"JERICHO"
Joint Evaluation of Remote Sensing Information for Coastal And Harbour Organisations

A Project in the BNSC Earth Observation LINK Programme

Final Report to the British National Space Centre

21 December 1999

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Produced for the BNSC Earth Observation LINK programme, project no:
R3/003

1. Summary

This report presents results from JERICHO, an interdisciplinary research project (within the BNSC LINK programme) which has investigated the application of the wave measurements from satellites, with shallow water wave models, to the strategic planning of coastal defences.

JERICHO has been primarily a scientific project, but was directed by the practical strategic requirements of the Environment Agency (EA), who were a full participant in the project. The JERICHO team included 5 partners, the EA, Satellite Observing Systems (SOS), who managed the project and provided expertise on the use of satellite altimeter data, two partners from the Natural Environment Research Council, Southampton Oceanography Centre (SOC -experts in oceanographic applications of satellite data, and in statistical techniques), and Proudman Oceanographic Laboratory (POL - experts in the operation of shallow water models), and Halcrow Maritime who have also proven modelling expertise (with the STORM wave model).

One of the major achievements of JERICHO has been the demonstration that satellite altimeter wind and wave data have useful applications in coastal waters. The team has shown how these data can be used, in conjunction with shallow water wave models, to carry out detailed studies of nearshore wave climate. There is a scarcity of reliable *in situ* coastal wave data, even in UK waters, and the techniques that the team have developed allow studies in areas where they would otherwise not have been possible. Of course, these techniques may now be applied at any worldwide location. In immediate practical terms JERICHO has provided the Environment Agency with recommendations for monitoring wave climate, has identified the characteristics which may render areas more sensitive to changes in offshore climate, and provided the basis with which the possible impact of future climate scenarios may be judged objectively. JERICHO has also established the strength of the connection between the wave climate of western English and Welsh coasts and the North Atlantic Oscillation (the NAO).

Of course, as is almost inevitable in a scientific programme of such complexity, the JERICHO team encountered some problems. Perhaps the largest disappointment was the inability of the large scale coupled climate models, in their current state of development, to provide reliable projections of the atmospheric fields important to the forecasting of waves (e.g. the NAO, "storminess", etc.) Thus even where there is strong evidence of a connection between wave climate and the NAO, we do not believe we would be justified in using this connection to generate projections of future wave climate. Instead we opted to model some arbitrary "worst case" scenario, to test for potential coastal vulnerability. Also, the investigations were unable to identify a statistical relationship between the wave climate off the English east Coast and any large scale climate index.

2. Introduction & Objectives

Satellite radar altimeters measurements have enabled researchers to study the spatial as well as temporal variability in global ocean wave climate. Researchers at SOS and SOC have identified significant inter-annual variability, coherent over large areas, and have confirmed an increase in north-eastern Atlantic winter wave heights over the last 12 years (Figure 3-1). However, these measurements refer to offshore wave climate, and the impact on coastal areas is uncertain. JERICHO planned to address this aspect through the combined use of satellite measurements, in situ data, and shallow water wave models. Figure 2-1 illustrates the geographical context, showing the coverage of satellite altimeter data (in this case TOPEX), the locations of long term *in situ* data used in JERICHO, and insets of the three coastal locations selected for detailed modelling studies.

The deliverables covered two main areas - those required in the short-term to answer the question, 'how vulnerable might Britain's shoreline be to increasing wave heights in the North Atlantic?'. And those directed to investigating possible causal mechanisms such as 'teleconnection' between the global oceans (cf. ENSO) that may allow more confident predictions to be made.

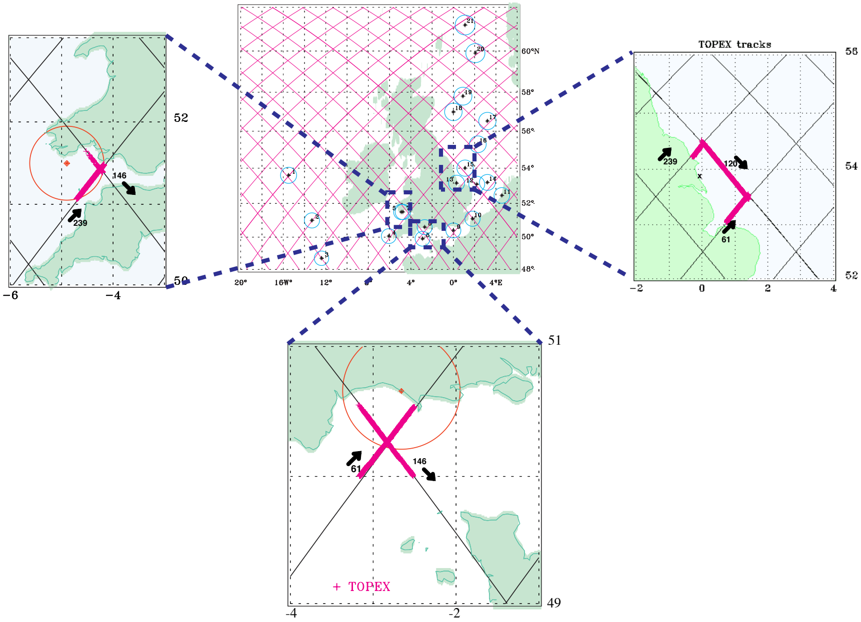
The initial main scientific objective of JERICHO was:

To investigate which parts of Britain's coastline may have experienced an increase in wave height similar to that observed by satellites in the surrounding seas, by a more detailed analysis of the satellite archive, augmented by advanced wave models capable of extending observed open sea wave conditions to shallow water coastal areas, and to link these results, where possible, with long-term 'in situ' wave measurements.

The ultimate economic goal of this investigation, with the Environmental Agency as the main customer, was:

To provide improved information on coastal wave conditions and inter-annual trends essential to the planning of Britain's coastal defences and to make progress towards developing a predictive capability.

Finally, looking beyond the benefits of the proposed co-operative research to our own Environment Agency, the proposal argued that it was in this country's best interests to merge the separate talents of the team members assembled here, to enable them to develop an investigative service to other countries concerned about the possible effects of global climate change on their own coastlines.



.Figure 2-1 Overview of JERICHO data sources and coastal locations. Main Panel - UK with TOPEX altimeter tracks (magenta) and in situ data sites, Insets- The three JERICHO coastal study areas, clockwise from left, Carmarthen Bay, Holderness and Lyme Bay.

3. Background & Context

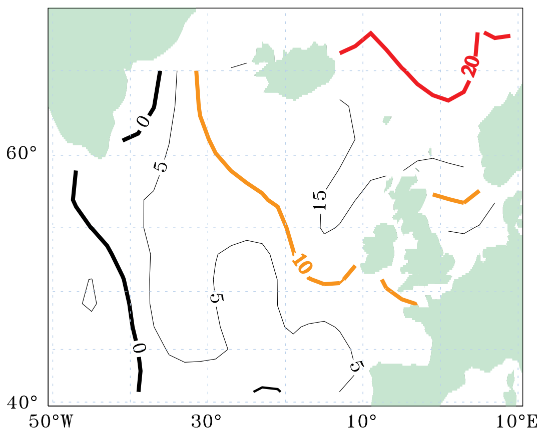
3.1 Satellite altimeter wave data

In 1978, one of the early ocean-observing satellites demonstrated that a precise radar altimeter could measure the height of surface waves to an accuracy comparable to buoy measurements. Mounted on a polar-orbiting satellite such a sensor held out the promise, for the first time, of monitoring wave climate over all of the global oceans. Unfortunately, the demonstration lasted only a few weeks and it was not until 1985 that another operational radar altimeter was launched. With an interruption of 18 months (1990-91) altimeter measurements of wave height have proceeded ever since. At present there are 2 spacecraft in orbit with active radar altimeters.

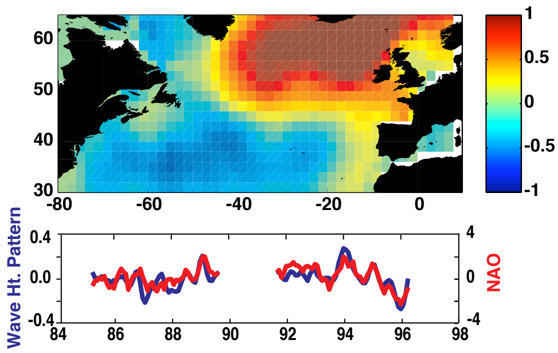
Observations of significant wave height made since 1985 are entered into the Satellite Observing Systems archive, 'Wavsat', and archived in 2° bins. Statistical studies can then be carried out to reveal, for example, average seasonal values from year to year or, of particular interest to the designers of marine structures, to calculate extreme values over the next 100 years. An upward trend would, of course, necessitate a re-evaluation of these estimates.

3.2 A changing wave climate

Although there were some indications of increasing wave heights in the North Atlantic from the analysis of visual observations (recorded over many decades by ships at sea) and from the records of ship borne wave recorders at a few locations, it was left to the uniform grid of repeated satellite observations to confirm that over a large area of the North Atlantic and Norwegian Sea wave heights have increased over the last few decades with inter-annual variability as great as 20%. A comparison of average winter wave heights (December - February) from 1985 - 89 and from 1991 - 95 demonstrates the rise over the North Atlantic and Norwegian Sea (Figure 3-1). Further work has shown that this increase has a very strong connection with the "North Atlantic Oscillation" (Figure 3-2). This research was carried out jointly by two of the JERICHO partners, Southampton Oceanography Centre and Satellite Observing Systems.



.Figure 3-1 The percentage increase in mean winter significant wave height, 1985-89 - 1991-96. Estimates from satellite altimeter data.



.Figure 3-2 The most significant pattern of wave climate variability in the North Atlantic (determined by EOF analyses), and the NAO, for the years 1985-1996.

3.3 In situ data

Because the altimeter is prevented from giving a true estimate of significant wave height if any landform enters its footprint, and because the footprint may be 10 - 15 km in diameter, the satellite record is unreliable close to the coast - the area of greatest interest to agencies responsible for coastal defences. Waverider buoys, and other devices, have been in operation around coastlines for longer than satellites but there are surprisingly few continuous long series of *in situ* measurements from which reliable statistics can be derived.

3.4 The need for models

The enormous rate of increase in the power of computers means that complex high-resolution models which calculate the change of surface wave characteristics on passing from deep to shallow coastal waters, impossible to contemplate 20 years ago, can now be utilised.

Given that wave heights have been shown to increase in the North Atlantic in recent years, the JERICHO project poses the question of how that increase relates to waves at the UK coast. It is intuitively obvious that increased wave heights in the open sea imply increased wave heights at the coast, but bottom topography and coastal morphology will complicate the problem and cause regional variations in the response. No satellite data are available near-shore and not enough buoy data exist to provide independent estimates, hence the solution is to combine existing offshore data with nearshore wave models to provide maximum benefit from the available information.

Another very important requirement was the development of a predictive capability. What has caused the increase in wave height? Is the changing wave climate part of a greater global climate change? Are we witnessing the effect of a global warming which may have started a trend that will continue for a very long time, or is this some sort of regional, decadal trend which may reverse quite soon?

The consortium that came together to address these questions is not only one of the most competent that could be gathered in this country. It also accords directly with the purpose of LINK programmes in that it links the necessary research into waves, tides and models now being carried out in two major NERC institutes with (i) a value-added company (SOS) which, with support from BNSC, has developed the most complete, spatially ordered, archive of satellite-derived wave heights (WAVSAT) in existence; and (ii) with the civil engineering company (Halcrow) that has developed the necessary software (STORM) to model the behaviour of waves in shallow water. The 'client' organisation is the UK Environment Agency which carries responsibility for this country's coastal defences. In every sense this is a case of harnessing the expertise that resides within NERC to the know-how developed by industrial partners to provide a national agency with the information required to plan its future strategy.

3.5 Recent studies

3.5.1 WASA

A MAST-funded programme called WASA has recently completed a study of waves in the North Atlantic using historical wind data (derived from pressure fields) to generate surface wave fields through the WAM model (Günther, 1998). The WASA programme carried out an analysis of historical wave measurements and a 40 year wave model hindcast. No satellite data were used in the study. WASA also carried out a model study of the effect of a doubling of atmospheric CO_2 concentrations on the wind and wave climate of the north-east North Atlantic Ocean and the North Sea. The results of the CO_2 experiment were inconclusive, with no significant change between the "control" and double CO_2 scenarios.

One of our partners, POL, was also a member of the WASA consortium and is therefore well-placed to assess the relevance to our programme of the models developed by WASA.

3.5.2 UKCIP

The UK Climate Impact Programme (UKCIP) produced a technical report "Climate Change Scenarios for the United Kingdom" in October 1998. In this document they assessed the consequences of various modelled climate scenarios on the (terrestrial) climate of the United Kingdom. They considered four emission scenarios:

Low Emissions scenario with "low climate sensitivity", 1% per annum CO_2 increase.

Medium Low The Hadley Centre's HadCM2 Ggd model, 0.5% per annum CO_2 increase

Medium High The Hadley Centre's HadCM2 Gga model, 1.0% per annum CO_2 increase

High IS92a emissions scenario with "high climate sensitivity", 1% per annum CO_2 increase.

Note: Since UKCIP (1998) was compiled, a further Hadley Centre model, HadCM3, has been developed. This model has a better representation of some processes and increased resolution in the ocean. Also referred to in this report is the HadCM2 Sa model, which includes the effect of sulphate aerosols as well as greenhouse gases.

We will not discuss the details of the UKCIP findings here, but state a few selected items.

They report confident predictions of:

- Increase in sea level of 20-80 cm around the UK by 2050.
- Increase in mean annual temperature of 0.7°C to 2.3°C by 2050.

They report, with lower confidence:

- An increase in winter precipitation (+6% to +15%, by 2050)
- A decrease in summer precipitation (0 to -18% by 2050).
- A decrease in the number of both winter and summer gales by 2050, but a return to current levels, and perhaps above, by 2080.

UKCIP (1998) places lowest confidence on predictions of changes in climatic variability - unfortunately the predictions needed most by JERICHO. Also, early investigations (Osborne et al, 1999) have found that these climate models cannot recreate recent trends in the North Atlantic Oscillation, thus suggesting a lack of confidence in their ability to predict future trends in the NAO. For the record, the HadCM2 model projects a decrease in the NAO by 2050, although with an increased variability. In contrast a climate model run at Hamburg predicts an increase in the NAO.

News releases have recently (25/11/99) been issued by the UKCIP following the completion of a regional study on the impact of climate change on the south east of England. We have asked for a copy of this report but unfortunately one was not available at the time of writing this report.

3.6 Conclusion

JERICHO has been an applied research programme; and therefore carried an element of risk. This risk existed because, to our knowledge, no previous attempt had been made to combine the offshore wave observations of a satellite with the *in situ* buoy recordings inshore, and to introduce shallow water models to 'bridge the gap' to the shoreline. Thus to some extent, JERICHO was entering uncharted waters.

Despite this risk, or perhaps as a consequence of it, the JERICHO programme was an exciting prospect. It was time that the altimeter record of waves, set to continue for several years, was applied to coastal zones and not just to shipping and the open sea.

Global warming, and the potentially damaging consequences to coastal defences as ice melts and sea level rises, is being treated seriously by a growing number of countries. The search for areas of economic importance to which satellite-derived information could make a substantial impact has continued since the launch of the first earth-observing satellites over 3 decades ago. Part of the difficulty in identifying activities that would benefit derives from the fact that satellite missions - particularly ERS-1 and ERS-2 - were designed primarily for scientific research. That is why most of the best analysis of data has been carried out by Principal Investigators within research organisations.

LINK support was required for this project because of the need to direct these scientific investigations to the shorter-term requirements of the Environment Agency, charged with protecting our coastlines from the ravages of the sea. None of the partners had the necessary resources to combine these separate elements in the way that LINK has achieved.

4. Key Achievements

In this section we identify the key achievements of the JERICHO project, in terms of new scientific findings, development of new applications and in providing wave climate information for the Environment Agency. The achievements are listed below and then discussed in more detail in subsequent sections. The italicised items identify those which directly address the Environment Agency's needs.

Satellite Altimeter Data

- Verification and application of altimeter data in near coastal regions (10-50 km offshore).
- Verification and first ever scientific application of altimeter wave period measurement.
- Identification of significant underestimation of wind speed by altimeter in certain coastal regions.
- *Characterisation and mapping of key features of wave climate around the UK.*
- *Mapping of statistical extremes in significant wave height around the UK, offshore and near the coast at the three JERICHO sites.*
- *Establish strength of connection of coastal wave climate to North Atlantic Oscillation*

***In Situ* Data**

- Identification of reliable long term *in-situ* data sets, and of organisations which operate best practice in archiving and providing data access.

Shallow Water Wave Models

- New applications of SWAN at Holderness, in Lyme Bay and in Carmarthen Bay.
- New applications of STORM model in Holderness, Lyme Bay and Carmarthen Bay.
- Comparison of ray tracing (STORM) and gridded spectral (SWAN) shallow water wave models.
- *Establish importance of key parameters (e.g. bottom topography, water depth, currents, bottom friction) on onshore wave propagation at different locations.*

Joint Applications (altimeter/models/in situ)

- Use of satellite altimeter data (time series or individual sets of extreme conditions) to set boundary conditions for shallow water wave models.
- At JERICHO sites, identification of different populations of significant wave height data dependant upon wave direction.
- *Estimates of extremes of onshore significant wave height at JERICHO sites.*

- *Identification of characteristics of areas least and most sensitive to change in offshore wave climate.*
- *Modelled worst case scenarios of wave climate change at JERICHO sites.*
- *Establish likely impact, in terms of wave climate, of modelled future climate scenarios from Hadley Centre.*
- *Recommendations for monitoring wave climate at selected UK coastal sites.*

In the rest of this section we progress through the different aspects of the JERICHO scientific programme. Firstly the verification, analysis and application of satellite altimeter wave data are considered, for coastal regions (Section 4.1), and then for offshore regions (Section 4.2). Next (Section 4.3) the *in situ* data are briefly discussed, followed by the applications of the SWAN and STORM shallow water models (Section 4.4). We then present the form of extreme value analysis that was applied to the different data sets and model outputs (Section 4.5), before discussing aspects of future climate scenarios that are relevant to JERICHO (Section 4.6). The largest section presents the results of the joint applications of wave models, satellite data and *in situ* data, individually for the three JERICHO sites at Holderness, Lyme Bay, and Carmarthen Bay (Section 4.7). Finally, we provide recommendations of requirements for monitoring future variability in coastal wave climate (Section 4.8) before reviewing the achievements of JERICHO against the initial aims of the project (Section 4.9). Readers are referred to the list of JERICHO Technical Reports in the reference section, which provide full technical discussions.

