processed through MaST

Two ways of generating descriptions of the climate were tried, firstly by analysing all the data from the 27 winter scenes processed by QinetiQ, then using the scatterplot modal values from these scenes.

Analysis of all data

Taking all the directions and wavelengths from the 27 scenes listed in Table 1, results in 18529 wavelengths and directions, ranging over the area marked in Figure 4. The minimum and maximum wavelengths are 56 m and 439 m respectively; the range of directions are from 202° to 335°. The means are 213 m and 275°.

The distributions of wavelength and direction are shown in Figure 12, and probabilities within specified ranges given in Tables 2 and 3. Note that because of the near-uniform distribution of wavelength over much of its range, Table 2 has larger bin sizes than the figure. Some information on the accuracy of estimates of direction and wavelength from the SAR processor would help to decide appropriate bin sizes.

Table 2 Percentage of wavelength observed in 50 m bins - λ is the mid-value, so e.g. λ=50 m gives the percentage from 25 to 75 m

λ(m)	50	100	150	200	250	300	350	400	450
%	0.62	15.40	21.94	16.59	20.03	15.53	8.99	0.84	0.06

Table 3 Percentage of wave directions (from) observed in 10° bins - tabulated 'dir.n's are the mid-points of the bins

dir.n	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340
%	<0.01	<0.01	0.01	0.06	0.50	4.0	20.3	38.9	6.3	17.8	11.0	1.00	0.21	0.03	<0.01

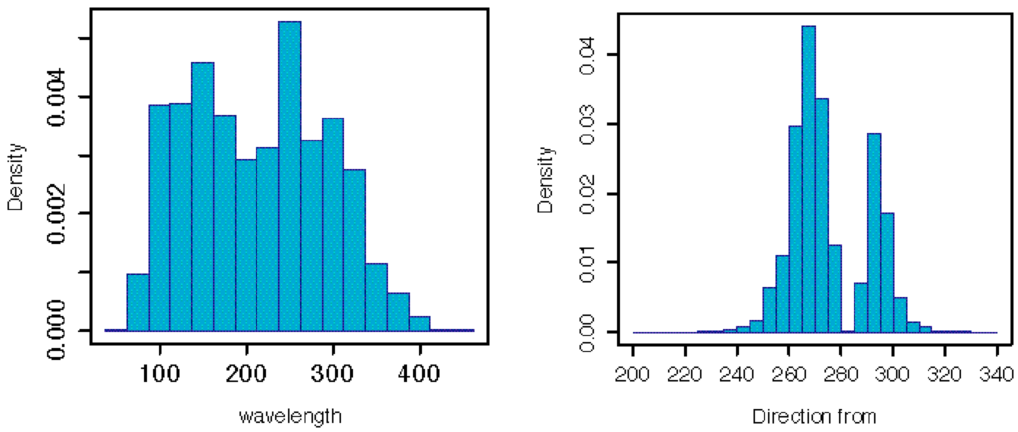


Figure 12 Distribution of wavelength in m (left), and direction (°) from which the waves are coming (right) from 18529 values from 27 scenes during Nov - March

Spatial variability

To see whether there was any discernible spatial differences over the area of analysis, data were extracted into 0.5° latitude by 1° longitude bins, from 59.5 to 60.9°N, 4° to 8°W; and the mean and standard deviations of wavelength and direction calculated. Results, together with the number of data in each bin, are given in Tables 4 and 5.

Table 4 Number, mean and standard deviation of wavelength (m) in 0.5° by 1° bins

	wavelength	***8° - 7°W***	***7° - 6°W***	***6° - 5°W***	***5° - 4°W***
	N	1354	2498	1856	775
60.4° - 60.9°N	mean	232	211	194	212
	s.d.	83	84	77	57
	N	2087	3684	2151	987
59.9° - 60.4°N	mean	220	203	210	228
	s.d.	81	80	78	62

Table 5 Number, mean and standard deviation of wave direction in 0.5° by 1° bins

	Direction (from) °	***8° - 7°W***	***7° - 6°W***	***6° - 5°W***	***5° - 4°W***
	N	1354	2498	1856	775
60.4° - 60.9°N	mean	272	279	277	276
	s.d.	15	15	15	14
	N	2087	3684	2151	987
59.9° - 60.4°N	mean	274	275	274	276
	s.d.	14	14	15	15

The mean directions are remarkably constant throughout the area. The mean wavelengths are more variable, but there is no obvious pattern. With, on average, about 2000 data values in each bin, the standard error of the mean wavelength, assuming independent data, would be around 2 m, (s.d./√2000) so the differences in mean wavelength would be highly significant. But the data are not independent, coming from a small number of scenes; so without further knowledge of the degrees of freedom involved, it is impossible to say whether there is really any evidence of spatial differences.

Analysing the data by even smaller bin sizes, of 0.2° latitude by 0.4° longitude, we get the mean wave periods and directions given in Tables 6 and 7; while Table 8 gives the number of data in each bin.

Table 6 Mean wave period (s) in 0.2° latitude by 0.4° longitude bins

Lat° \ Lon°.	7.8	7.4	7.0	6.6	6.2	5.8	5.4	5.0	4.6	4.2
60.8	12.8	12.3	11.5	11.4	11.2	11.4	10.8	11.0	11.4	12.2
60.6	12.4	12.0	11.6	11.3	11.4	11.2	10.6	10.8	11.3	12.1
60.4	11.9	11.6	11.4	11.3	11.1	11.0	11.1	11.5	11.8	11.9
60.2	11.9	11.6	11.2	11.2	11.3	11.1	11.4	12.0	12.2	11.7
60.0	12.0	11.8	11.4	11.0	11.2	11.4	11.8	11.9	12.0	12.3
59.8	11.3	11.0	11.3	11.1	10.9	11.2	11.8	11.7	12.0	12.1

Table 7 Mean wave direction (°) in 0.2° latitude by 0.4° longitude bins

Lat° \ Lon°.	7.8	7.4	7.0	6.6	6.2	5.8	5.4	5.0	4.6	4.2
60.8	264.5	273.9	277.2	276.9	280.9	276.0	276.2	274.4	275.8	271.8
60.6	266.7	272.7	276.3	277.0	277.0	276.5	280.4	279.4	275.9	274.0
60.4	273.3	272.8	272.5	274.2	276.0	275.2	276.4	274.1	278.7	279.9
60.2	272.5	275.0	276.2	273.9	273.1	273.8	274.0	274.2	274.5	278.5
60.0	271.3	275.4	277.9	277.8	275.7	274.3	273.6	273.6	276.3	276.5
59.8	282.5	278.5	275.9	278.0	276.4	275.6	270.5	272.8	274.0	271.8

Table 8 Number of values of period and direction (°) in 0.2° latitude by 0.4° longitude bins; and total by longitude

Lat° \ Lon°.	7.8	7.4	7.0	6.6	6.2	5.8	5.4	5.0	4.6	4.2
60.8	89	189	223	301	244	221	189	134	84	32
60.6	159	296	379	462	451	355	327	266	173	74
60.4	199	338	447	599	606	436	446	283	208	171
60.2	251	429	565	578	632	413	341	174	154	123
60.0	199	348	551	529	559	385	310	216	138	116
59.8	45	110	204	195	245	123	134	130	98	96
Total	942	1710	2369	2664	2737	1933	1747	1203	855	612

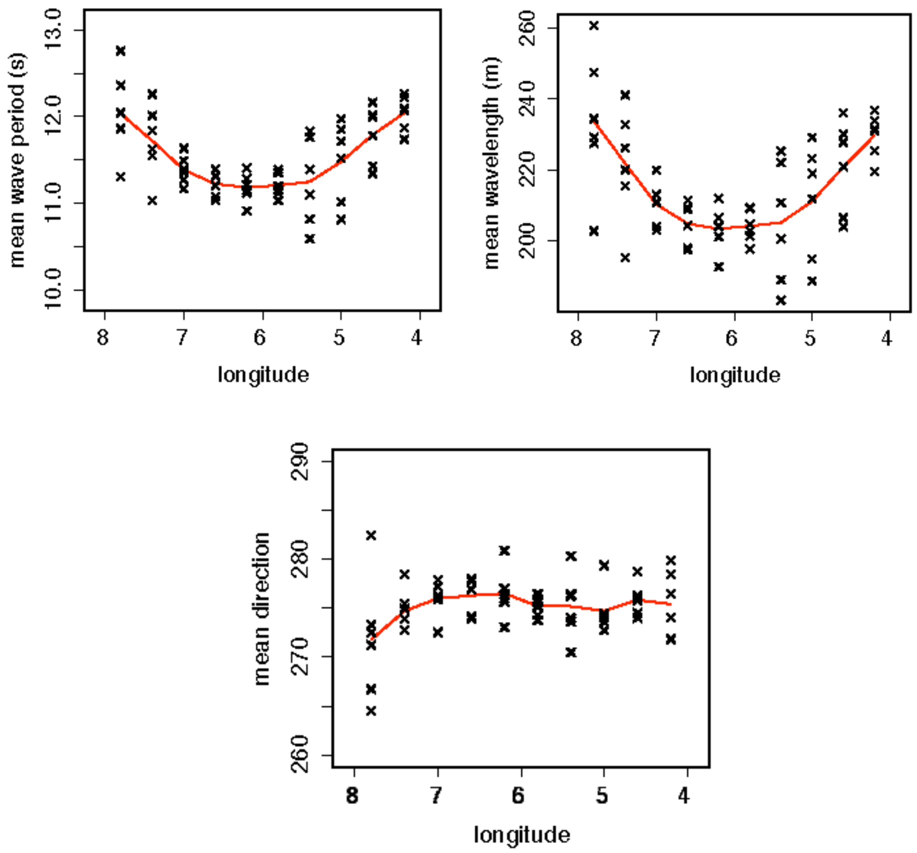


Figure 13 Mean wave periods (top left), wave lengths (top right), and wave directions (lower panel) in 0.2° latitude by 0.4° longitude bins against longitude. The red line gives the mean values.

There is no significant linear relationship between either mean period or mean direction against latitude or against longitude - nor is there a linear relationship between either and latitude + longitude. However, Figure 13 (top left) shows an intriguing non-linear relationship between wave period and longitude - but the reduction in spread of the means around 6° - 7°W is probably due to the larger number of data from which these means were calculated - see Table 8. There is a similar pattern in the mean wavelength, (Figure 13 top right) - as expected, because of the dispersion relationship - but no similar pattern in the mean directions, as shown in Figure 13 (lower panel); nor in the distributions against latitude.

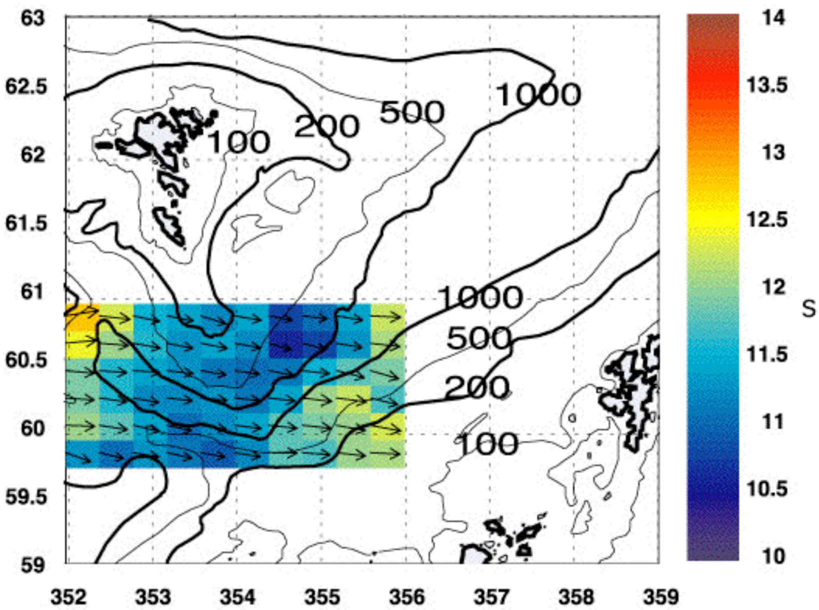


Figure 14 Plot of mean wave periods (s) and directions in 0.2° latitude by 0.4° longitude bins; and map of water depth (m). Wave period scale on right.

Figure 14 presents the same data in a different way, illustrating the spatial structure of the mean wave period, overlaid on a map of water depth in the area analysed.

Analysis of scatterplot modal values

Now turning to the 27 scatterplot modal values - the maximum of the bivariate distribution of wavelength and direction, with 25 m and 10° bin size. Figure 15 (left panel) is the sunflower plot of these values. Histograms of wavelength and direction are in Figure 16.

Figure 15 (left panel) shows that the dominant wavelength and direction are 250 m from 270°, in 7 - or 26% - of the scenes. It also shows that 27 scenes are insufficient to derive any more detailed information on the joint distribution of wavelength and direction. A % scatterplot of all 18529 data, in Figure 15 (right panel), gives the 'peak' bin, at 250m and 270°, with 8% of the data; the second peak is at 100 m, from 290°, with 6% of the data.

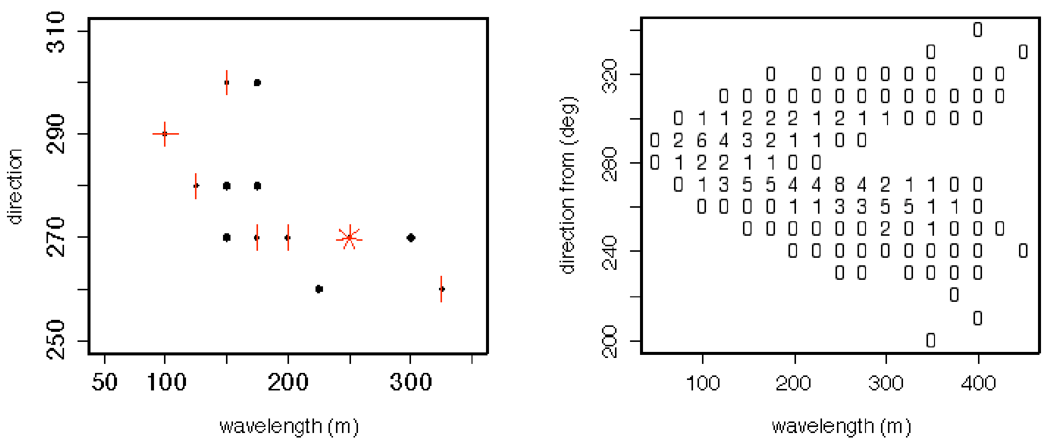


Figure 15 Sunflower plots of the 27 modal values (right) and scatter plot of % in each bin for all 18529 data (right) from the bivariate distributions of wavelength and direction

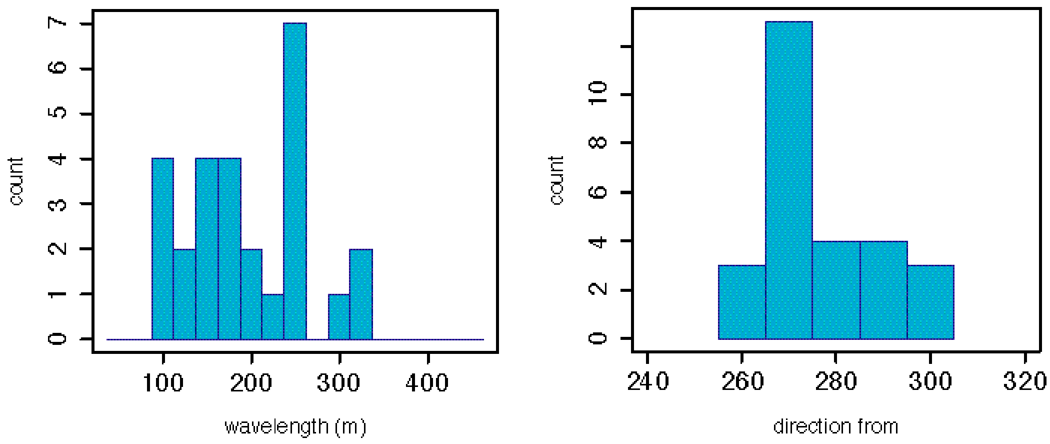


Figure 16 Distribution of 27 modal wavelengths (left), and directions (right)

2.3.6 Conclusions

Analysis of the data from 27 SAR scenes produced by the current QinetiQ MaST application has revealed a number of questions concerning the accuracy of these data and the sampling variability in estimates of wavelength and direction obtained from the 200 pixel by 200 pixels analysed. Some difficulties are specifically linked to the current wave processing algorithms employed within the MaST package, others are generic to satellite SAR imaging of the ocean surface.

With regard to generic SAR limitations it is known that satellite SAR cannot image shorter wavelength waves in the azimuth direction, and this wavelength cut-off can be calculated. It is also known that SAR can only offer useful wave measurements when the wind speed is between 3 and 13 ms^{-1}.

We have also observed what appears to be a distortion of the distribution in wave direction and a gap in this distribution aligned with the SAR range direction.

However, after reference to the literature, it does seem that this dispersion is more pronounced in the data processed through MaST and analysed for this project than in other data sets, offering the possibility that the distortion may be ameliorated to some extent by importing improved processing algorithms into MaST. Currently, the MaST application employs a linear approximation to the non-linear processes of velocity bunching and tilt modulation, and does not take into account hydro-dynamic modulation It may be that other “Model Transfer Functions” may perform this process more effectively

In spite of these uncertainties concerning the data, this investigation has been a useful study into possible methodologies for producing estimates of climate statistics of wavelength and direction.

The extraction of the modal, or peak, wavelength and direction from their bivariate distribution gave only 27 values of each parameter. These provided estimates of the most likely joint value, as well as the average wavelength and direction; but 27 is far too few for any further analysis of their joint distribution.

Using all the data appears to give sufficient numbers for a more detailed analysis, and revealed evidence of variation in mean wave period and mean wavelength with longitude across the area analysed, from 4°W to 8°W. However, we need further investigation into the accuracy and independence of these data before error estimates can be produced. Allowance should also be made for the widely varying data numbers from the SAR scenes.

The SAR gives indications of wavelength and direction which should be able to help in the provision of climate statistics at any location, although the limited range of wind speeds for which the SAR works will remain a problem and these data will probably have to be combined with information from other sources. However, considerable further work is needed, both to establish the accuracy of results from the processing of scenes and to determine how best to analyse these results, before SAR can provide a reliable and useful contribution to climate statistics.

Unfortunately all data in this part of the project were from descending passes, and so it was not possible to look at differences in wave measurements between data from ascending and descending passes.

2.4 NEAR REAL TIME MONITORING

2.4.1 Overview

A prototype Near Real Time (NRT) wave conditions monitoring service has been provided through a web based map server displaying present and recent sea state conditions in the NE Atlantic region. The user is able to select data sets, zoom into and out from selected areas, move backwards and forwards in time, and query individual data points (Figure 17).

This service is provided through an upgrade of the SOS/met.no[4] "CAMMEO" service, which is based on the "Metoc" web map server originally developed by CMR (Norway) and implemented by met.no, and which accesses data from near real time data feeds from SOS based on XML format data products. This GIFTSS project has helped support the inclusion of EO data on to the Metoc system, and benefits significantly from the substantial prior development work with Metoc supported by the European Space Agency. The bottom panel of Figure 2 provides an overview of the processing chain. Hourly inputs of data are loaded onto the central MetOc data base which maintains a 10-day running archive. These data are displayed through the CAMMEO MetOC web map server. EO and buoy data are supplied by SOS, and combined with other data (ship observations, met ocean forecasts, etc.)

2.4.2 Description of Data Sets Available

In the demonstration, altimeter data (wave height, wave period and wind speed), ASAR *wave mode* data (swell peak wavelength, direction and significant wave height), and scatterometer data (wind speed and direction) are processed in Near Real Time (within 3 hours of the time of the measurement) and made accessible through a user friendly web-based map server. The wave mode data set is acquired by SOS direct from ESA, who process the data in NRT using the new "ENVIWAVE" algorithms (Engen and Johnson, 1995). It should be noted that the (A)SAR *wave mode* data are not processed through the QinetiQ MaST package. The MetOc server also provides access to a number of other data layers, amongst them a wave model nowcast (from met.no). Table 9 details the EO data sources and Figure 17 provides demonstrations of some of the outputs from this CAMMEO service. SOS has issued a user guide (SOS, 2005).

Table 9 EO Data table for the near real time wave monitoring service. See the left hand side of the panels in Figure 17 for the CAMMEO "codes" referred to in column 2. Surface buoy data are also available.

Instrument	Source/ CAMMEO code	Parameters	Spatial overage	No. of passes /day over area of interest	Delay
Altimeter	Jason / jas1 ERS-2 / ers2 Envisat/ envi[5]	Hs, U10 Tz, Sig steepness	Whole region, along track data at 7 km res.	~6 / day	< 3 hrs
ASAR *wave mode*	Envisat / envwm	Swell direction, period & Hs	Whole region –along track products at 100 km separation	*~ 2 / day*	< 3 hrs
Scatterometer	ERS-2 / e2wi Quikscat / scat	Vx, Vy	Whole region, 25 km x 25 km cells	2 / day 500 km swath 2 / day 1800 km swath	< 3 hrs

[4] *Met.no is the Norwegian Meteorological Service*
[5] *Envisat altimeter data available from 18 May 2005.*

The EO data are available at geophysical data record maximum resolution (~7 km along track for altimeter data, at 100km intervals for the ASAR *wave mode* data, and on a 25 km x 25 km grid for scatterometer data).

It was not possible to establish a Near Real Time processing chain for SAR *image mode* data within the project, but a demonstration of SAR *image mode* data was incorporated (with a dummy date), to provide an illustration of what may be possible if such a scheme were implemented.