4.1 Satellite Altimeter Data in Coastal Regions

4.1.1 General Problems in Applications

Historically it has been easier to measure waves and estimate wave climate at near-shore sites than in the open ocean, but using the altimeter, the reverse is true. The satellite has problems in making measurements within a few kilometres of the coast, and the wave climate has much greater spatial variability in coastal waters than in the open ocean. Moreover, the altimeter has its limitation in that it does not give directional information; nor does it give spectral information- only an estimate of zero-upcrossing wave period from an empirical algorithm derived from open ocean measurements.

The altimeter's problems are:

(a) If there is any land within the radar footprint then the reflected pulse shape and strength are upset and wave height and period - as well as wind speed - cannot be retrieved. Sometimes spurious values are returned but quality control eliminate these. So no data are obtained within about 5 - 10 km of the coast, depending on wave height.

(b) If the satellite is travelling from land to sea, then the altimeter has to 'home in' to the sea surface. This can take 3 - 6 seconds, during which the altimeter travels 20-40 km. TOPEX altimeter appears to have a further problem as it comes off land in that the first one or two 1 Hz estimates of Hs are invariably higher than those further offshore. This is thought to arise from the along-track smoothing applied onboard TOPEX incorporating the spurious, discarded data.

The size of the problem is illustrated in Figure 4.1 which shows the location of TOPEX records off Lyme Bay. The track approaching the shore from the SW gets within a few km of the coast, while the first location with good data from the track coming off the land from the NW is about 38 km from the shore.

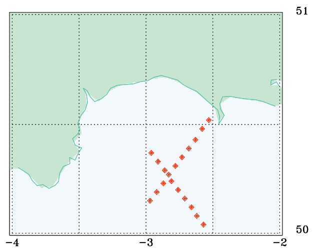


Figure 4-1 Locations of TOPEX data off Lyme Bay

Studies of the spatial variability of wave height in the open ocean - even an analysis of data from the centre of the northern North Sea by Tournadre and Ezraty (1990) - indicate that wave climate may be regarded as stationary over a radius of 100-200 km. So altimeter data obtained over a large area, say within a box of 2° latitude by 2° longitude, can be used to estimate the wave climate throughout the box. In coastal waters wave climate can vary over much smaller distances, along the coast as well as perpendicular to it. So wave climate can only be estimated from altimeter data within a few km of the satellite track - and for this purpose TOPEX, with the smallest repeat period of any altimeter, of 10 days, is the most useful. Deriving wave climate away from the altimeter tracks, requires help from either buoy or other *in situ* measurements or a fine mesh wave model; and even along the track such help is required to provide directional information.

4.1.2 Verification of near coastal altimeter data

Three altimeter wave and wind parameters have been used in JERICHO: significant wave height (H_s), wind speed (referenced to 10m above the sea surface - U_{10}), and zero upcrossing wave period (T_z). Whilst H_s and U_{10} are routinely provided in altimeter data sets, T_z is a parameter extracted from altimetry by a new procedure developed at Southampton Oceanography Centre (Davies et al., 1999). This is the first time that this T_z estimate has been derived, tested and applied in a research context.

Most calibration/validation exercises on altimeter wind and wave data have considered only open ocean data. These exercises (see Cotton, 1998) have shown that, after calibration, open ocean altimeter wind and wave data are remarkably accurate and reliable (residual root mean squares between co-located altimeter and buoy data are 0.3 m for H_s, 1.3 ms^{-1} for U_{10} and 0.7s for T_z). However it is possible that these calibration corrections may only be applicable to open ocean conditions. As JERICHO is a coastal study, it was important that altimeter wave and wind data were verified in coastal seas. Thus *in situ* data were compared with co-located altimeter data at a number of sites around the UK (Figure 4-2 and Table 4-1).

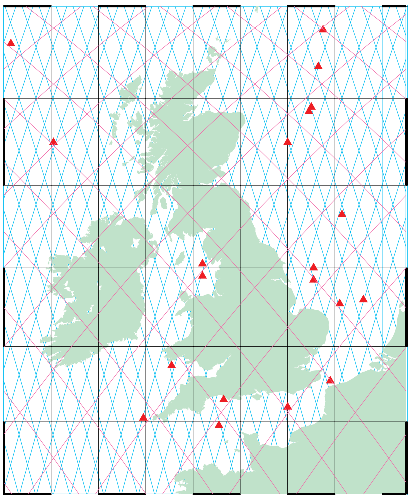


Figure 4-2 Locations of *in situ* data (red triangles) and altimeter tracks . Magenta lines indicate TOPEX tracks (10 day repeat), blue lines ERS-2 tracks (35 day repeat).

The most significant conclusions for coastal applications are:

Altimeter Significant Wave Height (H_s)
Robust and accurate. The residual root mean square (r.r.m.s) accuracy is everywhere better than 0.45 m, and less than 0.36 m at the North Sea sites.

Altimeter 10m Wind Speed (U_{10})
An important new result was that the altimeter was found to consistently underestimate wind speed in regions which have less exposure to the open ocean. It is likely that the state of wave development is an important factor. Thus whilst the altimeter data at exposed sites in the northern North Sea and Carmarthen Bay show no underestimate, altimeter data at sites with less exposure (in the southern North Sea) underestimate by 28-32%. The r.r.m.s. accuracy of the co-located data was at all times better than 1.5 ms^{-1}.

Altimeter Wave Period (Tz)
The altimeter provides an estimate of T_z to an rrms accuracy of 0.8s in the English Channel, and 0.5 s in the North Sea. However, it becomes less reliable under conditions of low wind speed and moderate to high waves. Effective limits of use are not less than 2 ms^{-1} for wind speed or *pseudo wave age* not higher than 12. (Pseudo wave age is an estimate of the state of development of the waves, Glazman and Pilorz, 1990) Altimeter wave periods do not cover as wide a range of values for a given wave height as *in situ* data.

	Name	lat (N)	lon (E)
1	K3	53.58	-15.55
2	K2	51.02	-13.35
3	K1	48.72	-12.43
4	Seven Stones	50.06	-6.07
5	St Gowan	51.51	-5.00
6	Channel LV	49.91	-2.92
7	SWALES	51.50	-4.75
8	Lyme Bay	50.50	-2.86
9	Greenwich	50.24	0.00
10	Sandettie	51.06	1.48
11	Ijmuiden	52.46	4.56
12	Leman	53.10	2.20
13	BoyGrift	53.49	0.39
14	K13	53.22	3.22
15	W.Sole	53.70	1.15
16	Villages	54.03	0.12
17	K17	55.33	2.33
18	Ekofisk	56.55	3.21
19	K16	57.00	0.45
20	Forties	57.80	0.90
21	Frigg	59.90	2.07
22	N North Sea	61.20	1.10
23	Holderness	53.93	0.03

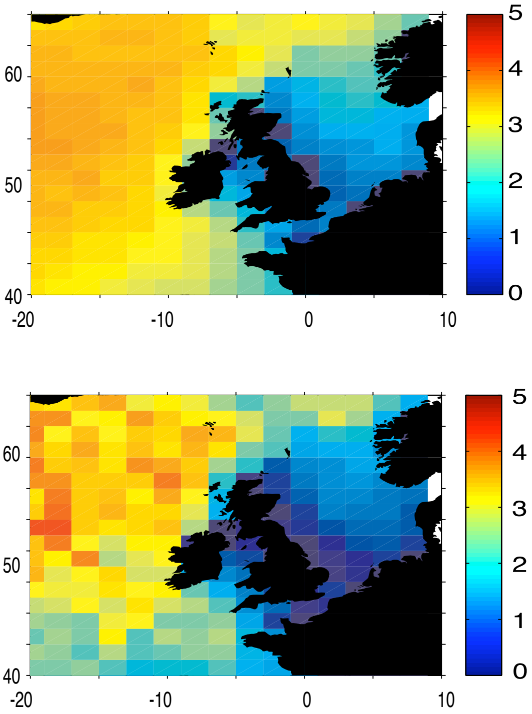
.Table 4-1 Locations of *in situ* JERICHO data

4.2 Altimeter Derived Offshore Wave Climate

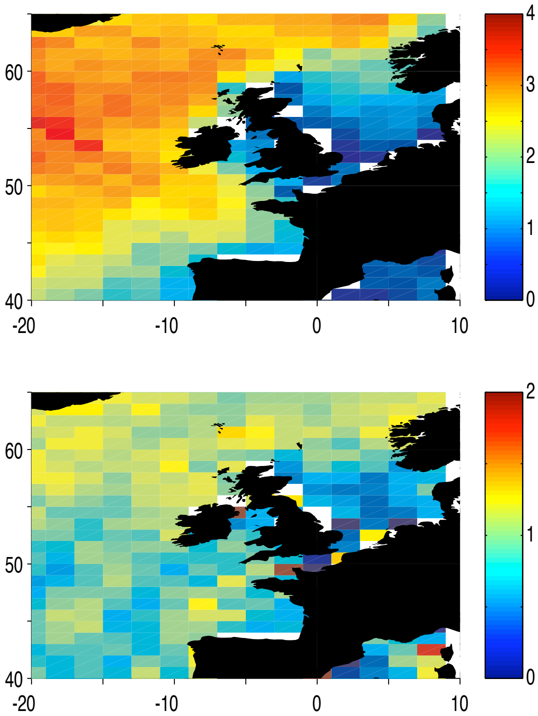
4.2.1 Introduction

Altimeter data allow us to generate a large scale overview of the offshore wave height climate around the UK, providing an essential context for viewing the coastal studies of JERICHO. This section presents an analysis of monthly mean significant wave heights on a 1° latitude by 2° longitude grid. Altimeter data from ERS-1, ERS-2 and TOPEX/Poseidon were used, from October 1992 to September 1998.

The wave climate can be considered as consisting of three parts: the mean climate, the annual or seasonal cycle and non-seasonal variability on both the short term (within year) and long term (between year). Within year variability is hard to characterise and is effectively the response to individual storms, hence only longer term, between-year, variability is considered here.



.Figure 4-3 Long term mean (top), scale in m, and variance in H_s (bottom), scale in m^2.



.Figure 4-4 Range (m) and time of maximum (month) in annual Hs cycle.

4.2.2 Mean Climate

From Figure 4-3 it is clear that the west coast of Ireland and Outer Hebrides experience the highest mean significant wave heights (3 m) and variance (3 m^2). Off the English and Welsh coastline, south west Wales and western Cornwall see the highest mean significant wave heights (2.0 - 2.5 m), whilst the English Channel and Eastern English coastline experience the lowest mean values and lowest variance. (see also Table 4-2).

4.2.3 Annual Cycle

A simple sine model for the annual cycle was used to define the annual cycle in H_s (see Figure 4-4). The annual range in H_s (i.e. the difference between winter and summer) decreases eastwards into the English Channel and southwards into the North Sea (from > 3 m at 20° W, to 1 m or less at the south-eastern tip of Kent). The time of maximum wave height may occur slightly earlier in the southern North Sea, early January, than it is elsewhere, particularly to the north-west of Scotland, where it occurs in early February (The colour key starts at 0, 1st January, and ends at 2, 1st March). We have also found that the annual cycle describes less of the variability in the sheltered regions (~30-50% of inter monthly variance explained in the southern North Sea) than out in the North Atlantic (~70% variance explained at 15°-20°W). This effect may be genuine, but could be a consequence of the poorer sampling of the sheltered regions by the altimeter because of greater data loss, and higher spatial variability, near the coastline.

4.2.4 Climate Variability

Whilst the seasonal cycle accounts for a large part of the variability in the monthly mean data, between year variability is also important. We all know from experience that some winters can be much stormier than others. It is therefore important to establish the nature of this year to year variability, and to try to answer some key questions:

Does the variability form part of a long term trend, or is it cyclical? If the latter, what is the time scale?

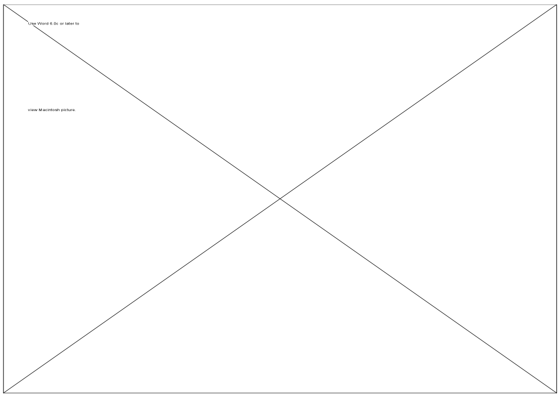
Can we identify the driving forces behind this variability, and through this understanding generate predictions of future wave climate over the next 10-50 years?

The mean winter significant wave height in the north-eastern Atlantic increased significantly between the 1960's and 1990's, and this increase was highly correlated with a rise in the North Atlantic Oscillation (NAO) index. The NAO is the anomaly in the pressure gradient across the north eastern Atlantic and is widely recognised as a key indicator of the state of the Atlantic and western European climate. Carter (1999) provides a comprehensive review. Estimates of the extent of this rise in H_s vary, but acceptable values seem to be a 0.03 m/yr increase in the mean winter H_s in the north-east Atlantic and 0.02 m/yr at Seven Stones, over a period of about 25 years. There is some recent evidence to suggest this trend may have slowed down. Although this trend may have extended as far east as the northern North Sea, there is no evidence to suggest any similar increases in the central and southern North Sea.

	mean H_s (m)	variance H_s (m)	H_s annual range (m)	H_s variance. explained by annual cycle	between winter variance explained by NAO	sensitivity of winter mean Hs to NAO	sensitivity of 100 yr Hs to NAO
Outer Hebrides	*3.3*	*3.0*	*3.0*	58%	79%	0.42	1.28
Carmarthen Bay	*2.1*	*1.5*	*1.2*	55%	54%	0.21	0.69
Lyme Bay	*2.0*	*1.2*	*1.5*	50%	13%	0.10	0.38
Holderness	*1.5*	*0.8*	*0.5*	25%	-		

.Table 4-2 Characteristics of significant wave height climate at selected UK sites. Sensitivity to NAO is defined as the change in H_s parameter (m) per unit change in NAO.

Figure 4-5 shows the variations in the (smoothed) NAO index since 1860, providing a historical context. A significant increase between the 1960's and 1990's is clearly seen. It is also apparent that the high level of the NAO in the early 1990's was the highest sustained level since records began, although multi-decadal cycles of similar amplitude have occurred in the past. There is an indication that the NAO may have recently entered a downward phase in the long term cycle, though more years data are required before this can be confirmed.



.Figure 4-5 Time series of the winter North Atlantic Oscillation (taken between Lisbon and Iceland)

4.2.4.1 Statistical analyses: "EOFs" and "CCAs"

In recent years a number of statistical techniques have been used to identify coherent patterns of climate variability and to correlate them with patterns in other parameters or with known key climate indicators. Empirical Orthogonal Function (EOF) analyses identify statistically independent "modes" of variability in data sets. Canonical Correlation Analyses (CCAs) provide a way of identifying correlated modes of variability in different data sets. Preisendorfer (1988) provides a full background. Although these statistical analyses provide no physical explanation for the patterns they reveal, they can establish important characteristics of variability.

Thus an EOF analysis was carried out on the gridded altimeter wave height data. The first mode of variability (which explains 55% of the non-seasonal variability in the data) is shown in Figure 4-6 (also see Figure 3-2 - which shows the same mode over a larger area and time period). This "mode" is particularly interesting because the time series closely resembles that of the North Atlantic Oscillation or NAO. The spatial pattern is also highly characteristic of climate features linked to the NAO.

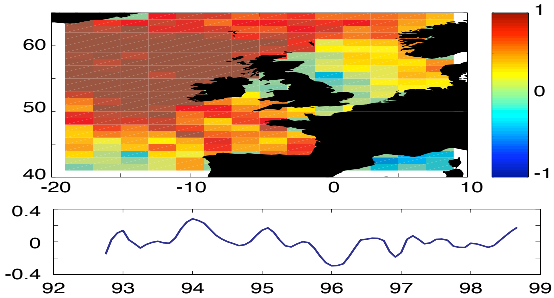
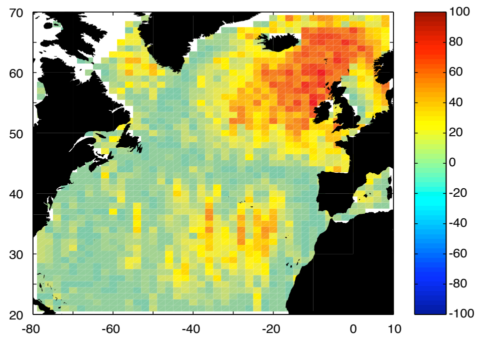


Figure 4-6 The first "EOF" mode in monthly mean Hs in the NE Atlantic (annual cycle removed). The top panel shows the spatial pattern, the bottom panel the times series.



.Figure 4-7 The influence of the NAO on the mean Hs (as % of inter-annual variance explained) from a canonical correlation analysis.

A canonical correlation analysis was carried out to establish the correlation between the NAO and the inter annual wave climate variability (as represented by the EOF modes). On the large scale, over the whole north east North Atlantic (Figure 4-7) 64% of the variance is connected to the NAO, whereas there are differing strengths of connections with the between winter variability at the three JERICHO sites (54% at Carmarthen Bay, 13% at Lyme Bay, no significant connection at Holderness, Table 4-2). This table also gives the 'sensitivity' of the winter mean H_s to changes in the NAO. For instance the wave climate off the north-west of Scotland (the Outer Hebrides) is highly sensitive, such that a unit change in the NAO will induce a 0.42m increase in the mean winter H_s, and a 1.28m change in the 100 year return value. Of the JERICHO sites, Carmarthen Bay is most affected by the NAO (0.2m change in mean H_s, 0.69 m change in 100 yr H_s per unit NAO change). Holderness is not significantly affected.

4.3 In Situ Data

Figure 4-2 and Table 4-1 gave the locations of the *in situ* data used within JERICHO. These data sets were selected because they promised continuous long term measurements. Data were made available to JERICHO either free, or at the cost of production only by the British Oceanographic Data Centre (BODC), the UK Meteorological Office, Seadata (now Fugro GEOS), Loginfo A.S., and the Netherlands public body Rijkwaterstaat. In fact, even with these carefully selected data sets, data quality problems were still experienced. Typically these problems were prolonged data drop outs, incorrectly set or unset default values, and unnecessarily coarse resolution. In particular there were problems with UKMO derived data for the west coast and English Channel. Data provided by BODC, Fugro GEOS, Loginfo and Rijkwaterstaat, mostly from the North Sea, were found to be more reliable.

4.4 Shallow Water Wave Models

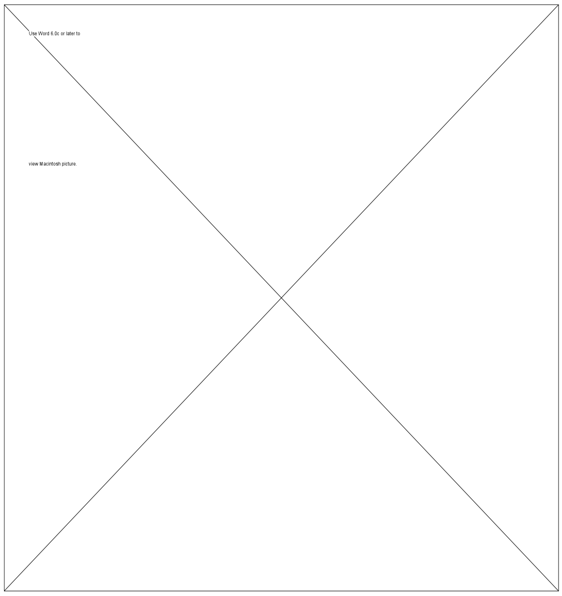
4.4.1 Coastal Wave Climate

Coastal wave climate refers to patterns of wave conditions which prevail from year to year and their inter-annual variability. Knowledge of wave climate allows predictions to be made of the frequency of occurrence of certain types of event which may impact on coastal defences or morphodynamics, see e.g. Hedges et al. (1991). Information on the waves at any particular coastal location is sparse. Some information may be obtained from wave atlases e.g. OCEANOR World Wave Atlas. Usually coastal management plans e.g. Barber and Thomas (1989) are based on a limited number of quite short-term wave data sets carried out within the study. A data inventory has been made for coastal wave data (Brampton and Hawkes, 1990) which may appear sufficiently dense but often the data do not cover more than one year or one winter. The longer time series that are available offshore and from satellite data are too far offshore to be applicable. This is why it is necessary to use wave transformation models to convert the more prolific offshore data to inshore. The EUROWAVES project (Sclavo and Cavaleri, 1999; Cavaleri et al., 1999) aims to provide wave statistics for the whole European coast, by a combination of observations and modelling.

4.4.2 The "STORM" Model

For the JERICHO shallow water studies Halcrow has used the STORM model to transfer the deep water wave climate to the shore, with the aim of determining whether changes in deep water wave climate will have any effect on the wave climate experienced at the coast at the three JERICHO sites: Holderness, Camarthen Bay and Lyme Bay.

Halcrow's spectral wave transformation model is based on ray tracing. At the offshore point, in addition to the integrated parameters, (H_s, significant wave height, T_p, peak period, θ_m, mean direction), STORM requires a full frequency spectrum and information on the mean direction and spreading. The modelling procedure comprises three stages: establishing the data grid system, setting up the ray paths for each inshore location (a new setup is required for all combination of water depths and wave periods), and then finally transforming a time series of wave conditions at the offshore boundary to the onshore site.

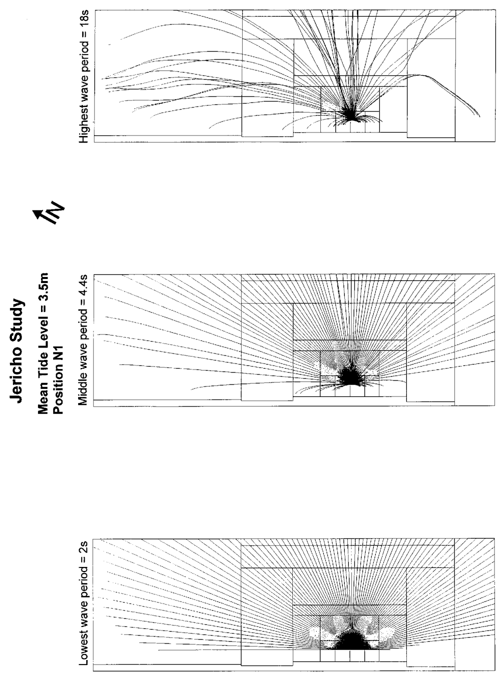


.Figure 4-8 STORM model grid for Holderness

The STORM grid for Holderness is shown in Figure 4-8. The figure demonstrates the nested grids at 50 m, 100 m, 200 m, and 500 m. For this grid, the program then calculates the paths of wave rays (lines orthogonal to the wave crests) as the wave propagates from element to element across the bathymetric model, using a circular arc technique (Figure 4-9). This may be done for specific tide levels and ranges of wave periods, tracking to or from a number of study points.

For the JERICHO studies we used the STORM model in its "backward tracking" mode, which provides an accurate and detailed study of the wave climate and is the basis of wave height and energy determination. The waves are tracked in a range of directions from the study point.

A simple model such as STORM can be run economically over a long period, and so generate inshore wave statistics.

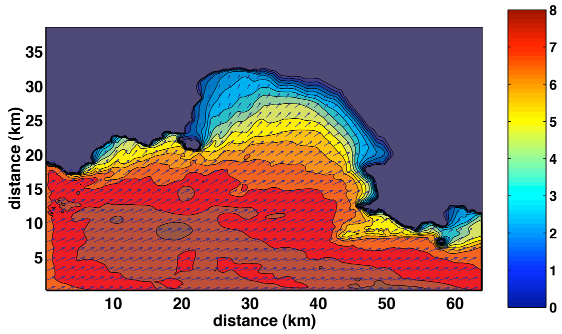


.Figure 4-9 Example of ray paths for the STORM model for three different wave periods at one water level

4.4.3 The "SWAN" Model

The SWAN 3rd-generation spectral wave model is a state-of-the-art model which includes all relevant physical processes explicitly. This is a phase-averaged model specifically designed for the nearshore zone (Ris et al., 1999; Booij et al., 1999). Note that spectral wave modelling may be applicable to a minimum water depth of about 5m. By this depth non-linear wave effects are important and depth-limited wave breaking becomes important. Certainly the SWAN model is not applicable inside the surf zone. It has been suggested that the assumed Rayleigh distribution (for individual wave heights) is not applicable in shallow water or that a new definition of Hs is needed. Phase-resolving (e.g. Boussinesq) models are required at the shallow water limit and to deal with the physics of diffraction around obstacles and breakwaters, for example. One of the benefits of SWAN is that it produces a 2-D map of wave heights over the whole model area rather than just predictions for a single location as in ray-tracing models (see Figure 4-10). The SWAN model proved able to reproduce wave events given good boundary input spectra at Holderness (Figure 4-11)

The SWAN model was also used to test the characteristics of wave transformation over the nearshore zone from about 20 km offshore in about 30m water depth to within 1 km of the coast in about 5m mean water depth. The model has been used to investigate the effect of variations in important physical parameters controlling wave height at the coast: offshore wave height and period, water level, bottom friction and depth-limited breaking. Errors can be introduced due to errors in bathymetry e.g. changes in charted depths. Secondary effects are the exact form of the boundary conditions, local wind and triad wave-wave interactions. The model's triad interactions were found to be apparently over-active in generating higher harmonics and were therefore switched off. The inclusion of spatially-homogeneous currents was found to have a minor effect, producing a Doppler shift in predicted frequencies and small changes in wave height. However the spatial variation in current should be included especially in an area of complex bathymetry such as Carmarthen Bay where current refraction is likely to be important (Barber and Thomas, 1989). This requires simultaneous solution of a 2-D hydrodynamic model, ideally at the same resolution as the wave model. Also SWAN does not include wave-current interaction in the bottom friction term which is probably important. A very detailed review of the physics of SWAN has been carried out by Dingemans (1998), who recommends further developments which need to be carried out to improve the accuracy of forecasts in the coastal zone, especially if these are to be applied in morphodynamic models.



.Figure 4-10 Map of wave height contours from SWAN for Carmarthen Bay with arrows showing mean wave direction

4.4.4 Comparison of SWAN and STORM Models

A comparison of the SWAN and STORM models was carried out for the largest recorded event at Holderness in the *in situ* data (1-2 January 1995). Statistics for this event are given in Table 4-3. See also Figure 4-11. The figure indicates that the performances of the SWAN and STORM models at Holderness were comparable, with SWAN slightly more accurate at N2, but STORM more accurate at N1. SWAN overestimates the wave height at N1 (suggesting the need for a larger bottom friction coefficient) but follows the water-level modulation better. At N2, SWAN is more accurate than STORMS.

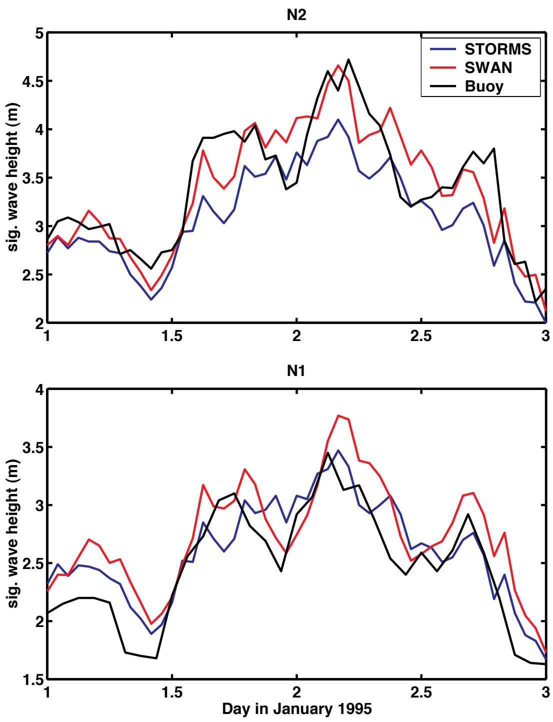
4.5 Extreme Value Analysis

A key Environment Agency requirement was the size of extreme events that could be expected at the shoreline. The techniques to provide these estimates of extreme values can be confusing to the non-expert, and are not always correctly applied. To provide some guidance we include a brief introduction of the techniques applied within the JERICHO studies.

Results from an analysis of gridded altimeter offshore data are presented in this section, but the results of analyses at the JERICHO sites will be presented later, in Section 4.7, where the joint application of models, altimeter data and *in situ* data are discussed individually for the three JERICHO sites.

	Mean *Hs* bias *(model -buoy)* (m)	Std. Dev. (m)	*Hs* model (m)
Station N2 (depth=14.3m, 49 data points)			
SWAN	-0.03	0.33	3.39
STORM	-0.33	0.32	3.09
Station N1 (depth=7.0m, 17 data points)			
SWAN	0.24	0.21	2.70
STORM	0.07	0.23	2.58
Station N11 (depth=12.7m, 17 data points)			
SWAN	0.39	0.23	2.87

.Table 4-3 Comparison of the significant wave heights produced by STORMS and SWAN with observations at Holderness for 1-2 January 1995. (depth is given at mean sea level)



.Figure 4-11 Time series of SWAN and STORM vs observed data at N2(top) and N1(bottom)

4.5.1 Theory

The basic problem is to estimate the extreme value of the significant wave height (H_S), and the associated mean zero-upcross wave period. These can be estimated from the extreme H_S, together with assumptions about the limiting steepness.

The N-year return value is defined as that which is exceeded on average once in N years. This is a precise definition if the data occur at regular time intervals, with the return value of parameter x given by

$$\text{Prob}(X<x)=1 - 1/Nn \qquad (4.1)$$

where Prob() is the cumulative probability distribution of X and n is the number of observations each year.

H_s is a continuous parameter (although it can only be measured to useful accuracy from a time series at about 0.5 hr intervals) and such measurements are highly correlated. So there is no obvious choice for n. However, the usual assumption is to use the number of 3-hours in a year for n, i.e. 8*365.35 = 2922. This strictly gives the wave height which, if measured at 3-hr intervals would be exceeded on average once every N years. Due to correlation in the data, bunching of extremes will occur, in a very large, long-lasting storm successive 3-hr values might exceed the N-year level, so more than N years would be expected before the next event. On the other hand, even higher waves can be expected between the 3-hr measurements. Experience indicates that the choice of n=2922 is a reasonable compromise.

Another approach is to define the N-year return value as the maximum annual value which is exceeded on average for one year in N. This avoids the 'double counting' of waves from the same storm - but disregards the 2nd, 3rd,... highest storms during the year.

Estimating the N-year return value of H_s therefore requires us to estimate the cumulative probability distribution - Prob() in equation 4.1. Given a sufficient number of years of data, then a value of x with probability of 1-1/Nn could be interpolated from the data, but we do not have anywhere near a sufficient number for this, so we have to fit the data to some theoretical distribution and extrapolate. There is no theoretical or physical justification for any particular distribution. Several have been used, including the 2-parameter and 3-parameter Weibull, and the log-normal distribution. The one used in this report is the Fisher-Tippett Type 1 (or Gumbel) distribution, which has been found to provide a reasonable fit to Hs data, particularly to data from open waters around the UK. For example, this distribution was used to obtain indicative values for 50-year return values of H_s around the UK in the 'UK *Guidance Notes'* (Department of Energy, 1990). It is given by:

$$\text{Prob}(X<x)=F(x)=\exp\left(-\exp\left[-\frac{(x-\alpha)}{\beta}\right]\right) \qquad (4.2)$$

where α and β are location and scale parameters respectively and the following relationships hold

$$mode=\alpha$$

$$median=\alpha-\beta\log_e\log_e(2)\approx\alpha+0.3665\beta$$

$$mean=\alpha+\gamma\beta$$

$$\text{where } \gamma \text{ is Euler's constant} \approx 0.57722$$

$$variance=\frac{\pi^2\beta^2}{6}\approx 1.64493\beta^2$$

The plotting position used in our figures for FT-1 data is that recommended by Gringorten (1963):

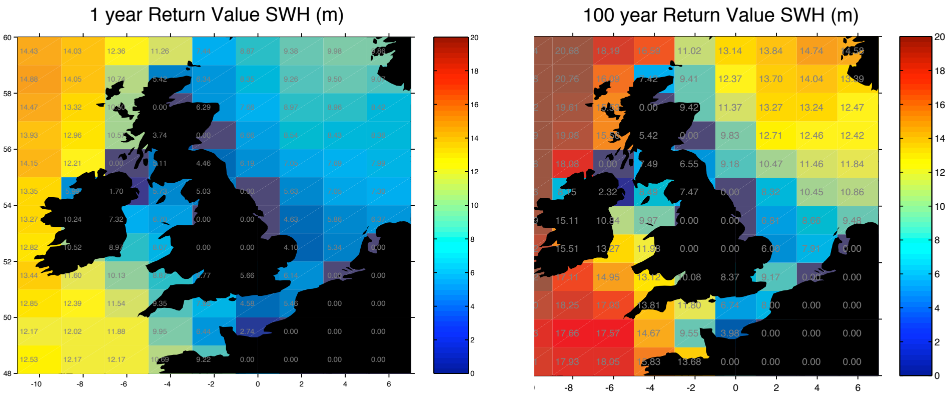
$$\text{Prob}(X<x_{(i)})=\frac{i-0.44}{n+0.12}$$

where $x_{(i)}$ is the i^{th} ordered value, $x_{(1)} < x_{(2)} < \ldots x_{(n)}$ (n is the number of data points in the analysis).

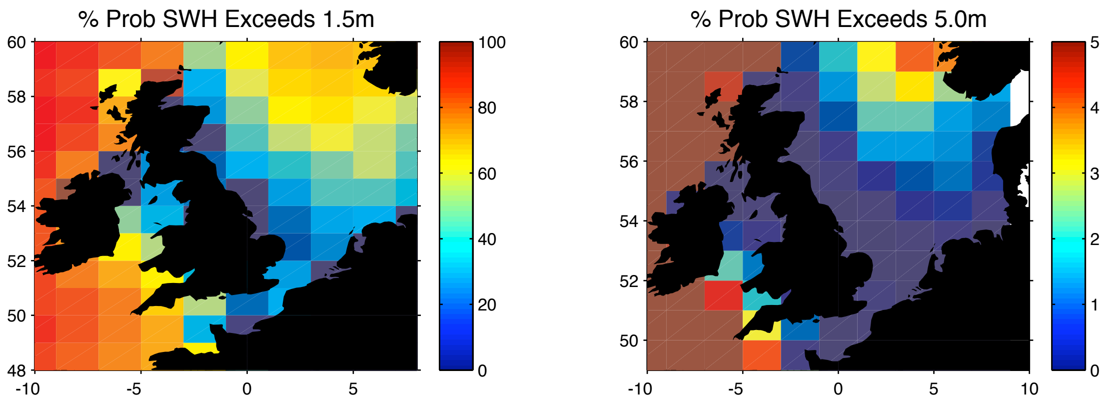
4.5.2 Offshore altimeter data

The extremal analysis for offshore data follows the theory outlined above. The mean and variance of significant wave height were calculated for each grid square and used to derive the FT-1 location and scale parameters (α and β). Return values for selected intervals, or probabilities of exceeding certain H_s thresholds were derived from equation 4.2.

An appendix to this report contains charts of exceedance probabilities and extreme values estimated in this way. Figure 4-12 and Figure 4-13 provides examples of such charts.



.Figure 4-12 1 year and 100 return values for significant wave height from gridded altimeter data .