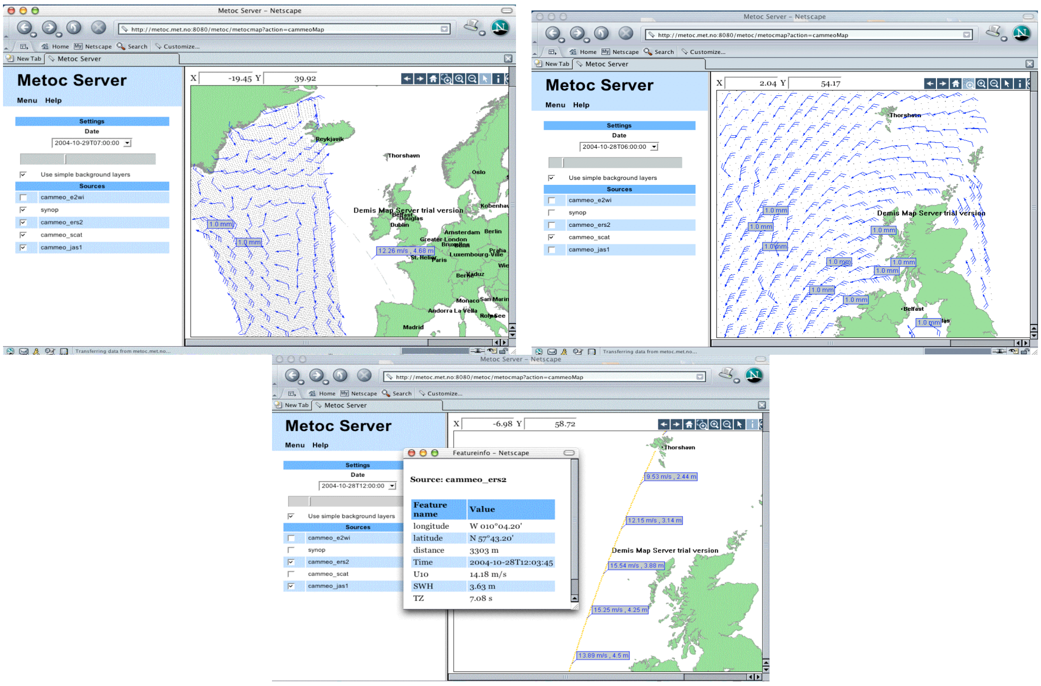


Figure 17 Example web map server display, with scatterometer (top panels), and altimeter (bottom panel) data.

2.4.3 Altimeter Data Processing and availability

Presently, Jason, ERS-2 and Envisat altimeter data are provided. These data are "pulled" to SOS by an automatic file transfer (ftp[6]) initiated every 10 minutes. The data are de-coded, quality controlled and calibrated, and then if they lie within the larger CAMMEO region (the whole of the North Atlantic region), reformatted (into XML format) and transferred via ftp onwards to a server at met.no.

This process takes place completely automatically, and has been found to be very reliable with a very low failure rate. The service specification gives a requirement for 99.9% reliability of the data processing, and twin servers are used to ensure this is achieved. If all three satellites and the data feeds are fully working in fact up to 12 passes a day are recorded over the North Atlantic.

Although altimeter data are also potentially also available from Geosat Follow-On and TOPEX, data from these satellites is not available in Near Real Time.

[6] *ftp – file transfer protocol, standard process for transferring files over the internet*

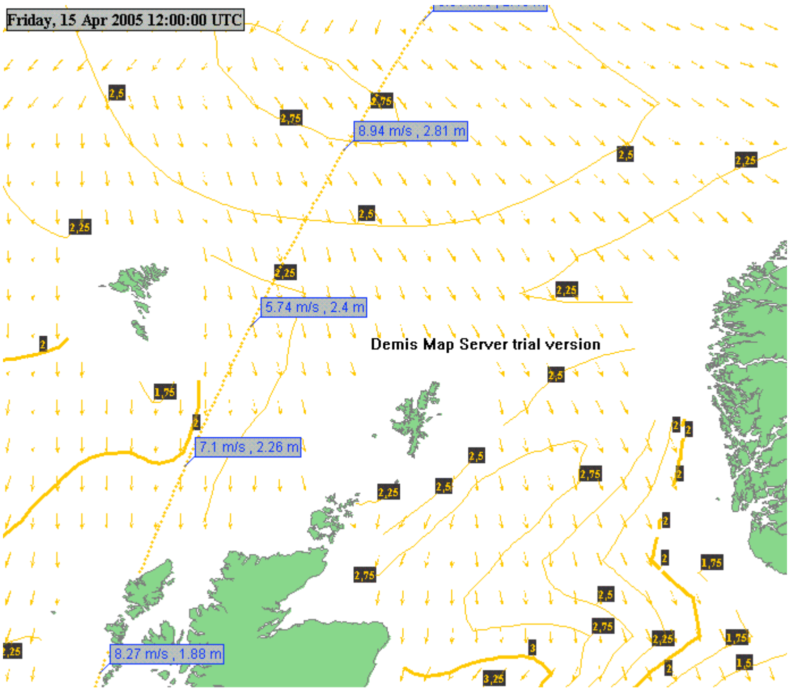


Figure 18 ERS-2 along track altimeter data (descending pass, running North East to South-West) overlaid on Norwegian Met Office Wave model predictions for significant wave height and dominant wave direction for 12 UTC on 15 April 2005

Figure 18 shows altimeter data combined with output from the Norwegian Met Office wave model. Although the display is not ideally suited, it is possible to compare the model predictions with the altimeter measurements, which in this case show reasonable agreement.

Possible improvements to the display could provide some immediate graphical representation of the altimeter measurement (or an option to switch to along track labelling at shorter intervals). Also it would be useful to have options to display the altimeter derived wave period, to enable comparisons with the model predictions. At present access to the full altimeter wave data set is possible either by clicking separately at each point on the altimeter track and reviewing the text box that is subsequently displayed, or by using the 'tooltip' feature that provides pop-up details of data when the cursor is over a data point.

2.4.4 ENVISAT ASAR *wave mode* Data Processing and availability

Near Real Time ENVISAT ASAR *wave mode* data products, which provide mean wavelength and direction, significant wave height, and wave energy in 24 x 36 wave length / direction bins, are generated by ESA processing facilities. These data are processed by ESA and made available to approved organisations (which includes SOS) in NRT (most in under 3 hours) on a central data server. The QinetiQ Mast application is not used in processing the (A)SAR *wave mode* data set.

Within the CAMMEO system, the ENVISAT ASAR *wave mode* data are processed in a similar way as the altimeter data. An automatic script transfers over new wave mode data, decodes them, quality controls them, checks for data in the CAMMEO region and, if they are, reformats them and sends them onwards to the MetOc server. In principle there should be data from the same number as passes as are available from the ERS-2 altimeter, as ENVISAT and ERS-2 are on the same orbit, with a time offset. However, we have found that in practice disappointingly little wave mode data are coming through the process. In fact data are only making it onto the server and display for one orbit every 4 or 5 days. This situation requires further investigation.

In addition we now understand that a second ESA ENVISAT NRT FD data server is available, and it is planned to start uploading data from this server in the near future.

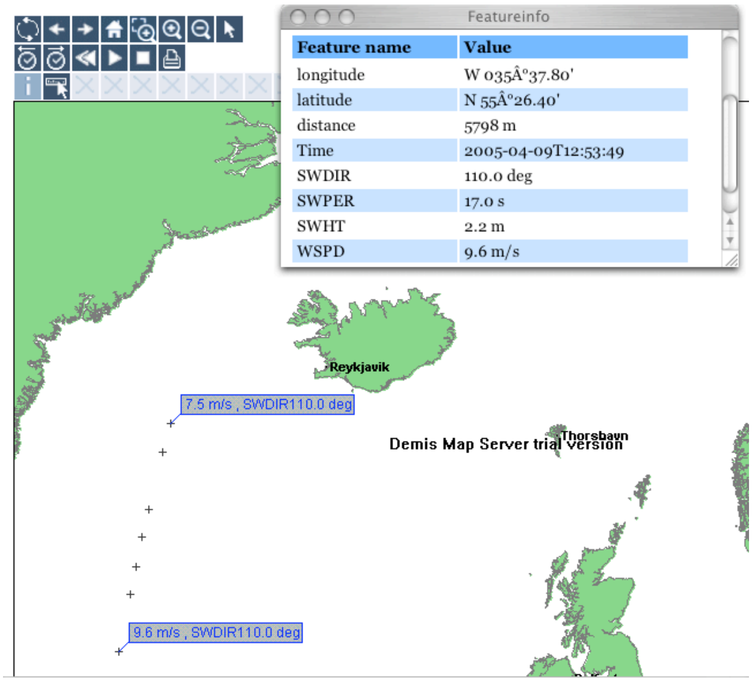


Figure 19 NRT display, with ENVISAT SAR *wave mode* data

Figure 19 illustrates an example of ENVISAT *wave mode* data from a descending pass in the North-Western Atlantic on 9th April. Again, at present, to access the full set of information it is either necessary to click on individual points and review the information box then displayed, or use the 'tooltip' feature. Improved display options are being discussed with the organisation responsible for the display software (Christien Michelsen Research, Norway), at the least this would include vector display of wave direction.

2.4.5 ENVISAT ASAR *image mode* Data Processing and demonstration

It is possible to establish a processing chain that would directly receive SAR *image mode* data through the QinetiQ West Freugh ground station, pre-process this image, transfer it down to QinetiQ Farnborough, automatically process this image with the MaST application and then reformat and send onwards to the CAMMEO server. A similar processing chain for ship and iceberg detection is already in place and being used on a regular basis at QinetiQ. Unfortunately the financial resources were not available within this project to acquire new SAR *image mode* data to implement and test such a chain in NRT for swell wave detection, but there are no technical barriers to modifying the processing chain already in place to suit this application. To provide an illustration of the output possible from such a system, a dummy SAR *image mode* data set (produced from two of the images processed in phase 1 of the project) was reformatted, labelled with a false date, and fed into the CAMMEO processing chain. Figure 20 demonstrates these data.

Again the display format is not optimal, and ways to implement a vector representation are being discussed.

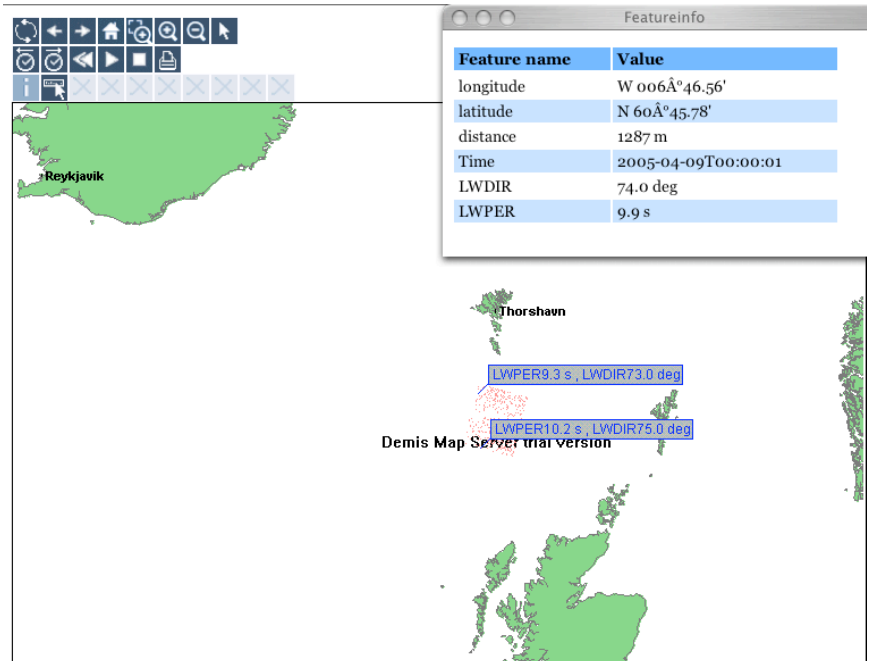


Figure 20 NRT display, with demonstration ENVISAT SAR *image mode* data

2.4.6 General Comments

The Near Real Time processing chain for individual products has been successfully demonstrated, and the web based map server implementation provides a very quick response to user queries.

Some improvements could be considered to suit the HSE/BNSC needs better, as follows:

- Improved visual/graphical representation of altimeter and SAR WM IM wave data.
  - Vector representation of direction information
  - Colour key or more frequent data labelling along track
  - Options to include extra parameters (wave period, significant steepness) on the main map display.
- Whilst the quality of data seems satisfactory the throughput volume of ENVISAT SAR *wave mode* data is disappointing. The cause of the low volume of these data making it through to the display needs to be investigated and rectified.
- A NRT SAR *image mode* chain could be established by QinetiQ, and could provide a significant increase in directional wave information available.
- When cycling the data displayed backwards and forwards in time, often no data are displayed. It is not clear to the user if this is due to slow response of the system (the remote computer, the internet connection or the client computer), or simply because there are no data in the region of interest. A way of providing information on whether data are available would be useful.
- HSE /BNSC are specifically interested in a reasonably localised region. An option to focus specifically on a selected region (and to go straight to that region on connection) would be useful. Alternatively a separate 'theme' could be developed within the current WMS specifically for HSC/BNSC. This would require a user to login. On login the user would be automatically directed to a homepage tailored to suit their user requirements. This may include restrictions on which data layers are visible (e.g. sensitive data could be made available to only HSE users), default mapping to the AOI, and inclusion of other functionality such as means of querying the data.

- Wider time windows (than 1 hour) might allow data from a number of satellite passes to be viewed at once, and allow an improved (and wider) comparison between model predictions and satellite measurements.

Figure 21 provides an illustration of the type of display / analysis that might be possible if improved display of wave parameters were available. This figure is a screenshot from the MetOc server, comparing satellite measured winds (blue) to model predictions (red). Good agreement is seen in the North East Atlantic, but there are some clear discrepancies in the Northern North Sea, directly to the east of the Shetland Islands.

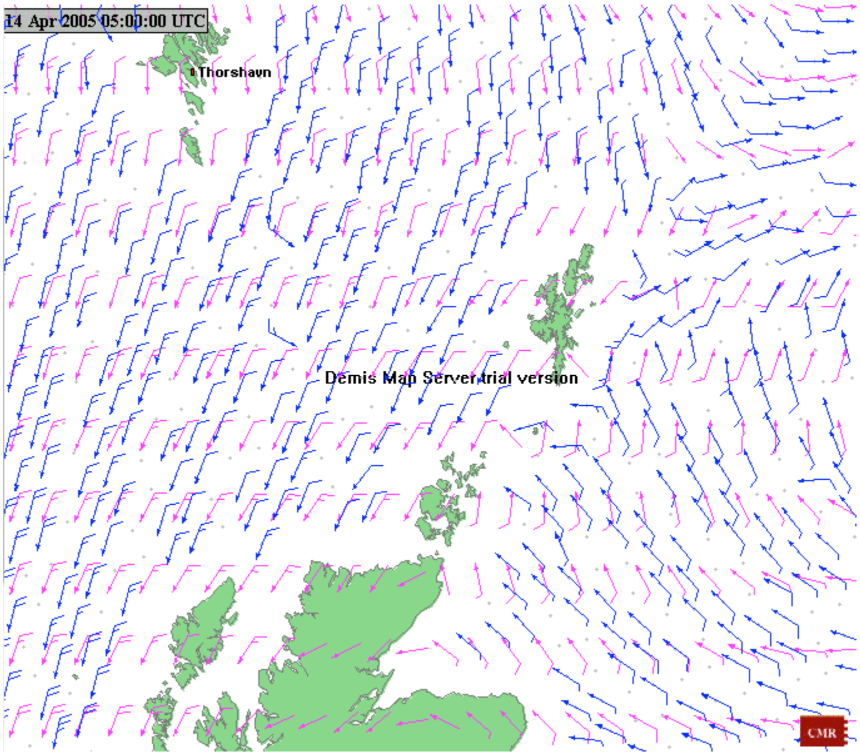


Figure 21 NRT display, comparing scatterometer wind data (blue arrows), with Norwegian Met Office model predictions (red) for April 14th 05 UTC

3 EVALUATION OF EO WAVE DATA SET

3.1 INTRODUCTION

This section reviews the accuracy of wave products available in near real time data and through compiled wave statistics. A brief assessment of NRT data, and of altimeter and SAR *wave mode* derived wave climate statistics is provided. The bulk of the assessment concentrates on the new SAR *image mode* data produced during the second phase of this project.

3.2 NEAR REAL TIME WAVE DATA EVALUATION

Near Real Time (NRT) data are provided at the best available resolution with no averaging. Procedures including quality checking and application of necessary calibration corrections are applied as part of the automatic data processing chain. We provide brief summaries of the accuracy and reliability of the individual measurements, and an assessment of the performance of the NRT processing chain as experienced during the brief trial carried out for this project.

3.2.1 Altimeter Data

Overview

The radar altimeter provides one measurement every 1 second (or 6-7 km) along satellite ground track. Wave parameters are estimated as a spatial average over 5-10km diameter region. Altimeter measurements of significant wave height and 10m wind speed have been extensively validated and applied. Recent work at Southampton Oceanography Centre has developed a technique for the estimation of wave period. This has been recently validated against model and *in situ* data and modified (Caires *et al*., 2005).
It is in theory also possible to derive estimates of significant steepness, peak period, and wave speed, but none of these parameters have been derived from altimeter data before (to the authors' knowledge). A first application should be tentative until careful validation has been carried out.

Accuracy

Significant wave height: accuracy 0.3m (0.5 - 15m), resolution 0.01m
10m wind speed: accuracy 1.5 ms^{-1} (0.5 - 15 ms^{-1}), resolution 0.01 ms^{-1}
Estimate of zero upcrossing period (experimental), accuracy 1 s (4-15 s), for wind speeds greater than 4 ms^{-1}.

(Potentially) significant steepness – A function of significant wave height and wave period. No direct validation has yet been carried out.
(Potentially) peak period – derived emprically in a similar fashion to zero upcrossing wave period, but further development required.
(Potentially) wave speed (proportional to wave period). But validation would be difficult

Reliability

Altimeter measurements are generally robust. No measurements available when non-ocean feature lies within altimeter footprint. Very heavy rain (centre of hurricanes of intense tropical storms) can attenuate and corrupt signal.

NRT Processing Chain Performance

As reported in section 2, Jason, ERS-2 and ENVISAT altimeter data are processed. The automatic processing chain is initiated every 10 minutes, and includes ftp transfer from the ESA FD archive, quality control, calibration and reformatting, and then onward transfer to the met.no server. The service specification gives a requirement for 99.9% reliability of data processing, achieved through the use of twin processors.

If all three satellites and their data feeds are fully operational up to 12 passes a day are recorded over the North Atlantic.

3.2.2 ENVISAT ASAR *wave mode* Data

Overview

The ENVISAT ASAR operates a continuous wave mode over the ocean which takes a "Snapshot" imagette of the wave field over 10km x 6 km region every 100 km along track. A new processing scheme (Engen and Johnsen, 1995) has been implemented in the ESA Near Real Time ENVISAT ASAR *wave mode* processing chain. The new scheme makes use of the cross spectra to resolve a previous 180' ambiguity in wave direction. All ENVISAT ASAR *wave mode* data demonstrated in this project have been processed, by ESA, with this new scheme.

The ENVISAT ASAR wave product provides an estimate of the ocean wave spectrum in 24 wavelength bins (from 30m to 800m) and 36 direction bins, and derived (long wavelength) parameters of significant wave height, mean period and peak period. An estimate of the azimuth cut-off wavelength is also provided. The movement and imaging process of the SAR distorts the measured wave spectrum. One of the features of this distortion is a lower cutoff in the measureable wavelength in the azimuth direction, which varies between 100m and 400m. This distortion affects all SAR wave products, whatever processing scheme is employed.

As for the altimeter, the estimates of swell and period could in theory be used to derive estimates of (long wavelength) significant steepness, peak period, and wave speed. The same caveats apply.

Accuracy

Johnsen *et al* (2004) have provided a recent validation against the ECWMF WAM wave model. We report their findings here

Significant wave height:	r.m.s accuracy	0.8m (3 - 7m)	for all data
		0.6m (3 – 7m)	for longer waves only[7]
Mean period ,Tm:	r.m.s accuracy	1.7s (7-14 s),	for all data
		1.1s	for longer waves only
Peak Period, Tp	r.ms accuracy	3.1s	
Mean direction	r.m.s accuracy	1 rad	
Peak direction	r.m.s accuracy	1 rad	
10m wind speed	r.m.s accuracy	2.2 ms^{-1}	

Significant steepness – as for altimeters, can be derived from Hs, and Tm, but applies to long wavelengths only
Wave speed can be calculated directly from peak period.
Neither has been directly validated

Reliability

Best reliability is for seas with periods between 8-15s, and wind speeds between 3-13 ms^{-1}.
Cannot see wavelengths lower than the azimuth cut-off in the along track direction (ranges from 100-400m, mean value is 235m).
Azimuth cut-off is higher for higher wind speeds.
Wind-sea distorted away from azimuth direction toward range direction.

[7] *In fact by comparing SAR and model data derived by integrating the wave spectrum for waves greater than 12s.*

Significant wave height is overestimated at low wind speeds, and underestimated at high wind speeds.

NRT Processing Chain Performance

ENVISAT ASAR *wave mode* wave spectrum files are pulled from the ESA NRT file server, quality controlled and reformatted, and then transferred to the met.no server. To date the volume of data throughput has been disappointing with only a low number of records being displayed. The possibility of relaxing the quality control criteria is being considered. It is also planned to start uploading data from a second ESA ftp site in the near future.

3.2.3 SAR *image mode* Data

Overview

An operational processing chain for extracting wave data from SAR *image mode* in Near Real Time does not currently exist, although the necessary basic infrastructure elements are in place and could be assembled by QinetiQ, using SAR images received at West Freugh station.
This assessment of SAR *image mode* data considers data processed through the QinetiQ MaST application. It is important to remember that SAR *wave mode* data and SAR *image mode* data have been subject to different processing schemes.

Accuracy

At present QinetiQ are using the MaST application to produce wave data from the SAR *image mode*. MaST provides wavelength and direction for resolved wave trains, at a selected sub-scene resolution. A 180° ambiguity is retained for wave direction. This project represents the first use of the QinetiQ MaST package to provide wave data for an operational application. Although we have endeavoured to provide as thorough an assessment as possible further work is required to provide a full validation. As reported in section 2.3, some problems have been identified with the MaST processing scheme and some ways to achieve possible improvements identified.