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.Figure 4-13 Percentage probabilities that Significant wave height exceeds given threshold

4.5.3 Nearshore Altimeter Data

Offshore, all data from an area such as 1° latitude by 2° longitude can be used to estimate the parameters of the FT-1 distribution taken to describe the H_s distribution throughout the area. Nearshore, because of the relatively large changes in the distribution of H_s over a few km, this approach is not possible. However, estimates of the H_s distribution can be obtained by analysing TOPEX H_s values at each location in the data set. Except near cross-over points of the ascending and descending TOPEX tracks this only gives one measurement every 10 days, so in 6 years data there are only about 200 values from which to estimate the two parameters of the FT-1 distribution. However, these values are independent, unlike the 3-hourly measurements from a buoy, so the reduction of information in these altimeter data compared to a few years of buoy data is not nearly as severe as a simple comparison of the numbers of records would suggest - and the TOPEX data include between-year variability since October 1992.

Estimates of extremes from TOPEX along-track data for the three locations, Holderness, Lyme Bay and Carmarthen Bay are discussed in later sections, in conjunction with analyses of model and *in situ* data. Of particular interest are the results for Lyme Bay, where the TOPEX track into the Bay (Figure 4.1) provides an example of the value of these data in assessing changes of wave climate towards the shore - of direct importance at this location and useful for validation of the wave models of Lyme Bay.

4.5.4 STORM Model Extremes

The input for the STORM model was a time series of spectral wave data, which STORM then transformed into a time series at the inshore point. These transformed data were then used in JERICHO to estimate N-year return values. As we will see, such further processing should be carried out with care. If a simple approach were applied, in which it was assumed that all the data fit a single prescribed distribution function, then erroneous results can follow. It was thus found necessary to adopt a more rigorous approach, which involved a check of the fit of the data to the selected distribution function, and the subsequent "censoring" of data to exclude anomalous low values from the data set.

4.5.5 SWAN model extremes

The SWAN model was applied to the 1-year, 100-year and 1000-year extreme events as obtained from extreme value analysis of the offshore wave data, whether from buoy or satellite altimeter. The offshore data are assumed to be in sufficiently deep water that they are unaffected by tidal water level. These events were used as input to SWAN, which then treated them as actual events. An appropriate wave period and water level had to be selected. The extreme wave period was also obtained from the offshore data. SWAN requires an estimate of peak period to determine the offshore boundary condition in terms of the full wave spectrum. This was derived from the observed offshore zero-up-crossing period by a linear relationship. The water level selected was the equivalent 1-year, 100-year or 1000-year water level derived from Dixon and Tawn (1994) which combines tide and surge levels. This combined event may give an overestimate of the probability of occurrence of the extreme wave height, but errs of the side of 'worst case scenario'.

4.5.6 Appropriate use of the STORM and SWAN models

The SWAN model explicitly includes the various physical processes and some parameters, such as the bottom friction coefficient, which can be 'tuned' to produce good results for each of the different sites, given sufficient *in situ* measurements. It can also output integrated parameters such as H_s, Tz over the whole model grid rather than at a single point. Full 2D (frequency-direction) spectra can be output at any number of specified points. The STORM model possibly models wave propagation and refraction more accurately due to its very high spatial resolution nearshore. It can be run for a long time e.g. several years in the same time that SWAN takes to run several days. The output can then be analysed to give the full wave climatology directly. However, the STORM model does not explicitly contain the effect of dissipation. It is also not possible to include the effects of wind, surge or currents in the STORM model.

The joint probability analysis for waves and still water levels often discusses the effect of surge e.g. HR (1998), Alcock and Carter (1986), but not tide. The largest possible waves inshore will occur at high water (since the water depth is the limiting factor for wave height at the coast) so tides and surges should be taken into account for the extreme analysis of waves in less than about 10 m mean water depth. Often the high water case (worst case scenario) only is considered. Surge effects may be important locally, but are secondary to tidal effects. An increase of water level due to a storm surge may not always occur at times of large wave height because the optimum wind direction for producing a large surge may not correspond to the conditions required for large waves (In fact a negative surge i.e. a reduction in water level may occur at some locations depending on the coastal configuration.) The joint probability of inshore waves and water levels may be addressed by fitting statistical distributions to the wave height, water level and wave period (e.g. Owen et al., 1997). If the dependence is treated in a statistical way, however, certain physical processes may be overlooked.

Halcrow's STORM model has to be run for a specific time period (to get the correct tidal water levels), and in principle can be run for an extrapolated 'future' scenario. The time variation of water depth is included in the model but cannot be altered from the predicted tide for the selected time. For calculating the extremes the STORM model may appear more appealing than the approach of modelling a single event (as in SWAN), because the STORM model can generate a time series of data which may be analysed to provide statistically derived estimates of extreme values. Also we have the problem of correctly representing the complex issue of joint probability (combined effects of wave height, water level and wind). It is not necessarily the case that the 100 yr wave event offshore simply transforms to cause the 100 yr extreme onshore. Unfortunately, because boundary condition data are only available for the STORM model for a few years, one has to be careful when extrapolating the statistics beyond the 10 yr extreme event. This is because it is expected that for the really big events, the limitation due to water depth will be much greater, causing the distribution of wave heights to be truncated. Thus for the 100 yr and 1000 yr event the SWAN results may be of higher accuracy despite the fact that the joint probability problem is only approximated. It is encouraging that the general agreement of the two models for the one year extremes is good. Further development of extreme value analysis in shallow water is needed, whichever model is used.

4.6 Future Climate Scenarios

One of the aims of the JERICHO programme was to use the best available climate predictions to derive projections of the wave climate for the next 50 years. This was never going to be a simple task and has indeed provided the team with the greatest challenge. In the end we have been unable to provide wave climate projections, frustrated by a basic lack of predictability in the climate fields that force the wave climate. Below we briefly discuss the approach that was taken.

So far as climate models are able to predict future climate patterns and wind/wave fields, we have the following general predictions for the next 50 years. This summary is based on the results from the EU Waves and Storms in the north Atlantic (WASA) research programme (WASA, 1998), and the UK Climate Impact Programmes Technical Report, "Climate Change Scenarios for the United Kingdom", (UKCIP, 1998) which assessed the consequences, for the UK, of various climate scenarios as modelled by selected large scale global climate models.

1) The mean value of the NAO is set to decrease by 2050, though its variability is predicted to increase.

2) There is no indication that the (NAO related) recent increasing trend in mean winter waves off the western approaches and west coast of the British Isles will continue. If anything the general indication is for a slight decrease.

3) There is a suggestion (from WASA) that mean and extreme waves in the North Sea may increase slightly (10-20%) - However this increase is within the range of the variability that has been experienced in the past 50 years.

4) There is a projected decrease in the number of winter gales over the UK by 2050.

5) Sea levels are confidently predicted to rise, in the range 18-80 cm by 2050.

6) Extremes of water level heights from a storm surge model are predicted to increase in the North Sea, though again within the range of variability experienced in the last 50 years.

Given an existing trend in an environmental variable we are faced by the problem of whether this will continue into the future or not. This is a non-trivial problem. One solution is to extrapolate simply the currently observed trend but we are faced with the possibility that what we have observed is not a trend at all but simply the 'up' part of a cycle which is about to turn 'down'. Thus any prediction based on extrapolation must be suspect. A much better approach is to use some physical basis for the prediction. In terms of climate prediction there are the climate models being run at centres such as the Hadley Centre in the UK and DKRZ in Hamburg in Germany. Not only do these produce predictions of future conditions but they also give results for alternative scenarios, for example differing amounts of CO_2 or aerosols. Unfortunately for JERICHO these models at present do not include wave models so we need to find some way of converting from the meteorological variables in the model output to wave parameters suitable for prescribing the boundary conditions in SWAN. Ideally we would run a wave model such as WAM driven by the climate model winds. This was done in the WASA project using the output from the Hamburg model.

In JERICHO we chose a more statistical approach. In essence our technique has been to establish a relationship between present day meteorological conditions and offshore waves at our three sites. Assuming that these relationships continue to hold in the future we can compute the expected wave conditions for driving the shallow water models. Initially our intention was to use North Atlantic pressure fields as the meteorological driving variable, however although we could obtain the Hadley Centre future pressure fields we could not, within the time, decode the present day ECMWF fields from the British Atmospheric Data Centre (BADC). Instead of using the actual pressure fields it was decided therefore to use the North Atlantic Oscillation (NAO) Index instead. Results from this form of analysis of historical data have been presented earlier in Section 4.2.4.1 Once we have established such a relationship it is trivial to apply it using NAO values from the climate forecast, and assuming that this relationship is robust to any changes in the climate system we can forecast the average significant wave height or the 100 year return value at some point in the future..

In order to use this method we need to have confidence in the NAO values produced by the climate model. As well as forecasting, the Hadley Centre model has been used in hindcast mode to recreate the past. Whilst not expecting such a model to reproduce the past climate accurately it should capture the main features of the past climate. One such feature is the increase in the NAO since the 1960's (this has correlated with the increase in NE Atlantic wave heights). Unfortunately none of the Hadley simulations with or without greenhouse gasses simulates this rise in the NAO effectively (Osborne et al, 1999). Moreover, the UKCIP (1998) places least confidence in representations of future variability, and the Hadley model predicts a fall in the NAO in the next fifty years whereas the Hamburg model predicts a rise, so it did not seem sensible to place too much faith in any individual model climate outlook. Thus it was decided that we could not rely upon the Hadley (or other global circulation model) predictions.

The JERICHO team therefore agreed instead to model some selected "worst-case" scenarios. The worst scenario would be an increase in mean water level, plus an increase in tidal high waters, combined with an increase in wind speed. An increased frequency of storms without an increase in the maximum intensity could be very significant for coastal defences in its impact on structures. It is very difficult to assign errors to these predictions. Coastal wave height is limited by water depth so is not as likely to increase even if the offshore waves increase unless a relatively large change in water depth is predicted. Offshore wave height could be increasing due to the NAO effect. Rising water levels are predicted globally due to climate change but the change in level is not very large and regional and local estimates are required. The team therefore settled on modelling a 20% increase in the 1 year return significant wave heights (corresponding, for Carmarthen Bay, to a 2-3 point rise in the NAO, Table 4-2) and a 10% increase in the 100 year return values, together with the predicted increases in sea-level.

4.7 Joint Application of Models, Satellite Data and in situ data

4.7.1 Introduction

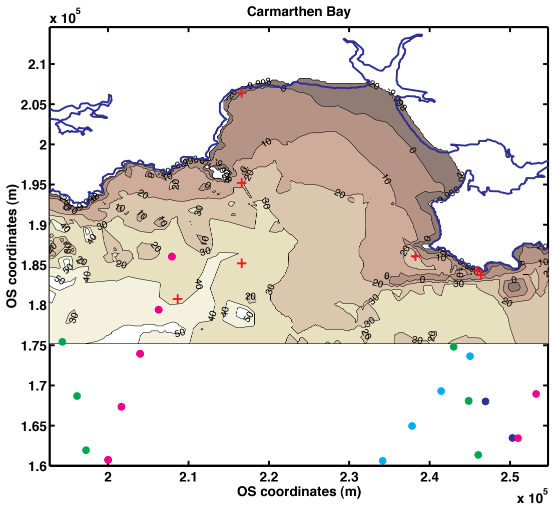
A major aim of JERICHO was to investigate how satellite, *in situ* data and models could be used together to investigate shallow water coastal wave climate, and so derive information of value to the Environment Agency. The individual qualities of each data set are well established. Satellite altimeter data provide highly accurate measurements of a limited range of sea state parameters with good large scale spatial coverage, but have infrequent revisit periods and cannot provide information within 10 km of the coastline. *In situ* data are only available at a number of limited locations, but can provide continuous time series of a range of spectral and directional wave parameters. Finally, wave models can be highly sophisticated and can provide a range of wave parameters right up to the surf zone at the coast. However, models are only as good as their internal representation of the physical interactions and as the data that are used for boundary conditions. This section discusses the methodology which was developed in order to combine, to best advantage, the individual qualities of each of these data sets.

The layout of this section is as follows. We first discuss in general terms the requirements of the STORM and SWAN models for boundary conditions and how the altimeter data (and *in situ* data) have been used to meet these requirements. We then consider individually the methodology and results from each of the three JERICHO sites.

4.7.2 Wave Model Boundary Conditions and Altimeter Data

In general there is a mis-match of time and space scales between satellite observations and model requirements for input data. The satellite data are relatively sparse in time and are concentrated along discrete tracks, which are unlikely to coincide with model boundaries, although when available it has locally high resolution in space (along-track) and in time and is now building up a substantial time series (over 10 years).

The aim is to utilise the data available from satellite altimeters to derive boundary conditions for the coastal wave model which can then be used to derive the wave energy in shallow water areas. Figure 4-14 shows the SWAN model area for Carmarthen Bay. In this case the model ideally requires input at each boundary point i.e. at the spatial resolution of the model grid (here 200m) although this may be provided by interpolation, the input must be physically consistent otherwise the boundary error may corrupt too large an area of the internal solution.



.Figure 4-14 Carmarthen Bay SWAN model area - positions of output points are red crosses, altimeter tracks are circles (dark blue = TOPEX 146 [down track], light blue TOPEX 239 [up track], magenta ERS-2 [down track], green ERS-2 [up track]).

The wave parameters available from the satellite consist of estimates of significant wave height (H_s) and zero up-crossing period (Tz). For the largest wave events the assumption of wind-sea is probably acceptable and the JONSWAP spectrum is a reasonable approximation in water depth greater than 30m.

The extrapolation from the nearest altimeter observation to the model boundary is site-specific, depending on the coastal configuration and the proximity of the satellite track (see later in section, 4.7.2.). The best solution may be nesting the coastal wave model within a coarser model covering a wider area in which the satellite data can be related directly to the nearest grid-point (Monbaliu et al., 1998). Ideally we need ocean to continental shelf-scale model hindcasts, plus satellite data assimilation to improve these as necessary, driving an intermediate-scale wave model (5 km) such as PRO-WAM (the version of WAM developed in the EC PROMISE project), which can also be enhanced by assimilation of satellite data. This can then provide optimum boundary conditions for SWAN or STORM.

A key component of this project has been investigating a methodology for combining satellite altimeter and *in situ* wave data with wave model studies to obtain the best estimate of wave climate in coastal waters. The investigations at three, very different, locations around the UK coast, described below, indicate that it is not possible to lay down a simple, generic methodology, it depends upon the nature and exposure of the site, the quantity - and quality - of altimeter and *in situ* data and the availability and precision of numerical wave models.

4.7.2.1 Model Boundary Requirements

Both wave models require a full 2D (in frequency and direction) wave spectrum to be specified on the boundary, so it is necessary to make some assumptions about the actual shape of the wave spectrum. Using the significant wave height, H_s, and peak period, Tp, and assuming a JONSWAP spectral shape, the boundary condition can be supplied. The JONSWAP spectrum uses a peak period as one of its principal parameters. While this is a standard parameter output by analysis of wave buoy measurements, it is not necessarily a very good choice, since an erroneous period can easily be chosen if the buoy spectra are noisy or there is a bimodal spectrum. Some assumption has to be made to relate the peak period to the altimeter-derived upcross period. At least a mean or peak wave direction has to be provided from some source e.g. a wave buoy or an archive of wave model hindcasts such as the WASA data set (Günther et al., 1998).

The STORM model requires a time indexed series as input. We have seen that the altimeter can provide a time series (albeit at 10 day intervals along each track) of significant wave height and zero upcrossing wave period measurements, and these values can be used to fit an idealised JONSWAP spectrum, as above.

As described above, altimeter data were not available right at the model boundary, so some transformation was required. The details of this transformation are specific to each site and are discussed below.

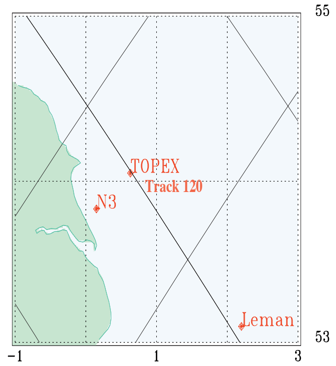
4.7.3 Holderness

4.7.3.1 Altimeter Derived Boundary Conditions (at N3)

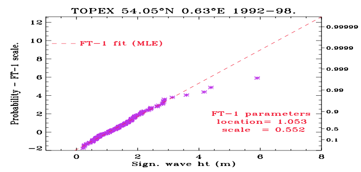
Figure 4-15 shows the locations of measurements available to estimate wave climate, including extremes, off Holderness. The numerical wave models require input at their outer boundary at location N3. There were two other buoys, N1 and N2, nearer the coast. Data from the TOPEX Track 120 were used; the data from the tracks coming off the land, with the satellite travelling from SW to NE, were either missing or of dubious quality and were not used.

The relationship between Hs along TOPEX Track 120 and Hs at N3 was found to depend upon the wave direction. Wind directions measured at Leman were found to be a useful indicator of wave direction off Holderness.

Figure 4-16 shows the distribution of Hs measurements from the 1992-98 TOPEX data at the location nearest to N3: 54.05°N 0.6°E - (35 km distant). The highest value of 5.9 m, recorded on 19 February 1996, is higher than the expected maximum from that distribution in 7 years of TOPEX sampling, but fitting a 3-parameter Generalised Extreme Value distribution does not give a statistically better fit. The 100-year return value - assuming 3-hr sampling - is 8.0 m, with s.e. of 0.4 m.

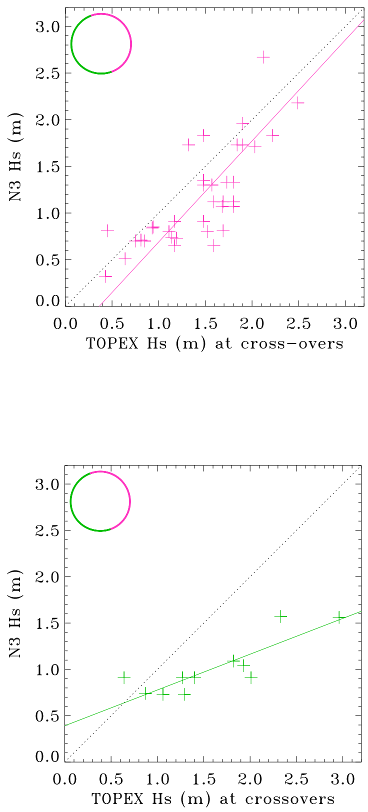


.Figure 4-15 Altimeter tracks and in situ data sites at Holderness



.Figure 4-16 Distribution of Hs from TOPEX Track 120

To compare wave heights along Track 120 with waves at N3, TOPEX data from the cross-over points of Track 120 and those off the coast (tracks 061 and 239) were extracted when within 15 minutes of a measurement at N3. It was found that the correlation between the TOPEX and N3 Hs pairs was dependent upon the wave direction measured at N3. Figure 4-17 shows the relationship for the two cases: waves from 340°-160° and waves from 160°-340° - i.e. roughly onshore and offshore.



.Figure 4-17 Comparison of Hs from TOPEX and buoy at N3 by wave direction at N3: from 340°-160° and 160°-340°.

The principal component fit for the onshore waves (340°-160°) shows no significant difference between Hs from TOPEX and at N3; while offshore waves are related by :

Hs (N3) = 0.386 Hs(TOPEX) + 0.392 (4.3)

Clearly this relationship should not hold for very low waves along the TOPEX track - with Hs(TOPEX)< Hs (N3) for Hs(TOPEX)<0.64m.

So a set of Hs values at N3 was derived from Hs values at the nearest TOPEX location, adjusting by Equation 4.3 if the TOPEX Hs value was greater than 0.64 m and if the wind direction at Leman was from 160°-340°. The wave direction was taken to be the same as the Leman wind direction. The wave period, Tz, was taken as that estimated from the TOPEX data, but if the TOPEX Hs was adjusted, then Tz was also adjusted, using:

$Tz(N3)/Tz(TOPEX)=\{Hs(N3)/Hs(TOPEX)\}^{0.6}$ (4.4)

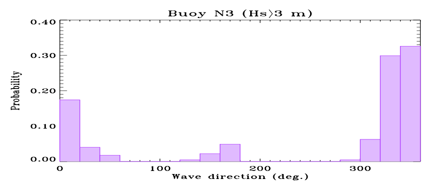
deduced from JONSWAP measurements, assuming a constant wind speed (Carter, 1982).

4.7.3.2 Altimeter derived extreme wave heights

Because very high waves are expected at N3 and along the TOPEX Track 120 with onshore winds, when there is no evidence for any systematic difference in Hs at the two locations, it was decided that extreme Hs at N3 would be the same as from the TOPEX track. The results shown in Figure 4-16 were used to derive the parameters given in Table 4-4.

Zero-upcross wave periods (Tz) of these high waves were estimated assuming a significant steepness of 1/12 to 1/16. Wave direction was assumed to be from 340° to 140°, with the most likely direction to be from the North - during the one winter of measurements at N3, most wave with Hs> 3m and all waves with Hs> 4m were from between 300° and 010°, see Figure 4-18.

Analysis of the derived N3 data set gave an estimate for the 100-year return Hs (from an FT-1 fit to onshore waves) of 8.3 m - not significantly different from the 8.0 m in Table 4-4.



.Figure 4-18 Wave directions at N3 when Hs> 3m.

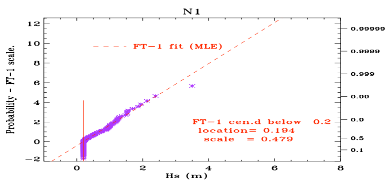
4.7.3.3 STORM modelling

The objective of the modelling was to transform waves from location 'N3' to positions 'N1' and 'N2', and assess the performance of the model through a comparison of the actual recorded waves at 'N1' and 'N2' with the transformed waves. A further comparison against the SWAN model was carried out by considering transformed data from a specific storm event at Holderness. Finally the satellite derived time series would be transformed to generate an inshore time series.

Direct comparison of model output to wave data at N1 shows that transformed wave heights are very close to the measured ones. For the important storm period of 31/12/94 - 07/01/95 and 07/02/95 - 14/02/95, the transformed wave heights follow the measured wave height very closely (Figure 4-11). This demonstrates that the STORM model performs very well for the Holderness site over storm periods.

To generate a longer time series, and subsequently a representative distribution of H_s, the altimeter derived N3 H_s data set was used to generate transformed Hs data sets at N1 and N2. Figure 4-19 shows the resulting distribution of H_s at N1. The model outputs a minimum

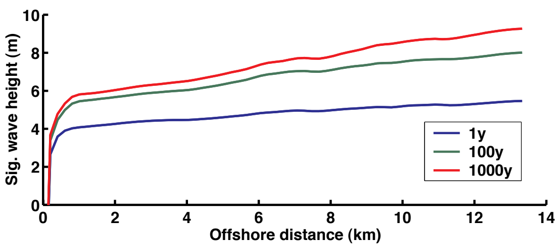
Hs of 0.2 m, so a censored FT-1 was fitted, to data above that level. If the data were not censored, then they provided a poor fit to the distribution, and much lower, clearly incorrect, estimates were generated. The existing Halcrow 'black box' procedures did not allow for this censoring, and hence the inshore time series data were provided to Satellite Observing systems for analysis. The 100-year return value of H_s from an extrapolation of this fit (without any consideration of water depth) is 6.2 m. A similar analysis at N2 gave 100-year return value of 6.9 m.



.Figure 4-19 Cumulative probability distribution of Hs at N1, with censored FT-1 fit.

4.7.3.4 SWAN modelling

The SWAN model has been used to transform the altimeter derived extreme wave events (1, 100 and 1000 year) at the model boundary to the nearshore zone. It was also used to generate "worst case" wave extremes based on extrapolated water level (+80 cm) and a projected 20% (for 1 year returns) or 10% (for 100, and 1000 year return values) increase in offshore wave heights. The results are shown in Figure 4-20 and Figure 4-31. The effect of increasing offshore wave height is much more important than the effect of water levels except very near the coast.



.Figure 4-20 Hs against offshore distance for the SWAN model at Holderness.

Table 4-4 compares the SWAN and STORM results, and the altimeter derived values for offshore.

4.7.3.5 Discussion

There is good agreement between the 1 year events modelled by SWAN and the 1 year extreme values derived from the STORM time series, as expected following the earlier comparison. However, there is significant disagreement between the 1000 year values, with SWAN giving much lower values than STORM. Detailed consideration of SWAN output showed that gradual shoaling in the offshore bathymetry at Holderness results in the nearshore wave heights being depth limited. Therefore, at Holderness, a large increase in the offshore wave height (e.g. over 3.5 m for the 1000 year event) will only cause a relatively small increase onshore (1.5 m). The extreme analysis of the transformed output from the STORM model merely extrapolates the distribution from the input data (gathered over 5 years) to the longer 100 or 100 year period. This analysis provides a purely statistical extrapolation and does not take into account any physical limiting effects on waves. This is an interesting result, and indicates the care that should be taken in extrapolating from a relatively short time series of data, without consideration of the physical limitations of the coastal location. We therefore suggest that the SWAN estimates for the 100 and 1000 year events are the more reliable.

N-yr	1	100	1000
1°x2° alt data (offshore grid)	5.83	8.32	9.56
N3 (alt)	5.46	8.00	9.25
N2 (STORM)	4.48	6.91	8.11
N2 (SWAN)	4.59	6.31	6.84
+ sea level rise (83 cm)	4.65	6.44	7.05
Hs +20% (1y) or +10% (100, 1000)	5.57	6.70	7.21
N1 (STORM)	4.02	6.22	7.33
N1(SWAN)	3.92	5.04	5.38
+ sea level rise (83 cm)	4.04	5.29	5.66
Hs +20% (1y) or +10% (100, 1000)	4.57	5.38	5.72

.Table 4-4 Estimated return wave heights for Holderness

Sea level rise (+83 cm at Holderness) appears to have very little effect on the extreme events modelled by SWAN (a 26 cm increase in 5.6 m, 5%, for the 1000 year event at N1). A 20% increase in the offshore wave height induces an 11% increase at N1 for the 1 year event, and a 10% increase offshore induces a 1% increase in the 1000 year wave height. Wave periods and other spectral parameters output by the models are available, but not discussed here.

4.7.4 Lyme Bay

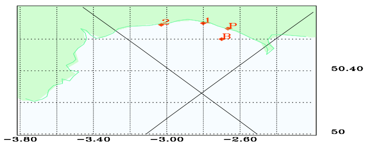
4.7.4.1 Altimeter derived boundary conditions

Sources of data for Lyme Bay are:

a. Met. Office buoy at 50.6°N 2.7°W. (09/92 to 12/97, but with some large gaps, notably 08/94 to 12/96)

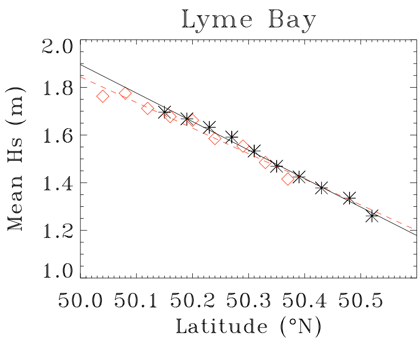
b. Data supplied by BODC from an IOS pressure sensor at 50.66°N 2.66°W (West Bexington) in a mean water depth of 10 m, (12/87 to 05/95)

c. Satellite altimeter data. TOPEX tracks 061 and 146 (10/92 - 12/98); see Figure 4-21.



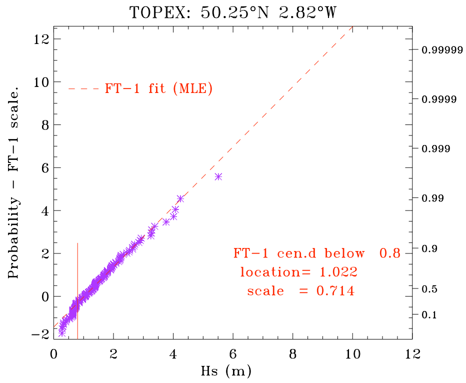
.Figure 4-21 TOPEX tracks and sites in Lyme Bay: 1 & 2 STORM model locations, B: Met Office buoy, P - West Bexington pressure sensor.

Analysis of the wave heights from the TOPEX Track 061 shows that the mean wave height increased towards the south, away from the coast. This trend was supported in the data from Track 146 (Figure 4-22). The pressure sensor data, although some way from Track 061, also showed that mean H_s was significantly lower towards the shore. A study of individual events and analysis by direction (estimated from the Met. Office buoy wind direction) showed that wave heights generally decreased towards the shore, with little directional effect.



.Figure 4-22 Mean wave height from TOPEX tracks across Lyme Bay; *: into Lyme Bay (Track 061), diamond: out of Lyme Bay (Track 146)

A data set, for input into the STORM model, was obtained from TOPEX data at the cross-over point near 50.25°N 2.82°W when wind measurements were available from the Met. Office buoy (to provide an indication of wave direction). Figure 4-23 and Figure 4-24 show the cumulative distribution of Hs from this data set and from the model output at 50.71°N 2.80°W.



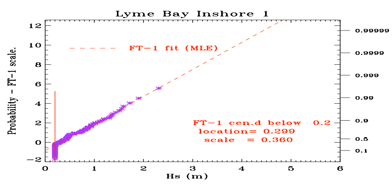
.Figure 4-23 Distribution of Hs from TOPEX data near 50.25°N 2.85°W input to the STORM wave model.

4.7.4.2 Extreme wave heights

Return values of Hs for the open waters off Lyme Bay were estimated from the TOPEX data at the cross-over point, Table 4-5. The 100-year Hs is 11.2 m (with s.e. 0.4 m) compared to 10.0 m from the smaller data set (Figure 4-23).

A range of zero-upcross wave periods, Tz, were estimated assuming significant steepness between 1/14 and 1/18, and these extreme waves were assumed to come from the SW.

However, this analysis does not include possibly the most destructive wave event in Lyme Bay in recent years, which occurred on 13 February 1979. Damage was especially severe at Chiswell on Portland, where waves, with a period of possibly 18 seconds, over-topped Chesil Beach, the crest of which is about 12 m above high tide level. The wind was easterly at around 10 knots. Further details are given by Draper & Bownass (1983). This most unusual and rare event is not reflected in the data or the analysis carried out to get the estimates of extremes in Lyme Bay given in Table 4-5 .



.Figure 4-24 Distribution of Hs estimated from STORM model, inshore location 1.

4.7.4.3 STORM modelling

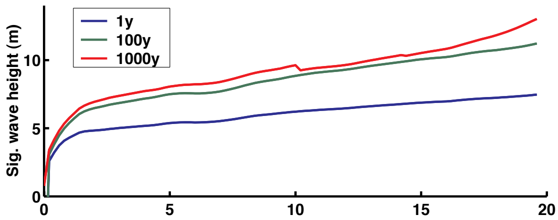
Three positions near to the shore were chosen for the inshore sites: West Bexington, Lyme Regis near Bridport (in 3m mean water depth) and Seaton, to the west of Lyme Regis (in 2 m mean water depth).

The time series described above were input to the STORM model and transformed values generated for the inshore points. These were input to an extreme analysis (Table 4-5). A large reduction in wave height is clearly evident from the TOPEX crossover point offshore (see Figure 4-21 for its location) to the near-shore sites, with 1-year return values estimated from the (censored) FT-1 distributions of 7.5 m offshore and of 3.5 m, 3.2 m and 3.0 m at the inshore sites.

4.7.4.4 SWAN modelling

As for Holderness, the SWAN model was used to transform the altimeter derived extreme wave events to the nearshore zone The results are shown in Figure 4-25 and Figure 4-31, and Table 4-5 compares these results to those from STORM, and to the offshore altimeter derived values.

No direct comparison of the SWAN and STORM models was carried out at Lyme Bay.



.Figure 4-25 Hs against offshore distance for the SWAN model at Lyme Bay

4.7.4.5 Discussion

All the evidence indicates a decrease in wave height towards the coast into Lyme Bay. The reduction must be due to a combination of effects: refraction, bottom loss, sheltering from the west and reduction in fetch with offshore winds; but the relative importance of these has not been determined.

N-yr	1	100	1000
1°x2° alt data (offshore grid)	7.95	11.80	13.72
TOPEX Xover (alt)	7.47	11.20	13.01
W Bex (STORM - ‘P’)	3.50	5.35	6.27
Lyme Regis (STORM - ‘1’)	3.17	4.01	5.66
Seaton (STORM - ‘2’)	2.97	4.51	5.27
W Bex.(SWAN)	5.49	6.68	7.13
+ sea level rise (80 cm)	5.66	6.98	7.45
Hs +20% (1y) or +10% (100, 1000)	6.12	7.06	7.50

.Table 4-5 Estimated return wave heights off Lyme Bay

At West Bexington in Lyme Bay we find a discrepancy even between the 1 year H_s values derived from STORM and SWAN. The SWAN values here are significantly higher than those from STORM (by almost 2 m). The cause of this disagreement has not been established.

The 1 year return STORM values for the inshore locations in the west of Lyme Bay, Lyme Regis and Seaton (also in shallower water, 3m rather than 10m mean water depth) are 0.3 - 0.5 m less than at the more exposed West Bexington location.

It may be expected that depth limiting of large H_s may not be as important in Lyme Bay, where deep water is found closer inshore. However, when we look at the figures in Table 4-5, we see that a 72% increase in wave height offshore (from the 1 yr to 100 yr) results in a 30% increase at West Bexington (from SWAN), whereas the corresponding increase in the inshore STORM values is over 75%. This suggests strongly that one should still be wary of the extrapolated 100 and 1000 year values estimated from the STORM transformed data.

The effect of the predicted sea level rise (+80 cm) has only a small effect (+17 cm on the 1 year event). The effects of any offshore increase in wave climate are also small. A 20% increase in the 1 year event at the SWAN model boundary increases the transformed inshore significant wave height (West Bexington) by 8%, a 10% increase in the 1000 year offshore value results in a less than 1% increase onshore.

4.7.5 Carmarthen Bay

4.7.5.1 Altimeter Derived Boundary Conditions

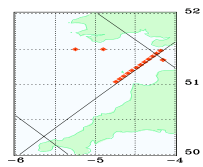
Data available in Carmarthen Bay were:

a. Met. Office buoy, off St Gowan, at 51.5°N 4.9°W Figure 4-26 (09/92 to 12/97)

b. Shipborne Wave Recorder data from the St Gowan Light Vessel, a few km west of the Met. Office buoy, at 51.5°N 5.0°W (1975 to 1978).

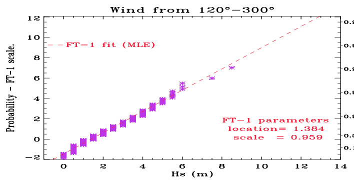
c. TOPEX satellite altimeter data (tracks 146 and 239)

d. WASA hindcast data (grid point at 51.5°N 5.25°W). (1954-59 and 1990-94).

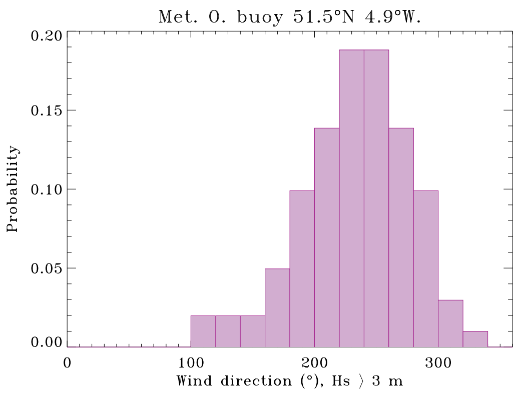


.Figure 4-26 Location of the Met. Office buoy (51.5°N 4.9°W), the WASA grid point (51.5°N 5.25°W) and of the TOPEX along track data.

At this location, because of the failure of the TOPEX data on the offshore track and the distance to the model boundary from the onshore track near the Devon coast - which was anyway affected by Lundy Island and the shallow waters around it - the best source of data appears to be the Met. Office buoy. Data for noon each day from December 1994 to December 1997 were extracted for analysis - September to November 1994 were excluded to get approximately the same number of records for each of the four seasons. These values did not fit an FT-1 distribution, but when the data were separated by direction - assessed from the Met. Office buoy wind direction - then data from 120° to 300° and data from 300° to 120° both presented a reasonable fit to the FT-1. See Figure 4-27. All high waves - greater than 3-4 m - were from the SW. The FT-1 fitted to the H_s with winds from 300°-120° (which occurred 41% of the time) had location and scale parameters of 0.863 and 0.522 m; the 100-year return value of 7.0 m, compared with 12.95 m for the 59% of the time with winds from 120° to 300°. This tendency for the higher waves to be associated with winds from the SW is illustrated in Figure 4-28.