In principle the same ENVIWAVE algorithms as used for ENVISAT ASAR *wave mode* data could be applied within MaST (though the SAR image data must be pre-processed into Single Look Complex format), and the same accuracy acheived as for the wave mode data above.

Reliability

In addition to the issues generic to SAR imaging of ocean waves (azimuth cut-off, limited wind speed window, distortion of short wavelengths to range direction from azimuth), we have also found some additional issues specific to wave products derived through the QinetiQ MaST application (again, see section 2.3)

NRT Processing Chain Performance

An NRT chain has not been established for the extraction of wave data from SAR imagery. The infrastructure exists to support such a processing chain, starting with reception of SAR imagery and automatic pre-processing at West Freugh, through to ftp and generation of wave parameters with MaST at Farnborough, onward ftp to SOS, and then finally to Met. No. A similar processing chain is already in place and being used on a regular basis at QinetiQ for ship and iceberg detection.
In principle, dependent upon approval of requests to ESA for image requisition, (A)SAR images could be downloaded from every ENVISAT and ERS-2 pass within the region. The number of scenes available to download each day will depend upon the size of the AOI specified, the existence of conflicting and higher priority requests on the (A)SAR instrument, and the availability of the West Freugh receiving dish (which is shared with other users).

3.3 WAVE STATISTICS EVALUATION – EXISTING KNOWLEDGE

3.3.1 Altimeter Derived Wave Statistics

No new altimeter wave statistics product has been derived during this phase of the project. This was not viewed as necessary as the use of altimeter data for the generation of wave statistics is now well established and widely accepted by the offshore community. Such services primarily focus on significant wave height (and wind speed) measurements. Individual measurements have been shown to be reliable, and calibration corrections exist to ensure homogeneity across data sets from different satellites. The use of altimeter data bases to estimate low probability return values, from the interpolation of recorded distributions, is also regarded as acceptable. It is in the nature of these estimates that they are difficult to verify, however, an observed consistency with equivalent estimates from other data sources (*in situ*, model hindcasts) where they exist provides confidence that altimeter derived values are accurate and can be used in other locations, where other data sources are not available.

To date, altimeter estimates of wave period have not been used to derive climate statistics. It is therefore not possible to comment on the reliability of such possible applications (or of secondarily derived parameters: significant steepness and wave speed). However, work is continuing at National Oceanography Centre and Satellite Observing Systems to further develop and test the new algorithms which show much promise,

3.3.2 SAR *wave mode* Derived Wave Statistics

Some organisations provide wave statistics derived from SAR *wave mode*. As an example, ARGOSS, in the Netherlands, combine the long wavelength information from the SAR *wave mode* with a wind sea spectrum estimated from the satellite scatterometer (Mastenbroek and de Valk, 2000), and so provides probability distributions of mean wave period, zero upcrossing wave period, and joint probability distributions of significant wave height and mean period, significant wave height and zero upcrossing wave period, and significant wave height and wave direction.

The ARGOSS web site provides validation information from direct comparison of individual measurements against buoy data, but not of the overall wave climate against other sources. They note that the best results are obtained in the Pacific and Hawaii (which have a climate dominated by long waves), with the worst results in the Gulf of Mexico (with a wind-sea dominated climate).

3.3.3 SAR *image mode* Derived Wave Statistics

To our knowledge, SAR *image mode* data have not previously been used to estimate wave climate statistics.

3.4 WAVE STATISTICS EVALUATION – SAR IMAGE DATA FROM THIS PROJECT

This evaluation is possible through the availability to the team of Faroes waverider buoy data (1999-2004), the ECMWF ERA40 wave climatology (1957-2002), and a voluntary observing ship (VOS) dataset (Gulev *et al.*, 2003) based on the Comprehensive Ocean Atmosphere Data Set collection (Woodruff *et al.*, 1998). The latter data set is climatological and could not be used for comparison of coincident data. Eight SAR scenes were analysed within Phase 1, contemporary with the Faroes buoy, and were compared with that data therein (Cotton *et al*, 2005). The 27 SAR scenes analysed within Phase 2 are from the period 1992-1998 and are compared here with model and VOS data from the same period.

3.4.1 Direct comparison of SAR derived wave products against coincident ECMWF ERA40 data.

(a) ECMWF ERA40 data

The period of the dominant wave and the direction of the dominant wave period at 6 hour intervals was extracted from the ERA40 database for a seven year period (1982-1998). Note that these variables have not gone through the quality analysis and corrections applied to the more basic parameters included in the KNMI wave climatology (http://www.knmi.nl/waveatlas). Since the 27 SAR passes are each at ~ 1130 UTC they can be reasonably compared to model output for noon on the appropriate day. The model is an advanced deepwater wave model which should give fairly accurate hindcasts for deep water with adequate meteorological inputs. The model operates on a 1.5° x 1.5° grid and data were extracted for the 9 grid points given by longitudes of 4.5°W, 6°W and 7.5°W and latitudes of 58.5°N, 60°N and 61.5°N. Data at 4.5°W, 58.5°N is null as this lies in the Scottish mainland. Only data from 60°N strictly lie within the study area (4°-8°W, 59°-61°N) but together data from the eight valid grid points give a useful impression of the likely spatial variability. In the following figures, data from each grid point is analysed separately and presented in a map orientation (westerly data on left, northerly on top). Directions and wavelengths are presented in Figures 22-24. There is some spatial variability, but the main features are common to all eight grid points. The majority of cases give directions between south and west, but there are several values north of west and few directions <180° particularly in the north of the study area. Most wavelengths are between 100 and 300m peaking in the range 200-250m, with a few shorter and longer wavelengths.

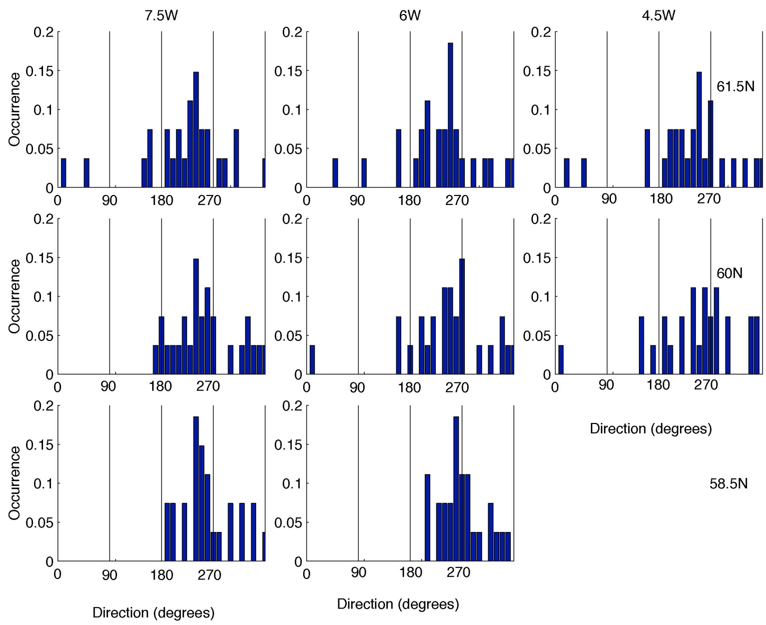


Figure 22 Occurrence of directions (from) among ERA40 data coincident to SAR passes, 10 degree intervals. Data from 8 grid points are arranged in a map-wise orientation.

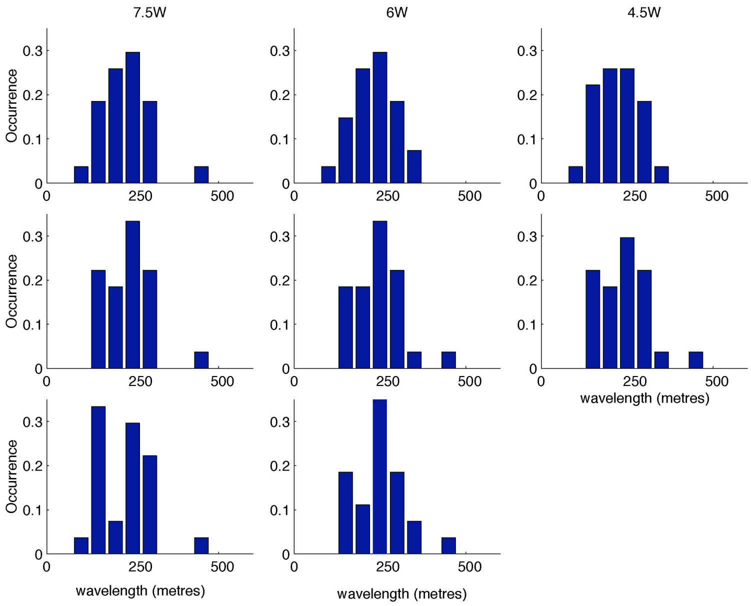


Figure 23 Occurrence of dominant wavelengths among ERA40 data coincident toSAR passes, 50 metre intervals. Data from 8 grid points are arranged in a map-wise orientation.

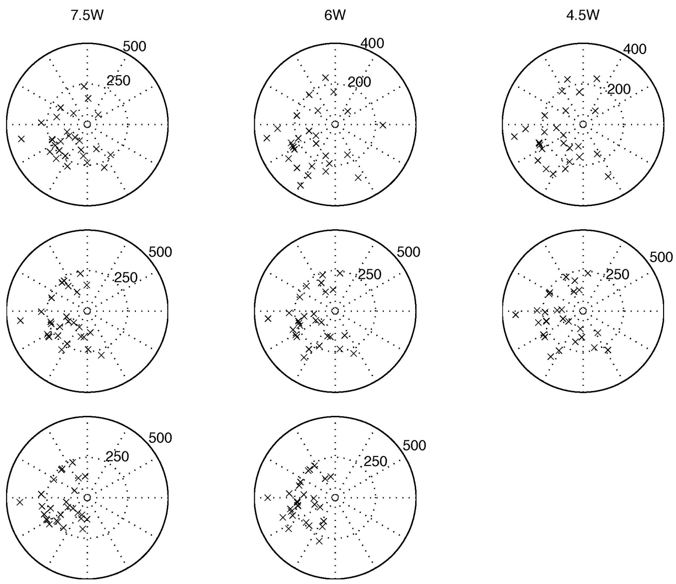


Figure 24 Polar plot of wavelengths (metres). and directions (from) among ERA40data coincident to SAR passes. Data from are arranged in a map-wise orientation.

(b) Comparison

Pairs of data from ERA40 and the 27 SAR scenes allow a direct comparison. Below, we plot the pairs of estimated wavelength and of direction. The results for wavelength are very encouraging with most data near a 1:1 line (blue diagonal). (Note however, that there are 3 coincident pairs at (235, 100)). There are no cases where the wavelength measured by SAR is substantially greater than that given by ERA40, but there are seven cases where SAR gives much shorter wavelengths (difference > 50m). There is no significant correlation in the SAR/ERA directions.

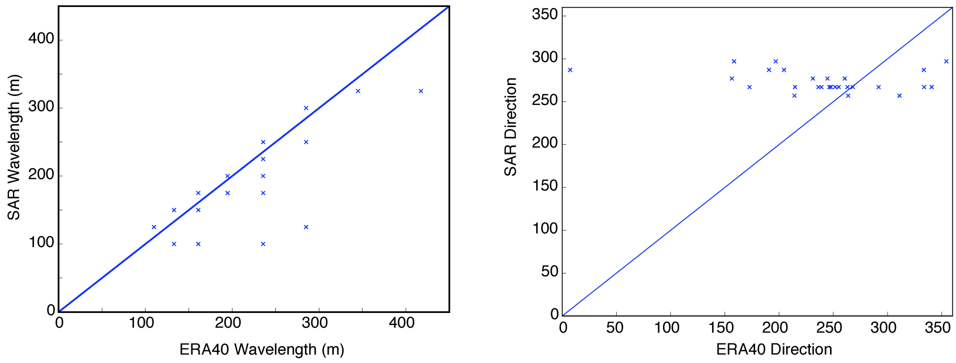


Figure 25 Wavelengths (left) and directions (right) from SAR and ERA40

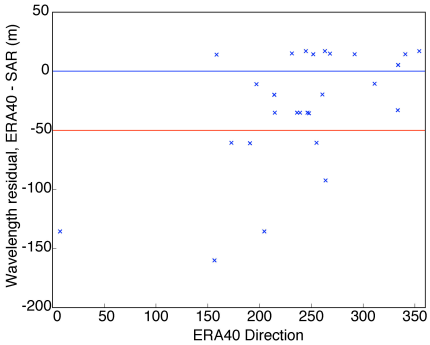


Figure 26 Residuals of wavelength plotted against wave direction by ERA40

In an effort to understand why SAR wavelengths are occasionally much shorter than ERA40 wavelengths, we plot the residual against ERA40 direction in Figure 26. Four of the seven large residuals occur when ERA40 implies the waves are from the southerly quadrant and a fifth occurs when ERA40 predicts a dominant sea from slightly east of North. In all these cases, as explained in Section 3.2.3, the sea predicted by ERA40 would be close to the azimuth direction for SAR down passes. This suggests that the error is usually with SAR.

3.4.2 Comparison of SAR derived statistics against equivalent statistics from

- Faroes waverider
- ECMWF ERA40 wave model climatology
- VOS climatology

(a) Faroes buoy

Figure 27 gives the distribution of wavelength (top left) and direction (top right) from 7419 records obtained by the waverider a few km SE of the Southern tip of the Faroe Islands during November to March (from February 1999 to February 2004). The wavelength was computed from the reported spectral peak frequency, and the given magnetic directions were reduced by 10° to obtain directions from true North. The top left panel of Figure 27 shows the lack of resolution at long wavelengths from the buoy analysis.

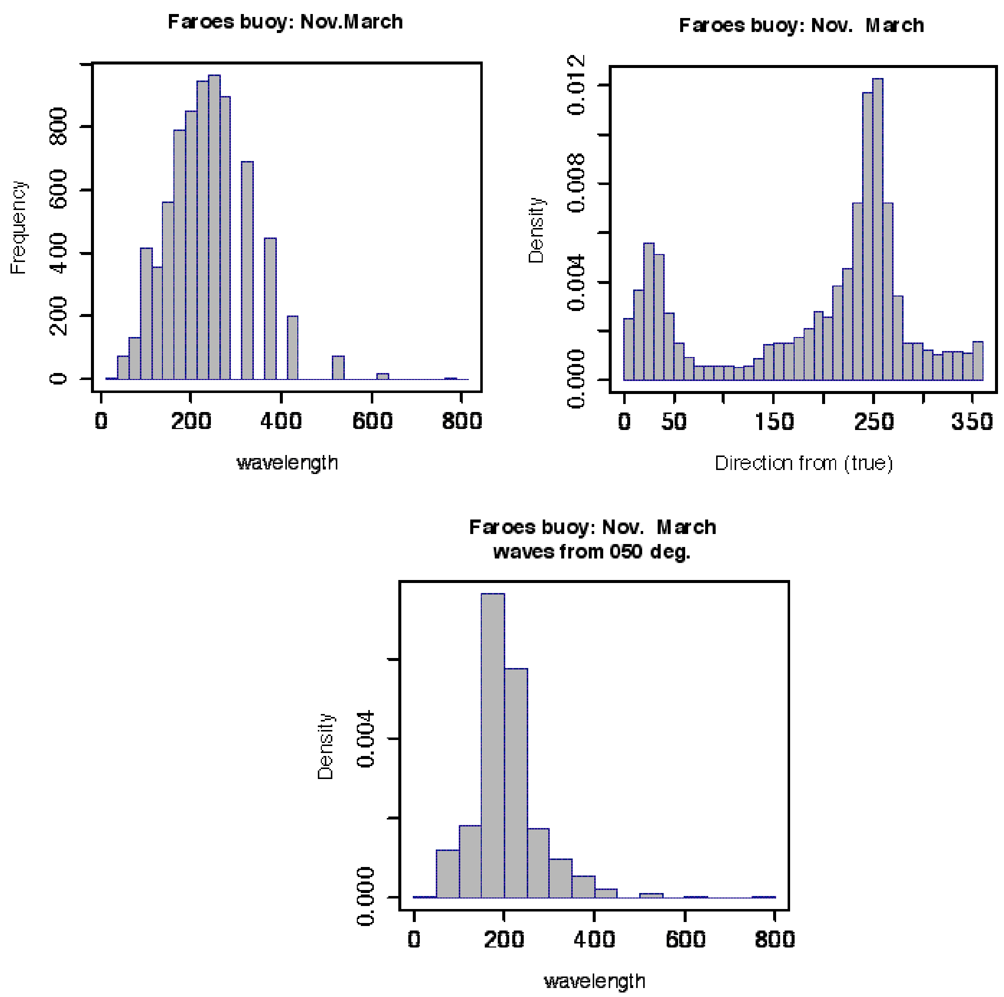


Figure 27 Distribution of wavelength (top left) and wave direction (top right) from the Faroes buoy records during November to March. The lower panel gives the distribution of wavelength when waves were from 0° to 50°.

The top -right panel of Figure 27 shows the peak direction around 250°, with a secondary peak around 30°. 19% of the waverider records had waves from between 0° and 50°. Moreover, these NNE.ly waves were similar in length to those from the SW, as shown in the lower panel of Figure 27, and included the longest wave observed by the buoy: 770 m, or 22 s.
The distribution of wavelengths from the buoy is more sharply peaked than other data sources. 55% of dominant wavelengths are between 150 and 250m and the mean wavelength is 229m.

(b) ECMWF ERA40

The data used are for the months of January February, March, November and December from 1992-1998 and as described in section 3.4.1. These form a large population describing the wave climate for these months in this period. These data are presented in Figures 28-32.

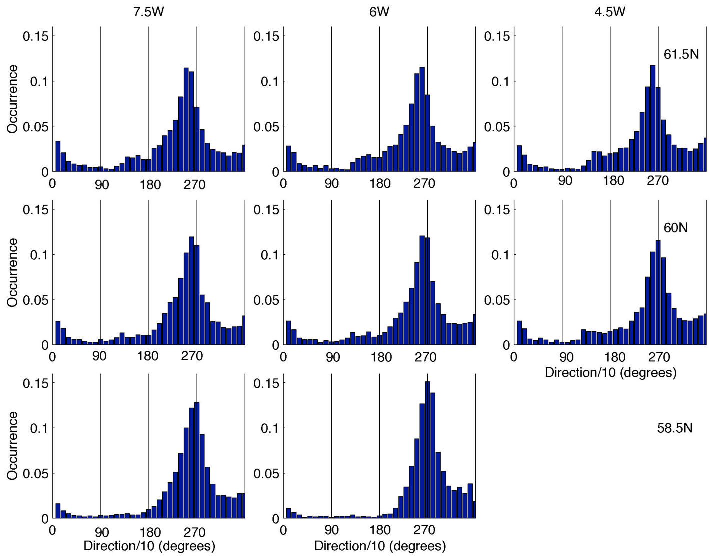


Figure 28 Occurrence of directions (from) among ERA40 data, 1992-1998, November-March, 10 degree intervals. Data are arranged in a map-wise orientation.

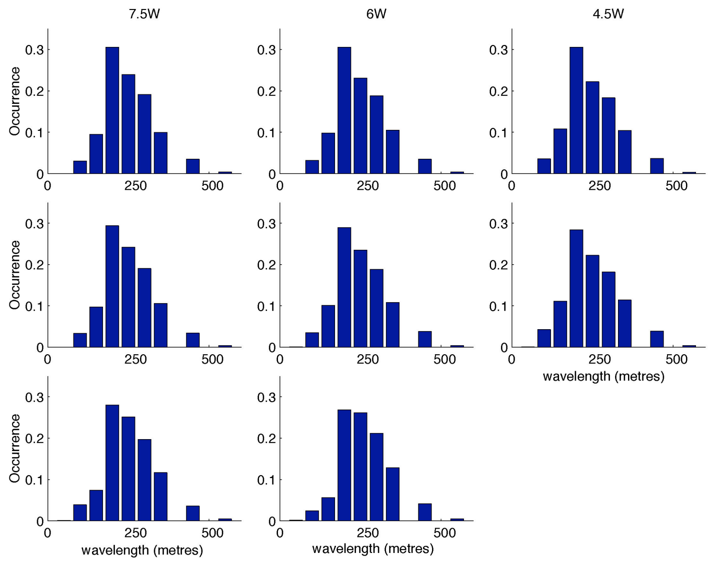


Figure 29 Occurrence of wavelengths among ERA40 data, 1992-1998, November-March, 50 metre intervals. Data are arranged in a map-wise orientation.

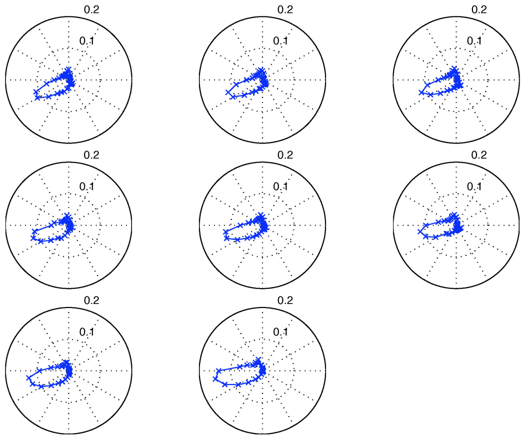


Figure 30 Polar plot of occurrence (radial co-ordinate) of directions ERA40 data, 1992-1998, November-March, 10 degree intervals. Data are arranged in a map-wise orientation.

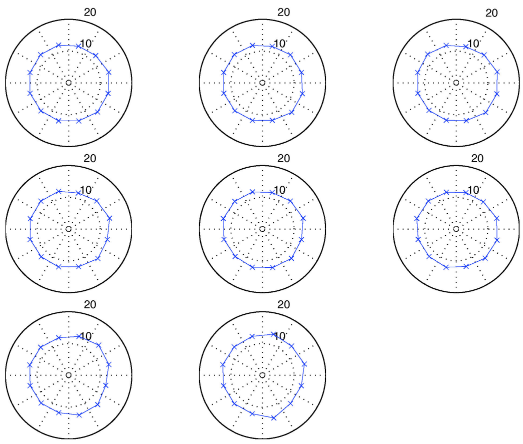


Figure 31 Polar plot of mean dominant period (seconds) from each 30 ° sector

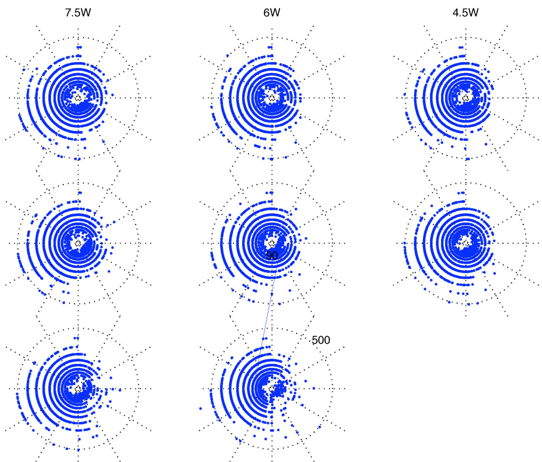


Figure 32 Polar plots of wavelengths (metres) and directions

(c) VOS wave climatology

Data from their climatology was provided by Sergey Gulev and Vika Grigorieva of IORAS, Moscow for the area 60°-61°N, 4°-8°W. Typically, there were of the order of 20 observations (not always of the complete set of wave characteristics) in each month in this area, but in some months there could be less than 10 observations. Thus, this data set is insufficient to fully describe the distribution of wave characteristics in each month and therefore the data provided by IORAS was limited to describing the average of each variable for each month. The standard procedure for VOS records is to report a wind/wind-wave direction and a wind-wave period, and a swell period and swell direction. Procedures at IORAS include definition of a dominant period chosen to be which of the two periods is identified with the highest wave period. Note also that the instructions to VOS participants is likely to lead to a measure of period akin to either "zero-crossing period" or "crest period" (Sergey Gulev, personal communication, 2005) either of which is likely to be 2/3 to 3/4 of the modal or peak period of actual interest. (see Tucker and Pitt, 2001). Directions for each month are calculated from a vector sum of phase velocity for all observations in that month. Directions for swell waves and wind waves are calculated separately. The data for 35 months, 1992-1998, November-March, are presented in Figures 33 and 34.

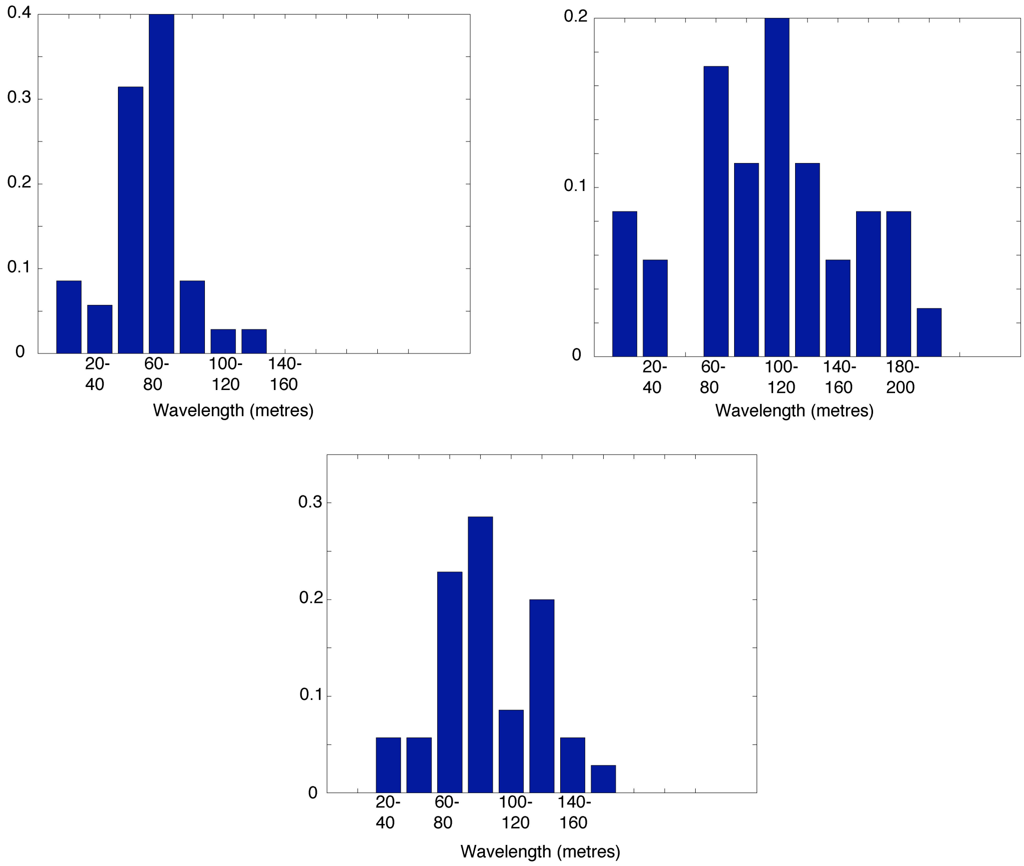


Figure 33 Occurrence of mean wavelengths of wind waves (top left) swell (top right), and dominant sea (lower panel) 10 metre intervals

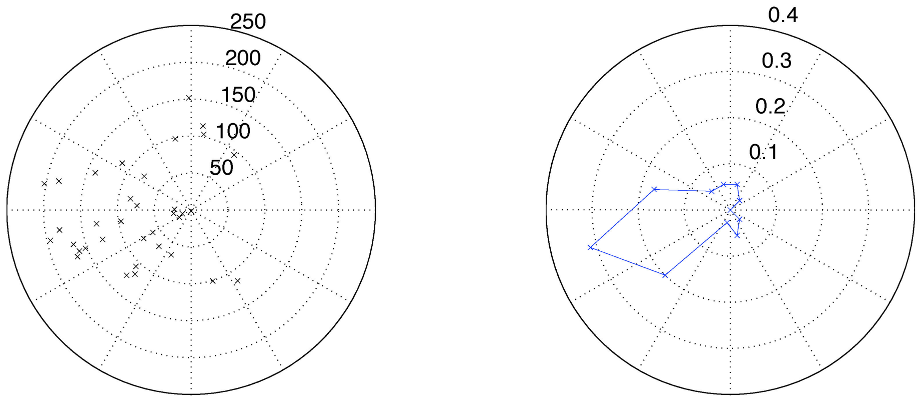


Figure 34 Polar plot of (left) swell directions and wavelengths (metres), and (right) occurrence of mean direction of swell, 30 ° intervals and swell

(d) Comparison

Comparing the three data sources described above to the SAR climatology (Section 2.3.5, figures 12 and 16), it is apparent that the SAR climatology captures the dominance of long waves from the west but both the angular and wavelength distributions from SAR appear unrealistically narrow. Before exploring possible reasons for this, it is worth discussing all four data sources and their special characteristics.

One of the most promising characteristics of SAR is that it offers a spatial resolution unrivalled by other data sources (see Section 2.3.5, figure 14). The ERA40 climatology does not match this high resolution but also offers evidence of subtle but significant spatial variability of the wave climate within the Scotland-Faroes channel. The most obvious feature in the ERA40 climatology is that waves from significantly south of west clearly dominate in the north west of the study region, but the dominant direction shifts close to west towards the south east. In the south, it is likely that the Scottish mainland and the Hebrides reduce the exposure to waves from more southerly angles; while in the north, the Faeroes may act as partial shelter from the north west. The occurrence of very long waves is also slightly lower towards the north, possibly due to obstruction of long wave waves from the north west.

The Faroes buoy is the best source of actual data, but its site may significantly impact on the results. Comparing the results from the Faroes buoy (Figure 27) and from ERA40 (Figure 28) a significant disparity in the occurrence of waves for the northerly quadrant is apparent. Errors in the ECMWF model or a climatic shift since the 1990s cannot be completely ruled out, but the distortion of the wave field by the Faroes and the surrounding shelf seems to be the most likely explanation for a slightly peculiar wave climate at the Faroes buoy site. Wave from north to northwest may be blocked, refracted or diffracted by the Faroe Island and surrounding shelf. Waves originating from the north-west may therefore arrive at the site from a more westerly direction, while waves originating from the north may eventually arrive from a more easterly direction. This may explain the pronounced and broad dip between two maxima at around 250° and 30° in the distribution of wind direction from the Faroes buoy. This compares to a less pronounced dip and a minor maximum at about 0° in the ERA40 distributions. Note that ERA40 is based on a 1.5° x 1.5° resolution deep-water wave model which will therefore poorly represent the influence of the Faroes. So we may expect that the Faroes buoy gives a much more accurate impression of wave climate at its site, but is very unlikely to be representative of wave climate further south for waves from 280° to 50°.

The VOS climatology provides the only actual in situ data for the region as a whole, but has some peculiarities. Note especially that the directions are vector sums of all observations in a given month. Therefore, we might expect a relatively narrow distribution of wave directions. In fact, the calculated swell directions populate a large sector from S to NNW peaking near WSW (Figure 34).

Having described some of the problems with the other data sources, it should be emphasised that whatever their exact direction, it is clear that waves from the Northerly sector are not uncommon and so the limitation of SAR observed wave directions to less than 330° among the (Figure 12, table 3) gives a poor representation of the true wave climate. Similarly, whilst waves from the south are relatively uncommon it is clear that they do occur, and so the very low occurrence of wave directions less than 230° among the SAR modal directions is also unrepresentative of the true wave climate. The SAR-estimated dominant direction of approximately 275^v appears to be reasonably accurate (possibly a little high) but as discussed in the next section this may be fortuitous and this accuracy is unlikely to be repeated anywhere that the wave direction is distant from the presumed range axis.

The comparison for wavelengths is far more favourable. The SAR data, the Faroes buoy and ERA40 all show a predominance of wavelengths from 100m to 300m. The wavelengths from VOS are much shorter but given their different definition, we expect these values to be approximately half the "dominant wavelength" defined in the other cases; therefore, the VOS results for swell waves are very consistent with the other data sources. The SAR data does not include wavelengths greater than 350m. Since there is no obvious reason why SAR would miss longer waves, it seems likely that it is just chance that longer waves from the west did not dominate on any of the 27 occasions. Note however, that ERA40 does suggest 400m waves from WSW on one of these occasions, (see Section 3.2.1). Note also that we have seen in Section 3.2.1, that SAR may severely under-predict wavelengths on some occasions. As discussed in the next section and elsewhere the absence of short waves (<100m) in the SAR database is wholly expected given the processing details and is a slight distortion of the true climatology.

3.4.3 Differences between SAR wave statistics from ascending and descending passes and a discussion of SAR imaging issues.

As shown in Figure 5, estimated directions from down track and up track SAR data are narrowly distributed around a central angle "the image angle", with a dip in occurrence at the precise image angle and a curious alignment of data along a number of curves. The total absence of data at the image angle is mysterious but other features of the data can be understood from previous work, notably a description of ERS SAR *image mode* wave processing by Kerbaol *et al* (1998) and details of ENVISAT ASAR *wave mode* processing by Johnsen (2005). In particular Figure 9 (from Kerbaol), shows some of the features apparent in this data set, albeit to a lesser extent. Very few waves are detected at a large angle to the range axis, and are limited to very long waves. The sparsity of retrievals at the range axis is attributed to the so-called peak-splitting effect (see Section 2.3.3, Annex A and Brüning *et al*, 1990).

The absence of any shorter wavelengths away from the range axis is due to the azimuth cut-off.. The general situation for the potential imaging of surface waves by SAR is illustrated in Figure 35 (taken from Johnsen, 2005). The maximum wavelength is set by the image size and the minimum detectable wavelength in the range direction is in principle only limited by the resolution of the image and the Nyquist criterion. The minimum wavelength in the azimuth direction depends on environmental conditions but is often in the range 200-300m (Figure 36).

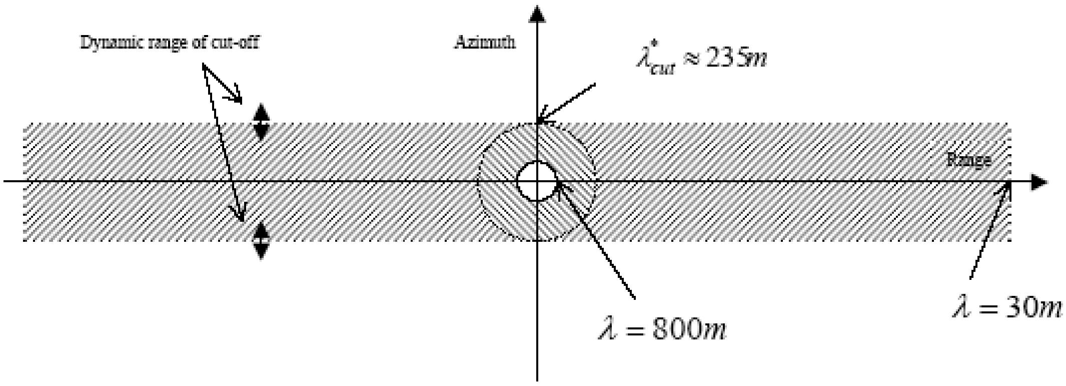


Figure 35 Range of wave resolution. Axes are wave numbers in the range direction and azimuth direction and the shaded area labels achievable resolution. Here for ENVISAT ASAR *wave mode* [from Johnsen, 2005]. Note that the satellite ground track lies in the *azimuth* direction (i.e up/down on this figure).

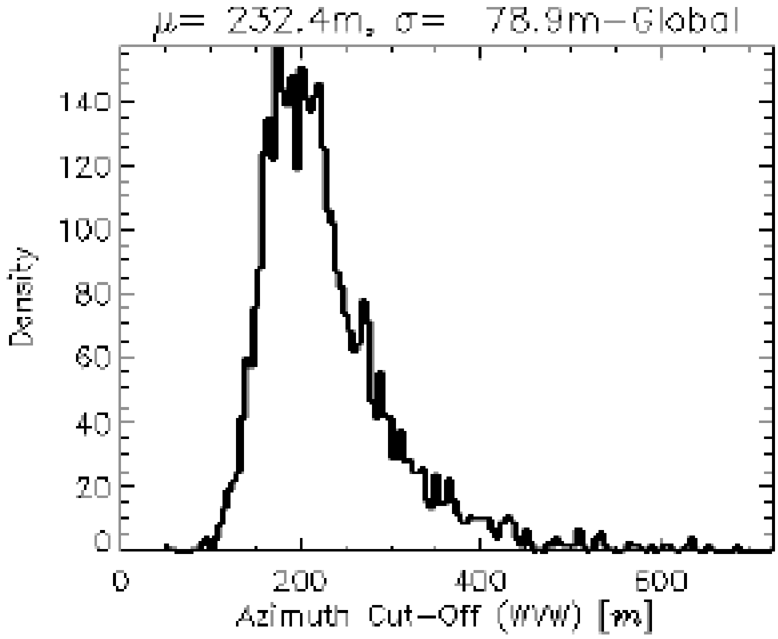


Figure 36 Calculated occurrences of azimuth cutoff for ENVISAT ASAR *wave mode* [from Johnsen, 2005].

Translating this background to the results from the MaST processing, the obvious interpretation is that MaST has an exaggerated limitation in detecting waves away from the range axis. The question then arises, what does the processing detect when the dominant waves are from a direction far from the range axis? It seems probable that given the complexity of natural seas there will usually be some sea from closer to the range axis and this will be detected instead. This is consistent with the observation in Section 3.2.1 that SAR often gives much shorter wavelengths than ERA40 when ERA40 predicts that the dominant sea will be near the azimuth axis.

3.4.4 The Effect of a Limited Wind Speed Window for SAR Derived Statistics

As has been noted in previous reports, the SAR's ability to 'see' waves is limited by wind speed; only imaging them if wind speed is in the range of roughly 3 - 13 ms^{-1}. (The upper limit is dependent on sea state and wave direction, and sometimes SAR will not image waves even when the wind is 11 ms^{-1}.)

The GIFTSS's area to the NW of Scotland is particularly windy in the winter. Here, altimeter data is used to investigate how wave climate derived from SAR in this area might be affected by 'wind cut-off'.

Median values of significant wave height, Hs, and wind speed, U, were taken from each transect of Topex and of ERS-2 crossing the area 60°-61°N, 4°-6°W during January and February (TOPEX from 1993 to 2004, ERS-2 from 1996 to 2004). This gave 248 values, of which one had U < 3 ms^{-1}, and 90 had U >13 ms^{-1}. Tp, the wave periods corresponding to the peak of the frequency spectrum, were estimated using Gommenginger *et al.* (2003), and the corresponding wave lengths were derived from the dispersion relationship.

The distributions of Hs given by all the data are compared to the truncated data set - although the QinetiQ MaST scheme does not provide estimates of Hs from SAR, these could be obtained if the SAR images were processed by the Engen and Johnsen (1995) scheme as included in the ESA processing chain for ENVISAT *wave mode* data and within the 'BOOST' scheme discussed in Phase 1 of the project (Cotton *et al.,* 2005). The distributions of Tp and the corresponding wave lengths are also compared.

Figure 37 is a plot of Hs:U, showing the many occasions with U>13 ms^{-1}, and indicating some correlation between Hs and U, suggesting that the distribution of Hs would be different from the truncated data set, limited by wind speed.

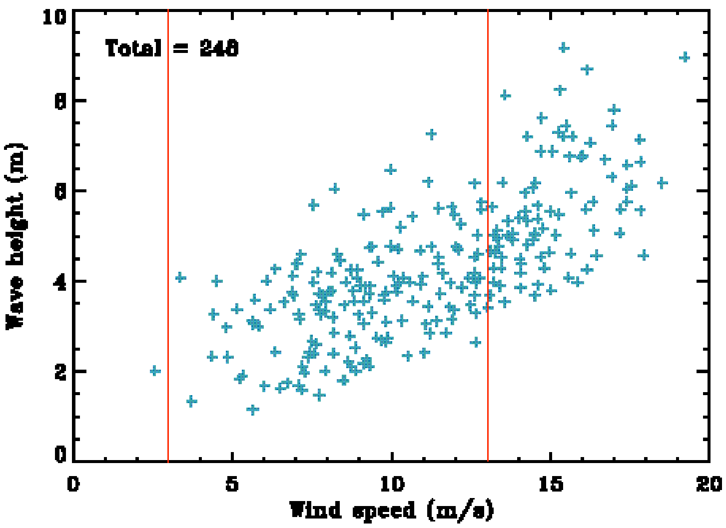


Figure 37 Distribution of Hs and U during January and February

Figure 38 shows that this is indeed so; the upper tail is most affected, as confirmed by Table 10. Clearly estimates of the percentage of high waves, including estimates of extremes such as the 50-year return value, would be seriously affected by the truncation.

The mean and standard distribution of all Hs were 4.33 m and 1.54 m respectively, and of truncated data were 3.62 m and 1.15 m.

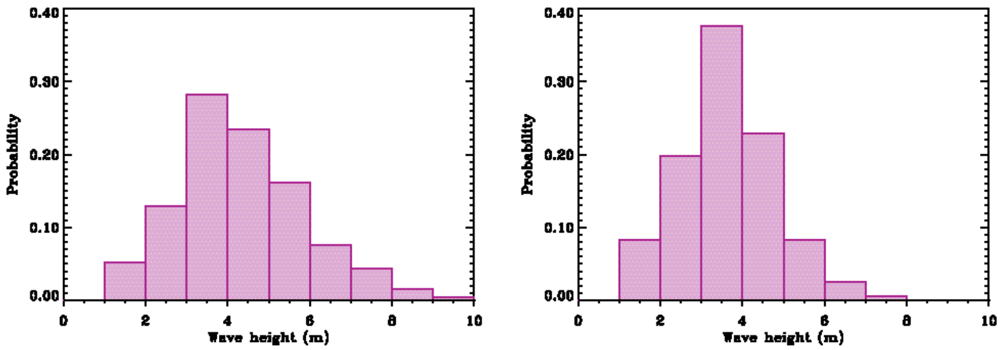


Figure 38 Distribution of wave height, left:all data, right: truncated data

Table 10 Wave heights (m) of specified percentiles. E.g. 50% of all data were >4.1 m, while 50% of the truncated data were > 3.67 m

%ile	*all data*	*truncated data*
10	2.33	2.11
20	3.12	2.61
30	3.54	3.10
40	3.86	3.36
50	4.10	3.67
60	4.54	3.88
70	5.01	4.08
80	5.59	4.45
90	6.47	5.26

Figure 39 shows the distributions of Tp.

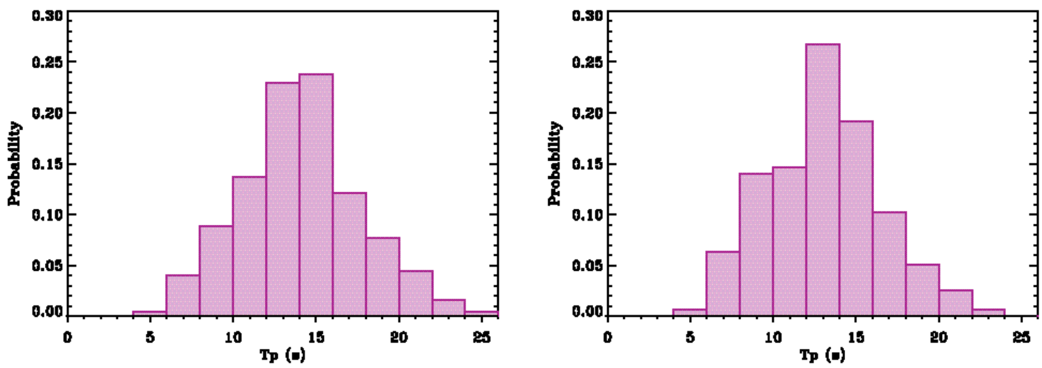


Figure 39 Distribution of peak period, left:all data, right: truncated data

The average of peak period seems less affected than Hs, with the mean lowered slightly from 14.1 s to 13.0 s in the truncated data set; but again the upper tail is reduced. The effect is more pronounced in the distribution of wavelength shown in Figure 40.