.Figure 4-27 Distribution of Hs from the Met. Office buoy, when winds were from 120° to 300°.



.Figure 4-28 Distribution of wind direction from the Met. office buoy when Hs>3 m.

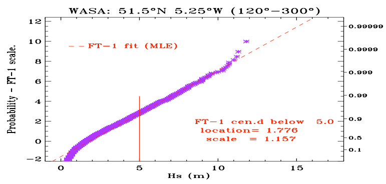
4.7.5.2 Extreme wave heights

The omni-directional return values should be obtained by compounding the two distributions from the Met. Office buoy measurements, for data from 120° to 300° and from 300°-120°, but extreme wave heights from the latter are so much smaller that the omni-directional values can be taken from the former alone. Results are given in Table 4-6.

Zero upcross wave periods were derived assuming a significant steepness at this relatively exposed site of 1/18 to 1/20. The direction of these extreme waves was taken to be from 250°.

An analysis of the St Gowan Light Vessel data for UK 'Guidance Notes' (Department of Energy, 1990) gives 50- and 100-year return values of Hs as 12.4 and 13.1 m, in very good agreement to 12.3 and 13.0 m from Table 4-6 (indicating no evidence of change in the extreme climate here between 1975-78 and 1994-97).

The WASA hindcast data does not appear to be from an FT-1 distribution - even data with waves from 120°-300°, as shown by Figure 4-29. Fitting only these data above 5 m gives a 100-year return value of 16.1 m. (This analysis was for the 1990-94 hindcast data set, the 1975-79 data set gave 16.0 m.) Fitting the 12 annual maximum Hs values from the WASA data set - ranging from 8.0 m in 1956 to 11.8 m in 1994 - to an FT-1 distribution gave a 100-year return value of 15.7 m, with s.e. of about 1.7 m. However we look at it, the 100-year return value from H_s appears to be greater than that from the St Gowan Light Vessel or from the Met. Office buoy. It is not possible to quantify how much of this difference is due to shortcomings in the data and in the hindcast model results and how much to the difference in exposure of the sites - clearly the WASA site is more exposed from the SW.



.Figure 4-29 Distribution of H_s from the WASA data 1990-94 with waves from 120°-300°; FT-1 fit to Hs>5 m.

The 100-year H_s were calculated at locations along the TOPEX track which comes off Devon. All values are lower than that for the UKMO buoy site in Table 4-6 with the largest of 12.1 m - with s.e. of 0.7 m not significantly different from the buoy value. There were the large changes in this value over short distances (10-20 km), especially in the vicinity of Lundy Island.

4.7.5.3 STORM modelling

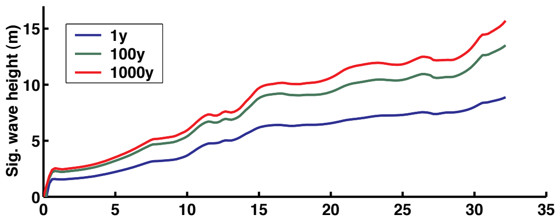
The objective was to transform recorded waves from the offshore position at St Gowan to the inshore points at Amroth and Worms Head. Amroth and Worms Head were decided upon after discussions between all involved in Jericho. It was decided to choose one point at a sheltered position, Amroth, and the other at an exposed position, Worms Head. Two series of model runs were carried out, in the first all 27127 records from the Met. Office buoy were used as input to generate a time series for extreme analysis. In the second the performances of the SWAN and STORM models during a single severe storm were compared.

First we consider the estimates of extreme H_s values at two near-shore locations. At Worm's Head, the more exposed site, with mean water depth of 30 m, an FT-1 fit to all hindcast Hs values >0.4 m gave a 100-year return value of 11.1 m (restricting the data by direction gave no significant difference). At Amroth, a very sheltered location with a mean water depth of about 5 m, an FT-1 fit to hindcast values above 0.4 m from 120° to 180° gave 100-year return value of 5.6 m; H_s from other directions were all 0.2 m or less. This estimate of 5.6 m is from an extrapolation into the upper tail of the fitted FT-1, with no consideration of the limited depth during part of the tidal cycle.

The comparison of SWAN and STORM revealed that SWAN underpredicted significantly with respect to STORM. At Amroth, this was almost certainly due to a difference of 2 m in water depth (SWAN depth less than STORM depth) at the inshore grid point. The difference at Worm's Head is not so easy to account for. It is thought that the discrepancies here may be because the bathymetry close to Worm's Head is very complex, and may not be fully resolved in the lower resolution SWAN grid. The higher resolution in STORM may allow for local focusing of wave energy (and hence higher waves) not seen in SWAN.

4.7.5.4 SWAN modelling

The SWAN model was used to transform the altimeter derived extreme wave events to points on the Carmarthen Bay Grid. Here we consider output for the nearshore sites of Amroth and Worm's Head. The results are shown in Figure 4-30, and Table 4-6 compares these results to those from STORM, and to the offshore altimeter derived values.



.Figure 4-30 Hs against offshore distance from Amroth

4.7.5.5 Discussion

Whilst the offshore return values from different sources agree well (apart from the WASA hindcast data, as discussed in the text), the values provided by SWAN and STORM show some disagreement. Given the results of the direct comparison discussed above, these differences may be expected.

N-yr	1	100	1000
1°x2° alt data (offshore grid)	8.87	13.12	15.24
St Gowan Light vessel		13.0	
UKMO buoy	8.54	12.95	15.13
Worms Head (STORM)	7.28	11.12	13.05
Worms Head (SWAN)	5.55	7.04	7.49
+ sea level rise (79 cm)	5.68	7.25	7.72
Hs +20% (1y) or +10% (100, 1000)	6.33	7.48	7.87
Amroth (STORM)	3.70	5.64	6.60
Amroth (SWAN)	1.56	2.27	2.51
+ sea level rise (79 cm)	1.57	2.33	2.58
Hs +20% (1y) or +10% (100, 1000)	1.80	2.45	2.68

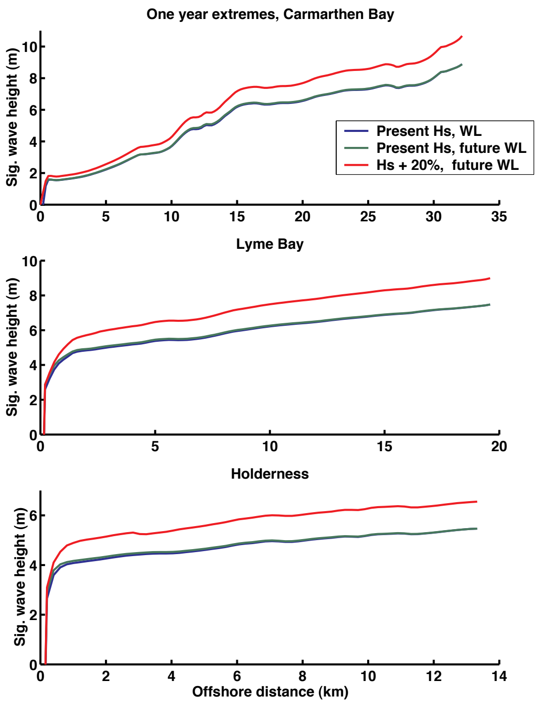
.Table 4-6 Estimated return Hs values in Carmarthen Bay

We can see that there is only a small reduction in the 1 year wave height from the model boundaries to Worm's Head (18% in STORM, 37% in SWAN), but a much larger decrease at Amroth (58% in STORM, 82% in SWAN). The 100 yr SWAN event at Worm's Head (7.49 m) shows an increase of 35% on the 1 year event (5.55m). At Amroth the absolute magnitude of the increase is smaller (1.56 m to 2.51 m), but is a larger fractional increase (61%)

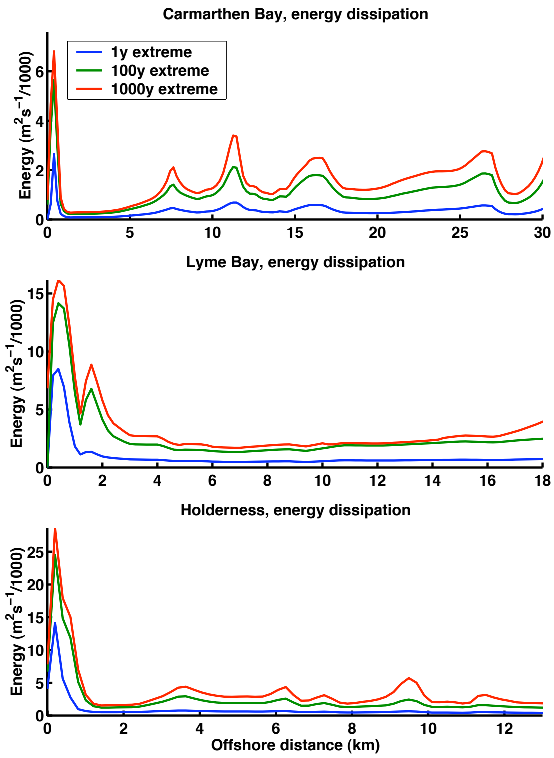
Once again we see that climate models' sea level rise (+79 cm) has little effect on the H_s values of the extreme events (which do not significantly change at Amroth, and only increased at Worm's Head by 10-20 cm). A 20% rise in the 1 year event at the model boundary results in an increase of 15% at Amroth, whereas a 10% increase in the 1000 year offshore value results in a 4% increase onshore. The equivalent increases at Worm's Head are 11% (1 year) and 2%.

4.7.6 Comparison of Inshore Sites

The three sites display different characteristics in the response of the inshore transformed waves to observed and predicted offshore waves. At Holderness the lowest waves are experienced offshore, with a moderate tidal range. The offshore waves cannot be related to the NAO, although offshore wave heights are strongly related to the NAO at the other 2 sites, more exposed to the North Atlantic. The topography at Holderness is quite uniform in the longshore direction and shoals gradually towards the shore. Largest waves approach from the north and combined wave and swell conditions are common. The offshore conditions can be well-modelled using either buoy data from N3 or the TOPEX altimeter data. At Lyme Bay the waves are larger offshore, the largest waves approaching from the SW. The tidal range is relatively small. The depths shoal gradually then steeply very near the coast. A wide range of fetch-limited conditions is experienced for waves from different directions in the English Channel which cause a complicated situation in specifying offshore wave heights. Also there are no suitable offshore buoy data, thus we have to rely on the TOPEX altimeter data, reduced by a suitable multiplicative factor. At Carmarthen Bay the bathymetry is much more complicated than the other sites and a more 3-dimensional picture of wave variation is required. The bay is more enclosed and more likely to experience a spatial variation in current which could make current refraction a significant factor. The largest offshore wave heights and tidal range are experienced here. Good offshore buoy data are available but the TOPEX tracks are rather far distant. There are no inshore measurements for model validation unlike the other 2 sites.



.Figure 4-31 Hs against offshore distance from SWAN for present and future climate water levels, and present and present +20% 1 year extreme Hs at model boundary.



.Figure 4-32 Dissipation of wave energy against offshore distance from the SWAN model.

The ability of the SWAN model to provide further insight into the physical processes is illustrated in Figure 4-32. Here the total dissipation of wave energy (from white-capping, bottom friction and depth-limited breaking) is plotted for a cross-section through each model. In fact a full map of the dissipation over the model grid can be drawn, which highlights areas with maximum dissipation, likely to be most affected by erosion (although this will also depend on other factors). The most work is done by the waves in the very nearshore zone, but it may be seen that the larger events lead to increased dissipation further away from shore.

Figures (4-20,4-25,4-30), and figure 4-31 all show offshore cross sections through the SWAN model grids which run close to, or intersect, the inshore output points (N1, West Bexington and Amroth) that were compared with the STORM results in section 4-7.

The results from the wave modelling can be largely explained in terms of the characteristic bathymetry of the three areas.

Going from the model boundary at Carmarthen Bay, there is a long stretch of almost flat but shallow (from the point of view of the 1 year extreme wave) sea bed followed by a 15 km stretch into the coast with a gradient of about 0.002. Much of the wave energy of the 1 year event is dissipated over these stretches and at 1 km from the coast the 1 year event has been reduced to a wave height of less than 2 metres. The offshore dissipation also explains why there is little difference (~60 cm) between the 1 year and 100 year events by this close to the shore.

In contrast, from 15 km to 1 km offshore at Holderness the gradient is lower than at Carmarthen Bay at 0.001. This, coupled with the lower wave height of the 1 year event in this sheltered area, leads to there being far less dissipation of the wave energy until much closer to the coast. At 1 km from the coast the 1 year event still has a wave height of 4 metres. A large amount of the dissipation occurs at Holderness in the last kilometre where the bathymetry steepens to a gradient of 0.01. This effect is shown by the large peak on the Holderness plot, Figure 4-31. The results at Holderness show a much larger difference at 1 km offshore between the 1 year and 100 year events (1.6m) compared with Carmarthen Bay. The vulnerability of the Holderness area is again demonstrated by the large increase in the area under the peak in Figure 4-31 for the 100 year event compared to the comparatively small increase in the dissipation further offshore.

The results for Lyme Bay lie between the other two. The offshore waves are higher than at Holderness but the bathymetry, while being gently sloping offshore has a longer stretch closer to the shore which is steeply sloping

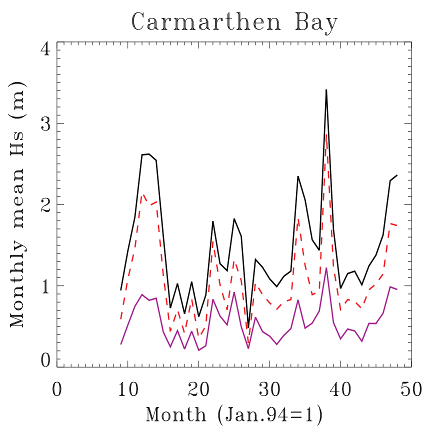
(~5 km compared to ~1 km at Holderness). This means that more of the energy from the 100 year event is dissipated somewhat further offshore than at Holderness so the impact of the very large event is less concentrated. This is shown by the secondary peak on the Lyme Bay plot (Figure 4-31).

The possible impact of increasing waveheight can be largely deduced from the comparison of 1 and 100 year wave events at the different sites. In the same way that Holderness is most vulnerable to damage from a 100 year event, it is also most vulnerable if the 1 year event were to increase in magnitude by a certain percentage. As shown in Figure 4-31, in comparison to a 20% rise in the 1 year event (which is an approximate projection of trend over the last 50 years), the projected rise in water levels of about 80 cm has little effect on the result.

It should be pointed out that these results are only for cross sections through the JERICHO selected points. SWAN can produce maps of the whole region and these demonstrate that there is considerable variation in the results along the coasts, particularly around the complex coastlines of Lyme Bay and Carmarthen Bay.

4.7.7 Impact of offshore variability on onshore wave climate

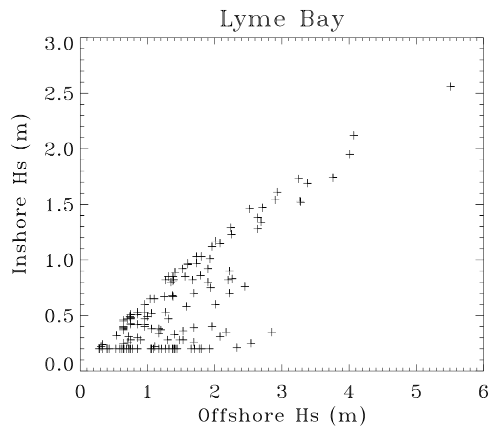
One of the aims of JERICHO was to investigate how changes in offshore wave climate transformed to changes in nearshore wave climate. As might be expected, different onshore locations showed different sensitivities to offshore variability.



.Figure 4-33 Monthly mean Hs in Carmarthen Bay, at: Met Office buoy (solid black line), Worm's Head (dashed red line), and Amroth (solid magenta line).

Figure 4-33 shows monthly mean H_s at three locations in Carmarthen Bay, from September 1994 to December 1997. Monthly values at Worm's Head seem to follow the Met Office buoy very closely (though slightly reduced), but those at Amroth apparently show an upper limit. Whilst all 3 sites experience higher wave heights in winter than in summer, the Amroth data do not reflect the more severe conditions experienced at Worm's Head and the Met Office buoy during the winters of 1994-95 (months 11-13) and 1996-97 (months 34-38). Thus although the more sheltered location at Amroth experiences the same number of storms each year as Worm's Head and the (offshore) Met Office Buoy, it does not see the same year to year variability in the amplitude of the maximum events as the more exposed locations.

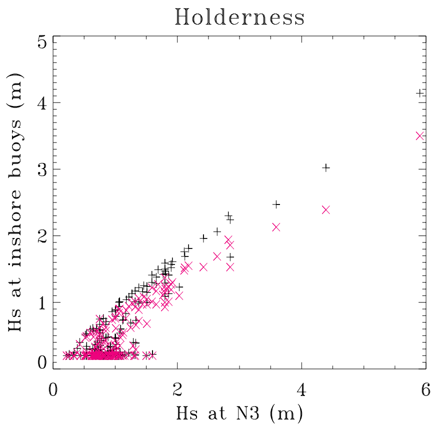
An attempt was made to reconcile the results of our studies with local observations. This was a more difficult task than expected, as reliable recorded observations of severe coastal wave events (e.g. overtopping of sea walls) are rare. We received (from the Environment Agency) information of individual events near Carmarthen Bay between 1994 and 1998. Whilst these individual events, which normally occurred at spring tides, cannot be directly related to the monthly mean wave heights in Figure 4-33, it is interesting to note the dates. Severe events were noted once in 1994 (Feb. - month 2 on Figure 4-33), twice in 1995 (Feb. and Dec., months 14 & 24), once in 1996 (Oct., month 34), twice in 1997 (Feb. and Sep., months 38 and 45), and twice in 1998 (Jan. and Mar., months 49 and 52). On the latter occasion, unfortunately occurring after the end of the offshore data, the sea wall at Amroth was overtopped. Whilst interesting, these few recordings do not allow us to identify the winters which provided the most severe inshore wave climate.