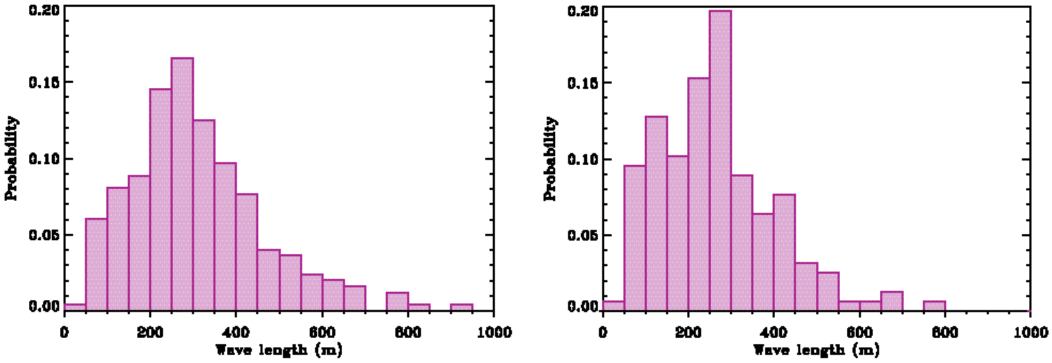


Figure 40 Distribution of peak wave length, left: all data, right: truncated data.

Note that this figure recalls an issue discussed in the previous section: SAR cannot resolve wave lengths of less than about 100 m in the range direction, and either misses or distorts even longer waves at an angle to the range direction. Fortunately in the winter months, north of Scotland, waves will be often close to the range direction (especially for descending passes) and much longer than 100 metres, but nevertheless there is likely to be this further distortion of the wave climate. Note also that the azimuth cut-off increases with wind speed, so that at high wind speeds it may be almost inevitable that the wave direction retrieved by SAR is very close to the range axis.

In conclusion, because of the high wind speeds often experienced during the winter, and because of the SAR's inherent inability (common to all SAR processing schemes) to image waves at these wind speeds, distributions of Hs, Tp and wave length obtained from SAR will be considerably distorted, especially in their upper tails. Estimates of average climate conditions may be acceptable, but estimates of extremes would be seriously in error.

3.5 SUMMARY

3.5.1 Altimeter Data

The ability of the satellite altimeter to provide accurate measurements of Hs, both in Near Real Time and in statistical analyses, is well established (rms accuracy 0.3m). A mean wave period parameter can also be derived and studies of individual values and compiled statistics have shown this to be accurate except in low wind conditions (i.e. < 4 ms^{-1}, otherwise rms accuracy 1s).
Algorithms exist to allow the derivations of other wave parameters from altimeter data, such as significant steepness, peak period and wave speed, but careful validation against a reliable reference data set would be required before any operational use.

3.5.2 SAR Data

The process by which SAR images ocean waves introduces a distortion of the wave spectrum which affects all SAR derived products. This includes a lower wavelength cut-off in the azimuth direction (for ERS-1, ERS-2 and ENVISAT this is oriented parallel to the satellite ground track), and a distortion of the direction of shorter wavelength waves towards the range direction (for ERS-1, ERS-2 and ENVISAT perpendicular to the satellite ground track), In addition SAR imaging of ocean waves is only effective when the surface wind speed (at 10m) lies between 3 ms^{-1} and 13 ms^{-1}. It was shown that whilst estimates of average wave climate conditions from SAR might be acceptable, this limitation would lead to a serious error in estimates of extreme conditions.

Within this project we have considered wave data generated through two routes.

ENVISAT ASAR wave mode

ENVISAT ASAR *wave mode* data are processed in Near Real Time by ESA, using the new"ENVIWAVE" algorithms (Engen and Johnson, 1995), which processes "Single Look Complex" SAR sub-scenes, resolves a previous 180° ambiguity and allows an estimation of significant wave height, wind speed, and provides a wave energy spectrum in 24 x 36 wavelength by wave direction bins. Initial assessment of the ENVISAT ASAR *wave mode* product outside this project has indicated that best accuracy is obtained in the wave period range 8-15 s (Hs rms accuracy 0.8m, Tm 1.7s, Tp 3.1s, direction 1 radiona). In principle wave speed and significant steepness (for longer waves) could be calculated but, as for altimeter data, careful validation against a reliable reference data set would be required before any operational use.

SAR image mode

Within this project .PRI (Precision Image –amplitude image only) SAR *image mode* data have been processed by QinetiQ using the MaST application. With the algorithms currently employed this application can estimate wavelength and direction from .PRI images at a selected resolution. The algorithms employed pre-date the "ENVIWAVE" algorithms, and apply linear approximations to represent the non-linear processes of velocity bunching and tilt modulation, but not hydrodynamic modulation. This process retains a 180° ambiguity in wave direction which is resolved by assuming the waves are travelling towards the nearest land.

Our initial analysis indicates a useful accuracy in wavelength (and so also period) may be obtained for waves travelling in the SAR range direction sector. However, wave directions appear to be unrealistically grouped close to the range direction. It is thought that the integration of improved Model Transfer Functions within MaST, used to process Single Look Complex Images (i.e. .SLC rather than .PRI) would improve performance.

4 ASSESS BENEFITS OF EO PARAMETERS

4.1 INTRODUCTION

The objective of this section is to assess the potential benefit of using new satellite data for wave statistics and NRT wave conditions monitoring, in comparison to presently available services.

This assessment covers the data products demonstrated and evaluated as part of phase 2 of this study, and also considers other options that are available: e.g. altimeter data demonstrated in phase 1, SAR *wave mode*, the use of the ENVIWAVE algorithms (Engen and Johnson, 1995) in processing SAR images. Following the assessments carried out in phase 2 of the project, the "grading" tables that were compiled in the phase 1 report (Cotton *et al.*, 2005) have been revised and these are included at the end of this chapter.

Separate assessments of the two categories of directional wave data from SAR are provided: data processed by the QinetiQ MaST application (with currently installed algorithms) and full 2-D wave spectra which are provided in the ENVISAT ASAR *wave mode* product (and can be provided by the application of the ENVIWAVE algorithms to SAR *image mode* Single Look Complex data).

4.2 WAVE STATISTICS

Availability and suitability of both EO and non-EO data were considered in Phase 1 as discussed in detail in Workpackages 1.1 (Woolf, 2004a), 1.2 (Carter, 2004a), 1.3 (Woolf, 2004b) and summarised in the final report of Phase 1 (Cotton *et al.*, 2005). Here we revisit the conclusions with particular attention to the additional information on SAR products from recent work.

4.2.1 Significant Wave Height

Altimeter

Individual measurements of significant wave height are typically accurate to about 0.3m (rms error) with no significant bias, at least in the range 0-10m.

The primary limitation of altimetry is sampling. With typically 4 altimeters available the estimated monthly mean of a 1x1 degree area will be accurate to about 0.5m or less. This error may double if only one altimeter is available. These issues were considered in WP 1.1 (Woolf, 2004a).

Altimeters orbit at an angle to the pole. The ground track of the TOPEX/JASON series is limited to within 66^{o} of the equator. The other altimeters cover an even larger area. Therefore there is no significant limitation in coverage

Altimeter data are available at the cost of reproduction[8]. In most cases, NRT data are of good quality, approaching that of the final archived versions.

SAR

MaST

The QinetiQ MaST processing scheme for SAR *image mode* data, with the presently installed algorithms, does not provide an estimate of significant wave height.

2-D Spectrum and ENVISAT wave mode

Application of the Engen and Johnson (1995) algorithms to both *image mode* and *wave mode* allows an estimate of significant wave height, but at best this can only be based on an

[8] *This is certainly true for Jason, TOPEX, Geosat and GFO. ESA policy for commercial use of altimeter data is not clearly defined*

integration of those waves long enough to image. Johnsen *et al.* (2004) estimate errors of approximately 0.8m with respect to ECMWF wave model data.

Sampling

Coverage is essentially global (given the right wind/wave conditions).

Thus far sampling by SAR has in practice been of the same order but more irregular than altimetry. ENVISAT ASAR should greatly enhance sampling but detailed figures are unavailable (Work Package 1.1, Woolf 2004a).

ENVISAT ASAR *wave mode* data should in principle supply a stream of up-to-date data, but so far in practice very little NRT data are available. According to ESA the only charge payable for ENVISAT ASAR *wave mode* data is for cost of production.

Combined Data Sets

Since coverage by SAR and altimetry are both sparse, there is an obvious benefit in using data from both. Scatterometry measures wind speeds rather than wave heights, but provides better coverage than either altimetry or SAR. Scatterometers also describe information on the forcing fundamental to waves.

For Near Real Time application, schemes have been developed to assimilate the long wavelength information from SAR *wave mode* NRT products into wave models, and so improve the model predictions (e.g. Breivik, *et al,* 1998). We understand that, currently, Météo France and ECMWF operationally assimilate ERS-2 and ENVISAT (A)SAR *wave mode* data. Recently Schulz-Stellenfleth *et al.* (2005) have proposed a scheme whereby model predictions can be used with ASAR *wave mode* data to generate a full wave spectrum where the ASAR *wave mode* data are available. This scheme offers a possible enhancement to the NRT system tested in this project

For statistical analyses Mastenbroek and de Valk (2000) have proposed a scheme that combines scatterometer and SAR *wave mode* data – using the scatterometer data to provide the short wavelength wind sea information, and the SAR *wave mode* data for information on long waves. Validation was limited to a relatively small number of co-locations and a more comprehensive validation exercise was recommended.

In principle, there is no reason why both the Schulz-Stellenfleth *et al.* (2005) and Mastenbroek and de Valk (2000) schemes could not be extended to apply to from SAR *image mode* data.

We have not been able to test such schemes within this project.

Comparison with Other Sources

Other sources have been described in Work Package 1.2 (Carter, 2004a). Apart from a very few data buoys the primary existing source of data are operational wave models (or reanalysis products for climatologies) and ship reports (compiled to produce VOS climatologies).

Visual observations of winds and waves by commercial ships have been archived for a century and a half, and became systematic following a resolution of the WMO in 1961. The most well known compilations of these observations are the OWS (Ocean Wave Statistics, Hogben & Lumb, 1967) and the more recent Global Wave Statistics (GWS, Dacunha and Hogben, 1989) which empirically corrects for biases that were identified in the earlier OWS. The main advantages of GWS⍁OWS are the length of the collection period, their suitability to shipping applications and the fact that they are well documented for the major shipping routes. The main drawbacks are the lack of information outside the main routes, the poor accuracy for wave periods (poorly estimated even by experienced observers), the lack of wind information, and some deficiencies in seasonal representation and in reporting extremes.

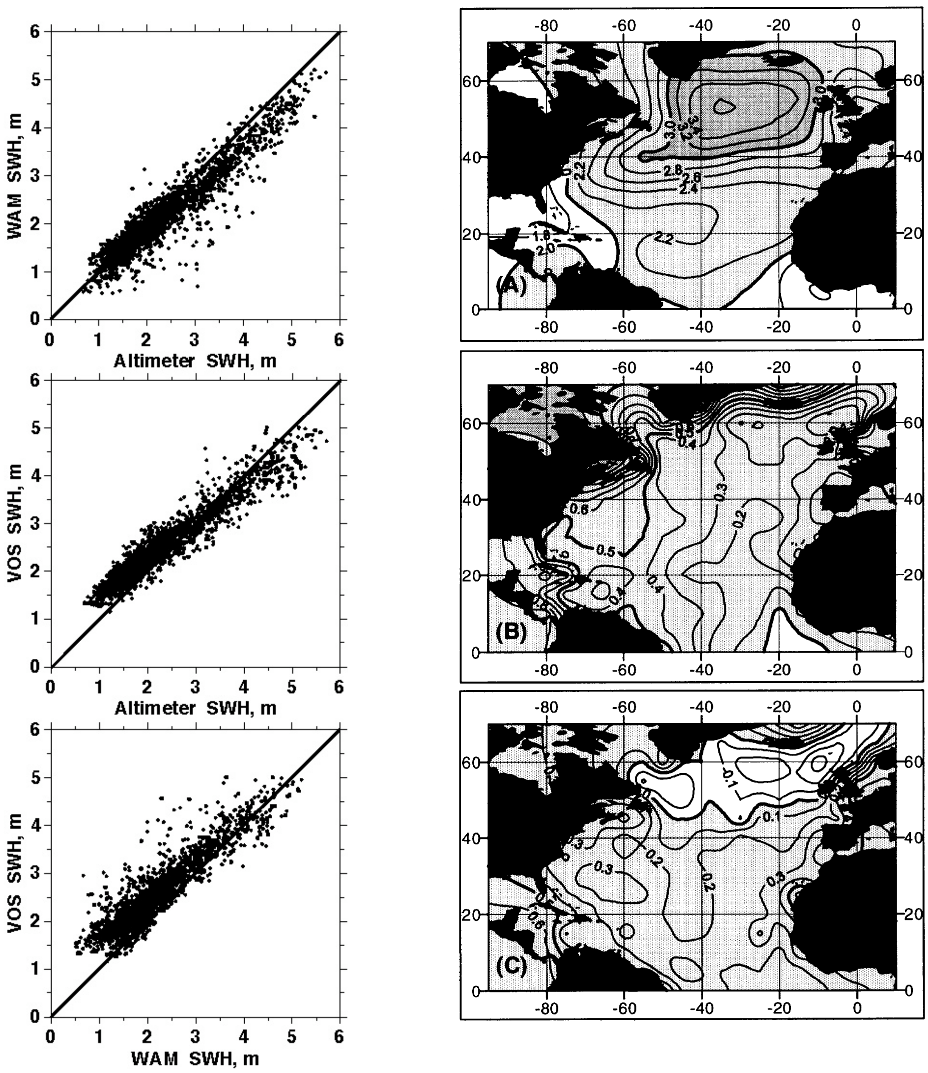


Figure 41 Comparisons of satellite data, model output and ship observations.
Left: Scatter plots of monthly means on a 5° x 5° North Atlantic grid, from the ALT, ERA/WAM and VOS data sets. top - WAM v ALT, (middle) VOS v ALT, (bottom) VOS v WAM.
Right: (A) Mean VOS significant wave height climatology (1985-94) and difference plots against WAM (B) and ALT (C). Contours in m.

Hindcasts compute wave heights from historical wind databases. The computer codes that simulate the physical wave processes have reached a good level of maturity, but errors and uncertainties in the input wind fields are amplified by this process, as wave heights are roughly proportional to the square of the wind speed. The quality of the results is thus often impaired by the lack of accuracy or of validation of the wind data, especially for regions where few observations are available, such as in most of the southern hemisphere. The main advantages of hindcasts are that they provide world wide, long-duration histories of waves. The main drawbacks are that they are proprietary and costly, that they depend on the personal skills of the analysts who verified and corrected the wind fields, and that they have limited accuracy in extreme conditions. However, it should be noted that the availability of satellite scatterometer measurements of winds during the last decade has significantly improved the accuracy of the wind field. Cotton *et al.,* (2001) compare three types of wave climatology: one derived from visually observed ship data, one from a 15 year hindcast and one from satellite altimeter data. They show that the visually observed data tend to overestimate low waves and underestimate high waves, as do the hindcast model output (though to a lesser extent- see figure 41). Interestingly, they also found that the hindcast and visually observed climatologies show different patterns of long term trends in the North Atlantic. The altimeter data do not, as yet, provide a long enough time series to consider decadal patterns of variability.

It is noted that HSE also has access to the NEXT/NEXTRA wave model hindcast data, though they were not analysed here

In the case of NRT: Ship observations are disseminated by the meteorological communications net and are available on the web e.g from Oceanweather. Forecasts from wave models are widely available and like the hindcasts these are a mature product. However, additional errors in the forecasts may occur through errors in weather nowcasting and forecasting. There are reports (mainly anecdotal, but see Carter, 2004a) of significant under-predictions of wave heights in some storms.

Recommendations

Climatologies: Statistics on wave heights from altimetry are probably the most reliable currently available, though closely rivalled by the best model reanalyses. The longer climatologies from model reanalysis and VOS are also extremely useful for providing insights into longer-term variability. VOS is also the main source of data away from data buoys on the relative contribution of swell and wind waves to the total significant wave height. The primary limitation of altimetry climatologies is limited resolution. The standard product from altimetry up to now has been a 2° x 2° resolution, monthly climatology. A 1° x 1° climatology is the best achievable from altimetry with present sampling; but note that the extension of such a climatology in future years requires maintenance of a similar constellation (~4) of altimeters, which cannot be guaranteed (See Table 13 in section 5, which lists planned future missions). A single altimeter is sufficient for a 2° x 2° degree climatology and future provision at this level is fairly certain. SAR *wave mode* seems to be able to produce a credible climatology (Johnsen *et al.*, 2004) but there has been little research on the bias associated with a varying angle between dominant wave direction and range axis. We suggest that further fundamental research on SAR is still required. In the future, the data on specific portions of the wave spectrum, especially information on swell, could be a very useful adjunct to significant wave height climatologies from altimeter data.

Near Real Time: Earth Observation cannot provide sufficient data coverage to entirely supplant wave model output. However, information from both altimetry and SAR is a useful “check” on model output that should be very useful if supplied as a well-designed “graphical overlay”. Scatterometer data also add context and should also be available as an overlay.

4.2.2 Wave Period / Wave Length

Altimeter

Root Mean Square errors in zero-crossing periods and mean periods are approximately 1 second (Gommenginger *et al.*, 2003). Errors in peak periods are much higher, about 3 seconds.
Sampling issues are likely to be similar to measurement of SWH but have not been quantified yet.
Altimeters orbit at an angle to the pole. The ground track of the TOPEX/JASON series is limited to within 66º of the equator. The other altimeters cover an even larger area. Therefore, there is no significant limitation in coverage

Altimeter data are available at cost of reproduction. In most cases, NRT data are of good quality, approaching that of the final archived versions.

SAR

SAR is most suited to measuring dominant period. All processing methods can at least measure peak period.

MaST

We have seen in Section 3.2.1, that MaST estimates of wavelength are generally within 50m of hindcast estimates. This is very encouraging and suggests an accuracy of 1-2 seconds of both estimates of dominant period in most cases. However, we found that on some occasions the MaST estimates could be unreliable, especially if the direction of the major sea is close to the azimuth axis

2-D Spectrum and ENVISAT ASAR wave mode

Johnsen *et al*. (2004) estimate errors of approximately 3.1s in ENVISAT ASAR *wave mode* data with respect to ECMWF wave model data. Where more of the wave spectrum can be retrieved, other periods – most reliably those primarily sensitive to the longest waves – can also be estimated. Johnsen *et al*. (2004) estimate errors of energy period ($T_p = m_{-1}/m_0$) of 1.7s.

The full spectrum processing schemes (e.g. Mastenbroek and de Valk, 2000,, and Schulz-Stellenfleth *et al*., 2005) may fare better, but a bias between range and azimuth is inherent in SAR, and we have found no exploration of how this feeds into errors of period.

Sampling

Coverage is essentially global.

Thus far sampling by SAR has in practice been of the same order but more irregular than altimetry. ENVISAT ASAR should greatly enhance sampling but detailed figures are unavailable.

Combined

Since coverage by SAR and altimetry are both sparse, there is an obvious benefit in using data from both. Scatterometry measures wind speeds rather than wave characteristics, but provides better coverage than either altimetry or SAR. Scatterometers also describe information on the forcing fundamental to waves. Procedures to combine data from different sensors and with models have been discussed in section 4.2.1

Comparison with Other Sources

The situation for wave periods is largely as described above (Section 4.2.1) for significant wave height, but relatively little information is available for all sources of wave period data. Caires *et al*. (2005) have recently compared altimeter, ERA40 hindcasts and buoy data on mean wave period; estimating corrections for altimeter and hindcast data and random errors in each. Generally the random error in mean wave period is less for altimetry than ERA40 suggesting it should be the preferred product. Estimated mean (zero upcrossing) wave period from altimetry is certainly a useful product where swell is not dominant, (Gommenginger *et al.,* 2003), but Caires *et al*. also find that these altimeter values of mean wave period are also reliable in swell conditions if the wind is moderate or strong. Zero-crossing periods from altimeter are likely to be similarly competitive but altimeters are probably not the best source of data on dominant/peak periods or swell periods (Gommenginger *et al*., 2003). The analysis described in Section 3.2.1 is encouraging with respect to both wave models and SAR in that both must have considerable skill in estimating the dominant period and wavelength. However, SAR has an “Achilles heel” in properly measuring seas closely aligned to the azimuth and this will surely bias SAR climatologies of wave period.

Recommendations

As for wave height, though the dependency of the accuracy in wavelength (and hence period) on wave direction is problematic and may undermine its use in NRT products. It is not known if this same dependency exists in the ASAR *wave mode* data (produced by the new ESA SAR processing scheme) as has been found in the ASAR *image mode* data processed through MaST. Whilst we note that climatologies including wave period (wave length) distributions derived from SAR *wave mode* data are commercially available, there is not sufficient detail in the accompanying literature to allow us to determine if this dependency on wave direction exists or is checked for.

Resolution of biases between range axis and azimuth axis inherent in SAR needs to be a research priority. Eventually, estimates of zero-crossing period and mean period by altimetry and dominant wave period / spectra limited to long waves from SAR will be useful complementary data for a combined climatology.

4.2.3 Wave Steepness

Altimeter

Altimeters can measure both significant wave height and zero-crossing period to a reasonable accuracy, so significant steepness is also achievable. However, it would be better to calibrate altimeter-derived steepness directly against wave buoys and this has not been done. The natural variability of steepness is not very broad so it remains to be seen whether estimated steepness will be sufficiently accurate to be of practical value.

Sampling issues are likely to be similar to measurement of SWH but have not been quantified yet.

Altimeters orbit at an angle to the pole. The ground track of the TOPEX/JASON series is limited to within 66° of the equator. The other altimeters cover an even larger area. Therefore, there is no significant limitation in coverage

Altimeter data are available at the cost of reproduction. In most cases, NRT data are of good quality, approaching that of the final archived versions.

SAR

The strength of wave imaging by SAR is closely related to wave slope. However, steepness is not a MaST product and is not a direct product of other processing schemes.

MaST

Steepness is not a MaST product, and as MaST does not provide significant wave height steepness cannot be calculated from MaST derived parameters at present

2-D Spectrum and ENVISAT ASAR wave mode

Some measure of steepness can be calculated from significant wave height and any period, but the accuracy of any measure is unknown.

Sampling

Coverage is essentially global.

Thus far sampling by SAR has in practice been of the same order but more irregular than altimetry. ENVISAT ASAR should greatly enhance sampling but detailed figures are unavailable.

Combined

Since coverage by SAR and altimetry are both sparse, there is an obvious benefit in using data from both. Scatterometry measures wind speeds rather than wave characteristics, but provides better coverage than either altimetry or SAR. Scatterometers also describe information on the forcing fundamental to waves. Procedures to combine data from different sensors and with model output have been discussed earlier.

Comparison with other sources

Wave steepness is rarely a published product, though it is generally implicit (and occasionally) explicit in climatological bi-variate tables or scatter diagrams of wave height and wave period (usually zero-crossing period), which summarise data from buoys[9].

Recommendations

Wave steepness from EO is currently a potential research topic. Since wave steepness is of practical value, there is a case for developing steepness estimates from both altimetry and SAR, but these will require careful calibration and validation. After that, the inclusion of steepness from EO in climatologies and NRT can be considered.

4.2.4 Wave Direction

Altimeter

Wave direction is not possible from altimetry.

SAR

MaST

The direction of long waves is readily apparent in SAR images, but in the case of the SAR *image mode* data processed through the QinetiQ MaST scheme data and evaluated in this project "seeing is not believing". The SAR data evaluated in this report were found to be strongly biased towards sensing waves along the range axis, a situation which if not improved upon would greatly undermine the value of SAR retrievals. MaST and other older processing methods include a 180° ambiguity. In this study, we could find no evidence that the MaST processing scheme, as currently implemented, has genuine skill in estimating direction. In an annex to this report QinetiQ further discuss some aspects of the MaST processing scheme, as applied to obtaining wave information. Modifications to MaST which could improve performance are being investigated by QinetiQ.

2-D Spectrum and ENVISAT wave mode

The Engen and Johnson (1995) scheme applied by BOOST and in the ENVISAT ASAR *wave mode* processing has solved the 180° ambiguity and some useful directional information is achieved. Johnsen *et al*. (2004) estimate errors of dominant wave direction of about 1 radian for ASAR *wave mode* processing. Note that even this accuracy is only marginally useful and there is much room for improvement.

Sampling

Higher sampling rates are required to provide distributions in different directional sectors. For instance if *n* samples are required to produce a reliable non-directional distribution of wave height, and it is desired to generate distributions in *m* directional sectors, then n^m samples would be required. Thus far sampling by SAR has in practice been of the same order but more irregular than altimetry. ENVISAT ASAR should greatly enhance sampling but detailed figures are unavailable.

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[9] *Bivariate distributions such as these require more observations, of the order of magnitude N^2 where N number required for univariate analysis.*

Combined

Coverage by SAR is sparse. Scatterometry measures wind speeds rather than wave characteristics, but provides better coverage than SAR. Scatterometers also describe information on the forcing fundamental to waves. It will often be clear from scatterometry that SAR retrieved wave directions are significantly different from wind direction, and therefore swell is implied. Schemes to combine SAR wit other data sets have been discussed earlier.

Comparison with Other Sources

Other data is limited to a few directional wave buoys and wave models. The reputation of wave models for estimating direction is not good, but at present wave models are almost certainly the best source of directional information (both climatological and NRT). The accuracy of SAR is not sufficient yet and the bias towards range axis may be critical. It is difficult to see how a useful climatogy of wave direction can be extracted from SAR without solution of the bias observed in the data products generated for this project. Similarly, an NRT product with an inherent bias is of doubtful use.

Recommendations

Better information on wave directions is wanted by operators.

However, the investigations carried out within this project have demonstrated that wave directions produced from SAR *image mode* data by the QinetiQ MaST application are not reliable, and that unless the reliability could he improved it would not be sensible to construct a climatology of directions from these data. Similarly, in a NRT product biased directions from SAR processed with the algorithms currently used in MaST may be more confusing than useful. A number of options exist to address this issue, perhaps the best option in the short term would be to implement in MaST the new algorithms developed by Engen and Johnson (1995).

Unfortunately we have not been able to establish to what extent the same difficulties may exist for SAR *wave mode* data processed by ESA with the new algorithms, but we would note that some organisations do offer commercial products which include wave direction statistics derived from SAR *wave mode* data.

It is known that useful directional data has been found both in research and in operational trials and therefore better results are possible with an adequate processing scheme. Adoption of the best currently available scheme and support for improved schemes are both advisable.

A graphical display of recent scatterometry will be useful as it will identify the direction of wind waves. Research on an improved (i.e. unbiased) retrieval of wave directions from SAR is a priority.

4.3 SUMMARY: REVISITING THE EVALUATION TABLE

In the phase 1 report (Cotton *et al.*, 2005), we summarised the expected usefulness of EO sources for various wave parameters, and for climate and NRT purposes, in the form of an Evaluation Table. Following the testing of EO products described in Section 3 of this report, it is worth checking our previous conclusions. The results of Section 3, have modified our confidence in retrievals of wave parameters from SAR images by the MaST application; especially for wave directions. A review of the limited evaluations of other processing systems suggests that these may be superior, but no current system has demonstrated good accuracy and reliability. Thus we have downgraded our expectation of “wave direction” and “directional spectrum” from SAR. The modified Evaluation Tables are given below as Tables 11 and 12. Grade definitions are given under Table 12.

Table 11 Gradings of EO derived wave parameters for use by HSE, with details of limitations and other aspects.

Parameter	Satellite Source	Validated accuracy	Limitations	Sampling in "Area of Interest"	Need for external data	Grade Stats / NRT
Significant wave height	Altimeter Hs (Ku)	rrms[1]< 0.3m Validated for 0 - 12m	No known environmental dependencies Values 7-20km from coast	At present 4 satellites 8 passes in total per day in AOI Along track resolution 7km	In situ for validation Models for better NRT coverage	1 / 3d
	(A)SAR: 2-D spectrum & wave mode	For ASAR wave mode rms[2] = 0.8m (0.6m if T > 12s)	Only for □ > 100m. Overestimates wave height at low wind speeds, "deviation" at higher wind speeds	Wave Mode (WM): ENVISAT ~ 1-2 passes per day Image Mode (IM): ENVISAT, ERS-2 and RadarSat 3-6 passes / day	In situ for validation Models for better NRT coverage	3bc / 3bd
	MaST	Not available				-
Wave period (zero upcrossing - Tz, or "mean" period, Tm	Altimeter (Hs and □0)	rrms[3] ~0. 8s	Performs better for wind sea than swell	4 sats: 8 passes per day Along track resolution 7km	In situ for validation Models for better NRT coverage	2e / 3d
	(A)SAR: 2-D spectrum & WM	For ASAR wave mode rms[2] = 1.7s, bias ~ 1s. (rms = 1.1 s T > 12s)	Only for □ > 100m. Bias (~ 1s)	WM: 1-2 passes per day IM: 3-6 passes / day	In situ for validation Models for better coverage	2bc / 3d
	MaST	Not available				-
Wave period (peak - Tp)	Altimeter (Hs and □0)	Limited validation indicates rrms[3] = 3.1s (1.7s for wind sea)	Difficulties in validation against buoy data. Tp algorithm requires further development	4 sats: 8 passes per day Along track resolution 7km	In situ and models for validation Models for better coverage	3be / 3bde
	(A)SAR: 2-D spectrum & WM	For ASAR wave mode rms[2] = 3.1s	Only for □ > 100m. SAR should provide better estimates of Tp?	WM: 1-2 passes per day IM: 3-6 passes / day	Models and in situ for validation Models for better coverage	2bc / 3d
	MaST		Only for □ > 100m.	3-6 passes / day	Models and in situ for validation Models for better coverage	2bc / 3d
Wave steepness = $f(Hs/Tz^2)$	Altimeter	Not tested	"Significant steepness" calculated from ratio of Hs and Tz^2, *but not validated*.	4 sats: 8 passes per day Along track resolution 7km	In situ and models for validation.	3ce / 3de
	(A)SAR: 2-D spectrum & WM	Not tested	Only for Wavelengths > 100m.	WM: 1-2 passes per day IM: 3-6 passes / day	In situ and models for validation	3ce/ 3de
	MaST	Not available				-
Wave speed, group speed, cg = g□/4□	Altimeter: f(T)	Not tested	Group speed, cg = g□/4□, *not validated*.	4 sats: 8 passes per day Along track resolution 7km	Models, in situ for validation.	3e / 3de
	(A)SAR: 2-D spectrum & WM	Not tested	Only for □ > 100m,	WM: 1-2 passes per day IM: 3-6 passes / day	Models, in situ for validation.	3ce/ 3de
	MaST		Only for □ > 100m.	3-6 passes / day	Models, in situ for validation Models for better coverage	3ce / 3de
Wave dirn spectrum	Altimeter	Not available				-
	(A)SAR: 2-D spectrum & WM	ASAR wave mode rms[2] = 1.0 rads for $□_{mean}$ and $□_{peak}$	Only for □ > 100m.	WM: 1-2 passes per day IM: 3-6 passes / day	Models,in situ for validation, & to resolve 180° ambiguity for ERS-2 Models for better coverage	3bc / 3bd
	MaST		Only for □ > 100m. Peak direction and wavelength only (not full spectrum)	3-6 passes / day	Models, in situ for validation Models for better coverage	3bc / 3bd

Table 12 Summary table with gradings of EO derived wave parameters for use by HSE

Source	"Grade": Wave Statistics / Near Real Time							
	Hs	**Tz,m**	**Tp**	**□p**	**Sig Stp**	**Wave Speed**	**E(□,□)**	**Wind Speed**
Altimeter	1 / 3d	2e / 3d	3be / 3bde	-	3e / 3de	3e / 3de	-	2[6] / 2[6]
(A)SAR WM[1,2]	3bc / 3bd	2bc / 3d	2bc / 3d	3bc / 3bd	3ce / 3de	3ce / 3de	3bc / 3bd	
MaST[1, 2, 3]	-	-	2bc / 3d	3bc / 3bd	-	3ce / 3de	4 / 4	
ASAR 2D Spectra (SARtool)[1,3]	3bc / 3bd	2bc / 3d	2bc / 3d	3bc / 3bd	3ce / 3de	3ce / 3de	3bc / 3bd	
Scatterometer[4]	*3b / 3b*	*3b / 3b*	*3b / 3b*	*3b / 3b*	*3b / 3b*	*3b / 3b*	*3b / 3b*	*1 / 2c*
GNSS Refl.[5]	*4e*	*4e*	*4e*	-	*4e*	*4e*	-	*4e*

1 - Long wavelengths > 100m only (could be greater, depending on local conditions and satellite orbit).
2 - 180° ambiguity in wave direction for MaST and ERS-2 SAR *wave mode*.
3 - High resolution information on spatial variability within scene available (e.g. for coastal variability).
4 - Scatterometer wind velocities have been use to estimate wind-sea spectrum through P-M relation.
5 - Technique still at experimental stage. SSTL have recently reported receiving GPS reflections on DM sats. Most recent research suggests a "Sea State Parameter" could be extracted.
6 - Altimeter estimate of wind speed useful as it provides simultaneous and exactly co-located wind and wave estimates.

HSE "Grade"
1 – Satellite can satisfy requirements with no supplementary data
2 – Satellite major source but other data required to derive estimates
3 – Other source more important, EO data can play important validation – quality control function
4 – With present state of the art satellite data cannot make useful estimate

2,3 are further sub-divided to identify issues that could be addressed to achieve a wider application
- a – no major issue – other sources better suited
- b – limited accuracy (including application according to environmental conditions)
- c – limited spatial sampling (i.e. better resolution in space required)
- d – limited temporal sampling (i.e more frequent revisits a priority)
- e – algorithm development required.

5 THE BENEFITS OF AN EO SYSTEM AND ESTIMATES OF COSTS

5.1 INTRODUCTION

In this section we consider benefits to HSE offered by products using EO data compared to existing methods.

We assess the added value offered by the systems we have demonstrated, and provide estimated Rough Order of Magnitude (ROM) costs for these services to allow a judgement of which aspects may offer the best value according to the sponsors' priorities.

5.2 EO DATA OVERVIEW

Satellite data provide global coverage. Altimeter wave data are robust against local environmental conditions, whereas the reliability of SAR data is reduced under low or high wind conditions. The satellite altimeter provides highly accurate measurements of significant wave height in all sea states, and also measurements of wind speeds and an estimate of wave period accurate to 1s. The main limitation of altimeter data is a lack of information on wave direction. The SAR can provide estimates of wave direction and wavelength information (for long waves), which is important to offshore operators whose operations are often sensitive to long period swell. The main limitation with SAR is that the imaging mechanism distorts the observed wave spectrum, especially for shorter waves, and that SAR cannot measure waves effectively when the sea surface winds are higher than about 13 ms^{-1}. There is also an issue within the UK of a lack of expertise (and involvement) in recent developments elsewhere in Europe which have resulted in improved procedures for extracting wave data from SAR.

We have seen in this report that some further testing and development of the MaST wave algorithm is necessary if it is to match the capability of other available SAR processing systems. At present there remain particular questions as to the accuracy of the wave direction information produced by MaST. However, one should bear in mind that most measurement systems have difficulty in measuring wave direction accurately. Even directional wave buoys quote standard errors in wave direction of 15°.

The future availability of EO data is a key issue, as any proposed system must have assured continuity of data supply. Table 13 lists the missions that are currently providing wave data, and the missions that are planned for the short-medium term.

Future Altimeter Missions

At present 5 ocean altimeters are operating. ERS-2 and TOPEX-Poseidon are operating well past their design life, and are unlikely to continue beyond 2005. Plans for any continuation of GFO beyond 2005 are not clear. There is coordination between Europe and the USA and current plans aim for a minimum of 2 altimeters to be providing data over the ocean up until ~2015. Cryosat is italicised in Table 13as its primary mission is to measure the polar ice sheets – whilst ocean coverage is likely to be limited, and there will be no NRT data stream, some "delayed mode" ocean data may be available.

Future SAR missions

At least 2 C-band SAR missions should continue to operate for the short – medium term (again to ~2015). The ESA "Red Sentinel" should carry a C-band SAR and so take over from ENVISAT. There are a number of other SAR missions operating and planned, but the RADARSAT series aside ocean data from these missions is not easy to access.

Future Scatterometer missions
Scatterometer data are important for numerical weather modelling, and missions are supported by EUMETSAT in Europe, and NOAA in the USA. Planned missions will provide twice daily global coverage of ocean surface wind data, as required by WMO guidelines.

GNSS Reflections
There is a significant amount of current research into the use of reflections from GNSS (Global Navigation Satellite System) satellites for measuring sea state and sea surface height. Whilst this research is not expected to yield wave information useful for offshore operations in the short term, it promises some potential capability in the longer term (say in 5-10 years). The key benefit offered by a GNSS reflections system would be a significant increase in sampling and coverage.

Table 13 Present and planned satellite missions providing ocean surface wave data

Type	Present Missions	End (Scheduled)	Planned Missions	Dates
Altimeter	ERS-2	2005?	*Cryosat*[10]	*2004-2007*
Altimeter	ENVISAT	2007	ESA "Blue" Sentinel	2010-
Altimeter	Topex/ Poseidon	2005?		
Altimeter	Jason-1	2007	Jason-2 ("OSTM")	2008-2011
Altimeter	GFO	?	NPOESS	*2011-2014*
SAR	ERS-2	2005?		
SAR	ENVISAT	2007	ESA "Red" Sentinel	2007/08 -
SAR	Radarsat	2005	Radarsat-2	2005-
Scatterometer	ERS-2	2005?	Met-Op / ASCAT	2005-2020
Scatterometer	Quikscat	2005	NOAA / CMIS	2008-2020
GNSS reflns	*GPS*	*?*	*Galileo*	*?*

5.3 NEAR REAL TIME WAVE MONITORING SYSTEMS

5.3.1 Existing Systems

The capability of existing NRT systems has been assessed in the phase 1 report (Cotton *et al*, 2005) and summarised in the previous section (Section 4). The main limitation of *in situ* data has been identified as the sparse coverage they offer, with only a small proportion providing wave direction information. There are also some questions regarding the reliability of measurements under extreme wave conditions.

Wave models can provide high-resolution coverage in time and space, but of course models provide now-casts and predictions, not measurements, and have their own known deficiencies. In particular wave models have most difficulty in accurately representing fast changing extreme conditions which, although relatively rare, are exactly the conditions which cause offshore operators the most difficulties. Also it is recognised that many wave models have problems in representing accurately the propagation of swell. To provide an insurance against model forecast error some organisations take forecasts from two different forecast providers, but then

[10] *Cryosat's prime mission is to measure the polar ice caps.*

what does one do if the two model predictions are in significant disagreement – as was the case for a storm encountered at Schiehallion on Jan 15th, 2003 (Box 1, figure 42)?

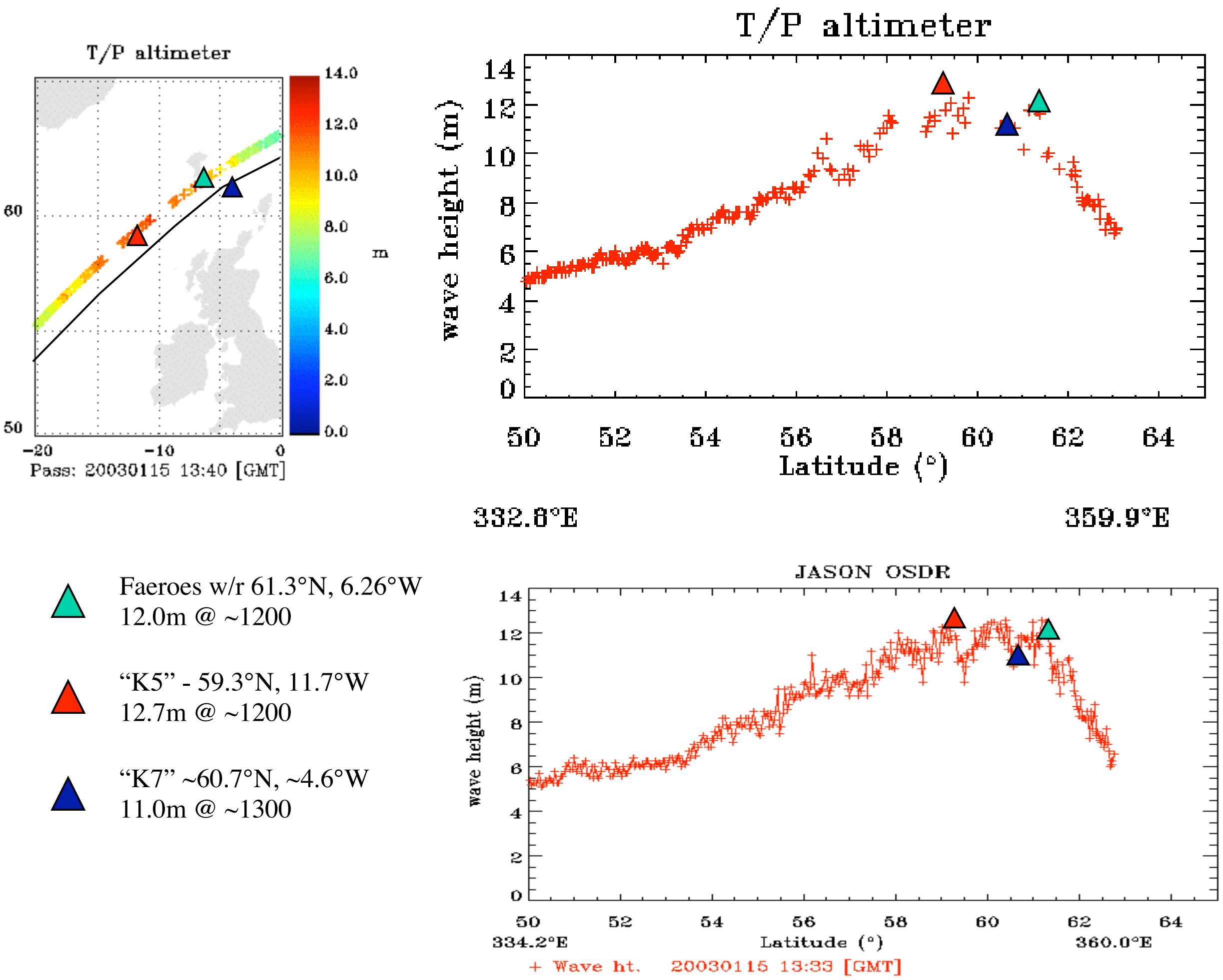

Figure 42 Altimeter Significant Wave Height Data for 1330-1340 UTC on 15 January 2003, close to the Schiehallion FPSO[11]. Top left (Topex and Jason ground tracks, locations of wave buoys. Top Right Topex Hs, Bottom right Jason Hs

Box 1

The BP Schiehallion FPSO was threatened in January 2003 by high storm waves. The officer in charge received 2 separate forecasts for the afternoon of the 15th – one of 16m significant wave height (H_s), and one of 12m. Given that the height of the maximum (H_{max}) can reach almost twice the height of H_s the outlook was grave. If the higher forecast wave value were correct then evacuation from the FPSO must be considered a serious option. A lower estimate would be more supportable.

JASON and Topex/Poseidon passed over the FPSO at 13:33 and 13:40. The observations of H_s are shown for each track together with buoy measurements from wave buoys in the surrounding area.

Each altimeter track confirmed the lower of the two forecast values of around 12m. If such information could be made available to the company in real-time, its contribution to a difficult decision could be considerable.