.Figure 4-34 Inshore (West Bexington) against offshore Hs at Lyme Bay.

Figure 4-34 presents inshore and offshore wave height data for Lyme Bay in a different way, this presentation selected because there are less data over a shorter time at this location. It seems that the height of the inshore waves scales linearly with that of the offshore waves, with no apparent maximum limit having been reached in the data sample available. Thus at Lyme Bay (West Bexington) one might expect that the inshore site would reflect in both magnitude and frequency the severe events experienced offshore. Ultimately of course the inshore wave height will reach a maximum limit, determined primarily by the water depth.

The situation at Holderness (Figure 4-35) seems similar to that at Lyme Bay. The inshore wave heights scale linearly with the offshore wave heights, with lower waves at N1 (the site nearest the shore). This would again indicate that, at least up to a certain threshold, an increase in the magnitude of offshore events will be reflected onshore. However we know from the SWAN modelling that the inshore wave heights are depth limited, and hence that increases in the offshore wave height beyond a certain threshold will no longer result in a corresponding increase onshore (see for instance the 100 yr and 1000 yr events in Table 4-4. The data set presented in Figure 4-35 simply does not cover a large enough data set to capture this effect.



.Figure 4-35 Onshore (N1-x, N2- +) against offshore (N3) significant wave heights at Holderness.

The general conclusion is that onshore sites will usually experience the same increase (or decrease) in the frequency of severe events as the offshore sites. However, any increase in the magnitude of such events will not necessarily be transformed onshore, as the maximum wave height that can be generated at some sites (Amroth, and to a lesser extent Lyme Bay and Holderness) is depth limited.

4.7.8 Conclusions

It is well established that the satellite radar altimeter can provide accurate and reliable measurements of wave height and wind speed over the open ocean. Within this report we have also shown that, in principle, satellite altimeters can provide wind and wave measurements over coastal waters, and provide otherwise unavailable information for shallow water studies. We have further shown that an accurate estimate of wave period can be derived from the altimeter data record. These data can be combined in gridded form to provide a large scale overview of wave climate.

Suitable satellite coverage of the coastal waters of the UK now cover a period of approximately 10 years. The recovery of wave heights from satellite observations is very useful to areas greater than approximately 10 km from the coastline. Thus, to be of direct use to coastal engineers these relatively deep water wave conditions have to be transformed to the sites of specific interest with help of a numerical wave model.

Wave direction is the one parameter the altimeter is quite unable to tackle. Although constrained to be onshore, the direction of approach of extreme waves can be wide. It would be helpful to obtain - possibly from the model results from this project - a clear indication of the required accuracy in wave direction at the model boundary. How this might be achieved could then be addressed.

Future altimeters are expected to ‘lock on’ to the sea surface in a much shorter distance, which would be helpful. Smaller distances between tracks and a more rapid repeat, say every day or 2 instead of the present 10 from TOPEX, would be very useful - but this combination of smaller distance between tracks and more rapid repeats would require a greater number of altimeters.

The detailed descriptions above of the various data and analyses applied at Holderness, Lyme Bay and Carmarthen Bay show the differences in approach required for each site. In all cases a more confident estimate of wave climate including extreme values have been obtained by utilising both *in situ* measurements and satellite data, but the approach varied significantly between the sites. This variation was needed partly because of the differences in data available at each, and partly from the different nature of the sites - especially their varying exposure to the open ocean.

Off Holderness, the wave buoy measurements, including wave directions, were very useful, even though they were only for one winter.

TOPEX data in Lyme Bay gave a valuable measure of the large spatial variability of H_s in coastal waters, even in quite deep water; this was also shown by the TOPEX data off the Devon coast.

There was no satisfactory altimeter data off Carmarthen Bay, so it was fortunate that the St Gowan Met. Office buoy appears to have given good data for a few years - and that there was a nearby Light Vessel with some data to support this conclusion.

The STORM and SWAN model results gave an indication of the evolution of waves into very shallow water, but the provision of input ‘data’ - wave height, period and direction - at outer boundaries fixed relatively close to the coast did cause problems. It would have helped to have had models covering larger areas so that boundaries were further offshore, where scales of spatial variability are larger and where altimeters coming off the land can be expected to make measurements. Models with local wind energy input (e.g. PRO-WAM or SWAN on a coarser grid) would be needed for this. Optimum boundary conditions might be obtained by use of an offshore wave model e.g. UKMO model with assimilated satellite altimeter data.

The results for the SWAN extremes prediction are site-specific. At Holderness the offshore wave heights are smallest, increasing through Lyme Bay to the largest waves at Carmarthen Bay. In Lyme Bay the water depth shoals steeply at the coast, whereas at Holderness and Carmarthen Bay the shoaling is more gradual. It is important to know how close the extreme wave event is to a depth-limited wave height. If the wave is already depth-limited an increase in offshore wave height will not have much effect on the coastal wave height.

We suggest that the SWAN model is more physically realistic than the STORM mode since it explicitly handles the various processes, but would note that there are limitations of both models as follows:

The STORM model requires time tagged data, to allow computation of the correct tidal levels. This means that that the time variation of water level cannot be altered from the predicted tide. No surge or change in mean water level can be added. Also no wind forcing or bottom friction is explicitly included. The extreme value analysis does not take account of water depth although that is included in the STORM model.

In the SWAN model, wind forcing, bottom friction and depth-limited breaking are explicitly included. There may be improvements to be made in the modelling of these terms and choosing the 'correct' value of the bottom friction coefficient is important. However, even if all these are modelled correctly, SWAN cannot be run for a long time series in order to extract statistics in the same way as the STORM model and the method used (transforming an offshore extreme event) does not allow us to specify the return period very well for the nearshore location because of the joint probability problem. Also, local wind forcing may start to become important again in extreme events so it is the combined probability of local wind, water level and offshore wave height that may be required.

Unfortunately we have found that the present assembly of climate models cannot provide reliable representations of the fields required for generating projections of wave climate into the future. Thus, whilst not having any evidence to suppose either an improvement or a worsening of coastal wave climate over the next 50 years, we modelled some example "worst case" scenarios, corresponding to arbitrary rises in offshore wave height. In most cases the rise in offshore wave height is reduced as the waves are transformed to the onshore sites. This is particularly so where the nearshore bathymetry is gently shelving, and deep water is not found close to the shore.

4.8 Recommendations for Monitoring Wave Climate Trends

Applications of wave data both coastal and offshore include the oil and gas industry (rigs, pipelines, ship operations), ship routing, coastal protection, waste disposal (planned and accidental), ecological studies (oxygen, temperature distribution and stratification), sedimentological studies, wave and tidal energy devices and flood warning. Data collected continuously (in real time) would be available for monitoring, determination of long-term statistics and assimilation into operational models.

Commonly used instruments for measuring waves include surface-following Waverider buoys and bottom pressure recorders (possibly with high-frequency current meters for directional waves (e.g. Wolf, 1997), wave staffs and arrays. These *in situ* instruments can be vulnerable to damage by the elements or by human interference and only give a point measurement. The bottom pressure recorder is only useable in depths less than about 20m and in fetch-limited conditions in much shallower depths since short waves are attenuated rapidly with depth. Recently satellite (altimeter and SAR) and other remote-sensing instruments such as HF and X-band radar have become available. These can record large volumes of data from a much larger spatial extent e.g. HF radar wave measurements can reach up to 20 km offshore from a coastal installation. An intercomparison of various wave-measuring devices was carried out at Holderness during the SCAWVEX project (Krogstad et al., 1999). Long time series are needed, at least 5 years and preferably 10 years to determine coastal wave statistics. For example the wave climate at Holderness could not be determined from 2 winters of data (Wolf, 1998), one of which happened to coincide with an El Niño event, reversing the normal pattern of SW prevailing winds which gives fetch-limited waves at Holderness and often bimodal mixed sea and swell spectra.

A limited network of offshore (20 km from shore) directional wave buoys would provide boundary conditions for fine-scale wave-transformation models and supplement the continuous satellite coverage. A set of coastal wave monitoring stations for model validation would also be very valuable, probably using bottom pressure recorders in less than 10m water depth. Occasional deployment of HF radar over a whole coastal cell would complete the picture.

It is difficult to identify positively regions that may be particularly vulnerable to changes in offshore climate. The characteristics which may indicate most vulnerability are deep water close inshore (e.g. Lyme Bay, Worm's Head), or exposure to the most severe wave climate (the south west coast). However, it should be noted that JERICHO has not looked at the problem of coastal erosion, which may respond to different influences.

4.9 Review against project aims

4.9.1 Main project Aims

In the initial JERICHO proposal, the main scientific objectives were:

To investigate which parts of Britain's coastline may have experienced an increase in wave height similar to that observed by satellites in the surrounding seas, by a more detailed analysis of the satellite archive, augmented by advanced wave models capable of extending observed open sea wave conditions to shallow water coastal areas, and to link these results, where possible, with long-term 'in situ' wave measurements.

The ultimate economic goal of JERICHO, defined by the Environmental Agency as the main customer, was:

To provide improved information on coastal wave conditions and inter-annual trends essential to the *planning of Britain's coastal defences and to make progress towards developing a predictive capability.*

As the project has progressed, the exact nature of the scientific project aims have changed in order to meet best the 'economic' goal, in close consultation with the Environment Agency. Thus the scientific aims of were restated, in 1999, as:

S1 *To gain access to the best wave climate information available to guide long term strategy for the coastal area.*

S2 *To generate the best estimates at the three JERICHO coastal sites of:*
S2a *likely future climate trends*
S2b *analysis of variability*
S2c *identification of the characteristics of areas (location, exposure, bathymetry) which are most likely to be vulnerable to a changing offshore wave climate.*
The EA would then be able to increase the priority of these identified areas for monitoring.

S3 *Recommendation of methodologies for further detailed studies:*
S3a. How to monitor variability in future.
S3b. Assessments of model reliability.
S3c. What modelling approach is most suitable
S3d. What in-situ data are required?
S3e. How are model boundary conditions best generated?

The Environment Agency's assessment of how well these aims have been met is provided in Section 5. It is fair to say that these goals have been largely achieved, except for the provision of a reliable estimate of likely future trends.

This problem was addressed by attempting to link the offshore wave climate to climate indices or large scale pressure fields, with the intention that predictions of these fields by climate models could then be used to generate predictions of wave climate. Whilst JERICHO was successful at establishing a link between the wave climate at St Gowan and (to a lesser extent) at Lyme Bay with the North Atlantic Oscillation, the team were unable to find a similar connection between the east coast wave climate and any similar sea level pressure gradient based index. Further work is required on this problem. Unfortunately a more fundamental problem then became evident, which is the inability of the present suite of climate models to predict accurately future climate indices or wind fields. A resolution of this problem is significantly beyond the resources of the JERICHO team. Nonetheless the methodology has been established which could take advantage of more reliable forecasts if and when they become available.

To support the main goals, a series of subordinate project aims were identified in the three separate phases of the programme

4.9.2 Feasibility Phase

4.9.2.1 Satellite measurements

a) *Can spatial resolution be increased?*
b) *How close to the coast can useful measurements be derived?*
c) *Can period (and wavelength) be extracted from the altimeter's signal to allow calculations of wave power to be made?*

Spatial resolution was improved by considering the individual data records, thus gaining altimeter data to within 10 km of the coast (for altimeter tracks going onto the coast off the sea). If altimeter tracks are coming off land, onto the sea, there is a 3-6 second (20 - 40 km) delay in regaining track and hence valid data. Altimeter estimates of wave period have been shown to be accurate to better than 1 second, provided that certain limits of application are applied.

4.9.2.2 Geographical sub-division

From the satellite record, which are the offshore regions over which waves might be increasing?

For this question and subsequent similar questions, it was decided early on that it was not helpful (or scientifically rigorous) to consider wave climate variability in terms of trends, but rather that patterns of variability should be identified and if possible linked to large scale climate indices. Hence this question was answered by identifying that the wave climate off the south and west coasts are correlated with the North Atlantic Oscillation. Unfortunately no link has been found between the wave climate of the east coast and equivalent climate fields/indices.

4.9.2.3 Buoy and other 'in situ' measurements

a) *Identify which coastal in situ data provide a long enough time series to allow trends to be studied.*
b) *Identify the North Sea buoys over which satellite observations have been made.*
c) *How representative is a time series at one location of conditions at other points along the coast?*
d) *How well-calibrated are the in situ data and how robust is the instrumentation?*

23 *in situ* data sets were identified, acquired, and analysed. Data were used in comparisons against satellite data which proved the reliability of the satellite data, and also indicated a lack of reliability in certain *in situ* data sets. Conditions close to the coast were found to be very localised, analysis of satellite data showed that wave climate could change across very short distances (e.g. 10 - 20 km). No significant differences in calibration could be found between the *in situ* data sets, though differences in resolution and quality control of archived data were identified.

4.9.2.4 Models

a) *What models exist that could be used to compute wave fields in shallow-water?*

b) *Evaluate the scale of the problems in linking the satellite output with buoys through the use of shallow-water wave models. Do variations in wave height climate offshore measured by satellites provide a useful indication of variations in wave height at the coast?*

The SWAN and STORM shallow water wave models were used. The problems in linking the models with satellite data were significant and only overcome after careful analysis, individual to each coastal location. A generic solution for the inexpert user is therefore not available. A possible improved solution has been suggested which includes "nesting" the nearshore wave models inside a larger grid coastal model.

4.9.2.5 End-User Priorities

Consult with the Environment Agency to establish their areas of priority around Britain's coastline.

The Environment Agency have been closely involved in defining the requirements for JERICHO. Early in the project three coastal sites were identified, Holderness (East Coast - open simple straight profile coastline, gently shelving offshore bathymetry), Lyme Bay (south Coast, wide mouthed bay, deep water fairly close to shore), and St Gowan (south west Wales coast, many inlets in bay and complex bathymetry). These sites were selected because they were areas of interest to the EA, and also because they represented different coastline characteristics.

4.9.2.6 General

a) *Compile a report that describes the wave-measuring programmes presently underway in and around the UK coastline and their relevance to this study.*
b) *Define the techniques that will be used to marry the satellite record to the buoys and hence to the shallow-water models.*

These points are addressed in JERICHO technical reports or meeting minutes.

4.9.3 Implementation Phase

a) *Investigate how the satellite record may be combined with shallow-water wave models to extend the record in selected locations up to the coast. Buoy records to be used as an independent check.*
b) *Prepare a report containing maps of the likely trend in wave height around selected areas of the UK coastline together with an indication of a confidence index based on tests with models and comparisons with buoys.*
c) *If feasible within the constraints of Jericho, carry out a limited study of possible causes of the observed increase in the satellite record.*

Point a) has been addressed earlier. With respect to point b) and c), as discussed before, it was not considered helpful to consider wave climate variability in terms of trends. Hence statistical techniques for identifying modes of variability, and their correlation with large scale climate indices were adopted. This technique enabled the quantification of the link between winter wave heights at St Gowan and Lyme Bay with variations in the North Atlantic Oscillation.

4.9.4 Validation Phase

a) *At the selected sites examine the altimeter and buoy water wave height data and shallow water model wave height output for trends.*
b) *If the trends are similar, examine the effect they would have on the values presently accepted in the model of the Environment Agency.*
c) *If the trend in the satellite and buoy records do not appear to be related then a possible cause will be sought.*
d) *Ascertain if the upward trend evident in the offshore satellite record is reflected in the shallow coastal waters.*
e) *Produce for each site the best estimate at the shore-line of the 50-year return wave, together with the best estimate of the trend over the last 10 years.*

Again it was decided to carry out the study in terms of variability, rather than trends. In fact it was found that insufficient time series of continuous data were available for studies over periods of more than 5 years. This was partly because analysis of altimeter data was restricted the period when TOPEX data were available (October 1992 onwards), and partly because *in situ* data were rarely available over a longer time. No differences were found in variability measured by buoys or satellites, and the models demonstrated a reduced sensitivity at some onshore sites (in terms of the magnitude of severe events) to offshore changes in climate. Estimates of 10, 100 and 1000 year return significant wave heights were generated for each site. It was not found possible to generate reliable estimates of future (or past) values of these parameters

4.9.5 Problems and actions taken in mitigation.

The major problems encountered during JERICHO were, in order of significance:

a) No reliable future scenario model output to allow predictions of wave climate.
action- Adoption of 'worst case' example scenarios.

b) No teleconnections found for east coast wave climate.
action- No solution possible before end of JERICHO.

c) Coastal *in situ* data often unreliable or not continuous.
action- Use *in situ* data for short term validation of models or satellite data only. Use satellite data for longer time series.

d) Altimeter data not available at model boundaries
action- Extra analyses (using comparisons against *in situ* data) required to derive transformation rules.

e) High spatial variability around UK coasts means 2° x 2° grid for altimeter data too coarse.
action- Further data processing required to generate 1° x 2° gridded altimeter data set. Limits data to October 1992 onwards.

f) Problems with Halcrow extreme analysis.
action- "Censoring" technique applied by SOS.

g) No valid altimeter data close to model boundary at Carmarthen Bay.
action- UK Met Office buoy data used instead.

5. End User Assessment

5.1 Aims

The Environment Agency's strategic aims for JERICHO were:

- To gain access to the best wave climate information available to guide their long term strategy for coastal areas.
- To receive recommendations on how best to monitor wave climate at key sites in the future.

The EA was also looking for answers to specific questions:

- What are the major influences/drivers of the wave climate of the coasts of England and Wales?
- Can we monitor offshore wave height using satellites?

How close to the coast can they provide useful information?

- Can computer models accurately simulate the consequences on nearshore wave climate of changes in offshore wave climate?

Can the effect be modelled for different shore types?
Can the effect be translated to "risk"?

- Is there a potential problem in the coastal zone from a worsening wave climate?

Might predicted sea level rise cause an extra problem?

5.2 Results

In general the EA is pleased with the results of JERICHO, they believe that the project has been well managed and has addressed most of their key problems satisfactorily. In particular they are glad to see the development and application of a methodology (combining satellite data, in situ data and models) which can be applied in monitoring future wave climate, though they are under no illusions as to the complexity of the problem, and of the limitations of the models and the technology. Whilst again recognising the limitations of the available predictions of future climate, which show no basis for concern regarding any immediate prospects of a worsening wave climate, they also have some basis for strategic planning. The project has also usefully highlighted some of the key differences between the west and east coasts.

There have been some disappointments. The currently available climate forecasts have not been sufficiently reliable to allow the JERICHO team to generate more confident predictions of future wave climate - this follows from a basic inability, at the moment, for the climate models to accurately simulate the North Atlantic Oscillation. It is also apparent that the SWAN wave model is still essentially a research tool, requiring careful set-up and interpretation of results. Similarly the results of STORMS need careful analysis. This means that the wave models are not presently suitable for non-experts to run within the EA, and so further application may require commissioned work from an external agency Finally, whilst recognising the benefit that satellites have brought to the project, it is clear that coverage is still not adequate for full coastal coverage. Some coastlines are not sampled by satellites, and for those that are, it continues to take several years to build a satisfactory data set for analysis.

The answers to the key questions that the Environment Agency posed are understood to be:

What are the major influences/drivers of the wave climate of the coasts of England and Wales?

The NAO is the major influence on the climate of the west coast, and to a lesser extent the south coast. The NAO has increased steadily between the 1960's and 1990's. In the mid 1990's the NAO appeared to reach the peak of a long term cycle, and in the last few years has now entered a decreasing phase. However, to confirm this one need to look over the long term, and a further 5-10 years pressure data are required. Unfortunately, at present there are no reliable model representations of the NAO, and so even the most sophisticated coupled global circulation models are unable to help.

Can we monitor offshore wave height using satellites?
How close to the coast can they provide useful information?

Relatively easy to achieve offshore, but there are problems close to the coast, leading to an effective operational limit of 10 km.

Can computer models accurately simulate the consequences on nearshore wave climate of changes in offshore wave climate?
Can the effect be modelled for different shore types?

It is clear from JERICHO that there continues to be a problem with a shortage of reliable *in situ* data. Thus, in order to get information closer to the coast, wave models are necessary, but these in turn require at least some short term validation data from *in situ* measurements, which will allow proper set up of the models, dependant upon such factors as the nature of the shoreline and the nearshore bathymetry. Once "set up" the models can then be used to study long term climate based upon more than 10 years archived satellite data..

Can the effect be translated to "risk"?
Is there a potential problem in the coastal zone from a worsening wave climate?
Might predicted sea level rise cause an extra problem?

The west coast and east coasts present different situations. The west coast will be subjected to a general mean sea level rise in the range 20-80 cm by 2050. The additional effect of waves is uncertain, but if the apparent downturn in the NAO is confirmed, a long term lessening of winter wave heights may be expected.

The East coast will also experience a rise in mean sea level (20-80 cm), but changes in storminess in the North Atlantic will not directly effect this coast.

The changes in sea level do not have a significant affect on the nearshore wave height, but will of course add cumulatively to water levels during storms.

5.3 Plans for exploitation and dissemination of JERICHO results.

The shorter briefing notes that are planned will be distributed around the local offices with responsibility for coastal defences and coastal planning.

The full report with its briefing notes will be circulated to:

- Dr Jan Pentreath, Director of Environmental Strategy and Chief Scientist
- Dr Geoff Mance, Director of Water Management
- Bryan Utteridge, Head of flood Defence
- All regional and area flood defence managers

It will also be presented to the Environment Agency's Section 105 project Group, and the secretary of the Coastal Chairman's group for circulation to the Coast Defence Forum Groups. The Environment Agency are also considering running a workshop at the national data centre in Bath.

Whilst there are no immediate plans for continued large scale co-operation, future EA implementation of JERICHO methodologies would most likely consist of targeted studies for specific at risk locations. EA also maintain a high resolution up to date bathymetry data base, future studies could make use of this.

6. Benefits to Industrial Partners

6.1 Halcrow Maritime

Halcrow Maritime have found that the Jericho project is very useful to coastal engineers in that it is a first step towards using satellite data to design coastal structures. The conventional method of obtaining wave information is either collecting measured wave data or purchasing model data from Met Office. The availability of satellite wave data will provide more choices for the engineers in term of reducing data costs. At some places both the Met Office data and measured wave data are not available. For these critical positions satellite data will play an important role. However, we have noticed that the satellite data are much sparser than Met Office data for a given time period. We hope that in future the coverage of satellite information can be improved to match Met Office data. Another necessary improvement to the satellite data is the provision of wave directions, important for coastal management and port design. In the Jericho project wind directions have been used to replace wave directions. This is a reasonable method. However, swell wave directions cannot be included.

As an end user we have found that it is not difficult to use satellite data for Halcrow's STORM model. This is an advantage of using satellite data because we do not have to change Halcrow's model system. Using satellite data is very similar to using other wave data. We expect other engineering firms will also be happy to use satellite data provided an improvement can be achieved as regard to data density and wave direction. Whilst the quality of satellite data is now well established, the key question determining future acceptance for applications is whether the satellite data can be made available at a competitive price, with a sampling density comparable to gridded model hindcast output.

Dealing with satellite data is a new direction for our engineering firm. From the JERICHO project we have learned a lot from our partners in data processing and extreme value analysis. We have also learned from comparisons against the SWAN model. We feel that the management of the JERICHO project has been excellent. We expect further collaboration with other JERICHO team members whenever our services are required. We are also very interested in participating in other LINK programmes.

6.2 Satellite Observing Systems

This report has focused on the problems of using satellite altimeters to measure winds and waves in coastal waters, and noted that - unlike buoy and other in situ instruments - altimeters provide more reliable estimates of wave climate in the open ocean. Because of this, much of SOS's efforts have historically concentrated on the open ocean; but many more organisations and people are concerned with the near-shore than with the open ocean. JERICHO has given SOS the opportunity to study in some detail the problems of using altimeter data in coastal waters, to see how these data can be employed together with conventional measurements and models to obtain a better knowledge of the wave climate there, and to consider how future altimeters might be adapted to provide more useful data.

SOS has been made aware of the need to consider modifications to its technique for estimating extreme wave heights when using data from coastal waters or from the STORM model: waves from different directions are likely to be from different probability distributions, model data can have a specified minimum wave height, requiring the fitting of a censored distribution.

In tackling these problems, SOS has benefited from interactions with the scientific expertise within NERC and the commercial experience of Halcrow Maritime

This study has illustrated considerable problems in estimating wave climate near and at the coast, and consequently the rather poor knowledge of the present climate at many locations - and a complete lack of knowledge of possible changes in future decades. But it has shown that satellite data can help both for studying specific locations and investigating more widespread climate change. It is hoped that SOS will obtain further work, building on JERICHO, to extend the application of altimeter data to improve knowledge of wave climate in coastal waters.

7. Exploitation

7.1 Benefits already experienced as a consequence of JERICHO

JERICHO partners have already experienced benefits as a consequence of their participation. These fall under two categories, developments in scientific understanding and new enquiries regarding applications or possible collaborations.

7.1.1 Scientific and Technical Advances

Key advances are listed below:

Improved understanding of the processes involved in shallow water wave transformation, including the critical effect of water depth in less than 10m.

Improved understanding of the SWAN model, its limitations and capabilities and needs for further development in the areas of wave-current coupled bottom friction, determination of bottom roughness, depth-limited breaking.

New applications of SWAN and STORM models to Holderness, Lyme Bay and Carmarthen Bay.

Comparison of SWAN and STORM models

Derivation of the connection between the UK west coast wave climate to the North Atlantic Oscillation.

First detailed assessment and application of altimeter wave period measurement.

Identification of significant underestimation of altimeter measured wind speeds under certain circumstances.

In addition Halcrow have gained useful experience within the JERICHO project, and see it as a potentially valuable approach to coastal problems.

7.1.2 Applications/Collaborations

Due to acquisition of expertise in using SWAN and further insight into nearshore wave processes POL have found further opportunities for work in shallow water wave modelling which is particularly relevant to the new CCMS programme FORCE (FORecasting Coastal Evolution). Further, the Environment Agency have consulted POL about a planned project using SWAN in a National Tidal Flood Forecasting Action Plan.

MAFF (Coastal Group) have also expressed an interest in the JERICHO project, and it is intended that results will be exchanged and compared with MAFF's own studies. SOS have also held preliminary discussions with members of the "EUROWAVES" consortium (from Norway, Greece and Italy), the co-ordinator of the MAST III "ESPED" programme and with the University College of Cork about possible follow on projects. JERICHO results have also been requested by the UK Climate Impact Programme.

7.2 Media

Following press releases issued by SOS and SOC, members of the team have on a number of occasions participated in radio and TV broadcasts featuring JERICHO:

Winter 1998 (David Cotton and Peter Challenor - BBC TV and radio national and local news items).

July 1999 (Peter Challenor and Judith Wolf, BBC TV morning news and radio 4 "Today" Programme).

7.3 Papers and Conferences

To date the list of papers and presentations is limited as it was first necessary for scientific work to be completed:

6th WISE (Waves In Shallow Environments) conference, 22-25 March 1999, Annapolis USA, J. Wolf, "Modelling using SWAN at Holderness".

Article on JERICHO in CCMS Newsletter 'Triton', December 1998.

2 papers at British Group of Altimeter Specialists (BGAS) meeting (UK Met. Office College, Reading, June 1999)

34 JERICHO technical reports (see reference list).

Papers in preparation

Shallow water modelling for the JERICHO project: J. Wolf, J. C. Hargreaves & R.A. Flather, CCMS-POL Report no. 57.

Specification of the cross-shore boundary condition for coastal wave models, J. Wolf

The effect of changing storm characteristics on 3 coastal environments. J. C. Hargreaves, J. Wolf & D. J. T. Carter.

Assimilation of boundary conditions into the SWAN model. J. C. Hargreaves

Conference presentations:

'The JERICHO Project', the JERICHO team - abstract to be submitted to MAFF conference on

WISE 2000 - J. Hargreaves

EGS 2000 Presentation on climate change effects

7.4 Distribution of JERICHO results

JERICHO dissemination will involve distribution of the full report to agencies with a high level of relevant expertise and of a set of A4 JERICHO summary technical sheets to other potentially interested parties.

The intended plans for dissemination of JERICHO results are:

- Distribution of full report to JERICHO partners; MAFF Coastal Group, JERICHO data suppliers (Fugro Geos, Southampton; UK Met. Office, Rijkwaterstaat, The Netherlands, Loginfo, Norway), UK Climate Impact Programme Office, EUROWAVES consortium
- Distribution of summary sheets to: Environment Agency (see Section 5 above), Hydraulics Research, Wallingford, Shell, BP, Chevron, Wimpey, CEPAS, Scottish and Irish Coastal agencies, UK Health and

Safety Executive, European Environment Agency (Denmark), Sheffield Centre for Earth Observation, ABP, ESPED consortium.

- SOS will establish and maintain a web site with downloadable main and technical reports. They will also (with SOC) generate a CD containing these documents.
- Press release to New Scientist, Science editors of Guardian, Independent, BBC

The five JERICHO Technical Sheets are entitled:

1. The JERICHO EO LINK Project - An overview

2. JERICHO - Coastal Applications of Satellite Altimeter Data.

3. JERICHO - The UK Offshore Wave Climate.

4. JERICHO - Characteristics of Coastal Wave Climate at Holderness, Lyme Bay and Carmarthen Bay.

5. JERICHO - Recommendations for Monitoring Coastal Wave Climate.

8. Future Plans

Plans for follow-on work to JERICHO fall into three categories: follow on proposals, further scientific research, and model developments

8.1 Follow-on proposals

- MAXWAVE proposal to EU FP5, extreme wave prediction, understanding, extreme wave processes, hindcasting.
- CCMS FORCE programme, southern North Sea modelling.
- Collaboration with EUROWAVES, ESPED consortiums regarding possible Framework V proposals.
- Collaboration with University College Cork Regarding possible Framework V bid.

8.2 Further Scientific research

A number of important scientific issues have been addressed within JERICHO, raising some interesting problems particularly worthy of further research. The most significant of these are:

- FORCE programme - POL will investigate decadal changes in wave climate due to changes in bathymetry and hence its feedback on sediment transport and implications for coastal evolution.
- In the long term, it is desirable to analyse in more detail the relationship of wave climate to atmospheric pressure fields, and also to compare contemporary wave data that supplement the altimeter data. (e.g. are variations in offshore wave climate largely the result of variations in swell or locally-generated wind waves?). First though, we suggest further investigation and exploitation of the simple linear model. e.g.

Does the simple linear model describe earlier winter wave climate data?

Are long term trends in winter wave climate solely explained by the NAO?

Is the correlation of wave climate to the NAO index limited to DJFM?

Are there long term trends in wave climate in April-November?

Can a different pattern of forcing explain variation in other seasons?

Is the dependence of wave climate on the NAO index linear?

If the linear dependence on NAO index is removed from the wave climate, are there any coherent patterns in the residual?

- The analyses of altimeter wind speed measurements near the coast should be included in the development of an improved wind speed algorithm.
- The altimeter wave period algorithm should be further tested against a wider range of *in situ* data.

8.3 Model developments

Further work will include developments of the SWAN and PRO-WAM models from shelf-scale (grid size 10 km) down to nearshore 10-100m). Also it is intended to develop further techniques to allow coupling between tide-surge and wave models. The implications for 3D turbulence models will be studied.

8.4 Technical Applications

Possible technical applications of the JERICHO studies include:

- The generation of "Risk Maps" for the UK coastline.
- Input the output of shallow water wave models into models of erosion and sediment transport.
- Local implementations of the JERICHO methodology.
- Use of the JERICHO studies to help define the optimal orbital configuration for the GANDER multi satellite altimeter mission.

9. Conclusions

JERICHO has tackled a difficult and complex problem, but has met in major part the aims set at the beginning of the programme. In addition they have prepared the ground for possible more detailed localised studies.

The project's main aim was to provide the EA with "improved information on coastal wave conditions and inter-annual trends essential to the planning of Britain's coastal defences and to make progress towards developing a predictive capability."

JERICHO has generated information about wave climate conditions (including seasonal and inter-annual variability) at all points around the UK coasts, on a 1° x

2° grid, and has created data sets (and explained the techniques) which will allow selected statistical parameters to be derived. At three locations shallow water wave models have transformed wave conditions from the model boundaries to nearshore locations. Analysis of these results showed how different factors affect the transformation of offshore waves, and provided an indication of which sites may be more vulnerable to increase in offshore wave climate.

The JERICHO team has also made good progress in developing a technique which may, in future, allow projections of future climate based on the output of large scale climate models such as those being run by the UK Met Office's Hadley Centre.

Further key achievements include the application of altimeter wave data to within 10 km of the coast. In fact we have demonstrated that the altimeter can measure variability close to the coast (10-50 km offshore) that could not be measured by other techniques. We have demonstrated that the altimeter can provide a useful measure of wave period, and have applied it in our studies. By running STORM and SWAN models together we have been able to identify the merits of each models and to define the best applications for these two types of model.

Through JERICHO, the LINK programme has bought together a team of experts with complementary expertise in the fields of shallow water modelling, wave statistics, the application and analysis of satellite data, and the analysis of climate data. Together, this team has made significant advances in the joint application of satellite data and shallow water wave models. They have generated results, and defined methodologies, which will provide the Environment Agency with authoritative guidance as it develops a strategy for coastal defences around the English and Welsh coasts.

Acknowledgements

Thanks to Marek Stawarz of GKSS, Hamburg, for providing wave model data from the "WASA" project (EU ENV4-CT97-0498)

Thanks also to Rijkwaterstaat (The Netherlands), and the British Oceanographic Data Centre (Bidston) for free provision of buoy and platform wind and wave data; to BP Exploration (Sunbury on Thames), Shell Exploration and Production (Aberdeen), Philips and Loginfo AS (Norway) for allowing the JERICHO programme to use their wave data; and to the UK Meteorological Office for providing buoy and light vessel data at extraction cost only.

The Holderness wave data were collected for the Ministry of Agriculture, Fisheries and Food under its Flood Protection Commission.

Data from Helwick were supplied by Bill Cooper, Associated British Ports.

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JTR-3 JERICHO Project Report - POL Sept. 1998, J. Wolf, Sep-98

JTR-4 St Gowan Wave Data D. Carter , Oct-98

JTR-5 Lyme Bay Data , D. Carter, Nov-98

JTR-6 Analysis of NE Atlantic Climate Variability, D. Cotton , Dec-98

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JTR-8 JERICHO Progress Report CCMS POL Nov 1998, J Wolf, Nov-98

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JTR-18 Analysis of wave height climate variability from 1° x 2° monthly means , D. Cotton, Jun-99

JTR-19 Analysis of altimeter wave period estimates in the North Sea, D. Cotton, Jun-99

JTR-20 Wind directions at Leman and wave directions at buoy N3, D. Carter, Aug-99

JTR-21 Application of STORMS in the Holderness region, Li Bin, Sep-99

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JTR-24 Application of SWAN in the Holderness Region, No. 3, J. Hargreaves, Sep-99

JTR-25 Waves and Winds in Lyme Bay, D. Carter, Sep-99

JTR-26 Estimating statistical extremes and exceedance probabilities from 1° x 2° monthly data set D. Cotton, Oct-99

JTR-27 Extreme wave heights off Holderness, D. Carter, Oct-99

JTR-28 Estimating waves in Lyme Bay for the STORM model, D. Carter, Oct-99

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JTR-30 Wave Climate at St. Gowan for JERICHO, D. Carter, Oct-99

JTR-31 Report on CCA of NAO and Wave Climate, D. Woolf, Nov-99

JTR-32 Factors effecting UK Coastal Wave Climate Change , D. Cotton, Nov-99

JTR-33 Helwick Wave Data, J. Wolf, Nov-99

JTR-34 Comparison of SWAN and STORM, J. Hargreaves and R. A. Flather, Dec-99

APPENDICES
(Available separately on request)

APPENDIX A. ***In situ*** **data**

APPENDIX B. **Satellite Altimeter Data**

APPENDIX C. **SWAN model**

APPENDIX D. **STORM model**

APPENDIX E. **Maps of Gridded Wave Climate (Monthly, Seasonal, Annual means)**

APPENDIX F. **Maps of Offshore Wave Extremes**