[11] *FPSO, Floating Production Storage and Offloading Installation.*

5.3.2 Benefits of an EO Enhanced NRT Wave Monitoring System

Given the acknowledged deficiencies in each of the individual sources of NRT wave data, the solution providing greatest benefit to the user is not one that relies on a single data source alone, but one that exploits the best characteristics of each. Thus the coverage supplied by wave model nowcasts, and forecasts (but with uncertain accuracies at any given time and location) should be augmented by actual measurements of the wave field from *in situ* and EO sensors. The measurements of the wave field, perhaps at a time/place some distance away from the specific event of interest, can be used to evaluate the accuracy/reliability of the wave forecasts available.

This is the essential logic behind systems such as CAMMEO, an EO-enhanced version of which was demonstrated for this project. The benefits to the user of the present system, as demonstrated, are:

- Access to 3 different sources of sea state information (EO, *in situ*, model forecasts from Met No.) for the North-Eastern Atlantic.
- EO data sources available now include 2 altimeters (wave height, wave period, wind speed), 2 scatterometers (wind speed and direction), and ENVISAT ASAR *wave mode* (wave period, wave height, wave direction, wind speed).
- SAR *image mode* data could be added to provide high resolution information over an area of particular interest.
- Updated every hour with the latest information.
    - Up to 4 satellite passes per day,
    - Model forecasts updated every three hours.
    - Surface data updated every hour.
- Fast interactive capabilities.
    - Zoom into and out of areas of interest.
    - Move back and forward in time.
- Capability to compare satellite, *in situ* and model information.

Updates could provide

- NRT SAR *image mode* data (high resolution swell period and direction).
    - A modified processing scheme could remove +/- 180° direction ambiguity and provide swell height and wind speed.
- Improved vector representation of wave fields.

5.4 WAVE CLIMATE STATISTICS SERVICES

5.4.1 Existing Systems

The capability of existing systems offering analyses of wave statistics has been assessed in the phase 1 report (Cotton *et al,* 2005) and summarised in Section 4 of this report. Instrument based *in situ* data (wave-buoys, ship borne wave recorders) have been used to generate wave statistics for specific locations, which are generally accepted to be reliable – but coverage is sparse. Also the cost of maintaining an offshore wave buoy are significant, of the order of £100k per year. Thus it may cost over half a million pounds to establish a climatology from a 5 year buoy deployment. Climatologies derived from visual observations have been widely used, but there are known issues in terms of accuracy and (fair weather) sampling bias.

Wave model hindcasts have become more widely used as a source of information for wave statistics, but various authors have noted that wave models do not accurately recreate the full extent of variability in wave fields. This means that the tails of the distributions do not always give an accurate representation of the true wave field distribution, leading to potential errors in estimates of low probability values (e.g. 50, 100 year return values).

5.4.2 Benefits of an EO Enhanced Wave Statistics Information System

The most important asset that all the EO sources share is that they all offer significantly improved spatial coverage than is possible from *in situ* data sources. They can offer wave statistics for any location on the world's oceans, and do not require any local installation or regional model set-up.

The satellite altimeter in particular provides robust and accurate measurements of significant wave height at all sea states, the only known performance dependency upon local conditions is that measurements are not acquired under very heavy rain or very close to the coast (within 20 km). Significant wave height statistics based on altimeter data are now widely used and accepted by both scientists and offshore operators. Scatter plots of wave height and wind speed have also proved useful for many clients. Altimeter databases include the effect of inter-annual variability, as they now cover a 20 year period. The recent development of a reliable wave period algorithm proved an important additional capability. The back catalogue of altimeter data (to 1985) can be processed to generate wave period and joint wave height wave period statistics which will include the effects of wave climate variability.

SAR (*wave mode* and *image mode*) data offer direction and wave period information for longer waves. Whilst there are known difficulties and environmental dependencies, SAR *wave mode* data are used in commercial wave climate data-bases. This is because there are only a limited number of sources of information on the period and direction of long waves, to which many offshore operations are highly sensitive, and it is important to have access to all data sources which can provide such information. Most, if not all, data sources have difficulty in providing accurate information on the long wavelength part of the wave spectrum, and so it is important to gain intelligence from as many different sources as possible.

EO data can be used to derive an independent EO waves statistics system which complements existing in-situ and model based systems. Further work is needed to investigate and assess how joint climatologies from EO data, *in situ* data, and model output could be assembled. This is necessary because each "type" of data source (*in situ*, model, visual observations, satellite data) contains inherent differences in terms of sampling rates and biases and measurement errors dependent upon local environmental conditions. These differences, which can be quite subtle, can result in significant differences in derived statistics. It is important to be able to see these differences and to try to understand the cause and the significance of them. Also it is essential to understand properly the sources of error in each data sources before attempting to combine them into joint statistical analyses.

So we would propose a wave statistics information service, which provided information based on an analysis of archived altimeter data (from 1985-present day), archived (A)SAR *wave mode* data (1991, or 2002, to the present day), and SAR *image mode* data (data available from 1991 onwards). The altimeter data base generated for Phase 1 of the project demonstrated some of the functionality, Figure 43 provides a "mock-up" of a possible user-interface to a waves statistics information service, based on CAMMEO.

The particular benefits of EO data in this application are:

- Improved spatial coverage on existing *in situ* sources.
  - Regular coverage of the whole NW approaches region, to within 20km of the coast for altimeter data (some to within 3 km), and to within ~200m of the coast for SAR *image mode* data.

- Long time series of altimeter data back to 1985.
  - Separate and joint distributions of Hs, Tz, and U_{10}
  - Altimeter Hs estimate robust under high sea states.
  - Statistics include effect of inter-annual variability.
  - Confidence in estimates of low probability return values for Hs.
- SAR *wave mode* data providing information on long waves back to
  - 2002 for ENVISAT ASAR *wave mode* (□, □, Hs, U_{10})
  - 1991 for ERS-1, then ERS-2 SAR *wave mode* (□[12], □)
- High spatial resolution wave statistics possible from SAR *image mode* data.
  - West Freugh archive coverage back to 1991.
  - (□[11], □) from existing MaST application, or (□, □, Hs, U_{10}) possible with new algorithms.
  - Coverage possible close to coasts (to pixel size, ~250m).

Future modifications could include:

- Generation of full wave spectra through a combination of long wavelength information from SAR *wave mode* and wind sea estimated from scatterometer data
- Development of techniques to combine information from altimeter, SAR *wave mode* and/or SAR *image mode*.

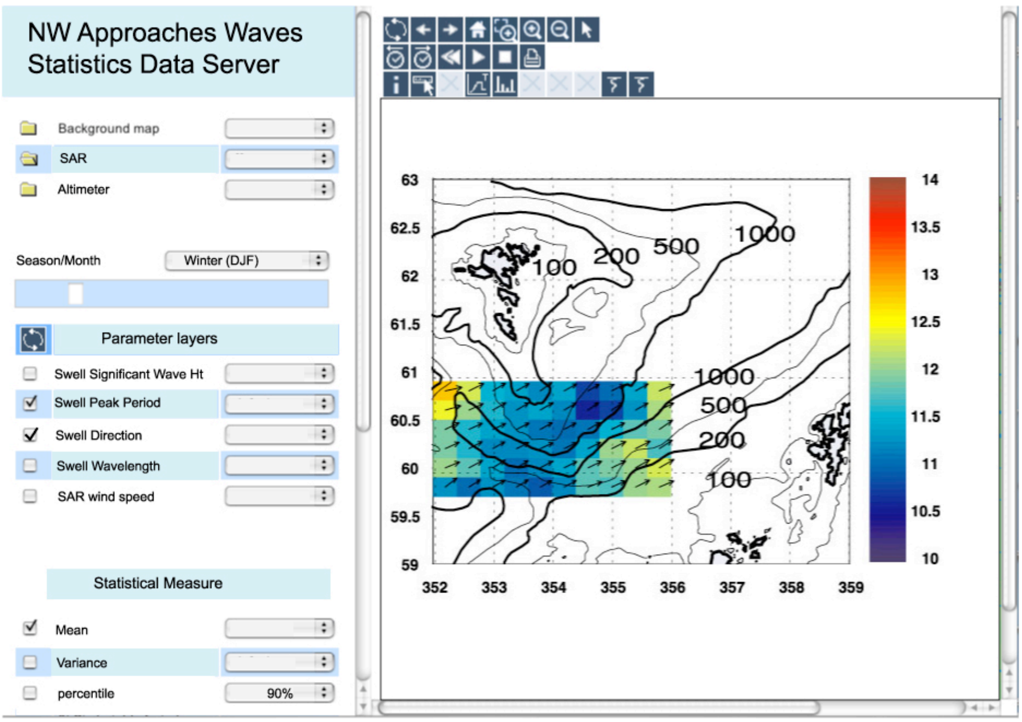

Figure 43 Example of possible user interface to a NW Approaches Wave Statistics Information System. Users could select data source, geophysical parameter and statistical measure, and form of data presentation. This example displays seasonal (winter) mean wave period and direction from SAR *image mode* data.

[12] *With +/- 180° ambiguity.*

5.5 EO SYSTEM COSTS

Table 14 summarises the estimated Rough Order of Magnitude costs for establishing and running an NRT NW Approaches Wave Monitoring Service, and an NW Approaches Wave Statistics Information Service. Further details of recommendations are provided in Section 6.

Table 14 ROM Costs and Implementation Time Scales for EO Enhanced Wave information Services.

		Implement -ation Cost	Annual Running Cost	Implemt - ation Time Scale
	Initial NRT NW Approaches Wave Monitoring Service (comprising recommendations 1, 2 and 3)	**£80k**	**£165**	
Rec. 1	Configuration and implementation of CAMMEO/MetOC web map server. Initial EO data set includes altimeter, ENVSAT ASAR *wave mode* and scatterometer data	£20k	£35k	6 months
Rec. 2	Upgrade MaST - Incorporate ENVIWAVE algorithms into MaST and test	£35k-£40k		3 months
Rec. 3	High Resolution Directional Wave Data Implementation NRT SAR *image mode* processing chain and integrate with existing NRT wave monitoring system.	£20k	£130k	6 months
	NRT System Developments			
Rec. 4	NRT Service Development 1: Full Directional Wave Spectra	£24k		12 months
Rec. 5	NRT Service Development 2: Severe Conditions Warning System Automatic warning of unusual or sever wave conditions	£24k		12 months
	Initial NW Approaches Wave Statistics Service (comprising recommendations 6 and 7)	**£150k**	**£45k**	
Rec. 6	Configuration and implementation of a web based NW Approaches Wave Conditions Analysis Service, initially with altimeter data.	£68k	£11.7k	6 months
Rec. 7	Large Scale Directional Wave Statistics Statistics from ENVISAT ASAR *wave mode* data	£72k	£18k	12 months
	Wave Statistics System Developments			
Rec. 8	Wave Statistics System Development 1: High Resolution Directional Wave Statistics for SAR *image mode* data	£701k	£5k[13]	12 months
Rec. 9	Wave Statistics System Development 2: Separate Wind Sea and Swell Statistics Development of techniques to generate separate wind sea and swell statistics	£24k		12 months

5.5.1 Costs of a NW Approaches NRT Wave Monitoring System

General

This project has been able to take advantage of the fact that the development cost of CAMMEO has been supported by other programmes. Thus the costs to HSE of implementation and subsequent operation are lessened. This initial scoping of the NRT system has assumed that a

[13] Assumes SAR image data for annual updates received through NRT system

bespoke system is established and maintained specifically for HSE use. Thus HSE would define the area to be covered, and the parameters to be provided.

The ROM set-up cost of £80k for a system providing access to altimeter, scatterometer, ENVISAT ASAR *wave mode*, ENVISAT ASAR *image mode* data (plus providing access to model forecasts and *in situ* data) includes:

- general implementation costs,
- implementation of an improved wave processing algorithm into MaST.
- establishing a Near Real Time processing chain for SAR *image mode* data,

Annual operating costs of £165k comprise

- operating a version of the CAMMEO system specifically for HSE/BNSC,
- processing of altimeter, scatterometer and ENVISAT ASAR *wave mode* data.
- acquisition and processing costs of SAR imagery (pre-processing, then processing with MaST).
    - Assumes 20 SAR images a month, for a region to be specified.

Options to Reduce Costs

Costs could be reduced by subscribing to a system that was shared with other users, and/or reducing the requirement for SAR image data. If the former option were considered, then other users would have a say in the area to be covered by the service, the parameters that were displayed, and the form of data presentation. This loss of specialisation would be compensated by significant reduction in cost roughly in proportion to the number of sharing users. The benefit of a shared web based system is that the inclusion of extra users do not carry significant extra cost.

The requirement for 20 SAR images a month could be reduced. One could argue that the best use of SAR *image mode* data is to provide information on spatial variability in wave fields at a high resolution (1-10 km). SAR *wave mode* data can be used to provide direction and wave-length information at the larger scale (100km resolution). Thus an option would be to focus the SAR *image mode* requirement on a particular region of high interest, and to routinely acquire only data for that region. It may be possible to display locations where SAR image data have been acquired, so that the user could request processing of images of particular interest.

5.5.2 Costs of a NW Approaches Wave Statistics Information System

Large Area Coverage - Altimeter and SAR wave mode Statistics

Costs were estimated to implement and maintain a 1° x 2° gridded monthly climatology, covering the full region 56°-64°, based on altimeter and SAR *wave mode* data (not including SAR *image mode*), with distributions, histograms, scatterplots, directional distributions, etc.

- Initial implementation costs of £150k include:
    - Establish web site
    - Load altimeter data and generate gridded statistics
    - Load SAR *wave mode* data and generate gridded statistics (inc Hs

- Annual running costs of £45k include:
    - Annual web site running costs
    - Altimeter data annual updates
    - SAR *wave mode* annual updates

Higher Resolution Statistics over Area of Key Interest

The full cost of retrieving, pre-processing and extraction of wave parameters from SAR Image data (detailed below) is higher. Unless there is a very high priority public interest requirement it would be difficult to justify the cost of full coverage of the whole NW approaches region.

The cost estimates for this service were based on a requirement for 5 samples a month[14], over a 5 year period (i.e. 300 independent measurements) a reduced area climatology (say 2° x 8°) from SAR *image mode* data, as follows:

- Implementation costs of £701k include:
  - initial image retrieval and processing,
  - process with MaST application.
  - implement ENVIWAVE algorithms.
  - generate gridded statistics.

- Annual update costs of £5k include:
  - (image acquisition and processing) - included in NRT running costs
  - (processing with MaST) - included in NRT running costs
  - Production of statistics.

It is clear that coverage from SAR *image mode* data of the full region (56°-64°N, 12°W-2°E) would be prohibitively expensive unless there were some commanding public good argument. This is why it is suggested that the altimeter and SAR *wave mode* data are used to provide the statistics at a coarser scale for the larger region, and the SAR *image mode* data are used to provide higher resolution information over a particular area of interest – the basis of the costs for recommendations 7 and 8.

Options to Reduce Costs

The cost of the SAR *image mode* data base could be reduced to less than half of the original ROM estimate if the requirement were relaxed to 5 samples per month over a 2 year period. However, then it should be acknowledged that the sample would not include the effects of inter-annual variability. Although these costs for processing SAR *image mode* data may seem high, they are comparable to that of deploying and maintaining a wave buoy (~£100k a year). The difference is that where a wave buoy will provide continuous measurements and a full wave spectrum at a single location, a SAR *image mode* based climatology will provide larger area coverage and information on spatial variability, but with less frequent sampling in time.

The costs of generation of gridded statistics (for both altimeter/SAR *wave mode* and SAR *image mode* data bases could be reduced if interactive data base querying and statistical analysis software were built into the web site.

5.6 SUMMARY

There are three generic sources of wave information: *in situ* data (buoys, ships), wave models (forecasts and hindcasts) and EO data.

In general terms the key *positive* aspects of each are:

In situ Data

- Well known accuracy and error characteristics.
- High temporal resolution.

[14] *The minimum sampling sufficient to provide statistics of mono-variate distributions, probably not enough to support bi-variate distributions, or distributions in a number of different direction sectors.*

- o Full wave direction spectra possible, and wide range of parameters.
- o Some sites with long time series.

Wave Models

- o Good coverage in time and space, and high resolution possible.
- o Full wave direction spectra possible, and wide range of parameters.
- o Hindcasts giving long time series.

Satellite Data

- o Known accuracy and error characteristics.
- o Global coverage.
- o High spatial resolution along track.
- o 10 yrs time series from altimeter and SAR.
- o Altimeter provides highly accurate all weather Hs measurements.
- o SAR provides directional information on long waves.

The key *negative* aspects are:

In situ Data

- o Poor spatial coverage (8 long term offshore sites for whole NW approaches region).
- o What happens to buoy motion in storms?

Wave Models

- o Predictions not measurements.
- o Greatest problems in most severe events, especially fast moving/ developing events.
- o Known errors in swell propagation.

Satellite Data

- o Limited resolution: long revisit intervals, altimeter offers limited spatial resolution across track.
- o SAR problems with azimuth travelling waves, and short waves.

It can be seen that each data source offers something that others do not. For instance - *in situ* data offer high resolution information in time, but poor spatial coverage. Satellite data offer world wide coverage, but relatively infrequent sampling in time. Model information can be provided at high resolution in time and space – but there are still key difficulties, particularly in representing fast moving severe events, the very events that can cause the most damage.

Thus any monitoring system must make use of all data sources, taking advantage of their complementary capabilities, rather than relying on one information source. EO data do not offer a replacement for other information sources, but an important complement to compensate for the limitations of existing systems. In particular EO data offer:

- o Improved spatial coverage of measurements of the wave field.
- o Measurements of direction and period of long period waves
- o Accurate measurements of wave heights in the most severe conditions
- o A basis for assessing the accuracy of predictions from wave forecasts.
- o Long time series and large scale sampling of the wave field to allow accurate estimates of extremes and low probability return values.

Thus what is proposed for HSE is an NRT system that provides access to all useful sources of wave information including EO data, and an EO wave statistics system that complements existing sources of wave statistics. Rough Order of Magnitude implementation and annual running costs are provided in Table 14.

6 RECOMMENDATIONS

6.1 INTRODUCTION

In this section we provide recommendations for the phased implementation and subsequent development of an operational NW approaches wave conditions monitoring and analysis service, comprising a Near Real Time system and a wave climate statistical analysis service.

These recommendations are designed to meet the following key priorities:

- Offer a useful capability in the short term (i.e. build upon existing capability, and available operational data sets), and plan for future incorporation of additional data sets and analysis capabilities.

- Satisfy the joint sponsor priorities of providing statistical analyses of archived wave data (including directional information) and a near real time wave monitoring service.

Recommendations are also provided for research and capacity building. It has become clear during the progress of the project that some attention must be paid to support and develop UK's expertise in processing of SAR data to produce wave information, in order to ensure effective exploitation of the existing UK capacity for ocean wave monitoring with SAR (specifically the West Freugh Ground station and SAR archive). To enable the UK to maintain its leading position in this research field some capacity building would be required, for instance through knowledge transfer between academic and commercial organisations, to include a contribution from European partners au fait with the latest developments.

ROM costs of the various aspects of the development plan are given in Table 11 (in section 5), Figure 44 provides an overview of the proposed implementation. We discuss the recommended implementation steps for the NRT Wave Monitoring Service, and the Wave Climate Analysis Service in separate sections below (6.2 and 6.3 respectively).

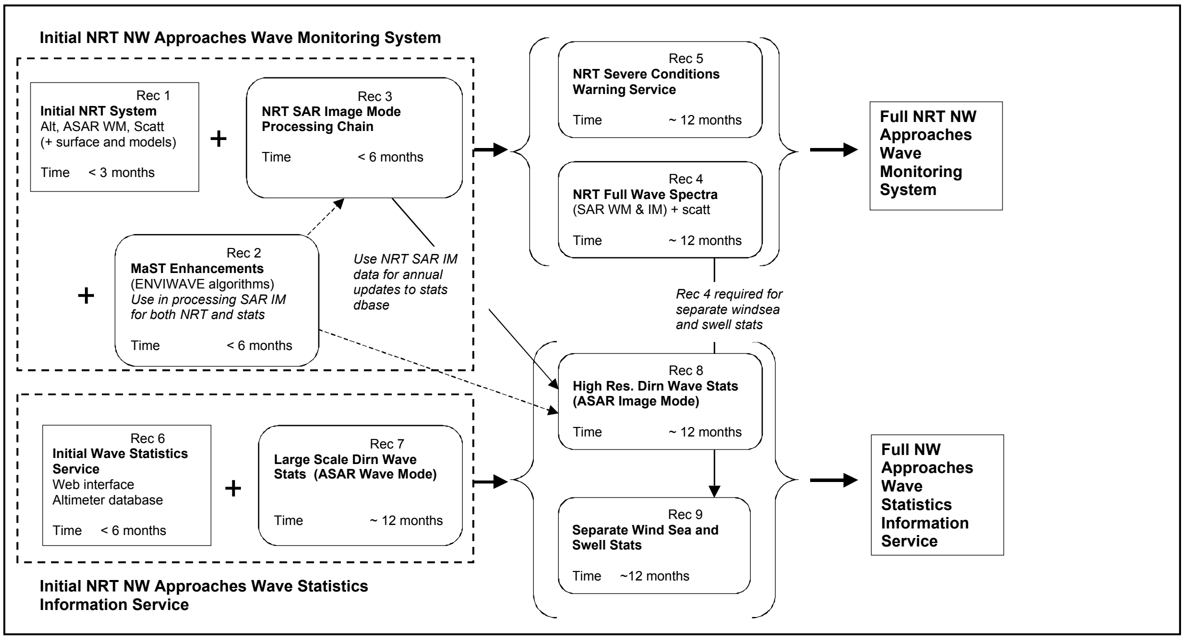

Figure 44 Proposed service development path and linkages between implementation options.

6.2 NEAR REAL TIME NW APPROACHES WAVE MONITORING SYSTEM

6.2.1 Overview

To provide a Near Real Time NW Approaches Wave Monitoring System we recommend implementation of the CAMMEO Web Map Server system, developed by Met No, Christian Michelsen Research and Satellite Observing Systems. A bespoke system would be developed in full consultation with the sponsors, who would establish specific requirements for the geographical coverage, geophysical parameters, presentation style, etc. Alternatively the sponsors could subscribe to a more general multi-user implementation of the CAMMEO/ MetOc system, with broader specifications designed to meet a range of needs from a number of different users, amongst them the sponsors of this project.

The benefits of adopting the CAMMEO/MetOc system are that the sponsors can be provided with an effective, easy to use Near Real Time NW Approaches Wave Monitoring System within a very short time frame. Enhancements can be incrementally added when developmental work has been completed. The CAMMEO/MetOc system is designed to accommodate additional data sets as a matter of routine.

The recommended steps for implementation incorporate five recommendations, three to establish an initial NRT wave monitoring service, and two to provide additional capability, as follows:

Initial NRT Service
Rec. 1. First Stage NRT service with altimeter, ASAR *wave mode* and scatterometer data.
Rec. 2. Upgrade MaST with improved wave processing algorithms.
Rec. 3. Establish NRT processing chain for SAR *image mode* data, and incorporate data stream into existing CAMMEO NRT system.

Service Developments
Rec. 4. Provide full directional wave spectra.
Rec. 5. Include severe conditions warning service.

6.2.2 Initial NRT Service Implementation: Recommendations 1, 2 and 3

Stage 1 Implementation – Altimeter, ASAR wave mode and scatterometer service

For first stage implementation we recommend the configuration demonstrated in Phase 2. Table 4 defines the satellite data that would be included initially: Jason, ERS-2 and ENVISAT altimeter data; ERS-2 and Quickscat scatterometer data; and ENVISAT ASAR *wave mode* data.

Recommendation 1 – Initial NRT NW Approaches Wave Monitoring Service

- Configuration and implementation of a version of the CAMMEO/MetOc web map server to sponsor specifications and for their sole use.
  - Includes altimeter, scatterometer and ENVISAT ASAR *wave mode* EO data (see Table 4), plus surface data, and wave model predictions.
- Annual running costs include
  - Maintaining and updating the web site, and project management
  - Processing of altimeter, scatterometer and ENVISAT ASAR WM data
- This stage 1 implementation possible within 3 months.

Stage 2 Implementation – Add SAR image mode Data to NRT Service

The first recommended incremental development to the NRT system would be to include SAR *image mode* data into the NRT processing chain. This would provide high-resolution directional wave information over a region to be specified by the project sponsors. Two steps are necessary – upgrade MaST and implement an NRT *SAR image mode* processing chain:

Enhance SAR Image Mode Processing Algorithms in MaST

Our evaluation of wave data from MaST has highlighted some problems. We believe that the ENVIWAVE algorithms (Engen and Johnson, 1995), employed by ESA to process the ENVISAT ASAR *wave mode* data offer an important enhancement on the algorithms currently employed within MAST. They remove the +/- 180° ambiguity in direction, and provide a measure of the wave energy at different wavelengths and directions – allowing estimates of significant wave height (and also mean wave period, and surface wind speed). Recommendation 2 therefore is:

Recommendation 2 – Upgrade MaST

- The new "ENVIWAVE" algorithms should be implemented by QinetiQ within MaST.
  - Includes evaluation of a test data set.
- Estimated 2 months to complete.

Alternatively negotiations could be initiated with a third party for processing of the SAR image data (e.g. with BOOST for the use of SARtool).

Once the MaST algorithms have been upgraded and tested, it is recommended that a NRT SAR *image mode* processing chain be implemented and wave data thus produced incorporate into the CAMMEO system:

Recommendation 3 NRT Service: High Res Directional Wave Data

- Implement NRT SAR *image mode* processing chain and integrate with existing NRT wave monitoring system.
- To acquire, pre-process and process with (upgraded) MaST 20 images / month in NRT over selected region
- Requires Recommendation 2, then can be implemented in 1month.

This would provide the high resolution data for annual updates to the Wave Statistics Information Service (Recommendation 8)

6.2.3 Medium-Long Term Developments to NRT Service: Recommendations 4 and 5.

We recommend two possible medium term developments:

Full range directional wave spectrum

Two techniques exist which could be implemented to generate full range directional wave spectrum. The Mastenbroek and de Valk (2000) approach uses co-located scatterometer and SAR data, and combines the high frequency wind sea inferred from the scatterometer wind vectors, with the long wavelength wave information that can be estimated from the SAR. The advantage of this approach is that it does not require input from a wave model, but the drawback is that it leaves a potential gap between the wavelengths of waves inferred from the two sources.
The second possible approach (Schulz-Stellenfleth et al., 2005) takes wave model forecast information co-located with the SAR data, and combines these two sources to generate a full

wave spectrum. The advantage is that this technique does not leave a frequency "gap", but the disadvantage is the necessity to rely on wave model output.

Recommendation 4 NRT Service: Full Directional Wave Spectra

- NRT generation of full directional wave spectra - two options:
- Shorter term, implement Mastenbroek and de Valk (2000) scheme
    - Generate wind sea spectra from scatterometer data
    - Merged with SAR *wave mode* & *image mode* long wavelength spectra
    - Estimated 3 months staff time required to support development
    - Achievable in ~1year
- Longer term, implement Schulz-Stellenfleth (2005) scheme
    - Acquire initial wave spectrum from co-located wave model forecast
    - Use as input to ASAR *wave mode* processing to generate full spectra
    - Estimated 3 months staff time required to support development
- Achievable in ~1year

Would provide the wave spectra for generating separate wind-sea and swell statistics (Recommendation 9)

Severe Conditions Warning System

An automatic severe conditions advice system could be implemented. The users would specify a set of conditions/criteria to trigger specific warnings, which for instance could include threshold values for significant wave height of wave period (perhaps accompanied by specifications on direction and location), and mismatches between forecast(s) and/or measured data. The system would automatically issue an email to the system users and system operators with details of the specific measurements/forecasts triggering the warning, and links to specific images and data sets.

Recommendation 5 NRT Service: Severe Conditions Warning System

- Automatic warning of unusual or severe wave conditions
    - Specified according to user requirements
    - Email warning with links to specific data sets/ images
- Estimated ROM development costs based on 3 months staff time
- Achievable in ~1year

6.3 NW APPROACHES WAVE CLIMATE STATISTICS SERVICE

6.3.1 Overview

To establish a NW Approaches Wave Climate Statistics Service we recommend a phased implementation of a web-accessible data base. Figure 43 in section 5 presented one possible model for the interface to the statistical data – incorporating a front page which provides a series of pull down menus to allow sequential selection of data source, wave parameter, statistical measure, and then month/season of interest. Buttons in the main display panel would provide access to functions which could allow for instance the user to focus on a region of interest, or for instance to generate "longitudinal" plots in time.

To support a full specification, and allow cost estimates with higher levels of confidence, discussions will be required with sponsors to agree:

- The level of desired inter-active capability.

- A series of required standard statistical measures that can be automatically generated from the statistical data base (e.g. mean, mode, variance, percentiles).
- Desired format for standard plots (histograms, scatter plots), tables, etc.
- Requirement for additional “non-standard” analyses which cannot (or should not!) be generated automatically: e.g. fitting and interpolating distributions, etc.

The basic recommended configuration is that satellite altimeter and SAR *wave mode* data are used to provide information for the whole area of interest (56°-64°N, 12°W-2°E) on a 1° latitude x 2° longitude monthly grid, and the SAR *image mode* data are used to provide wave statistics on the fine scale for a user specified area of interest (we have estimated ROM costs for a 2° x 8° region).

It is suggested that ENVISAT ASAR *wave mode* data only are used as the basis for the large directional wave statistics, and ERS-1 and ERS-2 SAR *wave mode* data are not included. Although the inclusion of ERS-1 and ERS-2 *wave mode* data would increase the time period covered (back to 1991), these data retain a +/- 180° ambiguity in wave direction, are not able to provide direct estimates of wave height, mean wave period and wind speed, and require a first guess estimate from a wave model as part of the processing scheme. They would therefore not form a homogeneous time series with ENVISAT ASAR *wave mode* data products, in which the +/- 180° ambiguity has been resolved, no wave model first guess is required, and the extra wave parameters are directly estimated.

The recommended steps for implementation incorporate four recommendations, two to establish an initial wave statistics analysis service, and two to provide additional capability, as follows:

Initial Statistics Service
Rec. 6. First stage statistics service with altimeter data.
Rec. 7. Add directional wave statistics from ENVISAT ASAR *wave mode*.

Service Developments
Rec. 8. Add statistics on fine scale spatial variability from SAR *image mode* data
Rec. 9. Add separate wind sea and swell statistics.

6.3.2 Initial Wave Statistics Service Implementation: Recommendations 6 and 7

Stage 1 Implementation – Altimeter derived wave statistics

Because the ENVISAT ASAR *wave mode* data set will not be available until 2006, an initial implementation (in 2005) of a NW Approaches Wave Climate Statistics Service would be based on satellite altimeter data only (using data from 1985 to the present day – with a gap from 1989-1991: from Geosat, ERS-1, ERS-2, Geosat Follow-On, TOPEX, Jason-1 and ENVISAT).

This initial implementation would include a web interface, designed to allow quick access to a range of required statistical parameters (see for instance Figure 43). The user interface would link to a statistical data base, directly access and display some basic statistical measures, and generate (or link to) figures and tables.

Statistical measures of Hs, Tz, U_{10} and significant steepness would be provided on a monthly 1° x 2° grid for the whole GIFTSS area (56°-64°N 10°W-2°E).

Statistical parameters would include monthly means, standard deviations, percentiles, histograms, scatter plots (e.g. Hs v Tz)

Recommendation 6 –Initial NW Approaches Wave Climate Statistics Service – Altimeter Derived Statistics

- Configuration and implementation of a web based NW Approaches Wave Climate Statistics Service
  - Develop and implement web interface to statistical data base
  - Initial data base incorporates altimeter data only on 1° x 2° monthly grid
- Implementation
  - Develop and implement web interface
  - Set-up altimeter statistical data base
- Annual running costs.
  - Running costs for web site.
  - Annual update of altimeter statistics data base.
- Achievable in 6 months.

Stage 2 Implementation - Large Scale Directional Wave Statistics from ENVISAT ASAR wave mode

We recommend that ENVISAT ASAR *wave mode* data are used to generate directional wave statistics for the whole region of interest (56°-64°N, 12°W-2°E), to complement the non-directional data available from the altimeter. ESA advise that 3 years (2002-05) of reprocessed (and so homogeneous) ENVISAT ASAR *wave mode* data should be available by 2006[15]. It is initially assumed that statistics would be generated on a monthly 1° x 2° grid, but this scheme could be revised once a clear picture of sampling frequency from this data product in our region of interest is established.

(Long wavelength) Wave parameters, would include: direction, wavelength, Hs, Tp, Tm, U_{10}. Statistical measures would include: monthly means, sds, percentiles, histograms, scatter plots, dirn v Hs, Tp, Tm plots.

Recommendation 7 –Wave Statistics — Large Scale Directional Wave Statistics

- Upgrade of waves statistics service to include statistics derived from (3 years) ENVISAT ASAR *wave mode* data on 1° x 2°, monthly grid (56°N-64°N, 12°W-2°E).
- Achievable in ~12 months (dependent upon availability of reprocessed ASAR *wave mode* data).

6.3.3 Medium Term Developments to NRT Service: Recommendations 8 and 9.

High Resolution Directional Wave Statistics (for maximum 2° x 8° area)

SAR *image mode* data would be used to generate directional wave statistics at high spatial resolution for an area of specific interest to the sponsors. Costs have been estimated for a 2° x 8° region, comprising 8 (1° x 2°) grid squares (Table 11). We assume a requirement for 300 images for each 1° x 2° grid square based on 5 samples per month over a 5 year period: We have suggested this is the minimum required to provide sufficiently frequent sampling to capture the monthly climate, and to cover a long enough time period to capture (some of) the effects of inter-annual variability. Note that this estimate is to allow for mono-variate statistical analysis. Higher sampling would be required for bi- or multi-variate analysis (including distributions in different wave direction sectors).

[15] *According to communication with ESA EO Help Desk, April 2005.*

Thus, this development would require: extraction and preprocessing of (8 x 300) SAR images from West Freugh archive, the processing of these images in MaST to provide the required wave parameters, extraction of modal parameters on sub grid, scale to be agreed, and generation of the desired statistical measures.

Wave parameters would include (for long waves), direction, wavelength, Hs, Tp, Tm, U_{10}.
Statistical measures would include monthly means, sds, percentiles, histograms, scatter plots, dirn v Hs, Tp, Tm plots

Recommendation 8 – Wave Statistics – High Resolution Directional Wave Statistics

- Upgrade of waves statistics service to include statistics derived from (A)SAR *image mode* data in a reduced, user specified, 2° x 8° region
- Implementation
    - Extracting and pre-process 8 x 300 archived SAR images,
    - Processing 8 x 300 images in MaST (enhanced by Rec. 2)
    - Producing wave statistics from these data.
- Annual updates.
    - Assumes new SAR image data acquired through NRT service (Rec. 3)
- Achievable in 12 months timeframe.

Separate Wind Sea and Swell Statistics

A further recommendation is to generate separate wind sea and swell statistics through a combination of long wavelength information from SAR *wave mode* and wind sea estimated from scatterometer data.
This links to Recommendation 4 – the generation of full directional wave spectra from this service development would be required to support this service addition.

Recommendation 9 Wave Statistics Service – Development 3: Separate Wind Sea and Swell Statistics

- Development of techniques to generate separate wind sea and swell statistics from full wave spectra (Rec. 4)
- Estimated ROM development costs based on 3 months staff time
- Achievable in ~1year

6.4 RESEARCH PRIORITIES AND CAPACITY BUILDING

The project team and sponsors have identified a number of priority areas for further research in two general areas:

- to develop data products where there is a requirement for new or improved wave information,

- to help understand how specific characteristics of the wave products may impact on the accuracy or reliability of higher level data products.

6.4.1 Priority areas for research

We have identified six specific studies, to address key requirements, which we believe could be addressed by short term, 3-6 month projects. We will discuss these in more detail with the project sponsors and investigate the possibility of running short research projects perhaps as collaborations between the industrial partners and Southampton Oceanography Centre.

- To carry out a test implementation of the "PARSA" SAR processing scheme (Schulz-Stellenfleth et al., 2005) using ENVISAT ASAR *wave mode* data, and co-located wave model forecasts.

- To investigate the effect on climatologies of SAR asymmetry between sensing in the azimuth and range directions.

- To develop and test methods to combine altimeter, SAR and scatterometer data for NRT wave monitoring applications, e.g. identifying long wavelength swell, generating information on wind sea and swell.

- To develop and test methods to combine altimeter, SAR and scatterometer data for climatologies – to enable the generation of joint distribution functions for parameters measured by different instruments at different locations and/or times, to generate wave spectra for the full frequency range, to generate separate and joint statistics for wind sea and swell waves.

- To develop and apply techniques to validate estimates of significant steepness.

- To continue the development and testing of altimeter wave period algorithms.

6.4.2 Capacity building

We have identified that effort is required to maintain UK's expertise in reference to recent developments in SAR imaging of wave fields – both in the understanding of the physical processes that contribute to the SAR imaging of the ocean surface and in the development of new techniques to derive wave parameters.

One possible action would be to initiate a Knowledge Transfer exchange (for instance as is supported through the NERC KTI scheme), between one or both of the industrial partners of this project and Southampton Oceanography Centre. This should be supported by either a CASE studentship, or through the recruitment of European expertise for instance through an ESA research fellow. We would suggest a minimum period of at least 6 months to allow intensive period of study on new developments in SAR processing, and to develop cost effective schemes to make best use of the QinetiQ SAR archive and the West Freugh ground station capacity.

7 SUMMARY

This project has carried out an in depth assessment of all aspects of wave products that can be derived from satellite measurements over the ocean, and which could form components of a North-Western Approaches Wave Conditions Monitoring and Analysis Service.

A demonstration service was established to demonstrate and evaluate key aspects of a full service: A near real time data service which – through a web page updated several times a day, provides the client with easy and fast access to present and recent wave conditions in the NW approaches, and a wave climatology and analysis service which provides information on expected conditions as they vary throughout the year and across the region of interest.

Satellite data can provide important information on wave fields in the NW Approaches Region. This area is often subject to severe wave conditions, and is increasingly the focus of new offshore activities, activities which can often only take place under precisely specified operating conditions. Thus it is essential to ensure an accurate knowledge of wave conditions in this region, both as they occur from day to day in Near Real Time, and in terms of the expected statistical characteristics of conditions based on a careful analysis of a reliable data base. Meteorological Agencies and offshore operators have established a number of *in situ* data sources to support these activities, but spatial coverage from these surface data sets remains poor. Satellite instrumentation can therefore play an important role by supplementing these limited number of *in situ* wave measuring instruments and providing measurements on a larger scale, covering the whole NW approaches region.

In summary - satellite data offer the capacity to make a significant contribution to improved operational safety of offshore activities taking place in the NW approaches to the UK. Table 11 and Figure 44 summarise the recommended steps on an implementation plan to establish a NRT NW Approaches Wave Monitoring Service, and a NW Approaches Wave Statistics Information System.

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GLOSSARY

AES-40	40 yr North Atlantic Wave Climatology, developed by Oceanweather
AOI	Area of Interest (56°-64°N, 10°W – 1°E)
ASAR	Advanced Synthetic Aperture Radar (carried on ENVISAT).
Azimuth	Orthogonal to direction of SAR look, for side looking SAR - along track direction
BNSC	British National Space Centre
BOOST	Young French SME, based in Brest, with SAR expertise
CERSAT	IFREMER laboratory dedicated to processing and archiving of satellite data - Centre ERS d'Archivage et de Traitement (http://www.ifremer.fr/cersat/en/index.htm)
DEFRA	Government Department for Environment, Food and Rural Affairs.
DMI	Danish Meteorological Institute
EC	European Community
ECMWF	European Centre for Medium-Range Weather Forecasts
ENVISAT	European Environment Monitoring Satellite, launched 2002.
ENVIVIEW	Software distributed by ESA to view ENVISAT data products, (including ASAR *wave mode*)
ENVIWAVE	EC "Framework" project to develop ocean wave products from ENVISAT.
EO	Earth Observation
EOLI	Online catalogue for ERS and ENVISAT data
ERA-40	ECMWF Re-Analysis. 40 year atmospheric hind-cast
ERS-1	1st European Remote Sensing Satellite (launched 1991)
ERS-2	2nd European Remote Sensing Satellite (launched 1995)
ESA	European Space Agency
FFT	Fast Fourier Transform
FNMOC	US Fleet Numerical Meteorology and Oceanography Center
FOAM	Forecasting Ocean Atmosphere Model. Ocean circulation model at the UK Met. Office
FOIB	Faroes Oil Industry Group
FPSO	Floating Production, Storage and Offloading Installations
ftp	File Transfer Protocol – standard (and shorthand) for internet transfer of files.
(EC) Framework Programmes	A series of EC science and technology support programmes
GAMBLE	An EC "Thematic Network", led by SOS to review future requirements for satellite altimetry.
Geosat	US Navy Altimeter Satellite (1985-90).
GIFTSS	Government Information from the Space Sector – BNSC programme to help UK government agencies implement information that has been derived from satellites
GFO	Geosat Follow-On - Follow on to Geosat (1998-)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System.
GRIB	Data format e.g for meteorological data as distributed on GTS
GTS	Global Telecommunications System – used by national met agencies to transfer/ exchange data.
HSE	Health and Safety Executive
IFREMER	French Government Oceanographic Research Institute (Institut Francais de Recherche pour l'Exploitation de la Mer
IM	Image Mode
Jason	Ku / C-band altimeter launched in December 2001.

JONSWAP	JOint North Sea WAve Project – a wave spectrum developed for fetch limited waves.
Ka-Band	Radar frequency band (18-40 Ghz), proposed for new technology satellite radar altimeters
KNMI	Royal Netherlands Meteorological Institute
Ku-Band	Radar frequency band (12-18 Ghz), commonly used by satellite radar altimeters
Level-0, 1, 2	Categories of data according to level of processing - Level-0 represent raw instrument output, level 2 data processed to provide geophysical parameters, with location and time.
MaST	Maritime Surveillance Tool. QinetiQ tool for analysing SAR data.
MAWS	Marine Automatic Weather Station (acronym for UK Met Office Buoys)
Météo France	French National Meteorological agency.
NAO	North Atlantic Oscillation (Index)
NRT	Near Real Time
NWP	Numerical Weather Prediction
NORUT	Norwegian Research Group, of not for profit companies, based in Tromsø
PRI	ERS SAR product (Precision Image product)
Quikscat	Ocean wind measuring radar scatterometer. Launched in 199 by NASA to replace instrument lost when ADEOS failed
RadarSat	Canadian commercial SAR satellite – to be replaced by Radarsat-2 in near future.
RAR	Real Aperture Radar
Range (direction)	Along direction of SAR look, for side looking SAR - across track direction
SAR	Synthetic Aperture Radar
SARtool	A tool for processing SAR data (ERS, Radarsat and ENVISAT), developed by BOOST
Scatterometer	Satellite radar instrument to measure ocean surface wind
Seasat	The first marine EO satellite, launched in 1978. Had a scatterometer, altimeter, SAR and radiometer.
Seawinds	The scatterometer instrument on board the Quikscat satellite.
SOC	Southampton Oceanography Centre
SOS	Satellite Observing Systems (UK)
SSTL	Surrey Satellite Technology Limited (UK).
TOPEX/Poseidon:	Ku/C band altimeter launched in 1992 by CNES/NASA
UKMO	United Kingdom Meteorological Office.
VOS	Voluntary Observing Ship (Programme) – agreement through which (mostly visual) ship observations are recorded and archived.
WW3	Wavewatch 3 – A 3rd Generation wave model used by NOAA.
WAM	A widely used computer model for wave generation, propagation and dissipation
WAMDI	Wave Model Development and Implementation Group
WM	(for SAR) Wave Mode.
WMO	World Meteorological Office

ANNEX - QINETIQ INVESTIGATIONS INTO MAST APPLICATION – "WAVE CLIMATE FROM SAR SCENES"

Available separately